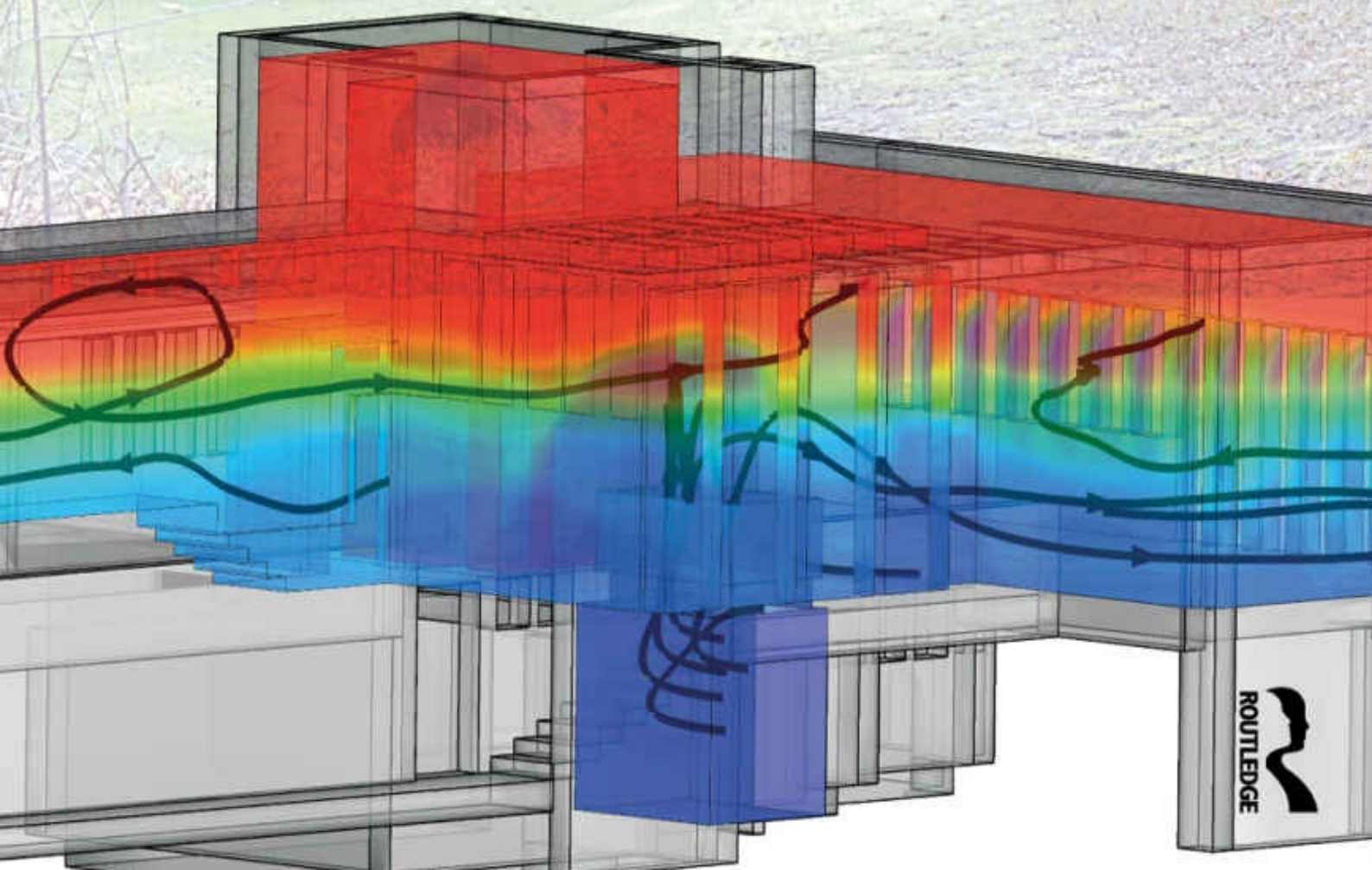


Ulrike Passe and Francine Battaglia

DESIGNING SPACES FOR NATURAL VENTILATION

AN ARCHITECT'S GUIDE



Designing Spaces for Natural Ventilation

Buildings can breathe naturally, without the use of mechanical systems, if you design the spaces properly. This accessible and thorough guide shows you how, in more than 260 color diagrams and photographs illustrating case studies and CFD simulations. You can achieve truly natural ventilation by considering the building's structure, envelope, energy use, and form, as well as giving the occupants thermal comfort and healthy indoor air.

By using scientific and architectural visualization tools included here, you can develop ventilation strategies without an engineering background. Handy sections that summarize the science, explain rules of thumb, and detail the latest research in thermal and fluid dynamics will keep your designs sustainable, energy efficient, and up to date.

Ulrike Passe is an Associate Professor of Architecture and the Director of the Center for Building Energy Research (CBER) at Iowa State University, USA.

Francine Battaglia is a Professor of Mechanical Engineering and the Director of the Computational Research for Energy Systems and Transport (CREST) Laboratory at Virginia Polytechnic Institute and State University, USA.

‘A virtual handbook of theories, principles, and concepts, *Designing Spaces for Natural Ventilation* is an essential resource for designers, researchers, and students. The authors present both historical and modern examples of successfully naturally ventilated spaces and offer discussions of recent research that challenge the perceptions of “coolth” and thermal comfort provided by air conditioning.’ – *Alison G. Kwok, Department of Architecture, University of Oregon, USA*

‘Through a comprehensive combination of traditional and contemporary case studies, clearly expressed basic concepts, and the strategies to implement them, this book provides a very useful guide to designing low energy, low carbon buildings using natural ventilation. A recommended reference book for both students and architects.’ – *Pablo La Roche, Professor of Architecture, Cal Poly Pomona University, Sustainable Design Leader, RTKL Associates, USA*

‘For far too long the design of natural ventilation systems has relied upon the architect’s magic arrow sketches or the engineer’s finite difference computations. Confusion regarding what a natural ventilation system can rationally accomplish has abounded. With the publication of *Designing Spaces for Natural Ventilation* building designers will find a valuable guide to this low-energy approach to space cooling and air quality. The journey to net-zero energy and carbon mitigation demands such a resource.’ – *Walter Grondzik, PE, Professor, Department of Architecture, Ball State University, USA*

Designing Spaces for Natural Ventilation

An Architect's Guide

Ulrike Passe and Francine Battaglia

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Notes

- 1 Lewis W. Leeds, *Lectures on Ventilation: Being a Course Delivered in the Franklin Institute of Philadelphia* (New York: Wiley & Sons, 1868).
- 2 See <http://koeppen-geiger.vu-wien.ac.at/usa.htm>.
- 3 Vincenzo Scamozzi, *L'idea Della Architettura Universale*, 2 Vols (Ridgewood, NJ: Gregg Press, 1964).
- 4 Ronald G. Knapp, *Chinese Houses: The Architectural Heritage of a Nation* (Singapore: Tuttle, 2005).
- 5 K. J. Lomas, "Architectural Design of an Advanced Naturally Ventilated Building Form," *Energy and Buildings*, 39(2), 2007, pp. 166–181.
- 6 C. S. B. Grimmond and T. R. Oke, "Aerodynamic Properties of Urban Areas Derived from Analysis of Surface Form," *Journal of Applied Meteorology*, 38(9), 1999.
- 7 Andres Giedion, *Die Architektur Der Davoser Alpthütten: Ernst Ludwig Kirchners "Alte Sennhütte" Und Ihr Vorbild* (Zürich: Scheidegger & Spiess, 2003).

Foreword

In our rapidly changing building markets, now is a great time for some architects to take stock of what products they offer their clients, work out how they can add value to their design repertoire, and broaden their skills base to reflect their chosen direction of travel. Near the top of many 'must have' lists will increasingly be the ability to design successful, naturally ventilated buildings. I say some architects because from where I am standing the profession appears to be broadening out into being many sub-professions. Some architects are destined to spend their lives as CAD operatives in large practices, a chosen few will find work as graphic artists giving form to the grand designs of ambitious architects and developers, many will flow out into jobs other than architecture, while the rest may be lucky enough to design, or refurbish, actual buildings. If you are one of the latter and keen to keep up with market trends, probably working in a very small to medium sized practice, then this book is essential reading for you because the buildings of the future will increasingly, for at least part of the year, be naturally ventilated.

The reasons for this inevitable growth of natural ventilation are many and clearly manifesting themselves globally as energy prices soar, power outages proliferate and more extreme weather events often render twentieth-century comfort solutions inadequate. People may think they want to be living or working in highly insulated, air-tight, lightweight buildings with unopenable windows over a long hot summer with full air-conditioning systems belting out comfort, but many are thinking again for two main reasons: cost and energy insecurity. For instance, those living in Adelaide, Australia, in January 2014 will have thought again, after the heat wave summer of 2013/2104 when against a background of months of rising temperatures, a record was set with five consecutive days of 42 °C and above with nighttime temperatures falling only to 31 °C. Our twentieth-century response would be 'turn on the air-conditioning', but many could not afford its high cost in their homes, particularly at peak tariffs at the hottest times of day, and others who could afford it could not enjoy it because of the rolling power outages that were experienced across the city. The association of power failures with extreme weather events is now a fact of life in the twenty-first century, a situation that will only get considerably worse with the rising temperatures forecast for the future in the Fifth Assessment Report on climate change published by the IPCC in April 2014.¹ So in many parts of the world including the USA the name of the game is increasingly to be able to design climate-resilient buildings that keep their occupants safe even when the power does fail.²

The optimal cooling solution during many seasons and at many temperatures, in many cities and buildings around the world, is to open the window and let the local breezes do the work. It is also the cheapest one. This is particularly the case in housing, where energy costs can be a critical issue, with more people falling into fuel poverty annually and with greater economic consequences as people have to make their own choice of whether to pay to cool or heat the house in extreme weather or pay for the mortgage.³ In 'developed' nations a clear relationship is emerging between the cost of energy, GDP (gross domestic

product, or the wealth of a country), and the quality of life of citizens, with talk growing around the world of the disappearing middle classes.⁴ The speed of the polarization of incomes and wealth globally over the last decade has amazed many pundits, and its implications are far-reaching; even for the comfortably off professional classes such as myself, the tendency to cut corners on comfort to lower heating bills seems stronger to me, year on year. For businesses, the idea that energy is a low priority for boardroom deliberations is fast disappearing, as the costs for energy begin, for some, to approach the costs of employing staff. On top of that, the drive to reduce carbon emissions from buildings is putting energy issues and costs way up on the management agenda, even for the global corporates for whom corporate social responsibility issues are increasingly associated with ‘brand’ value, in a fickle marketplace increasingly steered by the environment concerns of a social-media-literate generation. All these drivers to increase the use of natural ventilation may come as a real shock to a system where architects and engineers are no longer taught how to naturally ventilate buildings, and in cultures where whole generations of building occupants are addicted to, and adapted to, the artificial indoor climates that air-conditioning produces.

However, the architectural challenge is not only to achieve affordable, comfortable buildings, but to design better buildings using natural ventilation, to provide ‘delight,’ as the authors explain in [Chapter 6](#). The sensually exquisite feeling of a soft breeze cooling the skin in summer, the heady feeling of opening a window and inhaling the fresh cold air of spring or autumn, or the welcome warmth being pumped into a home from a sunlight conservatory on a winter’s day is hard to beat. The greatest of the traditional and modern buildings that are run for as much of the year as possible on free delightful energy are in essence themselves great natural ventilation machines that are powered by heat (temperature differences) and pressure (wind directions and speeds). At times of the day or year and in places where the ambient, outdoor air is healthy to breath, well-designed, naturally ventilated buildings generally provide infinitely superior climate experiences to those produced in mechanically conditioned buildings. They also provide that highly desired link between the building occupants and *nature*, beyond the walls and windows they are enclosed in. But to design a good naturally ventilated building takes real skill, and that is why, if you want to keep up with twenty-first-century building market demands, you should read and absorb the contents of this book.

Passe and Battaglia have set out systematically to provide a comprehensive introduction to the history, theory, and application of natural ventilation principles and practices in building design. They use language that architects are familiar with, and mathematical and computing tools that they can assimilate and apply, and provide clear directions on how to integrate the chosen air-flow and thermal storage systems into local climate contexts, ensuring that particular buildings in particular climates will be successful. It helps that Ulrike Passe is an award-winning architect and teacher who benefitted from an architectural education in Berlin, Germany, where most buildings are still naturally ventilated, before moving on to be an educator in the USA in 2006, taking on board the architectural ethos embodied in American building practices. Her co-author is Francine Battaglia, a mechanical engineer specializing in air and fluid flows, who in her current

role as Director of the Computational Research for Energy Systems and Transport (CREST) Laboratory specializes in using computational fluid dynamics and models to explore issues related to the thermal sciences, including the natural ventilation of buildings and the fire and combustion effects within them. The combination of these two skillsets produces a book that is architect facing, and yet rigorous in its engineering approach.

The book covers all the bases a practicing architect needs to know about when designing a successful naturally ventilated building, from the basic principles of how people adapt themselves, their ventilation systems and their buildings to achieve thermal comfort in different climates, to the three-dimensional design of rooms and buildings with their internal air pathways, to their envelope and window design, the mechanics of air movement and control and the thermodynamics of heat and coolth management and storage within buildings. The theory is illustrated and clarified with a rich array of case study buildings that will enable architects to envisage and extend their own palette of natural ventilation applications, opportunities, and approaches. The advice proffered on the correct modelling of ventilation is vital for a generation of computer-literate designers who need only the steps to follow to successfully capture the performance of buildings that are naturally ventilated, and the extensive images throughout the book are not only educational but also often inspiring.

It is inevitable that buildings will increasingly be run on natural ‘ambient’ energy for as long as possible, using appropriate combinations of diurnal or seasonal energy storage, and an expanded range of human behaviors to adapt to changing climates and rising energy costs. This book provides a thorough architectural foundation from which to create the conditions necessary to design successful naturally ventilated buildings that function well in practice. If, as a student or practicing architect yourself, you want to design low-energy, low-carbon, and truly sustainable buildings, and you don’t know how to achieve this already, please put ‘learn how to design for natural ventilation’ at the top of your ‘add value – to do’ list and buy, read, and apply the vital lessons contained in this book. In doing so, then enjoy – because you will, at heart, be learning how to design better buildings, and that in itself lends delight to the whole process.

Susan Roaf
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Notes

- ¹ See T. F. Stocker *et al.* (eds), *Climate Change 2013: The Physical Science Basis*. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Cambridge: Cambridge University Press, 2014).
- ² The Resilient Design Institute (www.resilientdesign.org) is a New York-based group working to promote ‘Passive Survival’ developments.
- ³ S. Roaf, “Transitioning to Eco-Cities: Reducing Carbon Emissions while Improving Urban Welfare,” in: Young-Doo Wang and John Byrne (eds), *Secure & Green Energy Economies* (Washington: Transaction Publishers, 2014).
- ⁴ B. Plumer, “Here’s Where Middle-Class Jobs Are Vanishing the Fastest,” *Washington Post*, 8/27/2013, <http://www.washingtonpost.com/blogs/wonkblog/wp/2013/08/27/heres-where-middle-class-jobs-are-vanishing-the-fastest/>.

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Illustrations

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Introduction

Why Do We Talk about Natural Ventilation Now?

Why We Need Natural Ventilation

Air is one of the four major classical elements and vital to human life. Ventilating an interior space is essential, yet most people know very little about the reasons we need constant air exchanges in buildings. It is not the oxygen we need – air contains plenty of oxygen, and only in very tightly sealed spaces would we run out of oxygen eventually. Very rarely do spaces still contain sources of toxic carbon monoxide, although this was a major concern when engineered ventilation launched as a field of research in the second half of the nineteenth century. Today, indoor air quality, thermal comfort, and energy are more important issues in occupied spaces. Ventilation is essential to remove odor particles and volatile organic compounds (VOCs) as well as humidity (90 percent of human exhalation is humidity), which are the most annoying indoor air quality disturbances to occupants.¹ It is also necessary to dilute CO₂, which can make occupants drowsy. Foremost, we ventilate to remove excess heat that accumulates inside buildings.

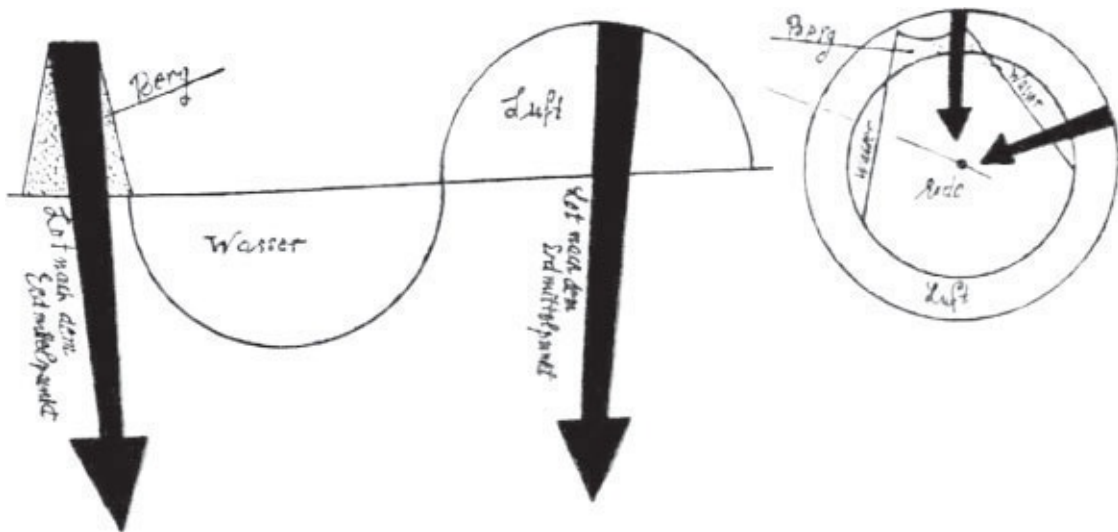


Figure 0.1

Erde, Wasser, Luft (Earth, Water, Air), drawing by Paul Klee for the *Pedagogical Sketchbook (Pädagogisches Skizzenbuch)*, originally 1925, Bauhaus Bücher, p. 37.

The amount of air needed to transport heat is much larger than the amount needed for all of the above stated reasons. In our contemporary mechanized world, most of this heat is removed using forced air cooled by refrigeration technology that relies on compression refrigeration machinery consuming large amounts of electrical energy. In fact, delivering plentiful fresh air into a space with as little energy as possible is a complex endeavor and can be tricky. But natural ventilation is truly underrepresented and could pick up much more of the load than in current practices. The reason this has not yet happened has to do both with the way buildings are designed and engineered and with the lack of acceptance of dynamic conditions. Control strategies are becoming more complex in hybrid situations, where natural ventilation and mechanical air conditioned cooling alternate.

Building occupants now commonly expect homogeneous and constant interior thermal conditions. The availability of fairly cheap comfort through air-conditioning makes occupants forget that there are times during the day or year when opening a window would provide similar comfortable conditions. On the other hand, the engineering request to control thermal comfort led to many office buildings being designed and constructed without operable windows.

Slowly, thorough research finds its way into standards, and the creation of an “adaptive thermal comfort model”² enables a better understanding of thermal comfort under dynamic weather conditions and a closer relationship between exterior conditions and interior comfort acceptance.

Benefits of Natural Ventilation

The direct benefits of natural ventilation are manifold. Ventilation itself is essential to human health, comfort, and well-being. Natural ventilation, if done right, can achieve all the above with much less energy than mechanical ventilation systems. Natural ventilation removes heat through temperature- or wind-driven pressure differences (or a combination of both), while providing fresh air (good indoor air quality) by removing or diluting particle load, odors, humidity, and Volatile Organic Compound (VOC) concentrations. Utilizing natural forces, air can remove heat that has built up or was emitted by occupants. Natural ventilation as a substitute for mechanical systems helps reduce cost for equipment, for ductwork, and for the space to house both. Natural ventilation can also cool down the building fabric over night by removing heat from thermal mass and providing additional energy storage capacity for the daytime. The air velocity can also cool a human body by evaporation, directly affecting human thermal comfort perception and increasing tolerance for slightly higher air temperatures with slightly higher air velocity.

Natural Ventilation and Design

When used properly, natural ventilation can provide a large amount of the required energy for free, without harm to climate and atmosphere. Naturally ventilated buildings need to be designed, operated, and controlled differently than mechanically ventilated buildings. Scheduling and control can become a major concern, when operational changes need to occur at inconvenient times for occupants. Nighttime ventilation, for example, may only be feasible from 2.00 a.m. until 8.30 a.m. when the air outside has finally cooled down enough to allow a breeze through the building, but occupants are either away from their workspace or asleep. Very few energy-saving advocates are actually so committed to actively and manually activate this change. Therefore, complex control strategies are needed. Control strategies are directly related to human behavior and are probably best executed by smart control systems that still need to give occupants individual influence as well, because current research shows that occupants are far more tolerant to thermal conditions in naturally ventilated spaces and in spaces over which they have individual control.² The perception of human comfort changes with higher air velocity provided by carefully designed natural ventilation.

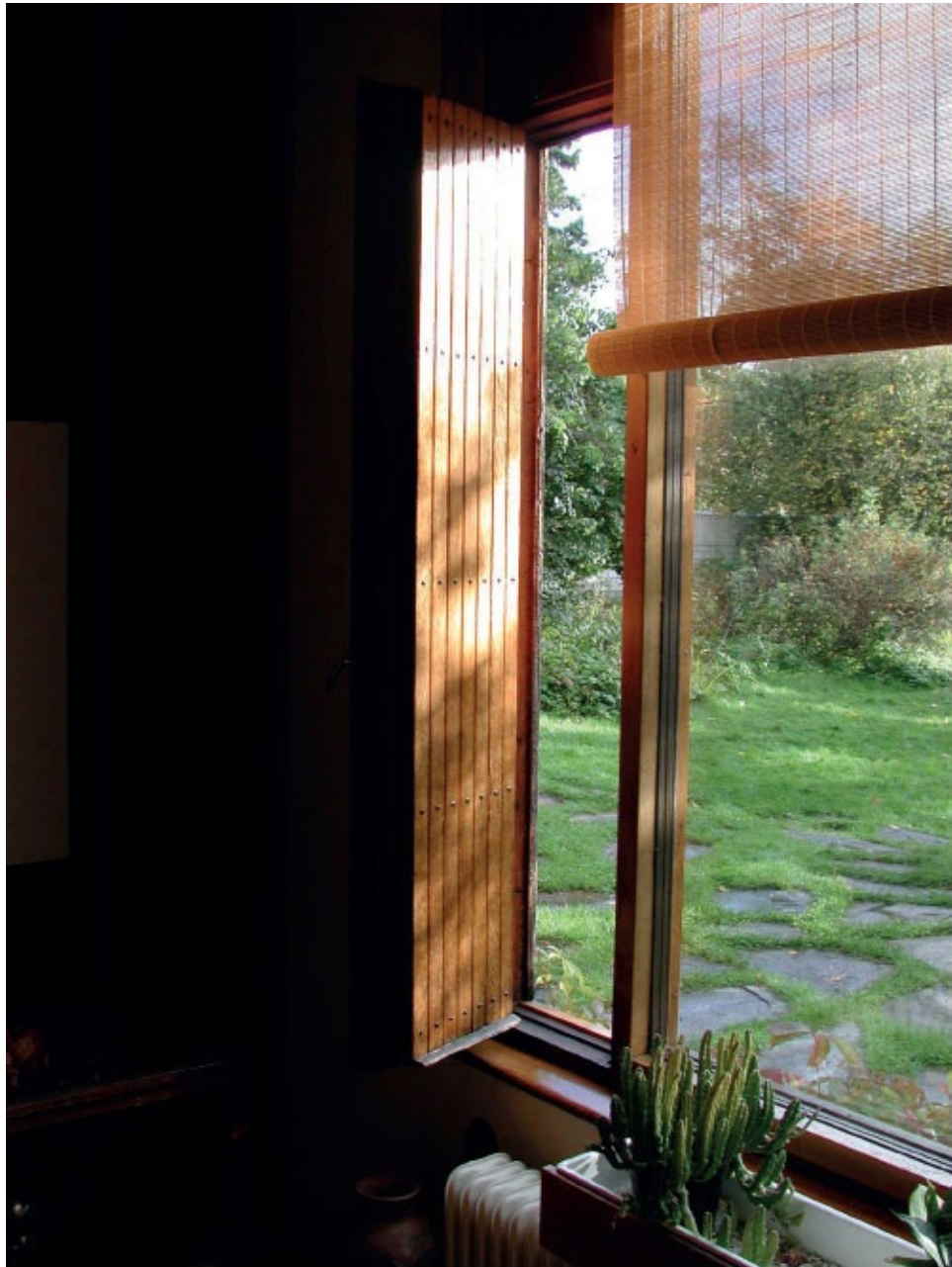


Figure 0.2

The operable window is the classic means for natural ventilation, as can be seen here in Alvar Aalto's own house at Riihitie in Munkkiniemi, Helsinki.



Figure 0.3

The three-dimensionality of space connecting spaces vertically and horizontally is essential for natural ventilation. This drawing conceptualizes the continuing surface of such a space for Haus Marxen in Germany by Passe Kaelber Architects, Berlin, 2001.

Building design strategies often do not yet integrate dynamic performance expectations, because appropriate design tools are still in development. How can designers ensure that window openings are optimized for all possible wind directions? If performance is considered at all, usually only intuition and experience drive performance prediction during the design process. Natural ventilation and daylight are complex, uncertain, and dynamic phenomena, design experience takes time to accumulate, and mechanization is often chosen because of the lack of basic design experience and guidelines. In order to provide sufficient air exchange rates that comply with minimum performance requirements for user comfort, most spaces are mechanically cooled, artificially lit, or lit poorly with natural light. With the goal to achieve high-performance, net zero energy buildings, architects need to be better equipped during the early design phases with both knowledge and design tools to predict dynamic performances of light and air movement.

Natural Ventilation and Energy

The architecture and engineering community is well aware of the fact that a large portion of building energy consumption is used to condition the indoor environment of buildings (by heating or cooling outdoor air to provide thermal comfort and improved indoor air quality). Much of this wasteful consumption could be avoided by changing the way buildings are designed. The numbers have not changed much in recent years: in 2009, US residential buildings consumed 39 percent of primary energy to condition the indoor environment.³ Since 1949, energy consumption in the United States has risen from 32×10^{15} (quadrillion) BTU to 102×10^{15} (quadrillion) BTU in 2007⁴ and is not predicted to decline any time soon. The combination of increased energy cost and energy usage has caused energy spending in the USA to increase from \$83 billion to \$1 trillion between 1970 and 2005.⁵ After adjusting for inflation, this is still an increase of 250 percent. It is urgent for both the economy and the community to conserve energy and reduce CO₂ emissions in order to mitigate the impacts of global climate change.

The best way to reduce energy consumption is to design for human comfort by exploiting natural forces around the building site.

Avoiding or reducing heat gains and losses while still maximizing quality daylight is the first step. New reports on good daylighting techniques and tools have recently emerged.⁶ Utilizing natural forces on site through an integrated design process is the second step to reducing energy consumption by natural ventilation and spatial strategies. Finally, these strategies should also lead to more refined architecture.

With the development of mechanical air-conditioning, building typology and the devices for heating and cooling have been separated in the design process.⁷ Modern technology seemed to make every form possible. This development is currently being questioned and tools are needed to allow and verify more sensible design strategies.

Interestingly, mechanical ventilation does not fully satisfy building occupants. They often feel that the environment is too hot or too cold, too draughty or too stuffy, and not always healthy.⁸ Complete user satisfaction is hard to achieve and is rarely found in post-occupancy evaluations. Ventilating buildings with natural driving forces is more complex than it seems. Ever since green design strategies aimed at saving energy and fossil fuel, there is a certain urgency to re-establish natural ventilation flows in architectural design, and the evaluation of natural air movement becomes more and more relevant.

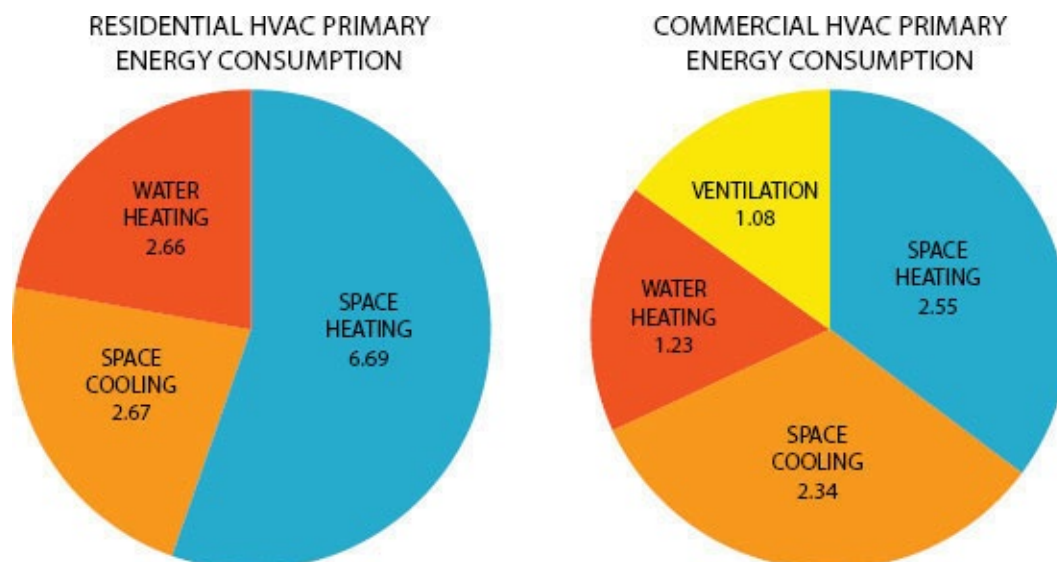


Figure 0.4

HVAC energy consumption by building end use in 2005 in quads (10 to the power of 15 BTUs or approx. 25 million tons of oil) (U.S. Department of Energy).

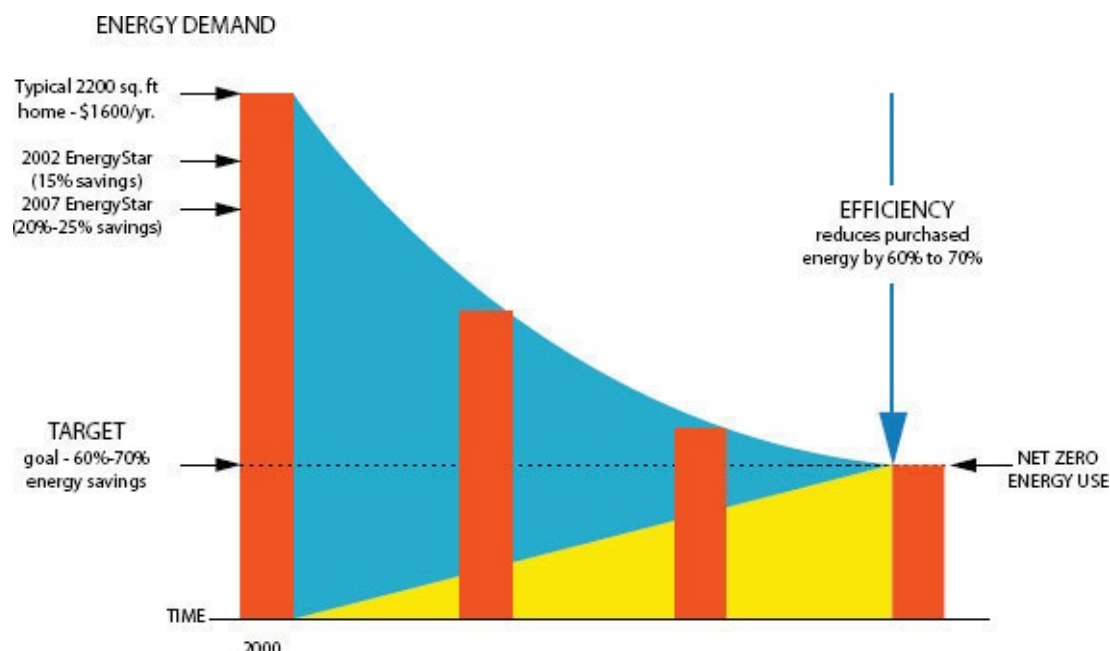


Figure 0.5

Approach for achieving netzero energy buildings: only with reduced demand will it be possible to cover energy demand with renewable resources.

The Literature Gap

While a growing number of contemporary architects desire the integration of natural

ventilation flow into architectural design concepts, the evaluation of natural air movement and related energy performance is still difficult because of the complexity of the underlying physics. There is an apparent gap between engineering knowledge of natural ventilation and its implementation into spatial design strategies by architects. Thus, two major issues based on our current research and teaching background and experience led to this book.

For one, although there are a variety of books on mechanical and natural ventilation available for engineers, providing current engineering research, no in-depth guidelines actually exist for designing architects. Existing literature communicates in a very technical manner and contains mathematical formulae many architects are ill equipped to incorporate for lack of knowledge, patience, or time. Although integrative design is on the rise, the first sketch, which sites the building in the landscape, almost always determines the success of the design for natural ventilation.

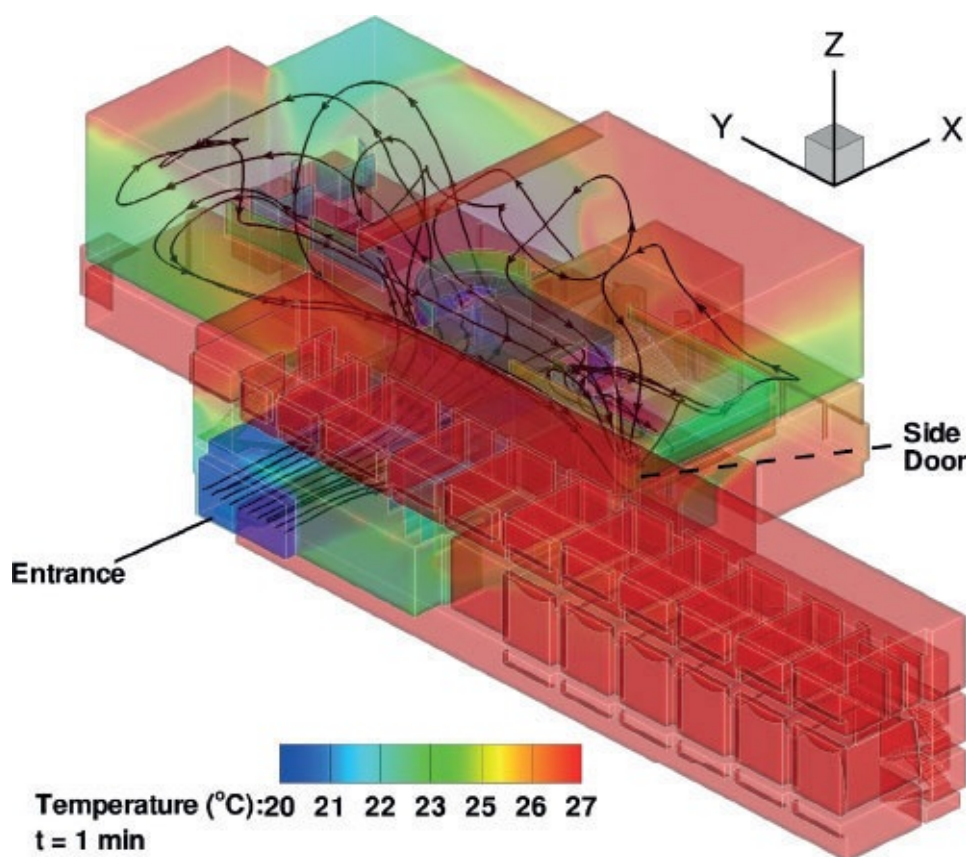


Figure 0.6

Air flow and turbulence model of the Viipuri library by Alvar Aalto, designed during the late 1920s and early 1930s based on a 1927 competition entry and completed in 1935.

The second issue is related to the complexity of thermodynamics. The interaction of natural ventilation flow with thermal heat transfer properties in solid materials is computationally very intensive and thus not well integrated into engineering and design prediction tools yet. Air velocity and thermal capacity of materials are difficult to simulate in one equation system, and turbulences in larger spaces cannot be predicted with certainty. For example, current energy evaluation tools such as Energy Plus do not model thermal stratification of air temperature. Therefore, further research into architectural design and fluid dynamics is needed. It is very complex in computational fluid dynamics

(CFD) to model flows between solid materials and air currents.⁹

What is Ventilation, and What is Natural Ventilation?

Ventilation describes the means to introduce fresh quality air into a space and extract exhaust, stale, polluted, or odorous air out of the space. Fresh air replenishes oxygen, although not to the degree generally believed. Unless occupying a submarine for multiple days, people will not run out of oxygen. Diluting CO₂ is a different matter, and increased CO₂ levels can make occupants feel drowsy. Without proper ventilation we will not suffocate, but air will start to feel hot and smelly. The use of natural driving forces is an underutilized design strategy to control the indoor environment. It is dynamic, always changing, but not always reliable. Air is also a means to transport thermal energy either for heating or for cooling to moderate thermal comfort.



Figure 0.7

Traditional wind catchers in the city of Yazd in Iran.

Air movement is caused by pressure differences, either in the form of wind on an atmospheric scale or in the form of stack effects created by temperature differences. The different effects are basically a matter of scale and build up around the building or within an opening, a room, or a shaft. Natural convection is caused by thermal gradients within the building or between the building and the atmosphere. Natural driving forces are thus intrinsically spatial.

In buildings designed to exploit natural ventilation, air must be able to flow freely through the building. Spatial layout, the idea of how different areas of a building connect, is very important when considering flow through a building. Thus, natural ventilation needs to be designed at the confluence of structure, building envelope properties, energy use, and form as well as occupational patterns, human comfort, and health (good indoor air quality). Most importantly, natural ventilation needs to be designed; it cannot be added

later.

What's in the Book?

This book is meant to serve as a handbook for architects to design spaces that can be naturally ventilated as long as outside conditions allow. It will show how to enhance architectural performance with the use of novel computational fluid dynamics (CFD) simulation tools. It is currently not possible for each and every architect to individually conduct CFD evaluations for each project. Therefore, the book sets out to bridge the gap between the science of fluid dynamics and architectural design by means of scientific and architectural visualization tools. Ventilation is not only the main means to introduce fresh quality air into spaces and extract stale and polluted air out of the space, but also a major means to transport energy within a building.

The reason why natural ventilation has been so difficult to evaluate is its complex, dynamic, three-dimensional nature. Temperature and air velocity distributions within a building are especially dynamic when natural convection is combined with external factors such as changing wind patterns, which directly influence the flow patterns within a building. In buildings designed to exploit natural ventilation, air must be able to flow freely through the building and opening sizes should be adjustable.

Ventilation is usually designed to provide minimum air exchange rate standards. Rates are considered more a quantitative than a qualitative issue, and therefore more an engineering concern than a concern for design. Natural ventilation needs to become a design discipline again, like daylighting, and be taught in design studios and not just in the technology classes as an add-on. The question is: How to achieve a certain healthy ventilation rate with natural means and how to achieve healthy air exchange rates with minimum energy consumption? Designing a building with natural ventilation requires knowledge of prevailing wind directions and weather data, as well as solar orientation and radiation intensity. However, constant good performance cannot always be guaranteed because of the unpredictable nature of wind.

Turbulence resulting from wind interacting with obstacles, such as buildings, is one of the last unsolved problems of classic physics. Depending on friction and velocity, they often occur inside and around buildings and in ductwork, and result in pressure losses.¹⁰ Turbulence can enhance or block natural flows.

Movement of sound, heat, energy, and fresh air within or through a space needs the potential for expansion. Air is constantly in motion, even if we only perceive the motion beyond a certain threshold.¹¹ Thus air exchange rates for comfort, energy, and indoor air quality purposes are a function of geometry, scale, and size of apertures. Smaller openings increase the air velocity; large openings slow air down. The basic assumptions are based on the law of conservation of mass: What enters on one side has to leave at the other side. But what goes on between the inlet and the outlet is important to know. Air flow investigations need to consider how exactly the shapes of interlocking volumetric connections affect the flow of air in three dimensions. The complexity of choices can be enormous. How to design for all eventualities? Which strategy for the combination of

openings is best?

Each space and site is different, and predictions of the interrelationship of the components of air flow patterns, for example the Venturi effect, buoyancy, stack effect, and cross-ventilation are intuitively integrated into the design proposal based on rules of thumb,¹² but are so far difficult to quantify with commercially available design tools that could easily be integrated into the design process.¹³ While the scales for solar radiation and light are not affected by size, wind and air velocity have scales for which data gathered from scaled models has to be reevaluated for situations at full scale. Within this book, the reader will find an overview of design strategies and advice regarding how to approach an iterative process of eventualities.

The Audience of this Book

The Indian architect Charles Correa points out that in the twentieth century,

architects have depended more and more on the mechanical engineer to provide light and air within the building. But in India, we cannot afford to squander resources in this manner – which is of course actually an advantage, for it means that the building itself must, through its very form, create the ‘controls’ which the user needs. Such a response necessitates much more than just sun angles and louvers; it must involve the section, the plan, the shape, in short, the very heart of the building.¹⁴

In this approach architecture truly serves as a passive-energy device, and its integration into a specific culture becomes vitally understood.

Mechanical ventilation on the other hand works against these natural flows by trying to mix hot and cold air by force, while the air is attempting to separate and stratify by nature. A homogenous interior climate as imagined by Buckminster Fuller or Yves Klein in the 1960s¹⁵ is an illusion and does not comply with the physics of fluid flow and motion. Le Corbusier also embraced mechanical systems and promoted ‘exact air’ in Ville Radieuse (Radiant City)¹⁶ as a means to provide healthy indoor air quality. The opposite has happened: indoor air quality has become a major problem leading to the sick building syndrome or other building-related illnesses.¹⁷

Thus, the content of this book was developed with the designer, student, or professional architect in mind. Of course it should also be able to speak to the engineer, and provide an overview for the educated and interested amateur. The book is an attempt to translate engineering knowledge into architectural drawings and case studies. Natural ventilation is a key factor in green, energy-efficient, climate-responsive design both in the developed and especially in the developing world. It should be read globally and applies to many climate regions. It should work well as a support for the intersection of technology teaching and the design studio because it touches on both sides of the architecture spectrum. The book will make fairly complex knowledge accessible to students and practicing readers, and function as an educational and teaching tool.

The Origin of this Book

Haus Marxen¹⁸ was built in 2000/2001 by Passe. Kaelber Architects in Germany with spatially interconnected volumes to support the air flow to such a degree that the temperature was kept within an acceptable range. In this approach, architecture serves as a passive-energy device. Underlying Haus Marxen is a clear spatial structure, which is based on a three-dimensional geometric grid of $3 \times 3 \times 3$ timber frame bays. This structure is overlaid by a spatial composition using volumetric proportions of the Fibonacci sequence, which connects rhythms and sequences of space on three different levels, opening up spatial connections for vision and movement as intuitively predicted by the architect and experienced by the user during the occupancy over the last ten years. Anecdotal information shows that natural ventilation flows in this house support the cooling and heating of the building. Yet, at the time of design and construction, there were no easily accessible design tools to quantify the spatial effect on this flow. This sparked the decision to embark on a ten-year journey to reveal the hidden physics of natural ventilation to the designing architect.



Figure 0.8

Haus Marxen by Passe Kaelber Architects, Berlin (2001): externally a compact tilted cube clad in timber panels.

What to Expect from the Book

The study of currently available engineering and scientific literature led to the approach to convey this knowledge through case studies and diagrams. Advocating the design of pleasurable spatial atmospheres and experiences, the chapters were developed with the following thoughts in mind.

Part 1: Theory and scientific background. This will narrate and highlight key background parameters, starting with the importance of space. Ventilation strategies start

with the flow path, issues of health, vernacular and historic precedents, climate, and thermal comfort. This sets the stage for further investigations of the different elements of the flow path.

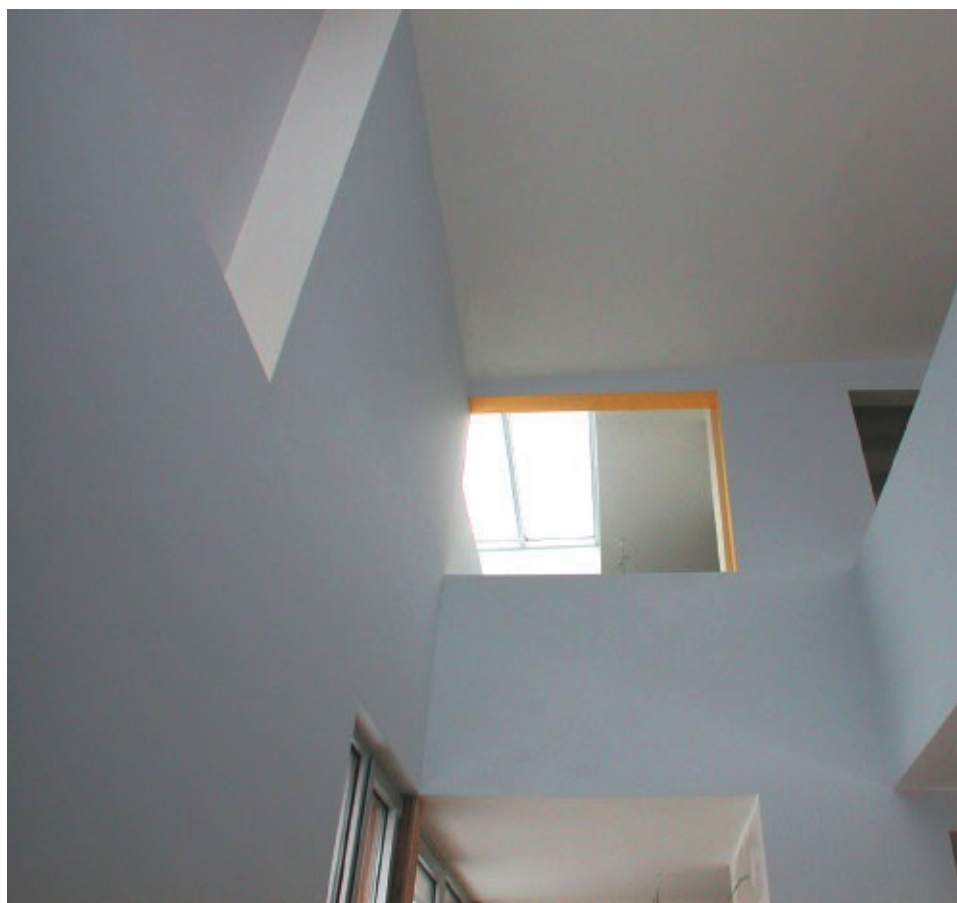


Figure 0.9

Haus Marxen by Passe Kaelber Architects, Berlin (2001): internally an open composition of vertical and horizontally connected spaces.

[Part 2](#) highlights the important parameters, starting with the driving forces behind natural ventilation: “pressure as indicator” wind and temperature differences, which form the basis to understand the flow rate. [Chapters 7](#) and [8](#) then discuss the proportion of the flow path and issues of spatial resistance. They highlight the strategies in a series of case study projects. Spatial strategies determine the main design parameters to develop a continuous ventilation path, and the resistance and the flow can be investigated together. [Chapter 9](#) focuses on the “façade as filter.” The façade openings are one crucial parameter to determine the flow rate and are therefore highlighted in the concept. [Chapter 10](#) follows up with control strategies.

The first chapters of the book use what is explained in [Part 3](#) in more detail: the tools to understand and visualize air – “making air visible.” As this is a textbook or guide, readers who are just interested in the simulation, rules, guidelines, and so on can always refer to [Part 3](#). It can be handled as an insert or parallel to the first chapters, which have a narrative. For every problem related to fluid motion by pressure (wind-induced) or temperature difference (convection) it is important to define the boundary conditions of the ventilation system to be studied. Therefore, the analysis of case study projects and the development of three-dimensional diagrams as communication tools were chosen.

For some readers, these final chapters might actually be the most interesting. When Haus Marxen was designed, the architects could only dream of the simulation tools now becoming available to the designing community at fairly little cost. Since the mid-2000s, computational time, which was previously the major limitation, has become more readily available and thus led to the accessibility of these new design tools for a broader audience. However, only few tools are in use to evaluate design beyond its visual impact and energy performance. The reader will find a list of commonly used tools at the end of the book, but as the field is rapidly changing, the list will never be complete.

Architectural space, which shapes air to enhance comfort, has had little place in the critical discourse about air and about architecture, and how it shapes air is only marginally taught in schools of architecture. Thus, in an ideal sense, this is a book between science and visualization and a book about space and air.

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Chapter 1

The Importance of Space for Natural Ventilation

Environmental forces create shapes and forms as demonstrated by the forces exerted by wind and water that formed the Grand Canyon in Arizona over a long period of time. While objects created to move through air are designed to lower resistance against air, buildings designed for natural ventilation need to build up resistance in order to facilitate the flow.

Shapes and forms can thus be created to enhance and support the effects of natural forces. Knowledge that the flow of water follows the rules of gravity unless under pressure led to the design of roofs that guide rainwater downwards. However, air can move in all directions depending on spatial pressure differences.

Only with the advent of mechanical fan-powered cooling were engineers able to create internal climate conditions without using the forces of wind and buoyancy. Forces of flow are evident in many engineered forms and systems such as the Hoover Dam.

Although air flow exerts less impacting forces, the forces of natural ventilation have played an integral part in the formation of architectural typology, visible in many architectural structures in various climate regions. In the hot-humid climate of Southern India, interior ceilings in Goa¹ are ornamented to form a broken grid, allowing warm air to rise into the height of the roof space, while windows and porches are constructed as breathable surfaces for cross-ventilation.



Figure 1.1

Grand Canyon, Arizona, USA, a natural landscape formed by the fluid dynamics of water and wind.

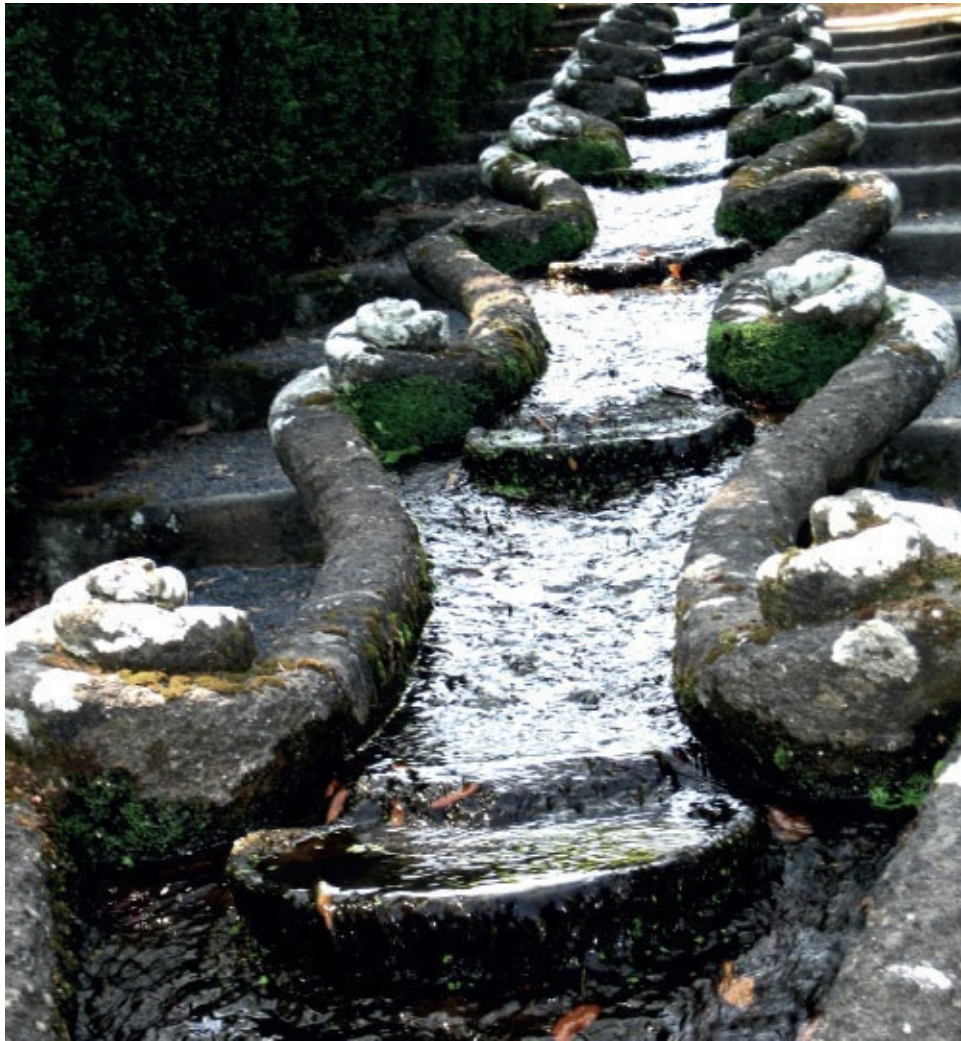


Figure 1.2

Fountain at Villa Lante at Bagnaia, Italy, attributed to Jacopo Barozzi da Vignola (sixteenth and seventeenth century) – specifically shaped to form turbulences in the flow of water and with that shape the sounds in the garden.



Figure 1.3

The forces of flow are reflected in the construction of the Hoover Dam (constructed between 1931 and 1936).

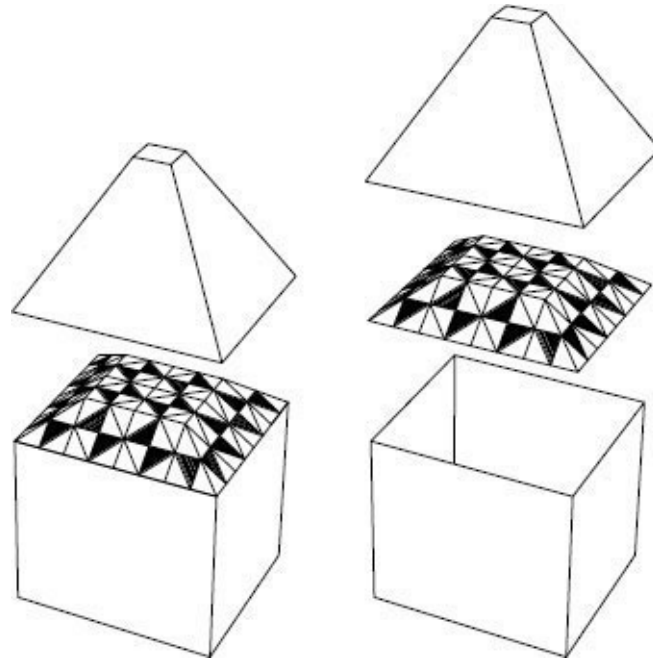


Figure 1.4

Steep roofs in hot and humid climates support stack ventilation as in this palace in Goa, India.

The desire to enhance natural ventilation also shaped multiple buildings in the era of the Modern Movement, and analysis of these spatial concepts will introduce the full spectrum of possible approaches to enhance natural ventilation in buildings today.

1.1 Connected and Detached Spaces

Cooling strategies based on natural ventilation are intrinsically spatial. Air passes from space to space through connecting apertures. The overall air exchange rate is only as large as the smallest passage allows. Air flow thus does not work well with singular, enclosed cell spaces, but needs interconnectivity. Depending on the design strategy, a corridor can have a connecting or a disconnecting function. It can connect separate spaces with an air stack or it can separate the wind from the leeward side, blocking air movement. Vents need to allow air to pass through doors or walls. Air is not pushed through a space, but pulled out of the space by a negative pressure difference.

Privacy as known in the contemporary Western world is an invention of modernity. The corridor is the main architectural feature that guarantees privacy by separating functions and spaces for individuals. In interconnected spatial situations, two issues can get in the way of privacy: sound and vision. Full acoustic and visual privacy is in direct contradiction to the development of a complete flow path through a building. Where air flows, vision is possible and sound can penetrate. Thus air-conditioning supported the separation of individual spaces in buildings, a development Robin Evans describes in detail in *Figures, Doors and Passageways*.² Lisa Heschong takes on the same observation of social separation through spatial means in *Thermal Delight in Architecture*.³ Evans traces the development of residential floor layouts to social patterns, beginning with Villa

Madama in Rome with its sequences of all interconnected rooms to functional rooms separated by corridors as spaces without quality of inhabitation in nineteenth-century mansions, while Heschong analyzes the relationship of thermal convenience and spatial composition.

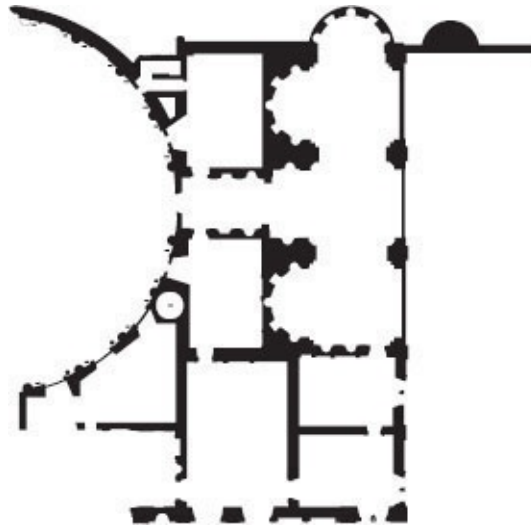


Figure 1.5

Villa Madama in Rome, Italy, design after Raffaello, started in 1518: each space develops its own geometry and the spaces are placed in connected sequence.

According to Evans, the corridor was originally inserted into the English country home to separate domestic servants from their employers and consequentially led to the notion of privacy of modern life. In most contemporary buildings, the corridor separates individual, personalized comfort zones.

1.2 The Driving Forces of Natural Ventilation Are Spatial

Natural ventilation needs natural forces to drive air movement and a three-dimensional flow path that leads fresh air into and stale air out of the building. Designing this flow path is a matter of space connectivity dominated by either vertical connection or horizontal connection, or a combination of both. The path should connect the areas within the building that promise the creation of the largest possible pressure gradient. Therefore, designing for natural ventilation starts with site planning and the investigation of external forces. The intensity of those forces is distinctly different in urban and rural context conditions.

Natural ventilation is driven by two major external forces based on pressure differences: wind (hydrostatic pressure differences) and the stack effect (density pressure differences). Inner city wind patterns and temperatures require very different approaches other than open sites. Macro- and micro climates also need to be considered. The overall results are determined by the interaction between these forces and resistances and obstacles within the flow path, which are determined by the building and its openings, as well as the relationship of the building and its context. The condition in an urban context, its roughness or smoothness, will instantly relate to the velocity and direction and seasonal or even daily patterns of wind. Natural ventilation cannot be added later as an add-on technology, but can only be implemented during the architectural design process. Natural

ventilation is directly related to the spatial composition of the flow path and the direction and intensity of the driving forces.

The resistance to flow in the path is determined by the building's shape, form, height, orientation, and internal spatial composition and the pressure building up against these obstacles. Ventilation through the building is determined by these variables and the obstruction to air flow they create. The ventilation rate is determined by the pressure difference acting across a ventilation path and the resistance of that path.⁴

Air is 'lighter' and less dense when temperatures increase, and rising hot air may lead to temperature stratification. Taking these physical properties into consideration, it is obvious that spatial composition plays a crucial role in enabling the movement of air. The spatial analyses of volumetric compositions of selected buildings identify the types of overlapping free-flow open spaces that constitute the main flow potentials. Flow paths are truly three-dimensional in all directions of space.

Free-flow open space, as distinguished from free-plan architecture,⁵ is defined as spatial composition that addresses flow and continuity along all three axes of space. Wall apertures, open passageways, niches, stairways, split level, interior windows, galleries or double height spaces connect such spaces. Enabling interlocking connections in plan and section, free-flow open space blurs the boundaries between individual rooms and between inside and outside surrounding space. Using the concept of partial enclosure, intermediate spaces are created that belong to more than one system of spatial relations and offer multiple possible movement patterns for air, light, people, and vision. Architects of the Modern Movement, such as Le Corbusier, often achieved the simultaneity of inside and outside through a solely visual connection. This apparent visual *flow* is achieved by sealing the interior of the glass box from its exterior climate. The "human subject has been displaced," as Beatrix Columina has aptly pointed out: displaced from nature and its environmental forces with positive (comfort) as well as negative (energy use) impact. She cites Le Corbusier "A window is to give light, not to ventilate! To ventilate we use machines; it is mechanics, it is physics."⁶

1.3 Houses with Impact on the Geometries of Flow

A ventilation path is spatial, because wind and buoyancy mostly act in combination. As a result, air can move up, air can move down, air can move across, and air can pivot, depending on the intensity of the driving forces and combinations of other influences only partially driven by gravity. In fact, air is constantly in motion, even if we cannot actually perceive this motion at velocities below two meters per second (395 feet per minute). This physical property of air was already known to early researchers such as Max von Pettenkofer, whose lectures on air⁷ were initiated by a public outreach request for public health education and are still valid information. The same can be said about Lewis Leeds' *Lectures on Ventilation*;⁸ these lectures were also the result of health concerns caused by bad air quality inside public buildings like schools and hospitals.

Space has to be composed to develop a pressure difference between two sides of the

building. It is necessary to provide a connection between the two sides to allow the right amount of flow. Ideally the amount of flow can be altered by changing the size and/or direction of openings. The height of the space thus matters. Space itself is important, but how do the shapes of these interlocking volumetric connections affect the flow of air in three dimensions when the air inside is constantly in flux? In order to take advantage of the physical properties of air – mass, pressure, temperature, and thus flow – interior space must take more than one climatic/seasonal condition into consideration. All contributing factors need to be considered in the design process. A designer needs to develop an iterative parameter matrix and apply the basic principles of the relationship between air flow and geometric proportion. Elements should be determined by volumetric proportions, not by planar composition and numbers alone. Natural ventilation has to be designed with dynamic variations in mind.

There are three major spatial principles that enhance natural ventilation; they are represented in three iconic buildings of the Modern Movement: the wind catcher, the stack effect, and cross-ventilation as represented by the Affleck House by Frank Lloyd Wright (1940) (an example of a Usonian House), also represented by the How House by Rudolph M. Schindler (1925) and the Esherick House by Louis Kahn (1961).

These three breathing houses utilize all basic spatial themes: the stack chimney, the wind catcher, and cross-connections, as well as a combination of all three. Depending on the outside conditions, the chimney and wind catcher can reverse within the same space, if designers are not careful or act without proper guidance. Whether a tall space acts as a wind catcher or a stack chimney depends on multiple factors: wind catchers always have to be directed towards the windward side and stack exhausts to the leeward side, where low pressure zones can pull the hot air out of the stack space. But wind direction can frequently change and so inlet and outlet might also change and reverse the flow path. Second, it is important to understand the density difference (temperature difference). The hotter the air will be at the upper end of the space, the more it is likely to act as a chimney, not a wind catcher.

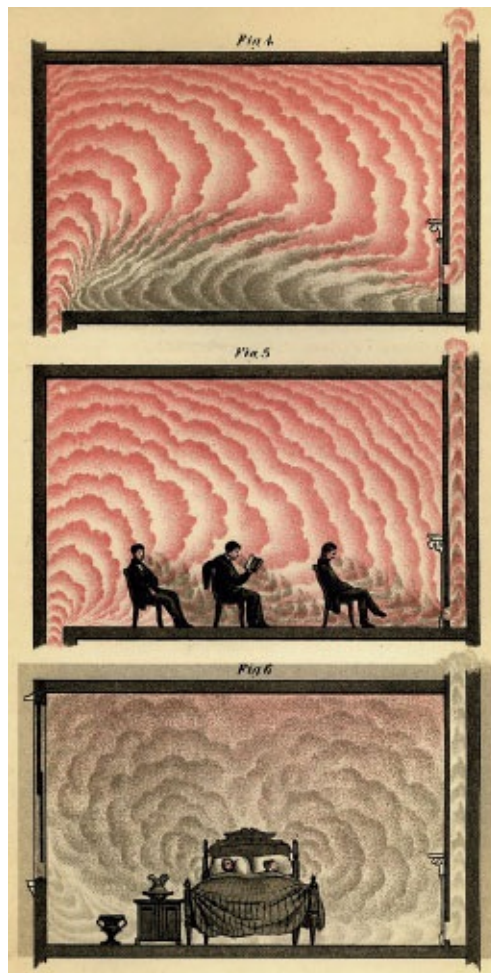


Figure 1.6

Historic visualization of air movement and energy distribution by Lewis Leeds.

1.3.1 Sliding Space: The Affleck House

Frank Lloyd Wright (1867–1959) established an architectural concept for the Midwest climate initially with his prairie houses in the early teens of the twentieth century and later in the 1940s with the Usonian Houses. The Affleck House was built in 1940 in Bloomfield Hills, a suburb of Detroit, Michigan. F. L. Wright developed the concept for the house following a call for proposals from *Life Magazine* for a ‘Dream House.’ He named his idea Usonian House, which turned into a prototype for low-cost suburban houses. The idea of the Usonian House is intrinsically related to the history of US American suburbanization and the dream of making low-cost single-family houses accessible for everybody. These houses represent the start of Wright’s second major career from the late 1930s onward.



Figure 1.7

Gregor S. and Elizabeth B. Affleck House by Frank Lloyd Wright, constructed in 1940: exterior view of the slope behind the house leading to the lower open porch.

The main features of the house are a modular approach to the construction, visible material patterns, and the development of a spatial kit of parts. Rosenbaum⁹ notes that “another contribution to the feeling of spaciousness is the visible two-by-four module, a grid that is etched into the concrete floor and the fiberboard ceiling ... this grid also complements the horizontal transom window, the board and batten wall units.” Another important characteristic was intended by “the indoor-outdoor qualities which ... glorified nature.”¹⁰ This relationship is not only visual, but experiential owing to multiple operable windows and a vertical shaft.

Two horizontally layered cubic volumes are placed at right angles as if sliding past each other. These two perpendicular spaces of different height are joined by a volume of double height that opens up at the intersection to the landscape below and allows air to be cooled over a stream of water below and be pulled up into the space, where the two sliding volumes meet.

Wind-driven air flow over a building induces positive (inward-acting) pressure on windward surfaces and negative (outward-acting) pressure on leeward surfaces; thus the building creates a pressure difference across the section that drives cross-ventilation. The wind velocity increases with the height of the building. Air enters the building on one side, sweeps the indoor space and leaves the building on the other side.¹¹



Figure 1.8

Gregor S. and Elizabeth B. Affleck House by Frank Lloyd Wright, constructed in 1940: the exterior porch space below the house with the basin below and the ventilation opening into the main living space above.



Figure 1.9

Gregor S. and Elizabeth B. Affleck House by Frank Lloyd Wright, constructed in 1940: operable floor to ceiling

window at the corner of the main living space.

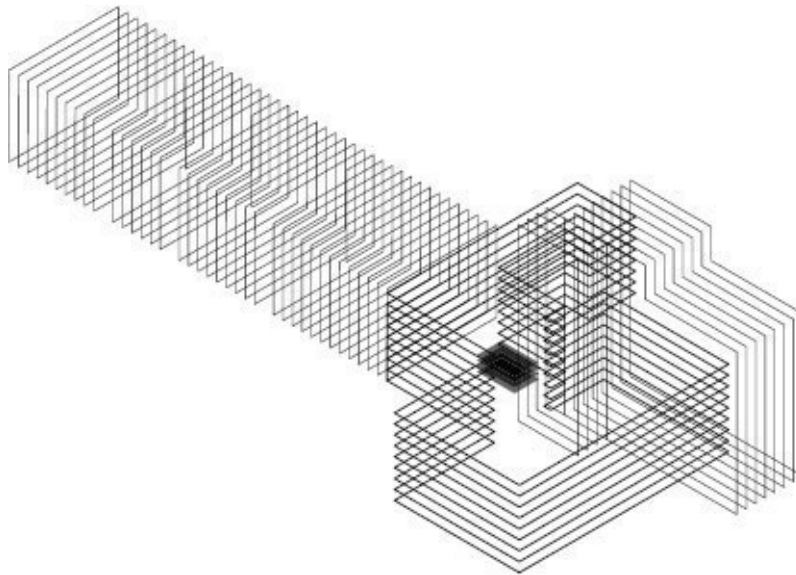


Figure 1.10

Diagram of main air flow path in the Affleck House.

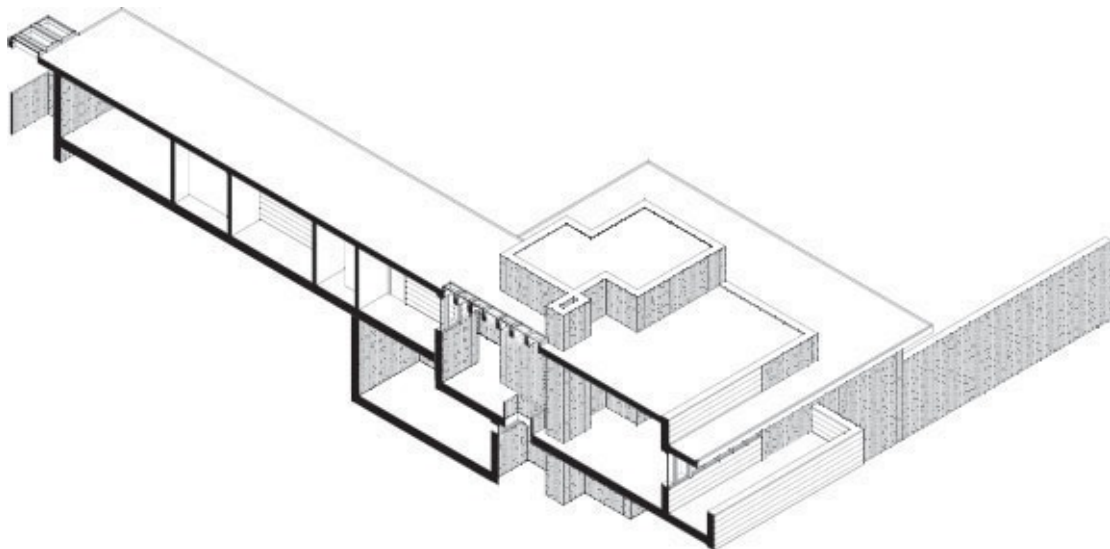


Figure 1.11

Diagram of spatial composition in the Affleck House.

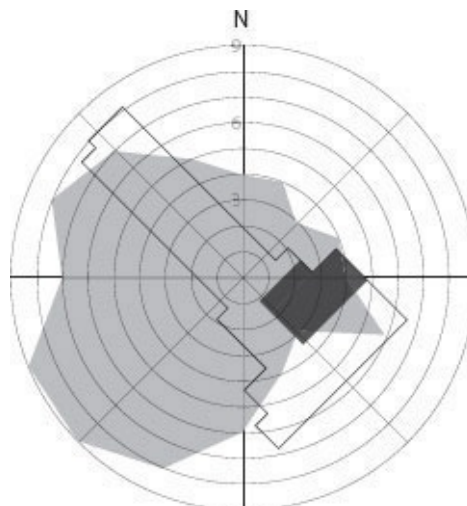


Figure 1.12

Wind rose (in m/s) for the location of the Affleck House.



Figure 1.13

The secret of the Affleck House lies in the horizontal window between the lower air porch and the main living space, which allows for an updraft air movement.

1.3.2 Bolted Space: The How House

Rudolph M. Schindler (1887–1953), who came to the USA from Vienna in 1914, designed the How House in Los Angeles, California, in 1925 for Dr. James Eads How. Schindler based the volumetric structure of the building on a sequence of strategic decisions, which were strongly related to the Californian climate, which he described as “paradise on earth.”¹² The How House is one of Schindler’s most spatially complex buildings, and in its design he elaborated on the ‘Raumplan’ concept, a ‘volume plan’¹³ first introduced by the Viennese architect Adolf Loos (1870–1933) as a spatial composition strategy. The ‘Raumplan’ in the How House is composed as a spatial flow of cubic volumes of various heights and scale aligned on a diagonal axis in space. At the central junction, a vertical shaft or well is bolted through all other main volumes, opening the house to the elements, thus enhancing natural ventilation on this mountainous site. This is a unique feature in modern architectural compositions, applicable only in the mild Californian climate, which has little precipitation. The main ventilation space is open to the venting air movement without barriers created by glass or other architectural materials. The diagonal space

actually catches the main wind directions perpendicular to the slope without building up resistance to the flow of air along the flow path, allowing constant air movement at low velocity.



Figure 1.14

James Eads How House by Rudolph M. Schindler in Los Angeles, CA, constructed in 1925: view of the house on the top of the hill.

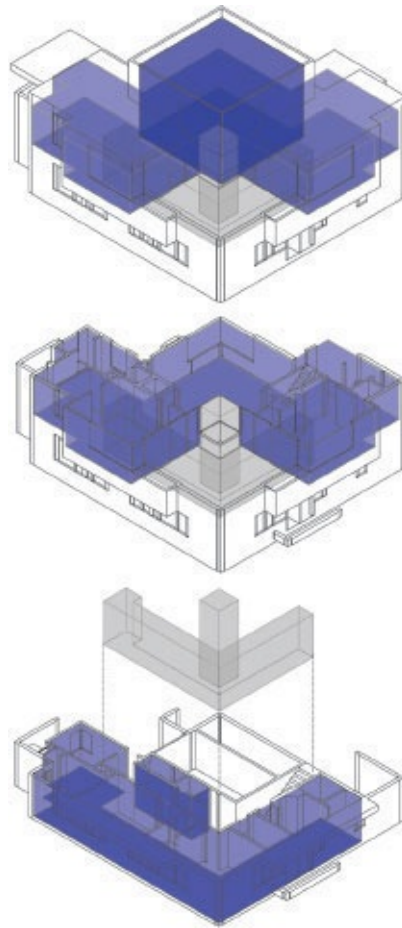


Figure 1.15

Diagram of main air flow path in the How House.

Schindler was aware of the potential of buildings to shape the flow of air as he strongly considered the relationship of air flow and space as a health issue in his theoretical texts. In an article published in the *Los Angeles Times* parallel to the completion of the How House in 1926 entitled “Care of the Body, Ventilation,”¹⁴ Schindler laid out his intrinsic concept for ventilation: “the building needs small openings on all sides of the building at various heights. It should be built in the concept of a basket. The openings should be formed as such that they reduce the air velocity to enable a constant hardly experiential exchange of air throughout the whole house.” The structure of the How House is therefore an elaboration on his own invention, the ‘Schindler Frame,’¹⁵ a modification of the wooden frame traditionally used for residences throughout the USA. Here he developed the ‘Raumplan’ concept, which was originally conceived for solid massive masonry structures in Central Europe, into a planar wooden construction system and modulated heights. Overall, the resulting spatial composition typically acts as a traditional wind catcher, pulling colder air of higher velocity from high up down into the living spaces to ventilate out hot air on the lower levels.

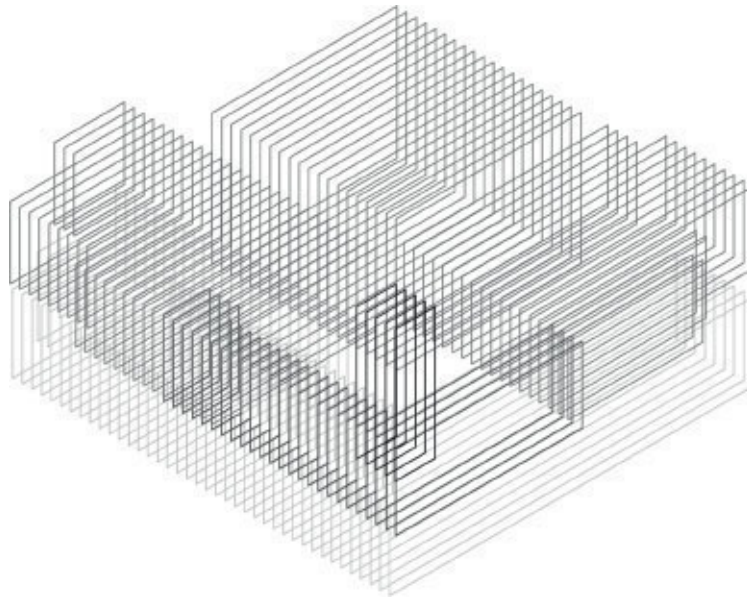


Figure 1.16

Diagram of spatial composition in the How House.

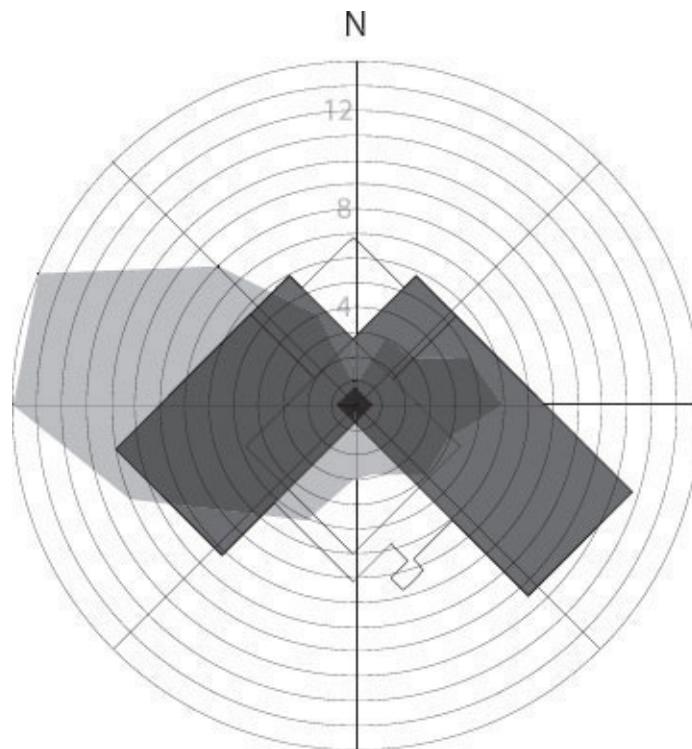


Figure 1.17

Wind rose (in m/s) for the location of the How House.

1.3.3 Incorporated Space: The Esherick House

When a connecting double height space is incorporated in an all-encompassing volume, spatial continuity is achieved in a compact vertical and horizontal volumetric composition. Warm air rises by convection, enabling stack effects because of the high spatial volume. The higher the spaces, the further away the exhaust air move from the comfort space of the inhabitants before collecting at the ceiling, where it can be exhausted. Wind can assist the stack effect by blowing over the stack and increasing the pressure differential. Stack effects and wind can thus work with each other or against each other depending on their direction, which is an important matter to distinguish as an architect. This topic is covered

further in [Chapter 7](#).

This compositional strategy of ordering space and air can be evaluated in the house built by Louis I. Kahn (1901–1974) for Mrs. Esherick in Chestnut Hill, Philadelphia, PA, in 1961. Its spatial composition is intentionally designed for natural ventilation and the façade includes wooden shutters to modify the flow. These shutters also contribute to the compositional complexity of the façade, as they are set back in the volumetric surface. Thus, the volume of the wall is shading the surface of the shutter while air velocity is increased at the same time because of the bottleneck effect of the inlet point. To reduce heat gain, the sealed glass surfaces are shaded with exterior blinds.¹⁶



Figure 1.18

Esherick House in Chestnut Hill, PA, design by Louis Kahn and constructed in 1961: street façade with closed shutters. The double height living room is on the right.

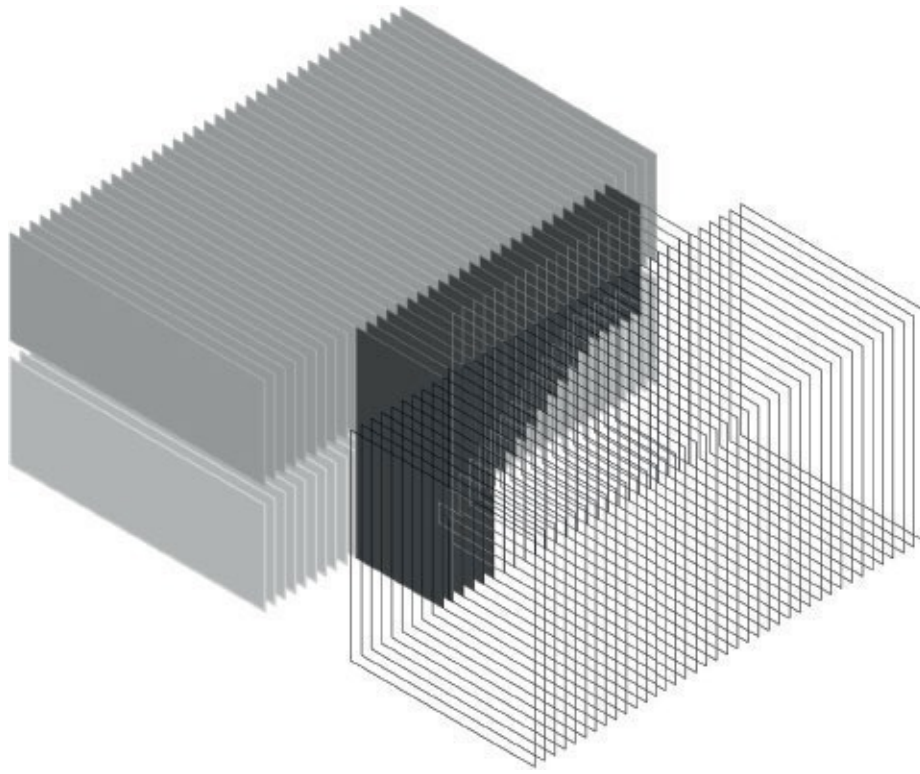


Figure 1.19

Esherick House in Chestnut Hill, PA, design by Louis Kahn and constructed in 1961: composition diagram of double height space within the larger cubic volume.

Kahn's architecture has often been described as a composition of volumes or spaces divided between server and served spaces. This analytical view indicates a distinction between the spaces that have a controlled environment and those that help to enhance and control this environment. In the Esherick House, this distinction of spaces is not applicable. Server and served space are one and the same, because the spaces of the house are designed to enhance natural ventilation. The spatial composition explores the connection of two single spaces and one double height space incorporated within a compact volume, which in itself is subject to a complex geometric composition. In this house, structure, space, light, and vents are intertwined in the same volumetric composition, enhancing immaterial movements of air and light. The spatial envelope in the Esherick House mediates the flow of light and air in a very distinct way, while changing the relationship between inside and outside.

Kahn's work is mainly known for its elaborate mathematical precision and beauty achieved by the implementation of ordering principles and using spatial structure on the basis of dimension and geometry. Gast¹⁷ developed a plan analysis of shifting axis and geometric proportion, but did not include the spatial height to elaborate on the volumetric proportion, which greatly contribute to the spatial complexity and air flow capacity of the house.



Figure 1.20

Esherick House in Chestnut Hill, PA, design by Louis Kahn and constructed in 1961: street façade with closed shutters. The double height living room is on the right.

In order to analyze air flow in the Esherick House, the understanding of space needs to go beyond the obvious established reading of the geometric composition, which has been extensively described as complex planar geometry. Rykwert¹⁸ noted that the building is designed as a cubic volumetric composition of $9 \times 9 (+1)$ modules with vertical proportions of $1 \times 2 \times 1$ and 2×2 modules.

Size and placement of openings manipulate air movement in space. A change in the relationship between inlet and outlet openings has significant impact on the velocity of air, allowing for the manipulation of air flow. It is crucial to understand the relationship of natural ventilation and space to be able to strategically place openings. In the Esherick House, openings for air and openings for light are designed not as one but as separate entities, which also enhances the changing relationship between interior and exterior. As Buttiker¹⁹ noted, closing the wooden shutters, which act as ventilation openings, hides the view to the garden and leads to a withdrawal into an inner world. In this scenario, only the clerestory window high up provides daylight and views to the sky. Opening the ventilation door refers the occupant back to the exterior view, opening the view to the garden, the weather, and the changing seasons. This situation enables the interior to be part of the greater flow of nature and air. The house can thus be seen as a physical obstacle, which distorts the laminar flow into unpredictable turbulent eddies through and around the building.

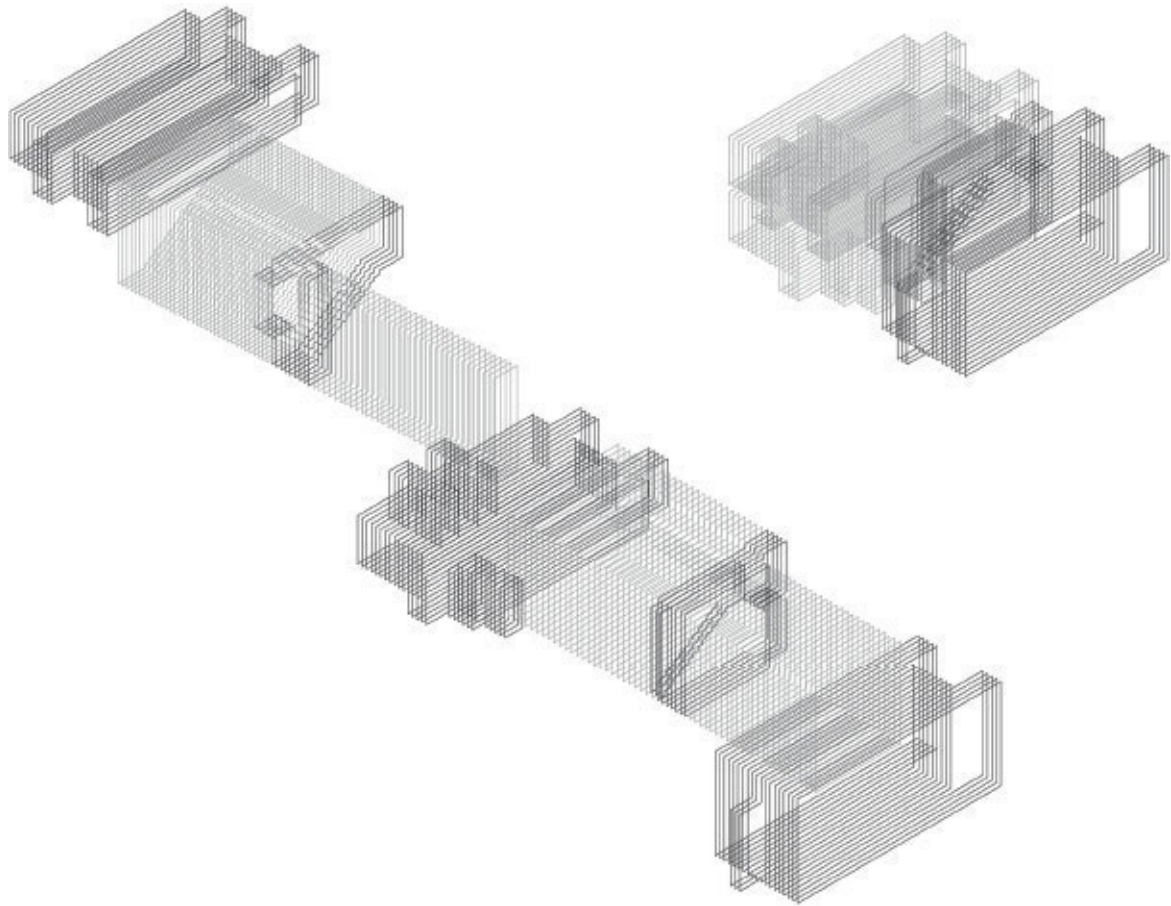


Figure 1.21

Diagram of spatial composition in the Esherick House.

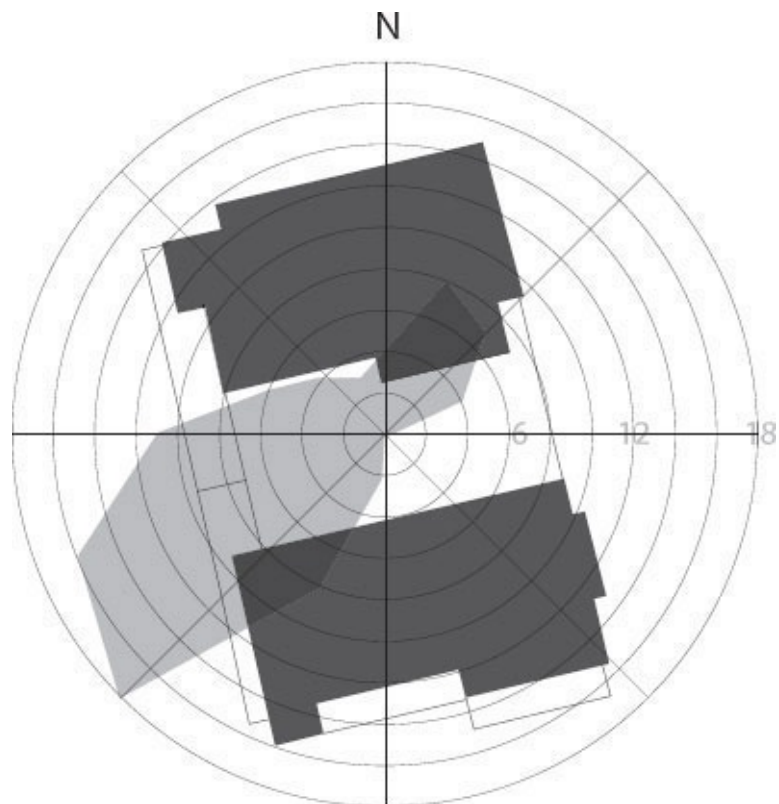


Figure 1.22

Wind rose (in m/s) for the location of the Esherick House.

1.3.4 The Atrium

Greek, Roman, and Renaissance atrium houses, public buildings, and palaces have had widespread influence on the building typology into the modern era and to this day.



Figure 1.23

Courtyard and garden of Palazzo Medici Riccardi by Michelozzo (1396–1472), commissioned by the Florentine Medici family in 1444.

Alvar Aalto and Charles Correa share a strong motivation in architecture to create an “opening to the sky.”²⁰ Both refer to the Pompeian patio house typology as their fundamental source, where the house is shaped around an opening to the sky or a semi-open courtyard as a climate-modifying device.

In his essay “Blessings from the Sky,” Charles Correa takes a similar approach. “Throughout human history, the sky has carried a profound and sacred meaning ... thus the great Hindu temples of South India are not just a collection of shrines and gopurams, but a movement through the open-to-the-sky pathways that lie between them.”²¹ With this in mind, he establishes the open-to-the-sky space as a main feature of design exploration in his Kanchanjunga Apartment building in Mumbai, India, where the porous envelope is supposed to allow the breeze of the Arabian Sea to naturally ventilate the apartments (see the case study in [Chapter 8](#)). Both Alvar Aalto and Charles Correa never allow this in-between space to be entered on center; it is always entered off-axis, relating the spatial configuration strongly to social patterns and cultural functions. This is also the most effective flow path, as it allows the air stream to reach all parts of the room. The typological interrelationship to the garden and hearth as the two main sources for the intermediate, interstitial space is evident. Mumbai-based Charles Correa had to build with less mechanical technology to meet requirements for user comfort. He seems to have

found a synthesis of his Western formation (Correa was trained at the Massachusetts Institute of Technology – MIT) and the architectural traditions of his home country, India, where he practices. His strong theme of a processional unfolding of spaces is also a reinterpretation of the pleasure garden, an equivalent to the *paradiso* in Mediterranean architecture.

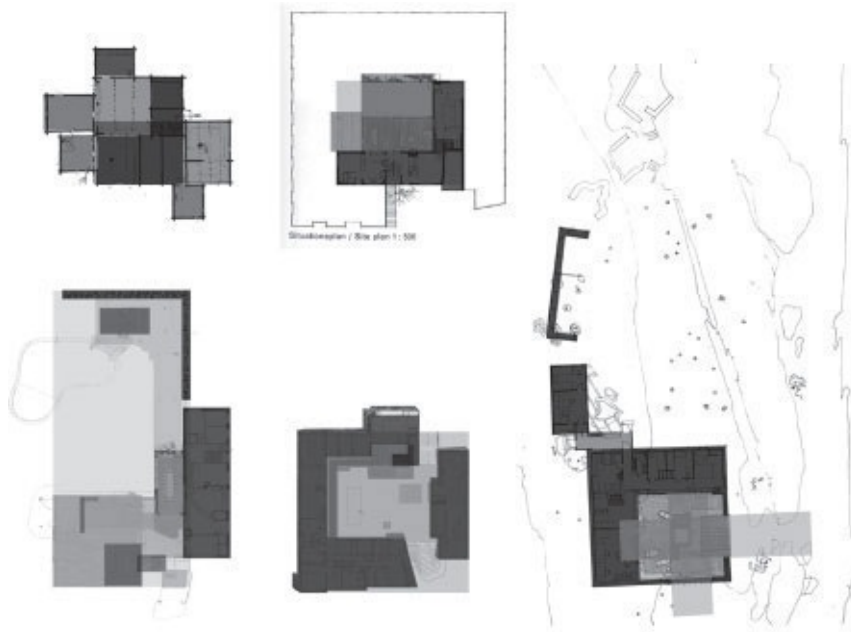


Figure 1.24

Courtyards in the works of Alvar Aalto relate to traditional farmstead layouts (from top left to bottom right): Carelian farmstead, Aalto House, Villa Mairea, Säynätsalo, Muuratsalo.

The courtyard or atrium acts as an interface to create an intermediate microclimate. This microclimate mediates between the severe outside climate and the more moderate, comfortable, or even delightful interior. To become this interface, the courtyard needs to be a protected in-between space that mediates the building mass required to create the microclimate. Thus the courtyard has to be surrounded by building mass, in order to protect these spaces inside this mass. Air and its ventilation patterns, which are shaped through the spatial composition, create a climatic membrane, which acts as a mediating interface. Glazed streets, loggias, verandas, or arcades have the same mediating function of relating the inhabited space to its climatic counterpart.



Figure 1.25

Town hall in Säynätsalo by Alvar Aalto (1952–1953): view up the exterior stairs to the raised courtyard, the chamber in the background.

1.3.5 The Northern Courtyard

One of Alvar Aalto's major works of the 1950s, the Säynätsalo Town Hall with its green raised courtyard, captures the sun, protects from the wind, and has a low height-to-area ratio, which allows the low angle of the northern sun to penetrate and warm the whole inner space. Courtyards are known in the respective literature as employing "ingenious natural cooling strategies."²²

Aalto's early writings ("Porraskiveltä arkihuoneeseen") for the *Aitta* 1926 sample issue²³ hinge on the idea of inner paradise, using Fra Angelico's (1400–1455) painting *L'Annunziata* as a metaphor to describe and envision the inside–outside relationship of space and climate in his beginning design work.

In this essay Aalto expresses his concern about the way one enters a room and how the room one enters into is connected to the exterior climate and the light of the sky. One could say that the roof lights he first explored at Paimio and Turku Sanomat, and further elaborated at Viipuri Municipal Library, are the open sky over a modern version of a classical amphitheater. His biographer Goeran Schildt argues that Aalto's aim is to let this entrance space appear like the inside space between other spaces rather than the sculptural surface of an inside space.²⁴ It is an inner exterior, as if entering the long Pompeian room open to the sky: the ancient atrium or the formless English domestic hall referring to open space as if it were open air.²⁵



Figure 1.26

Town hall in Säynätsalo by Alvar Aalto (1952–1953): raised green courtyard in full sunshine and sheltered from the winds.



Figure 1.27

Town hall in Säynätsalo by Alvar Aalto (1952–1953): looking out into the courtyard from the inner circulation arcade.

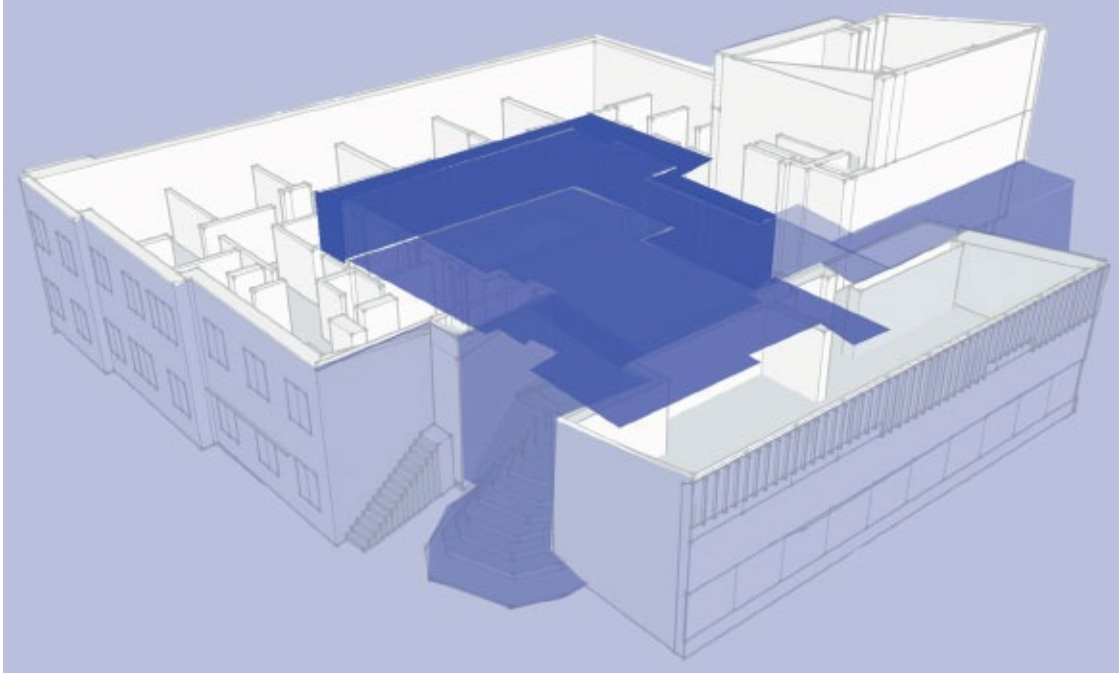


Figure 1.28

Diagram of main air flow path in the Säynätsalo town hall.

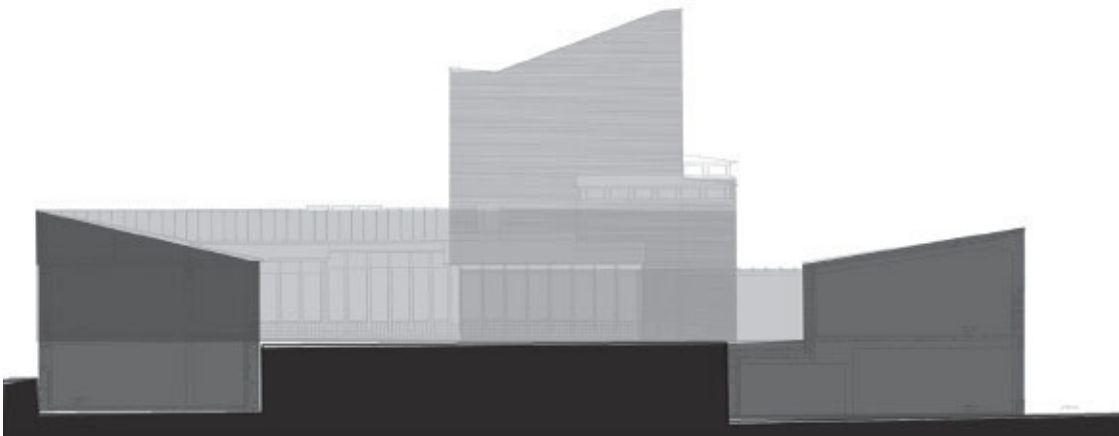


Figure 1.29

Section of spatial composition of raised courtyard in the Säynätsalo town hall.

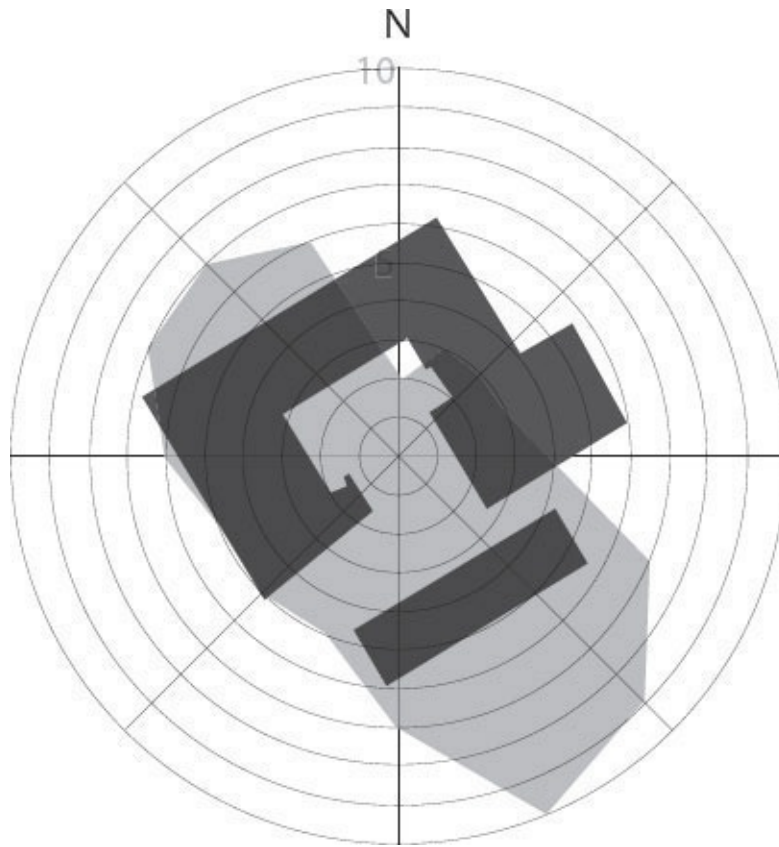


Figure 1.30

Wind rose (in m/s) for the location of the Säynätsalo town hall.

A courtyard in northern climates can also provide protection from detrimental winds and create a sheltered space. Studies of the relationship between wind velocity, pattern, and direction with respect to the proportions of the courtyard itself (height and width) support this approach. A courtyard creates a microclimate and protects from excessive wind while still enabling natural ventilation from the warm inner courtyard through the circulation space into the surrounding rooms. Contemporary double-skin façades have a similar calming effect.

Further reference to inherited spatial strategies such as wind catchers, atria, and double height spaces will be further elaborated in [Chapter 5](#) after introducing the details of the physics behind the phenomenon of flow.

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9. Alvin Rosenbaum, *Usonia: Frank Lloyd Wright's Design for America* (Washington: Preservation Press, 1993), p. 149.
10. Ibid., p. 191.
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Chapter 2

The Physics of Air Flow

The physics of air flow is a complex scientific field, as is the determination of its driving forces, which are based on pressure differences caused by wind, temperature, or a combination of both. In urban areas where street canyons create their own climate of temperature differentials and wind patterns, this becomes even more complex. The forces in nature and their relationships and proportions can be expressed in mathematical formulae based on specific laws of physics, but they can also be expressed in spatial or geometric proportions and thus have a direct relationship to architecture and design decisions.

This chapter is an attempt to ‘translate’ the basics of fluid dynamics for a non-scientifically trained design audience and to explain the major terms and units that provide the basis for the physics of natural ventilation based on existing literature.¹ For those interested in a more formal description, [Chapter 11](#) presents the mathematical equations that describe air flow and temperature relationships.

In order to fully understand the physics of natural ventilation, several systems and laws of physics need to be considered and integrated. They include fluid flow and wind patterns and how they affect each other – in particular, how natural forces are influenced and changed by obstacles in space that in turn need to be ventilated. Most of these laws are covered by the field of physics called fluid dynamics, which attempts to describe fluids in motion. Fluids can be liquids and gases, that is, everything non-solid.

Fluid dynamics examines velocity, pressure, density, and temperature as functions of space and time, all of which can change within the same flow field. An Eulerian description of the flow field provides a frame of reference for the flow field and focuses on one location in space and observes how the fluid flows through as time passes. Christian Ghiaus and Francis Allard² elaborate that by suitable differentiation with respect to time, the acceleration of a fluid particle can be determined at any position and time, as can the displacement of the particle from its position at an earlier time by integration. Pressure (p) and density (ρ) are also considered functions of position and time. A building’s interior space is considered a ‘vessel’ in which air can move freely under certain boundary conditions at the inlets and outlets. Mathematically speaking, velocity, pressure, and density are the dependent variables of flow that are functions of the independent variables position and time.

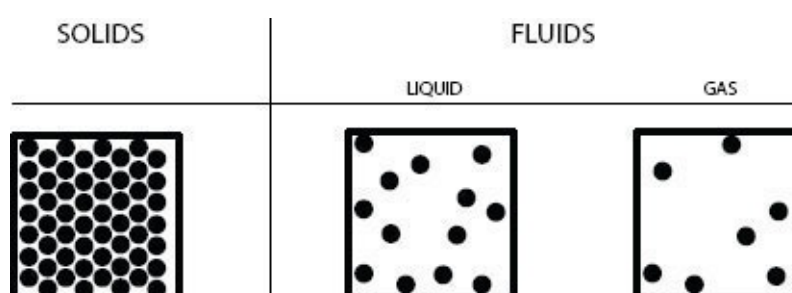


Figure 2.1

The material variables of solids, liquid, and gases are velocity, pressure, and density.

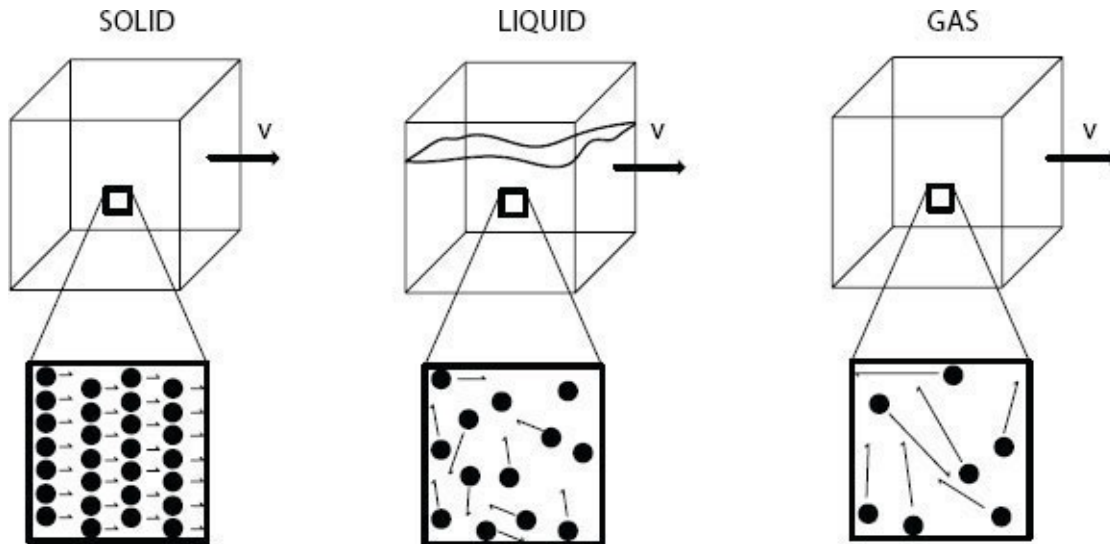


Figure 2.2

Difference in motion between solids and fluid: molecules in different sections of fluids can move in different directions in opposition to solids. All parts of a solid object can only move in one direction based on the center of their mass.

2.1 Solids and Fluids

According to Ghiaus and Allard,³ the basic difference between solid bodies in motion and fluids is that all parts of a solid body move together with respect to the center of its mass, either by movement along its coordinates or by rotation. A fluid can also move in relationship to its mass center and it is impossible to follow each fluid particle, and fluid dynamics focuses on the velocity of a particle at a given time. However, particles in a fluid can also move at different velocities with respect to each other and create a flow field.

2.2 Lagrangian Versus Eulerian Description as Frame of Reference

Lagrangian and Eulerian descriptions use different ways to describe the flow within a field. The Lagrangian description of flow follows the motion of one particle, while the Eulerian description explains the characteristics of a flow relative to fixed grid points, called laboratory points, through which the particle passes. In mathematical terms, Euler uses a fixed coordinate system to describe the movement of a particle, while Lagrange uses a moving coordinate system to describe the particle's path. *Lagrangian descriptions* of movement are very well applied to the movement of solid objects, while the *Eulerian description* of flow is more practical for the motion of fluids.

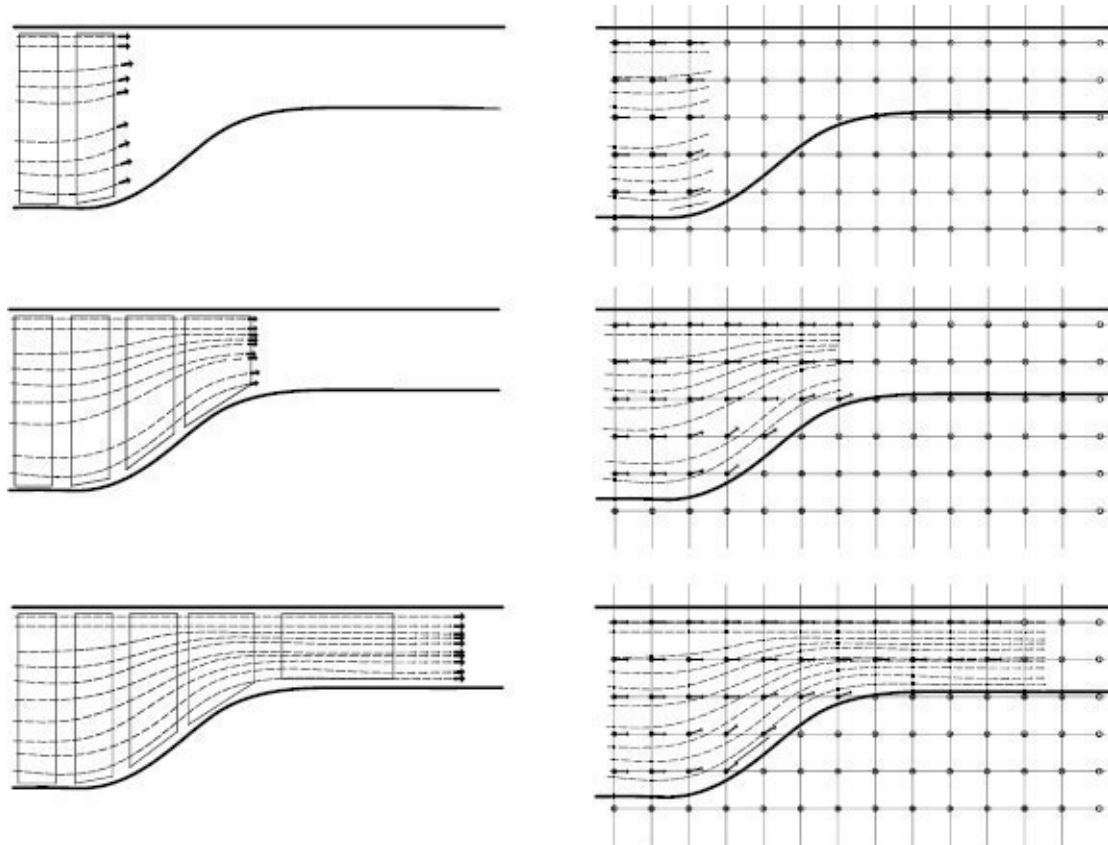


Figure 2.3

The Lagrangian description of flow follows each particle of a flow, while the Eulerian description of flow determines the flow based on how and when the flow passes through a grid point.

Air is not homogenous and its properties change with the factors mentioned earlier; it is a transient and dynamic matter. This behavior led to formulae with multiple variables; therefore obtaining precise information about fluid flow is an extremely difficult task. Some researchers even call it the last major unsolved physics question.⁴

Newton's three laws of motion set the basis for classical mechanics and they indicate the relationship between force or velocity of an object and the inertia of the object. Acceleration of an object is determined by an external force and the mass of the object. One of the forces acting on a body is gravity. Others are pressure and viscosity. Forces can also act on fluids and, even more complexly, forces can act within fluids. The *acceleration* of a body is directly proportional to, and in the same direction as, the *net force* acting on the body, and inversely proportional to its *mass*.

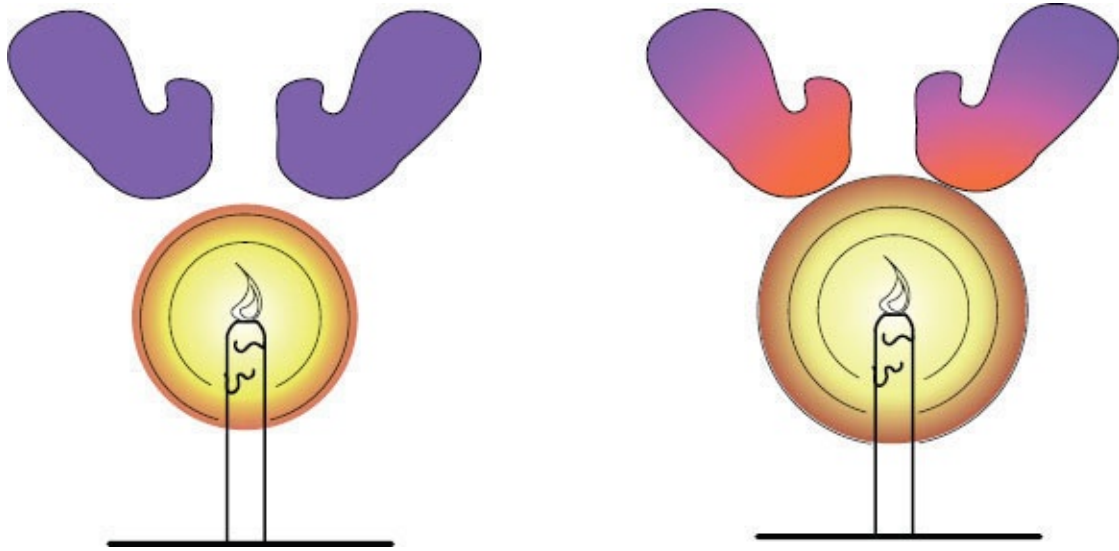


Figure 2.4

First law of thermodynamics: energy cannot be lost, but changes state transferred from body to body like warming hands on a warm object or fire.

The *laws of thermodynamics* are another very important set of laws that describe fluid motion. The first law is particularly important here: energy cannot be lost; it can only be transferred to a different state.

2.3 Properties of Air

The major properties of air are dependent on each other. The ideal gas law relates these properties:

1. Pressure
2. Volume
3. Density
4. Mass
5. Temperature

Temperature is a measurement of the kinetic energy of molecules in a substance. Air pressure is the force to which objects are exposed when air molecules hit them. Thus, with an increase in temperature molecules move faster and in turn the pressure on other surfaces increases. When the volume increases, density decreases. With a decrease in volume, temperature also decreases. There is thus a direct relationship between volume and temperature. So, when pressure increases for the same volume and mass of air, its density increases as well.

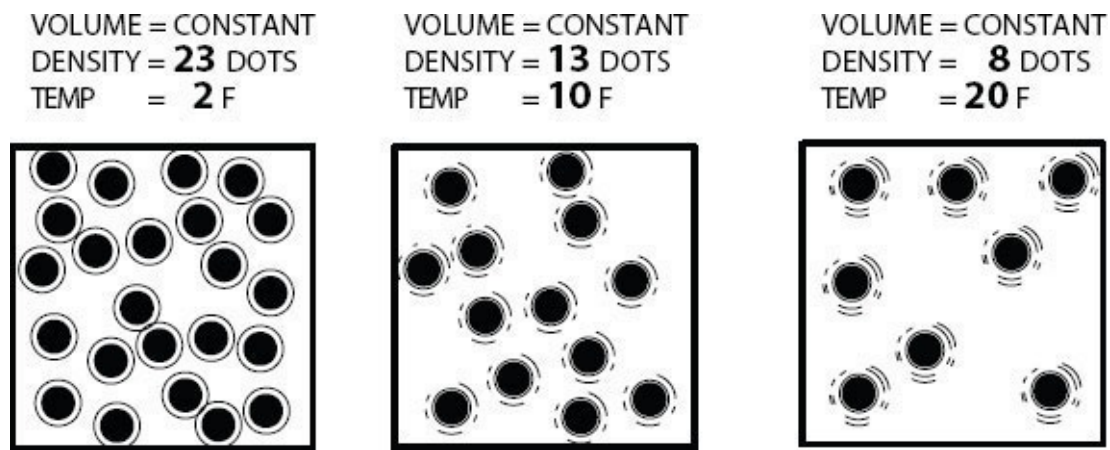


Figure 2.5

Properties of air are temperature, pressure, volume, and density.

The density of air at sea level and 15 °C (60 °F) is approximately 1.29 kg/m³ (0.08053 lb/ft³). Thus, the air inside a box with the dimensions of 1 × 1 × 1 m³ contains 1 kg of air. One ton of air has the volume of approximately 10 × 10 × 10 m³, which is about the size of a small residential house. The only reason the house can withstand and hold this weight is that the pressure of the air inside approximately equals the pressure of the air outside. When that is not the case, for example at an opening, the air moves in and out at the other end. The density of air is approximately 1.5 times larger at -40 °C (1.514 kg/m³ or 0.095 lb/ft³) as it is at 100 °C (0.9461 kg/m³ or 0.06 lb/ft³).

When air is in motion, a *velocity field* is coupled to those five major properties. Because air molecules can move against each other, a parcel of warm air can move upwards in a space at the same time as a parcel of cooler (heavier) air will descend.

2.4 Material Derivative

Newton's law of motion and the laws of thermodynamics applied to a fixed mass of a known matter only provide the property changes over time. For this description of motion, the Lagrangian description is used, because it describes the history of an identified moving particle. However, the Eulerian description is a convenient way to describe the Lagrangian viewpoint from a fixed frame of reference. The Eulerian description is used for a moving fluid, and this leads to the need to establish the

Eulerian expression of the rate of change of any property of a fluid particle as it moves through the flow field. The time rate of change of a fluid property, as measured by an observer moving with the particle, is called the material derivative of that property.⁵

2.5 Conservation of Mass – Conservation of Momentum

The law of 'mass conservation' basically states that the mass of a system remains constant over time. Conservation of mass can describe the amount of mass moving through an area at a particular velocity (referred to as mass flow rate). For example, if a volume of moving air needs to go through a smaller opening, its velocity increases, conserving mass. If a

force is executed on this fluid system, *conservation of momentum* indicates that the velocity of the system has to increase.

2.6 Forces on Fluid Particles

Fluid particles are exposed to two different types of force: the surface of a particle experiences the force per unit area, also called stress. These stresses are due to pressure and viscous effects. The other type of force is called the body force, because this force acts on the entire particle, not just the surface. A very important body force is the gravitational force, whose magnitude is the product of the mass of the fluid element multiplied by the gravitational acceleration. Depending on the altitude of the location, objects fall with an acceleration between 9.78 and 9.82 m/s^2 or approximately 32 ft/s^2 . Also, air and the Earth's atmosphere are exposed to the gravitational force of the Earth. For a volume of fluid, the mass is related to its density so that the gravitational force per unit volume is composed of the gravitational force and the acceleration multiplied by the mass.

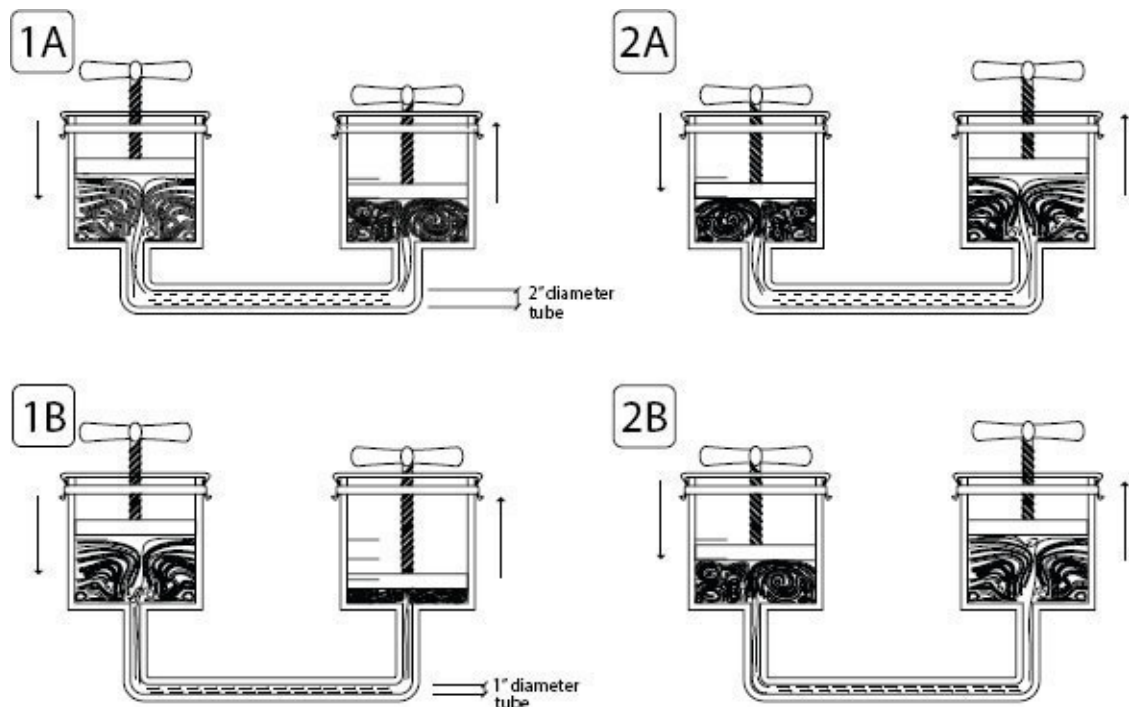


Figure 2.6

The law of mass conservation: with the same amount of pressure fluids travel faster through smaller openings as opposed to larger openings, as shown in both 1A/2A and 1B/2B, where 1A has a wider diameter and the arrows are shorter, and 1B has a smaller diameter with longer arrows. Note that the length of arrows denotes speed.

2.7 Navier-Stokes Equations

In physics, the Navier-Stokes equations,⁶ named after the French engineer and physicist Claude-Louis Navier (1785–1846) and the Irish physicist and mathematician Sir George Gabriel Stokes (1819–1903), describe the motion of fluid substances. These equations arise from applying Newton's second law to fluid motion and account for the forces described in [Section 2.6.](#), together with the assumption that the stresses in the fluid are the sum of a diffusing viscous term (proportional to the gradient of velocity) and a pressure term – hence describing viscous flow. Viscosity indicates the resistance of a material to

flow. Oil for example has a much higher viscosity than water. The Navier-Stokes equations are the major mathematical basis of all computational fluid dynamics practices today. Further information is provided in [Chapter 11](#).

2.8 Bernoulli's Equation

In fluid dynamics, Bernoulli's principle states that “for an inviscid flow, an increase in the speed of the fluid [that is, kinetic energy] occurs simultaneously with a decrease in pressure or a decrease in the fluid's potential energy.” The term ‘inviscid’ here refers to an ideal fluid that has no viscosity. Bernoulli's principle is named after the Swiss scientist Daniel Bernoulli (1700–1782), who published this principle in his book *Hydrodynamica* in 1738.⁷ The Bernoulli equation is very important for understanding the change of air velocity at inlets and outlets of buildings.

2.9 Boundary Condition

In order to understand viscous flow behavior, the physical conditions limiting the flow along its boundaries, the so-called ‘boundary conditions’ need to be taken into consideration. If the flow is time-dependent, there is an ‘initial condition’ which needs to be determined and from which the flow is evaluated. A variety of boundary conditions must be determined in order to characterize a certain flow scenario: inflow boundary, outflow boundary, or no-slip conditions along walls for example. A typical inflow boundary condition is prescribing a velocity such as the wind velocity into an opening. An appropriate outflow boundary condition is specifying pressure such as atmospheric pressure. The no-slip boundary condition of viscous fluids along a solid surface means that the outermost particles of the fluid stick to the surface of the solid boundary and have zero relative velocity, implying that the fluid does not move at the surface.

2.10 Turbulence

Most flows are actually unstable and thus exhibit turbulent behavior. The atmospheric boundary layer, jet streams in the upper troposphere, and most cloud formations are in turbulent motion. Most natural ventilation strategies also involve turbulent air movement. Laminar, straight parallel flow is actually an exception in nature. Non-turbulent flows are extremely rare, because most flows are unstable, in particular when they encounter obstacles. Because air can move in different directions reacting to pressure differences, turbulence can occur between two different flow fields and between fluids and solids. Laminar flow is seen only in small flow fields with high viscosity. Moving water in rivers, the wakes of ships, moving cars, and airplanes have flow patterns that are turbulent. Turbulent motion is characterized by disorder, irregularity, and randomness in time and space. It is difficult if not almost impossible to predict when and where turbulence will occur; it is also difficult to determine the form and shape of turbulent structures. This leads to a much more complex mathematical model for turbulence prediction, based on statistical analysis of the flow pattern.

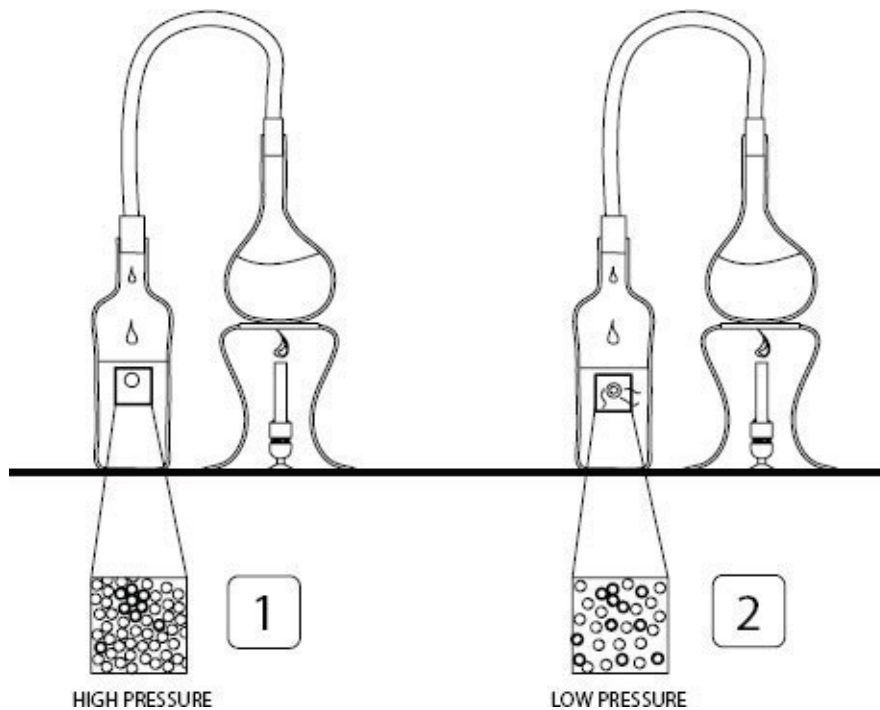


Figure 2.7

Depiction of the Bernoulli principle: an increase in fluid speed occurs simultaneously with the decrease in pressure. Pressure has an effect on diffusion, as shown here. Bottle 1 has a higher pressure than bottle 2; thus diffusion of the liquid from the heated flask is much higher in bottle 2 than in bottle 1.

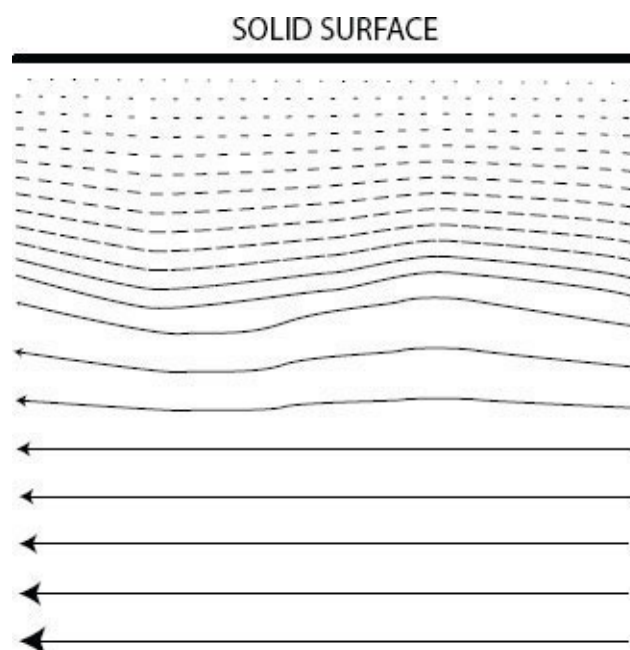


Figure 2.8

The no-slip boundary condition indicates that particles close to solid boundaries of fluid flow do not move, but ‘stick’ to the boundary.

An advantageous characteristic of turbulent flow for ventilation purposes is the fact that turbulent flow is very diffuse, which leads to very efficient mixing characteristics, for example, of fresh and existing air to improve air quality. However, this mixing also creates an increased rate of momentum, heat, and mass transfer. Turbulent flows cool more rapidly owing to better mixing. In addition, turbulent flow is truly three-dimensional, and is characterized by fluctuating velocities of a high order. Flow instabilities such as eddies and vortices develop when fluid flows encounter solid objects or other fluid flows. Fluid

motion is a dynamic space-time problem; fluid flow and turbulence are driven by a “constant supply of energy to compensate the viscous losses.”⁸ This energy driving the flow can come from shear or buoyancy forces and from wind. Because every turbulent flow is different and unique, the exact characterization of turbulence is an extremely difficult problem, but turbulent flows have common characteristics that can be identified and accounted for.

The steam plume rising over a hot cup of tea or coffee is one of the best-known visual images of a turbulent flow. Turbulence is necessary for the mixing of air streams, thus essential for good ventilation that relies on the exchange of air.

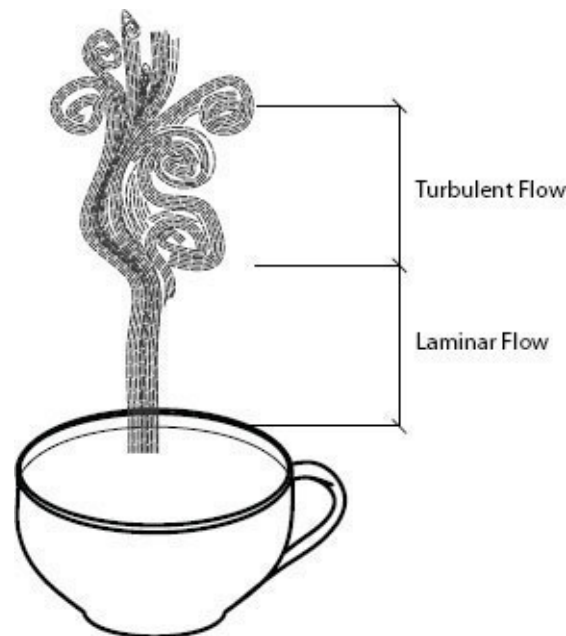


Figure 2.9

The turbulent flow is best depicted when very warm air mixes with fairly cold air, as can be seen in the plume over a cup of tea.

The characteristics of turbulence have been studied using numerical simulation and experiments. Turbulence typically starts fairly small, with a primary instability mechanism. These instabilities cause eddies – air movements turning in on themselves, creating secondary motions that are usually three-dimensional and will again become unstable. Turbulence is constantly causing strong, three-dimensional diffusion of all flow quantities: temperature, velocity, pollutant concentration, densities (due to temperatures), and others. These properties are the basis for good air quality based on mixing and dilution of pollutants, high humidity, and heat. Turbulence relies on outside energy from the environment. It is still a major research area in physics, mathematics, aerospace, and other engineering fields.⁹ Further reading about turbulence can be found in Francis Allard’s account.¹⁰

2.11 Reynolds Number

The Reynolds number is an indicator for the ratio of inertial forces to viscous forces. The Reynolds number is also used to characterize different flow regimes, such as *laminar* or *turbulent flow*. Laminar flow occurs at low Reynolds numbers, where viscous forces are

dominant; it is characterized by smooth, constant fluid motion. Turbulent flow occurs at high Reynolds numbers and is dominated by inertial forces, which tend to produce chaotic *eddies*, *vortices*, and other flow instabilities. It is almost impossible to precisely describe turbulent flows, as any airplane passenger will notice when experiencing unexpected turbulence. Turbulence occurs randomly in time and space. It arises from instabilities within the fluid flow. Reynolds numbers close to 600 lead to unstable boundary layers in zero-pressure gradients.¹¹ As a rule of thumb for boundary layer flow over a surface or object, turbulence can occur at a Reynolds number of approximately 200,000; however, flow inside a pipe can become turbulent at a Reynolds number of approximately 2,300.

2.12 K-Epsilon (Two Equation) Model

In order to better understand turbulent flow, numerical models have been created to approximate the outcome and characteristics of a turbulent flow. The most widely used model for air flow simulations in interior rooms is the k-epsilon model, which was introduced by Harlow and Nakayama in 1968.¹² This model is based on two equations: the turbulent kinetic energy dissipation rate equation, which refers to the kinetic energy within the turbulent flow, and the dissipation rate of the flow. The model determines that the “time-averaged turbulent energy per unit mass is the combination of the kinetic energies of many eddies of many sizes.”¹³ Referring to the different scales of motions within the flow, this kinetic energy is called the *turbulent energy spectrum*. The dissipation rate equation contains two variables, derived by a complex formula: the turbulent generation rate and the turbulent viscosity. Both variables refer to space, time, and material properties, which subsequently allow the determination of the mixing rate of the turbulent flow.

These computation-intensive calculations between the largest and the smallest eddies within a turbulent flow are still a challenge, even with the largest and fastest computers available, and therefore present an obstacle to air flow quantification for natural ventilation strategies. Thus, all solutions that are obtained for turbulent flow fields are approximations.

2.13 Buoyancy as the Basis for Stack Effect

The architect Vitruvius (born c. 80–70 BC, died after c. 15 BC) was the first to mention Archimedes of Syracuse’s *Eureka* moment,¹⁴ describing the moment when he discovered the relationship between mass, volume, density, and buoyancy.¹⁵ Archimedes’ principle is a fundamental *law of physics*, used in *fluid mechanics*. This physics law indicates that the upward *buoyant force* that is exerted on a body immersed in a *fluid*, whether fully or partially submerged, is equal to the weight of the fluid that the body *displaces*. In Vitruvius’ 9th Book,¹² in which he discusses the influence of the sciences on architecture, he used an anecdotal story to introduce the law of Archimedes.¹⁶ According to Vitruvius, Archimedes was requested by his king to determine whether a goldsmith had cheated with the weight of gold in a crown he crafted. While sitting in the bath tub, Archimedes realized that the water displaced by his body must be the same volume as his body.

Therefore he immersed the crown into water in order to measure the water it displaced, knowing that if the crown had silver mixed into the form, it would be bulkier than a pure gold crown and therefore displace more water. His measurement found the goldsmith guilty of fraud. It is not clear whether this story is actually true and took place as described, but that is not important here. What is interesting is the fact that Vitruvius already placed importance on the relations between architecture and the physics of air and fluids and how they might relate in good proportion to each other.

Air is constantly in motion, activated by thermal energy in the form of air temperature. Heated air becomes lighter and rises, while cool air descends towards the floor. Often air is in motion even when we cannot perceive it. The so-called stack effect is based on this buoyancy effect, where the weight of the air and the gravitational force that acts on the air are balancing, and with the buoyant force larger than gravity, air will rise up in a space.

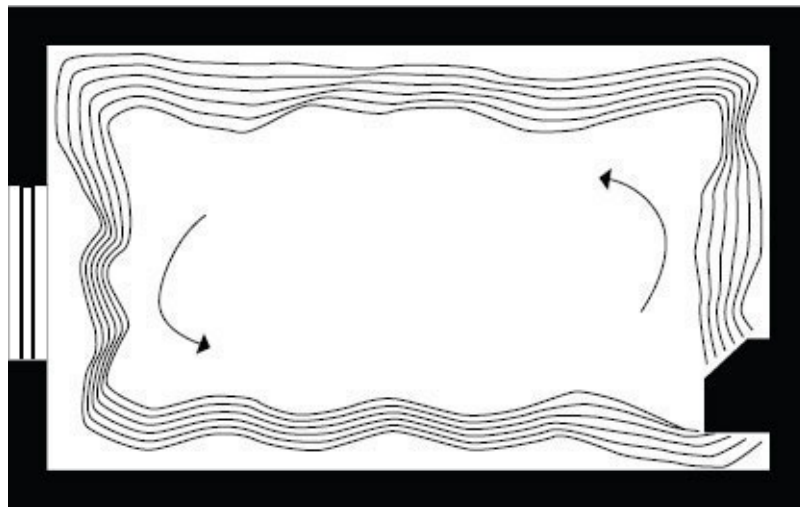


Figure 2.10

The buoyancy effect: warm air is lighter and less dense and thus rises over warm surfaces or objects. The buoyancy force can be stronger than gravity.

2.14 Forced Convection

If an external force is acting on the fluid, for example with the help of a fan or the wind, the transfer of energy due to temperature differences is known as forced convection and can also be described by the mass, momentum, and energy conservation equations.¹⁷

2.15 Fluid Dynamics of Weather

The major relationships in the fluid dynamics of air form the basis for the creation and formation of weather phenomena and patterns such as clouds, wind, and rain. Their movement is driven by the fluid dynamics of air together with gravitational forces and the Earth's rotational force, which causes the so-called Coriolis effect.¹⁸

*Web Weather for Kids*¹⁹ clearly depicts the elements that create the phenomena of weather described by atmospheric sciences. Interior environmental conditions follow the same physical properties as weather. Weather can be explained as a combination of temperature, pressure, volume, and density of air and so can indoor climate. The fact that

hot air rises is not only the key physical characteristic of natural air convection inside buildings, but also the key driver of weather phenomena. Combined with the property of air to hold more moisture when it is warm, it explains the origin of cloud formation as well as the origin of human thermal comfort conditions.

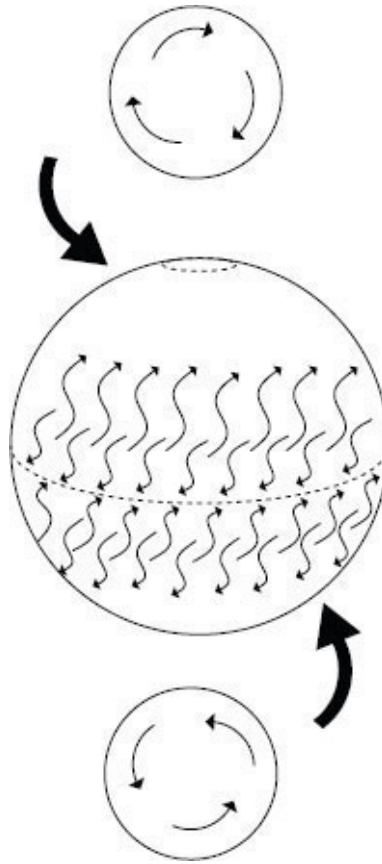


Figure 2.11

The Coriolis effect drives the movement of air in the Earth's atmosphere based on the rotational forces of the Earth and its gravity.

2.16 Air and Moisture

The ability of air as a mixture of gases to hold moisture is another major influence on the formation of weather and building interior conditions. At normal conditions close to ground, the pressure of hot air can hold more absolute humidity than cold air, as the psychrometric chart in Figure 2.12 shows. Here, the relative humidity level indicates the capacity of air at a certain temperature to hold moisture. When the temperature of a warm air sample drops and comes into contact with a cold glass surface, the water vapor condenses out of the air and creates small water droplets on the surface. The level of humidity has a strong impact on weather and building climate with its effect on human thermal comfort.²⁰

2.17 What is Wind? Wind and Obstructions / Wind in Urban Context

Wind is formed by large masses of air moving from high-pressure to low-pressure zones, which are created by temperature differentials. Wind is a large, atmospheric scale

movement of air around the Earth's globe. Wind as a force does have a scale, but the same forces apply to wind as they apply to small-scale movements of air in a test scenario.

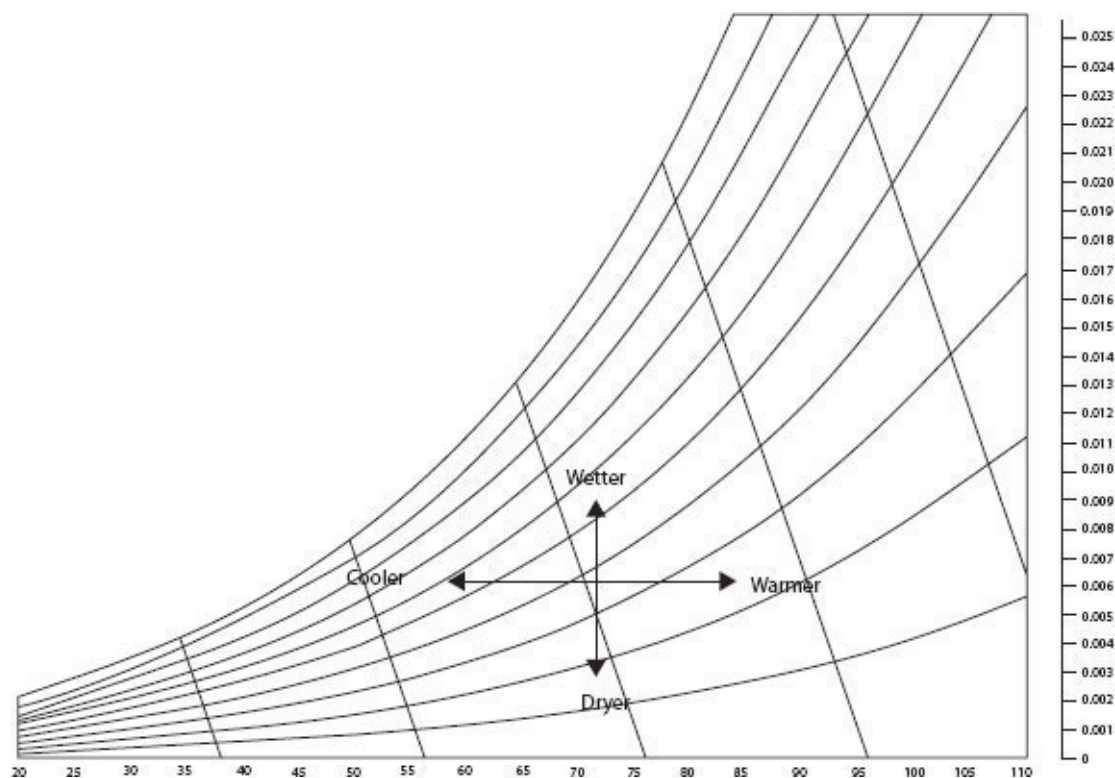


Figure 2.12

Psychrometric chart depicts the thermodynamic properties of gas-vapor mixture in atmospheric air. The horizontal axis indicates temperature in Fahrenheit, while the vertical axis shows pounds of water per pound of dry air.

2.18 The Impact of Fluid Dynamics Principles on Spatial Proportions

This brief review of the complex physical properties of air movement based on fluid flow mechanics shows the significance of spatial proportions, and even more of scale, to the physics of natural ventilation. Natural ventilation flow patterns are based on the creation of pressure and the resistance to pressure provided by the building in order to channel the flow through the intended path. The flow enables the mixing of interior and fresh exterior air on its way, utilizing the forces of the flow itself (wind and buoyancy). These proportional relationships keep the turbulent eddies constantly in motion, and the air will mix as long as there is an environmental force available.

Notes

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Chapter 3

The Importance of Fresh Air for Occupants' Health

As Steven Connor elaborates in *The Matter of Air*: “The ancient world was familiar, indeed, preoccupied to the point of obsession, with various kinds of vapor, exhalation, fume and spirit, most of which we would nowadays characterize as aerosols or similar suspensions of liquid or particulate matter in air.”¹ Air had also become a concern of physicians and public health specialists during the seventeenth century with the increase of public institutions such as schools and hospitals and the desire to prevent the spread of diseases. Steven Connor, meanwhile, notes: “Buildings sweat, age, excrete and they respire.”² We now understand that one major concern for indoor air quality is the off-gassing of building material in addition to occupant odors as well as the results of occupants' breathing.

The heating and ventilation engineer Lewis W. Leeds (1829–1896) in 1868 claimed that “Man's own breath is his greatest enemy.”³ This was the motto of his 1868 publication in his *Lectures on Ventilation*, one of the first guidelines on building ventilation strategies. The writing in these guidelines is crystal clear, and they contain fabulous color crayon illustrations based on the physics of room air circulation understood from experience at the time. Most of his recommendations for air inlet and outlet placement and their relationships still hold true today, because they are based on the physical property of hot air rising. However, Leeds' statement created a very costly misconception still encountered today: the belief that air-tight buildings prevent good air quality. The problem is indeed far more complex. Good air quality with lower ventilation rates can be achieved especially with fewer emissions from materials.

His lectures were a response to the death rate assigned to foul air in large East Coast cities of the USA in the late nineteenth century. These deaths and the health concerns they prompted are considered the beginning of ventilation science. One can draw an interesting and maybe even frightening comparison to today's large Asian cities and their smog levels, where asthma rates in children are attributed to bad outside air quality caused by industry and car traffic.⁴ When the exterior air is bad, where can healthy, fresh air come from? In addition, Lewis also pointed out the relationship between combustion for heating and the need for ventilation when he talks about Manchester: “We have nothing in this country [the USA] like this city [Manchester], where two millions of tons of coal are burned annually, the smoke from which fills the air and stretches like a black cloud far into the country.”⁵

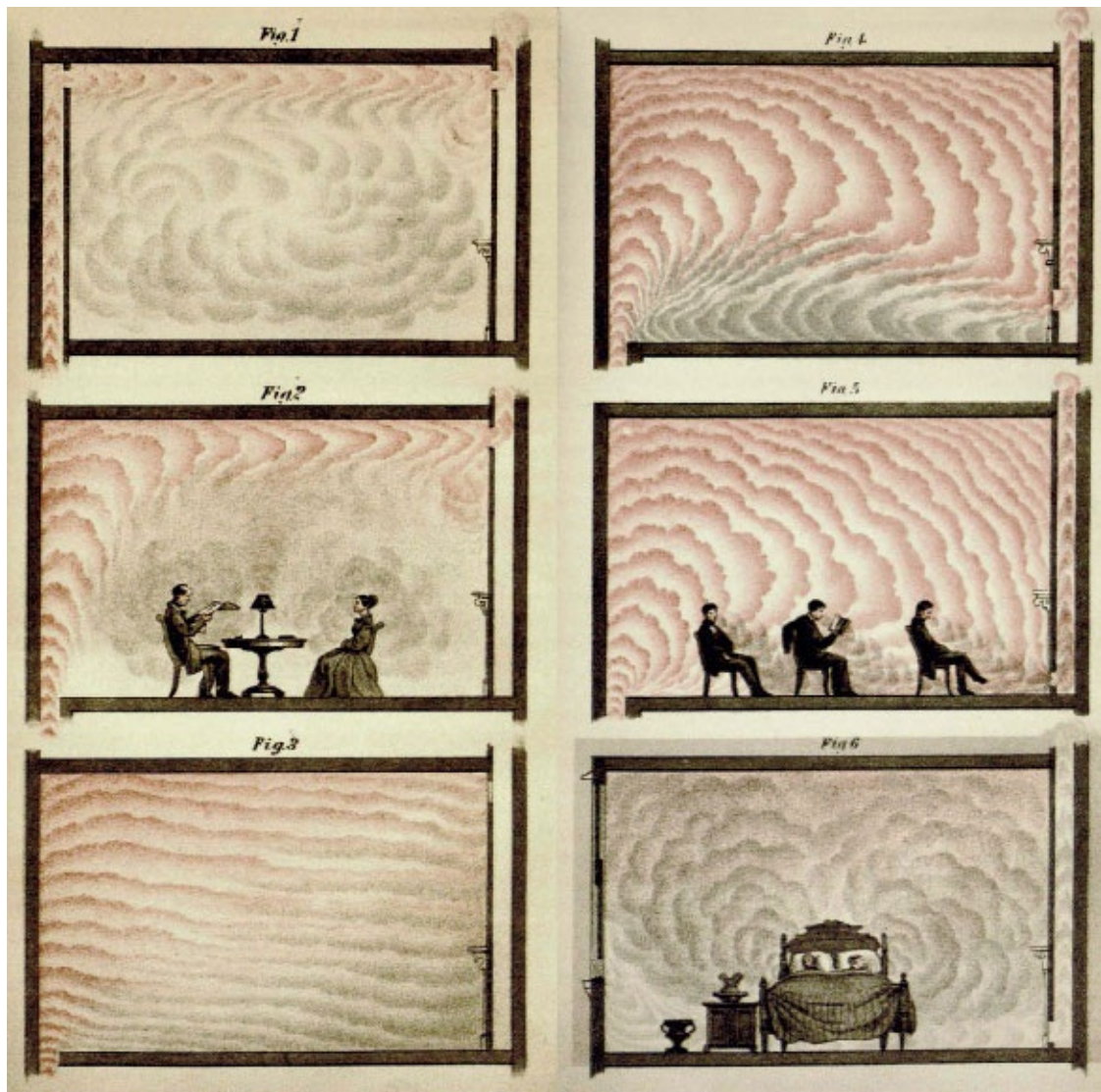


Figure 3.1

Lewis Leeds lecture on ventilation, Fig. 4, 5, 6, p. 29: nineteenth-century visualization of air movement inside interior spaces.³

3.1 What Is Air?

Based on research and experimental results we know that air is composed of 78 percent nitrogen, 20 percent oxygen, 2 percent carbon dioxide (CO_2), and a fraction of inert gases. Water vapor content amounts to only about 1 percent. Exhaled air contains about 4–5 percent less oxygen than inhaled air and 4–5 percent more CO_2 than inhaled air. Thus, even in air-tight buildings we will not run out of oxygen that soon, although we may find the air starting to smell bad. As a consequence, the reduction of emissions is one major factor in energy-efficient ventilation. Exhaled air has a relative humidity of close to 100 percent according to the *Whole Building Handbook*.⁶ It is commonly understood that we ventilate to have sufficient oxygen to breathe and to get rid of excess CO_2 . Although CO_2 is used to measure ‘stale air’, the concentrations which are determined to pose a risk to health are hardly ever achieved, even in the most air-tight buildings.⁷ Ventilation is primarily required to adjust humidity and remove excess heat, body odors, and materials’ emissions (VOC), which are major health concerns.

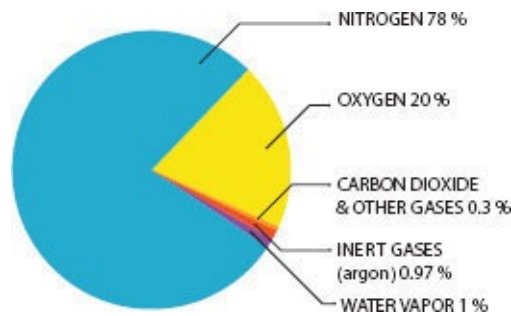


Figure 3.2

The composition of air as a mixture of gases.

3.2 Indoor Air Quality

Ventilation in general has two major goals: 1. cooling air and occupants through temperature reduction or cooling by evaporation using increased air velocity, and 2. maintaining appropriate air exchange rates to keep a proper composition of air, making sure it is not smelly or nauseating with too little oxygen or too many pollutants such as volatile organic compounds (VOC). Ventilation at a to-be-determined rate removes or dilutes pollutants to an acceptable level. Next to cooling, indoor air quality or indoor environmental quality (IEQ) is the major reason for ventilation and thus also for natural ventilation. This chapter discusses health-related ventilation reasons and provides a short history of the relationship of air and health as a basis of ventilation studies.

Many health issues are related to pollution of indoor air:⁸

1. Infectious diseases caused by airborne viruses or bacteria;
2. Growth of microorganisms in humid air, for example in humidifiers or within the building envelope construction;
3. Allergies and asthma caused by exposure to mold that thrives at high humidity indoors;
4. Lung cancer caused by exposure to tobacco smoke and radon decay products;
5. Cancer and skin irritation as well as allergies caused by VOCs and formaldehydes in the air;
6. Dizziness and nausea caused by odors, which can lead to dissatisfaction with the indoor environment;
7. Sick building syndrome (SBS).

Many research studies⁹ have shown that ventilation rates below 10 l/s (20 ft³/m) have one or more of those detrimental health effects on human occupants. Children and the elderly are particularly vulnerable to exposures to these pollutants at high levels.¹⁰

3.3 A Brief History of Air and Health Sciences

Prior to a modern scientific understanding of the world, even more properties and ailments were attributed to the influence of air.¹¹ In Greek philosophy, air was considered one of the four elements, together with fire, earth, and water.¹² Aristotle (384 BC–322 BC) added

“aether” as the fifth element to this list, and he assigned it to the stars, as they could only have been made of a different, divine substance. In his major treatise on materials, *On Generation and Corruption*,¹³ Aristotle searched for the reason why materials come about and how materials pass away, how changes happen, how materials get altered, and how growth occurs. The movement of air and how air can come out of water was part of his considerations. The origin of the four elements in classical thinking may even go back to Babylonian mythology and the *Enûma Eliš*,¹⁴ a text written between the eighteenth and sixteenth centuries BC. It describes five personified cosmic elements: the sea, earth, sky, fire, and wind. Thus the understanding that air is its own entity is many millennia old. The Greek philosopher Plato (427 BC–347 BC) assigned properties to the elements, and he considered air to be hot and wet. Plato writes in *Timaeus*: “So it is with air: there is the brightest variety which we call aether, the muddiest which we call mist and darkness, and other kinds for which we have no name.”¹⁵ Air was at the same time considered to be related with the spiritual beginning of life and soul as spiritual center of a human being.

Table 3.1 Historic elements across cultures

Culture	Fire	Earth	Water	Air	Fifth Element
Babylonia	N/A	Earth	Sea	Wind	Sky
Greece	Fire, primarily hot, secondarily dry	Earth, primarily dry, secondarily cold	Water, primarily cold, secondarily wet	Air, primarily wet, secondarily hot	Aether: added by Aristotle to represent the unchangeable
Hinduism	tejas or agni (fire)	bhūmi (earth)	ap or jala (water)	marut or pavan (air or wind)	vyom; or shunya or akash (aether or void)
Buddhism	heat or energy (fire)	solidity or inertia (earth)	cohesion (water)	expansion or vibration (air)	N/A
Egypt	yellow bile (fire)	black bile (earth)	phlegm (water)	blood (air)	N/A
Chinese Wu Xing	Fire (火 huǒ)	Earth (土 tǔ)	Water (水 shuǐ)	Wood (木 mù)	Metal (金 jīn)
Tibetan Bön	Fire	Earth	Water	Air	Space
Japanese	Fire: things that destroy	Earth: things that are solid	Water: things that are liquid	Air: things that move	Void or Sky/Heaven: things not of our everyday life

Source: http://en.wikipedia.org/wiki/Classical_element

Another health-related concept in antiquity was the *Pneuma*, also going back to Aristotle. *Pneuma* indicated spirit, breathing, and the power of life, and air is thus often considered synonymous with spirit and soul. *Pneuma* was the ancient Greek word for breath and thus relates air as an element to the living body and the soul as an aerial spirit.¹⁶

The presocratic thinker Anaximenes (585 BC–525 BC) saw air as the “arche”, the beginning of all things,¹⁷ relating “aer” to the very existence of humans, not just biologically, but also spiritually. In addition, air was also related to the immaterial, but also considered the foul bearer of all evil.

Other cultures, philosophies, and world views had similar categories. Buddha's teaching included four elements and connected air to vibration and expansion.¹⁸

In the Western scientific world, air became a subject of scientific study in the late sixteenth century, when the chemical composition of air was still mostly unknown and scientific inquiry circulated around the question whether a vacuum existed and whether what could not be seen could be extracted to achieve 'less than nothingness.' The means to investigate air in science was the air-pump, and vacuum was discovered as a scientific fact in about 1660 by Robert Boyle (1627–1691).¹⁹ The phenomenon was depicted in the 1768 painting *An Experiment on a Bird in an Air Pump* by Joseph Wright of Derby (1734–1797), now displayed in the National Gallery in London.²⁰



Figure 3.3

An Experiment on a Bird in an Air Pump by Joseph Wright of Derby, 1768, depicting the experiment, where a vacuum was created in a flask which contained a bird, robbing the bird of the basis for life: air.

3.4 Health and Well-Being

Health and well-being are strong concerns in ventilation science, and the appropriate ventilation rates required to provide a healthy environment are constantly debated with respect to the energy and equipment needed to condition the air.

For example, indoor humidity is considered a widespread cause of diseases in children because high humidity in indoor air promotes mold growth. Therefore, removal of humidity can reduce health risks, but it has to be clear that it is not the humidity that is the issue, but mold growth. On the other hand, if too much humidity is removed the dry air may cause other detrimental effects such as respiratory issues.

Historically many pathogens were originally considered to be spread by air, which led to the depletion of urban environments during epidemics, as described vividly in the

Decameron by Giovanni Boccaccio (1313–1375).²¹ But modern research showed that cholera epidemics, for example, were spread by contaminated water. Today, most influenza viruses are spread with a handshake and not by air. But in the modern environment new particles linger in the air, having a negative health effect on human occupancy: VOCs (volatile organic compounds), carcinogenic particles, formaldehyde, and combustion fine particles created as side products of gas burners and motor vehicles.²²

Exposure to fresh and thus healthy air was considered a major cure of tuberculosis in the early twentieth century, which led to the construction of major sanatorium buildings in the Swiss Alps, but also in Finland, exemplified by the Paimio Sanatorium designed by Alvar Aalto in 1932.²³

3.5 Architecture, Health and Air: Alvar Aalto's Paimio Sanatorium, Finland

Alvar Aalto's (1898–1976) design for the Paimio tuberculosis sanatorium (1932) marks a high point in his Functionalist period. Tuberculosis was considered a disease of the dense, urban, unventilated environment. Tuberculosis is in fact an infectious disease caused by micro-bacteria that affects the lungs and is transmitted through air. Therefore, sanatoria were built in remote mountaintop regions such as Davos, Switzerland, and were highlighted in the 1924 novel *Magic Mountain (Zauberberg)* by Thomas Mann (1875–1955).²⁴ Pure forest locations such as Finland were also considered appropriate sites to expose tuberculosis patients to plentiful fresh air and ventilation.

Sanatoria lent themselves very well to the new Modern Movement in architecture and the development of Functionalist architectural features. The ventilation of the patient wards in Paimio brought fresh air without draught into the patients' rooms through a specially designed double pane glass window, oriented to the sun, which preheated the ventilation air to a more temperate condition. The Paimio patient room windows can therefore be considered as predecessors of the many double-skin glass walls to come.

Another iconic architectural feature of the building is the open balconies, which were used to expose the patients to plentiful fresh air as a healing treatment.

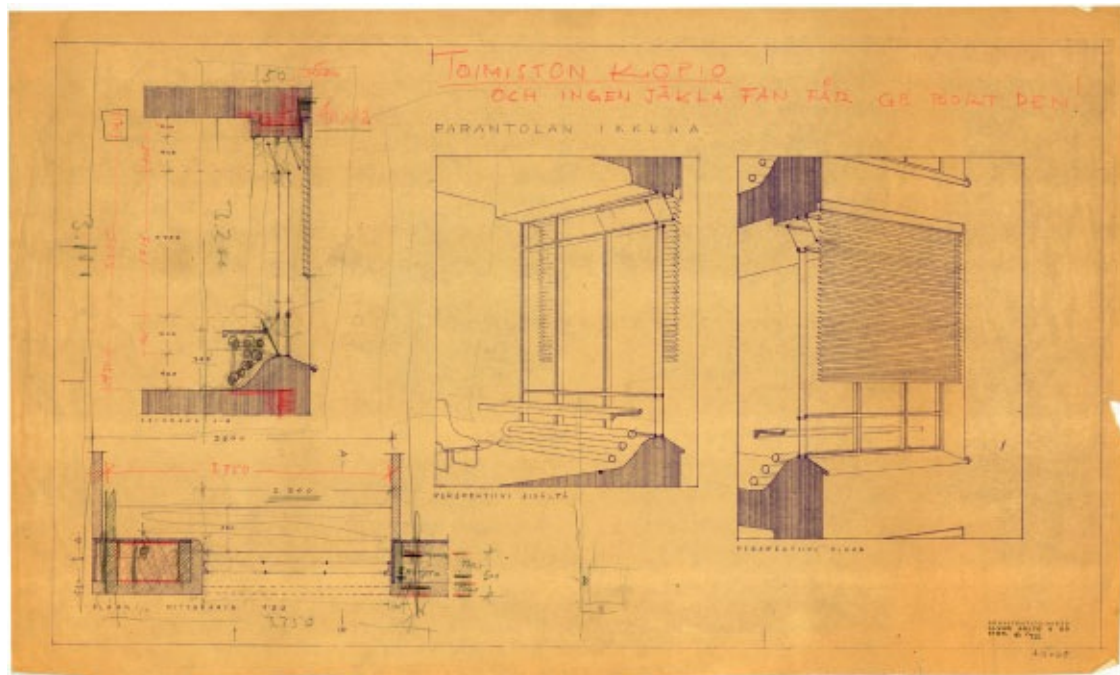


Figure 3.4

The original window detail for Paimio sanatorium provided two panes of glass for gently pre-warming the incoming ventilation air of the patient's room.



Figure 3.5

Providing open spaces for the tuberculosis patient, the iconic roof terrace exposes patients to fresh air. The terrace was glazed in the 1960s.

3.6 Breathing, Cooling, Cleaning, and Ventilation Rates

Max von Pettenkofer (1818–1901), one of the founders of public practical hygiene, delivered three public lectures on hygiene in 1873 called *The Relations of the Air We Breathe to the Clothes We Wear, the House We Live in, and the Soil We Dwell on*.²⁵ The development of public health as a subject of scientific inquiry started in Europe and the USA with the advent of large-scale public buildings, high-density living conditions, and an aspiration to conquer the desolate living conditions of the urban working poor.

With the sentence “We want air to nourish us and to keep us cool,”²⁶ Pettenkofer starts

his tripartite lecture by stating the incredible adaptability of the human body to various climatic temperature conditions and the resulting human metabolism. While humans adapt to both the arctic and the tropics, human body temperature only varies by a percentage of a degree Fahrenheit, whether it is 30 degrees Fahrenheit (~0 degrees Celsius) or 105 degrees Fahrenheit (40 degrees Celsius) outside. Cooling by evaporation and conduction according to Pettenkofer is a most significant and astounding means of cooling. He already understood that cooling is supported by air movement until air movement turns to annoyance and draught. Here, the surrounding conditions matter as much as the temperature of the air breeze.

Current health concerns related to indoor environmental quality in residential, public, and commercial buildings include asthma and cancer risks potentially caused by VOCs, radon, odors and chemicals, allergies, ozone irritation, and other respiratory symptoms. A vibrant debate is ongoing about the best approach to remove these particles from the air. The most obvious approach is to remove or reduce the source of the pollutant or to increase the ventilation rate in order to dilute and dispose of particles and to keep its concentration below a proven acceptable range.²⁷ However, these ranges have changed significantly over time and are still in flux.

Air change rates have become the most important validation parameter (next to temperature and humidity) for ventilation strategies. A ventilation strategy can only be implemented if it can provide the required ventilation rate on a continuous basis. Thus the rate in question becomes the minimum rate for a natural ventilation strategy, which is usually driven by dynamic and not by continuous homogenous forces.

Current ventilation rates for healthy indoor air quality are determined by the number of people occupying a space, their activity, and the volume and area of the space. There is no distinction made between the type of ventilation system and the environment in which the building is situated (for example urban versus rural). Supply air will always be considered fresh air and will replace or dilute the used/exhausted air in a given space independent of where the air is drawn from.

Recent findings indicate that there is very little evidence supporting the notion that higher ventilation rates actually do result in healthier indoor environments.²⁸ Considering the fact that high outdoor air supply rates lead to higher energy cost, the question is indeed crucial.

Recent research indicates that inhabitants favor natural ventilation. Seppaenen and Fisk²⁹ came to the conclusion that “buildings with natural ventilation are associated less with SBS symptoms than buildings with traditional mechanical ventilation systems and are also well accepted by the users due to the potential for individual controls.” Hummelgard *et al.*³⁰ compared user satisfaction rates in naturally ventilated buildings and in mechanically vented buildings, and although temperatures and CO₂ levels were higher, satisfaction rates were higher in naturally ventilated buildings. In addition, research has noted that increased ventilation rates would increase productivity and thus increase economic benefits due to salary costs for workers and less sick leave.³¹

Table 3.2 Breathing zone outdoor air flow rates according to ASHRAE 62.2-2031: Ventilation for acceptable indoor air quality (extracted from Table 6.2.2.1: Minimum Ventilation Rate in Breathing Zone)

Occupancy category	People outdoor air rate		Area outdoor air rate		Notes	Default values			Air class
	Rp		Ra			Occupancy density	Combined outdoor rate		
	I-P: cfm/Person	SI: L/s Person	I-P: cfm/ft ²	SI: L/s m ²		#/1000 ft ² (#/100 m ²)	I-P: cfm/Person	SI: L/s Person	
Educational facilities									
Daycare (through age 4)	10	5	0.18	0.9		15	17	8.6	2
Classrooms (age 9 plus)	10	5	0.12	0.6		25	15	7.4	1
Lecture hall (fixed seats)	7.5	3.8	0.06	0.3		150	8	4.0	1
Art classroom	10	5	0.18	0.9		20	19	9.5	2
University/ college laboratories	10	5	0.18	0.9		15	17	8.6	2
Music/theater/ dance	10	5	0.06	0.3		35	12	5.9	1
Food and beverage services									
Restaurant dining rooms	7.5	3.8	0.18	0.9		70	10	5.1	2
Cafeteria, fast food, bar	7.5	3.8	0.18	0.9		100	9	4.7	2
Kitchen (cooking)	7.5	3.8	0.12	0.6		20	14	7.0.2	2
Hotel/motel dormitories									
Bedroom, living room	5	2.5	0.06	0.3					
Lobby, pre-function	7.5	3.8	0.06	0.3		30	10	4.8	1

Multipurpose assembly	5	2.5	0.06	0.3		120	6	2.8	1
Office building									
Break room	5	2.5	0.12	0.6		50	7	3.5	1
Office space	5	2.5	0.06	0.3		5	17	8.5	1
Computer (not printing)	5	2.5	0.06	0.3		4	20	10	1
Public assembly spaces									
Auditorium seating area	5	2.5	0.06	0.3		150	5	2.7	1
Libraries	5	2.5	0.12	0.6		10	17	8.5	1
Museums / galleries	7.5	3.8	0.06	0.3		40	9	4.6	1
Residential									
Dwelling unit	5	2.5	0.06	0.3	F, G	F			1
Common corridor			0.06	0.3					
Retail									
Sales	7.5	3.8	0.12	0.6		15	16	7.8	2
Beauty salon	20	10	0.12	0.6		25	25	12.4	2
Sports and entertainment									
Gym, sports arena, play	20	10	0.18	0.9	E	7	45	23	2
Spectator areas	7.5	3.8	0.06	0.3		150	8	4.0	1
Disco, dance floor	20	10	0.06	0.3		100	21	10.3	2
Stages, studios	10	5	0.06	0.3		70	11	5.4	1

Notes: This table represents a diverse selection of occupancy categories; for a complete list, the standard itself should be consulted. The table is not valid in isolation; it must be used in conjunction with the accompanying notes published in the standard. The numbers are published here for information only.

Source: ASHRAE 62.2-2013 with permission

3.7 Indoor Air Quality Tools

The United States' Environmental Protection Agency has developed two indoor-air-quality-related programs and tools: the EPA Indoor Air Quality Building Education and Assessment Model (I-BEAM), a tool designed to provide guidance to building professionals and others interested in indoor air quality in commercial buildings, and Indoor airPLUS, which provides a variety of construction practices and technologies for new homes.³² Major construction and design features are covered including moisture control; radon and pest barriers; heating, ventilation, and air-conditioning (AC) systems; combustion pollutant control; low-emission materials; and home commissioning.

3.8 Building Materials and Ventilation

Material off-gassing is typically encountered with composites, glues, or adhesives and may cause major health concerns, which can be addressed by increased ventilation rates to

dilute the often toxic particles. The more effective approach in general and for natural ventilation design is to avoid harmful off-gassing from materials to the indoor environment in the first place. Environmental benign manufacturing³³ is a growing movement, which avoids various toxic compounds during the production process and subsequently during the lifetime of a material.³⁴

McDonough Braungart Design Chemistry's "Parameters for MBDC's Materials Assessment Protocol"³⁵ provides a system to classify material properties with regards to health and environmental risk factors. It distinguishes between human health criteria and ecological health criteria.

Human health criteria:

- Carcinogenicity
- Teratogenicity
- Reproductive toxicity
- Mutagenicity
- Endocrine disruption
- Acute toxicity
- Chronic toxicity
- Irritation of skin/mucous membranes
- Sensitization
- Other relevant data (skin penetration potential, flammability, etc.)

Ecological health criteria:

- Algae toxicity
- Bioaccumulation
- Climatic relevance
- Content of halogenated organic compounds
- Daphnia toxicity
- Fish toxicity
- Heavy metal content
- Persistence/biodegradation
- Other (water danger list, toxicity to soil organisms, etc.)

Notes

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 - 22 Mat Santamouris and Peter Wouters, *Building Ventilation: The State of the Art* (London: Earthscan, 2006).
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Chapter 4

Natural Ventilation and Climate

Environmental and climatic characteristics and conditions have a tremendous impact on the development of a spatial language for natural ventilation. Vernacular cultures manifested themselves out of necessity through a response to atmospheric and climatic properties, which were inscribed into architectural space. Humidity, dryness, heat, cold, and illumination intensity have left their mark in the built form, in roof types, surfaces, and opening proportions of buildings. Buildings were often positioned in relationship to the direction of the sun, the prevailing winds, and other influences. The need for vision, light, heating, and cooling is always based on the interrelation between the exterior climate and internal needs. This chapter outlines the major climatic terminology important to understanding the climate-related energy flow around buildings, which is critical in order to determine the resources available to drive the ventilation energy flow within a building.

Climate is a mean characteristic of daily and annual weather patterns driven by large-scale wind flow, precipitation, and the strong seasonal influence of solar radiation. Weather develops in the atmosphere's troposphere, which extends to approximately 10 km (6.2 miles) away from the Earth's surface. Long-term weather data is translated into a pattern of climate based on typical annual scenarios and reoccurring characteristics (i.e., seasons and their properties related to certain locations).

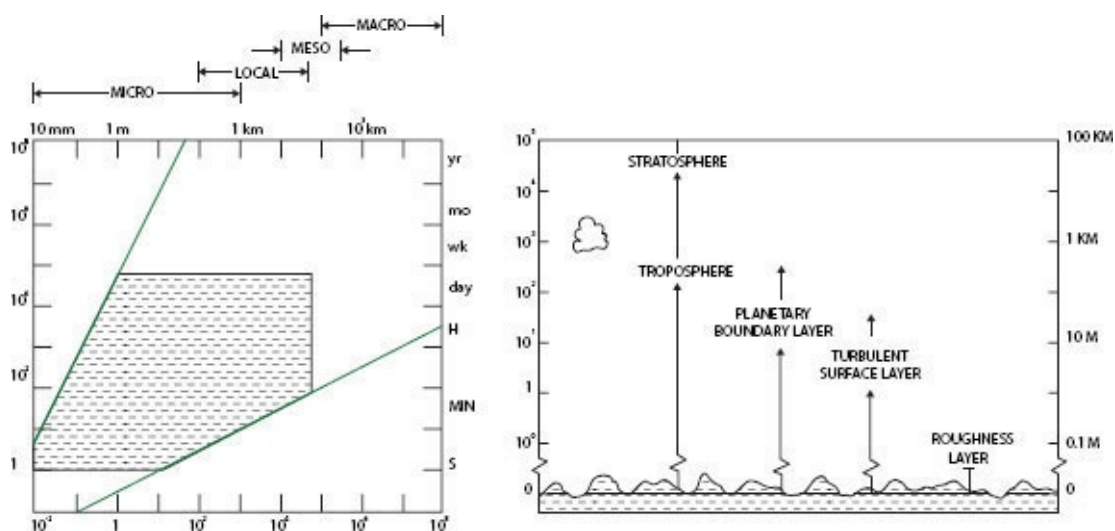


Figure 4.1

Weather/climate: the vertical structure of the atmosphere and the time and space scales of various atmospheric phenomena create the characteristic domain for boundary layer climate conditions.

4.1 Atmospheric Boundary Layer

The atmospheric boundary layer is the layer closest to and directly influenced by its interaction with the Earth's surface. This is the layer in which winds form and clouds and precipitation dominate the weather patterns. Wind flow is characterized by strong

turbulence in the low atmospheric layer that is generated by any ground obstacle or by thermal air flow instabilities. Thus, the Earth's surface influences the weather patterns and the weather patterns interact directly with the Earth's surface. Weather is a complex phenomenon created between solid matter of the multifaceted Earth surface and its vegetation, the oceans, and the gaseous shell of air enclosing the planet. Solar energy, gravity, and the Earth's rotational movement create the energy to initiate motion of the air. Air moves from high pressure to low pressure and thus the atmosphere is in constant motion across the surface of the Earth. The Earth's surface and the air are warmed by the sun; the air rises due to buoyancy and carries with it moisture evaporated from the Earth's surface and its bodies of water. Air volumes moving across the Earth's surface are constantly developing turbulence close to the surface. These turbulent flows decrease with increasing height. Wind is thus caused by air movement based on different air densities. Most often a statistical approach is used to approximate the possibility of turbulence and the prediction of what kind of wind can be expected at what time.¹

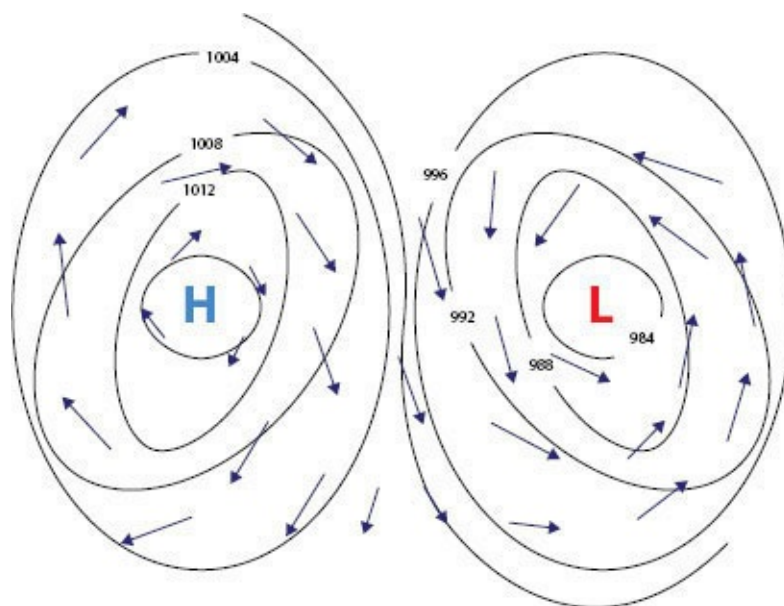


Figure 4.2

Wind forms between high and low pressure zones in order to even out the pressure differentials between the two zones.

Table 4.1 Aerodynamic properties of natural surfaces

Surface	Remarks	Roughness length z_0 (m)	Zero plane displacement (m)
Water	Still – open sea	$0.1\text{--}10.0 \times 10^{-5}$	–
Ice	Smooth	0.1×10^{-4}	–
Snow		$0.5\text{--}10.0 \times 10^{-4}$	–
Sand, desert		0.0003	–
Soils		0.001–0.01	–
Grass	0.02–0.1 m 0.25–1.0 m	0.003–0.01 0.04–0.10	≤ 0.07 ≤ 0.66
Agricultural crops		0.04–0.20	≤ 3.0
Orchards		0.5–1.0	≤ 4.0
Forests	Deciduous	1.0–6.0	20.0

	Coniferous	1.0–6.0	

Source: Adapted from T. R. Oke, *Boundary Layer Climates* (London; New York: Methuen, 1987), p. 57

An important indicator of surface conditions is the roughness length,² which is determined as a function of the nature of the ground and the geometry of existing obstacles, providing information on various terrain conditions.

Obviously, the force of gravity plays a significant role in the formation of weather. It holds the atmosphere around the Earth together and forms the counter force to the buoyancy of rising hot air. At a certain point, the gravitational force will be stronger than the buoyancy force of pressure differentials and the air will start moving back towards the Earth’s surface.

The second important force influencing the motion within the atmosphere is the Coriolis effect caused by the Earth’s rotation. The Earth is rotating around its axis, which stretches from the North to the South Pole. It causes the effect that an object at the equator moves at about 100 miles an hour (160 kilometers per hour) each day, while an object at the North Pole stands still. The Coriolis effect is a deflection of a moving object, when observed in a rotating reference frame. It comes into effect in the geostrophic flow, for example when air moves north from the equator and gets deflected into a counter-clockwise rotational motion, or when it moves south and is deflected in a clockwise motion. These motions can be seen in large-scale wind systems such as hurricanes. They follow a complex interaction of centrifugal forces and the forces caused by pressure gradients due to temperature (see [Figure 2.11](#): The Coriolis effect).

Urban areas create a boundary layer that is more unstable than the rural atmosphere because of the numerous obstacles and roughness factors.³ Temperature also plays a significant role as it increases towards the center of an urban area; thus urban areas create their own internal wind flows and gusts as part of urban microclimates.⁴

Understanding the velocity and direction at the inlet of a window is thus more complicated in an urban situation than it is in a rural situation, where the air flow through a building is based on pressure differences caused by wind or buoyancy or both. In urban surroundings, the natural forces are influenced by several factors, including⁵:

1. Roughness factor
2. Topographical factor
3. Wake factor

The roughness layer extends beyond the tops of surface roughness elements to at least one to three times their height and spacing proportion.

Experimental and computational definitions of these factors and their computational coefficients are the subject of major international research projects, foremost the URBVENT project⁶ funded by the European Community. Further information about the urban microclimate is provided in [Section 7.3](#).

4.2 The Science of Atmosphere and Climate

The Earth's climate is a large system of energy and mass exchanges and creates a balance between the solar energy system and the Earth's energy system.¹

The first law of thermodynamics (conservation of energy), which determines all energy balances, states that energy can neither be created nor be destroyed, only converted from one form to another. Four different forms of energy exist in the Earth's atmospheric system that are important to climatology: radiant, thermal, kinetic, and potential energy. The exchange of energy can occur in three different modes: convection, conduction, and radiation. The interaction of these forms of energy and these modes of transfer creates weather, and on a larger time scale climate.

According to Oke,⁷ the general system balance reads *Energy Input = Energy Output*. In climatic terms, this equality can only be valid over a longer period of time. Over shorter periods, the balance is not reached because of accumulation or depletion of system-inherent energy storage. Thus, the system balance should be more precisely written as *Energy Input = Energy Output + Energy Storage Change*. In the case of the Earth's climate, the Earth's surface acts as storage. Storing or retracting of solar radiation in the soil results in the rising or falling of soil temperatures. Wind systems are generated by horizontal thermal differences in the boundary layer.

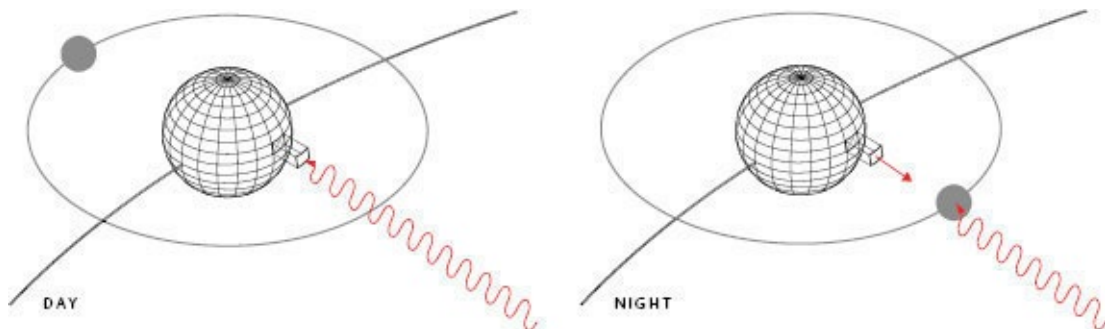


Figure 4.3

Thermodynamics and climate: thermal energy is constantly exchanged between the Earth's surface and the atmosphere by long-wave radiation, while shortwave radiation from the sun is absorbed by the Earth's surface.

Climate effects influencing natural ventilation strategies need to be evaluated on different scales.

XXXL = Atmospheric boundary layer: the atmospheric boundary layer moves across the rough and rigid surface of the Earth.

XXL = Macroclimate context: topography, solar geometry, lunar influence, landscape features.

XL = Meso-regional climate context: the larger extent of the site.

L = Local climate context: the features of a building site, neighboring buildings, and plants are related to the turbulent air layer that is in direct contact and interaction with them.

M = Building scale: the near building and interior building climate conditions.

S = Microclimate: the direct interaction between the building and the boundary layer around the building (indoor air quality / climate).

4.3 The Laminar Boundary Layer

The laminar boundary layer is the layer of atmospheric air with direct contact to the Earth. This is the definition for the very thin layer of air attached to the elements on the Earth's surface, which is basically a calm layer unaffected by the turbulent surface layer. The laminar boundary layer is only a few millimeters thick. It establishes a buffer between the surface and the more dynamic environmental condition above. The encyclopedia of climates is based on these scales of air layers.

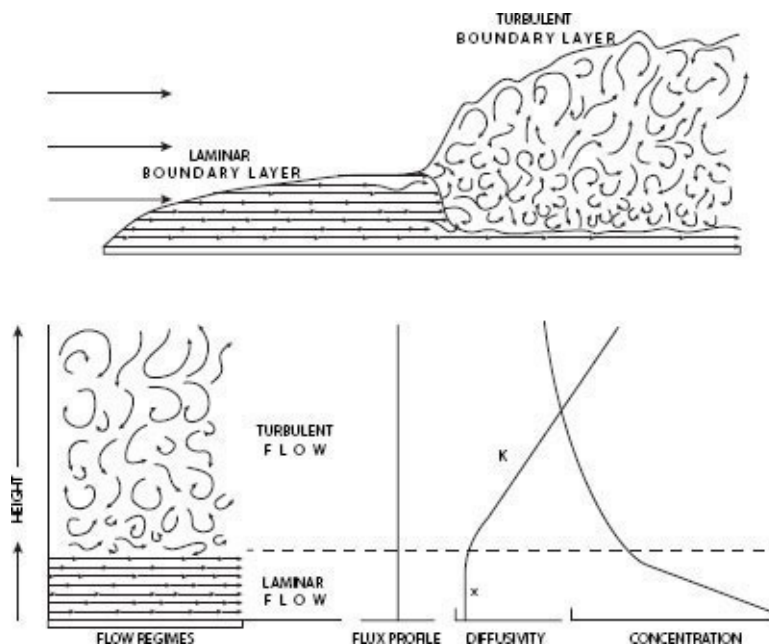


Figure 4.4

Laminar boundary layer: very close to the surface of the Earth the flow is laminar.

4.4 Encyclopedia of Climates

Based on the similarity of long-term weather patterns, which are generally called climate, Koeppen climate classifications were already developed in 1884 by the Russian-German climatologist Wladimir Köppen (1846–1940).⁸ These widely used world climate zone classification maps were based on vegetation, temperature, and precipitation.

Five main climate groups are identified in the system of the currently updated Koeppen–Geiger climate zone map:⁸

GROUP A: Tropical/megathermal climates

GROUP B: Dry (arid and semiarid) climates

GROUP C: Mild temperate/mesothermal climates

GROUP D: Continental/microthermal climates

GROUP E: Polar climates

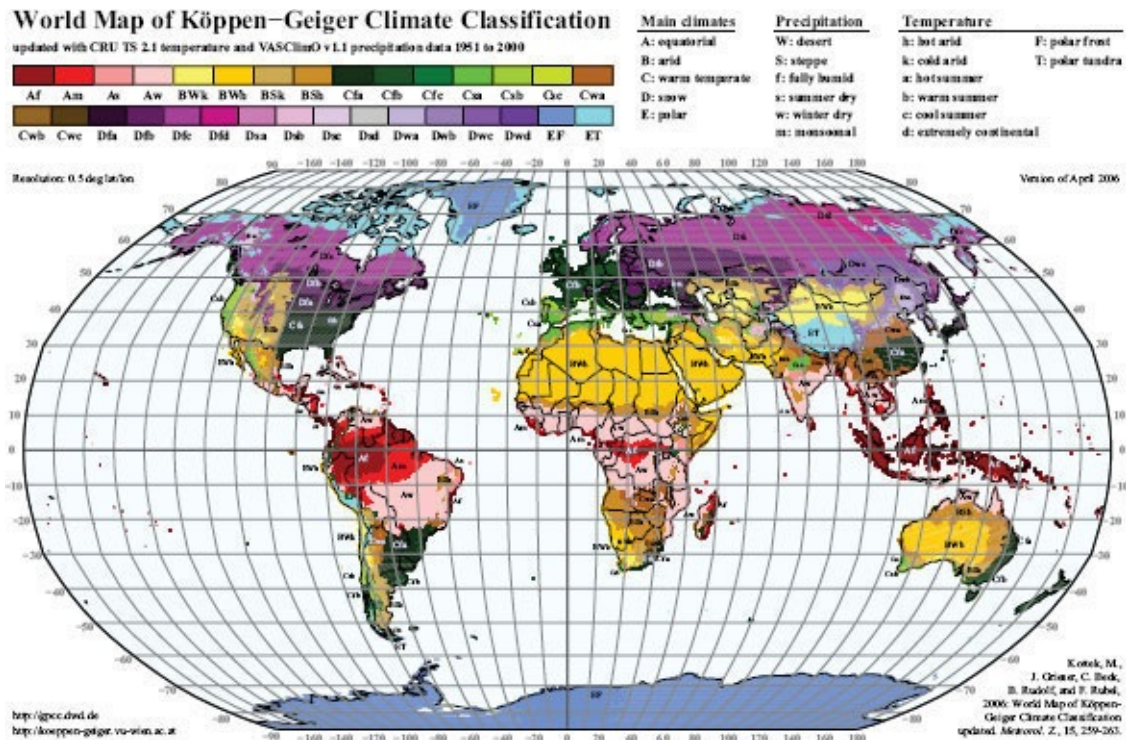


Figure 4.5

Köppen–Geiger map of world climates: these climate classifications are used worldwide to determine major climate characteristics of a region.

Each group is further divided into many fine-grained subcategories, which relate to precipitation and summer conditions versus winter conditions. Several modifications and clarifications have been added and suggested since the late nineteenth century in order to improve and fine-tune the system, and there are multiple suggestions for more fine-grained differentiations.

In the USA, the Department of Energy’s climate zone maps are based on ASHRAE⁹ and are more fine-grained, based on county lines. These maps are also used for prescriptive thermal insulation guidelines in the energy conservation codes.

Understanding the basic climate zone of a building site can provide preliminary input for the evaluation of ventilation strategy potentials. They can provide basic seasonal considerations about ventilation strategies and temperature differences. However, they do not yet take local or regional wind into consideration.

Climate scale winds are determined by wind patterns in the next layer of the climate scale. Many online sources are available to track wind resources: current, forecasted, and recorded.¹⁰ Multiple public and private services offer wind maps for most countries. The wind patterns can change significantly with the season as well as with local and microclimatic conditions. In the current age of internet information, many online resources distribute climate and specifically wind information.¹¹

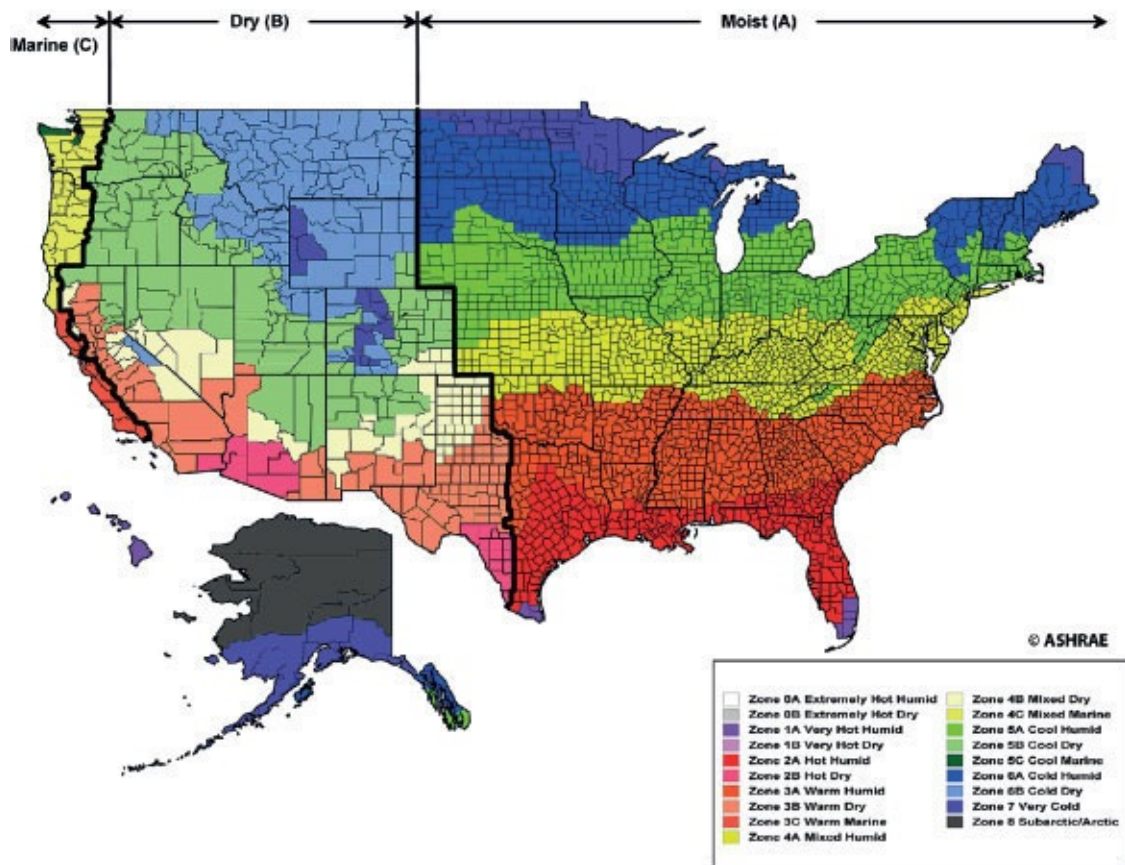


Figure 4.6

The climate maps of ASHRAE (American Society for Heating, Refrigeration and Air Conditioning Engineers) are based on heating degree days and used to determine prescriptive insulation requirements.

Large-scale topographical features are directly detectable on these climate zone maps. The north–south divide of the Rocky Mountains is the boundary between humid and dry climates in the USA; analogously, the Alps in Europe represent the boundary between temperate (cool to warm summers) and Mediterranean (warm to hot summers) climate zones.

4.5 Wind as a Resource

Multiple sources for wind information exist. Most resource sites address a specific audience – for example, the wind turbine industry – but wind enthusiasts such as surfers or sport sailors also use the Windfinder.¹² More information can be found in the resource section at the end of the book. Wind maps are published on a scale as large as the whole world¹³ or at continental or regional scales.

Wind maps for the United States are published by the National Renewable Energy Laboratory (NREL) and are mainly geared towards use as resource maps for wind energy producers.¹⁰

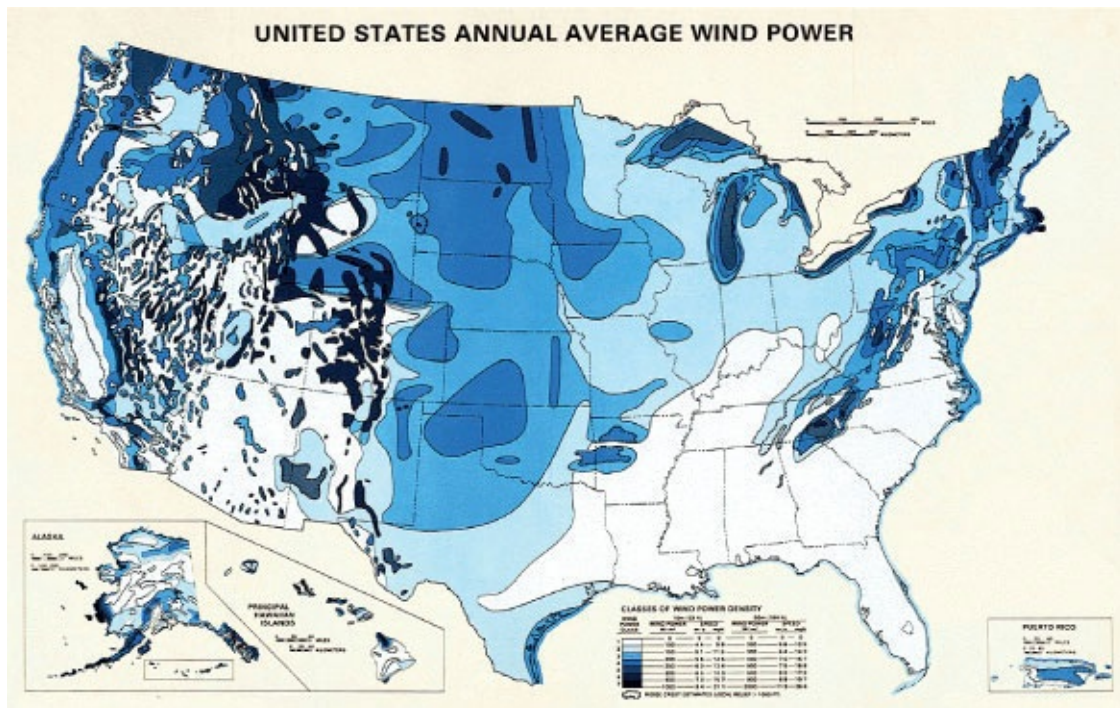


Figure 4.7

US wind resource map as published by the National Renewable Energy Laboratory (NREL); darker blue colors indicate higher wind power and velocity on an annual average.

4.6 A Brief History of Wind Notations

According to Nova,¹⁴ winds have been notated in a spherical rose of 360 degrees since antiquity, and the earliest notations go back to Philip of Medma (or Opunte), a disciple of Plato and Aristotle, who apparently drew one of the first diagrammatic notations of the winds, noting their names, directions, and characteristic qualities. Later, Aristotle and Thimostenes of Rhodos used the word *Thesis Anemon* (disposition of winds) for a similar graphic device. Current wind roses still use similar notation for each and every location in a multilayered notation. Wind roses are based on the compass of 360 degrees, noting the four cardinal directions and dividing the sphere into equal parts of quarters and thirds. Vitruvius already mentioned 24 distinctive winds in the second passage of his “Treatise on Architecture.”¹⁵ The current name *wind rose* has been used only since the Renaissance. A circle indicating the horizon, with concentric rings indicating intensities, and radial division for direction is the origin of the wind rose. It is still used today, for example in the weather visualization tool Climate Consultant developed by the University of California in Los Angeles.¹⁶

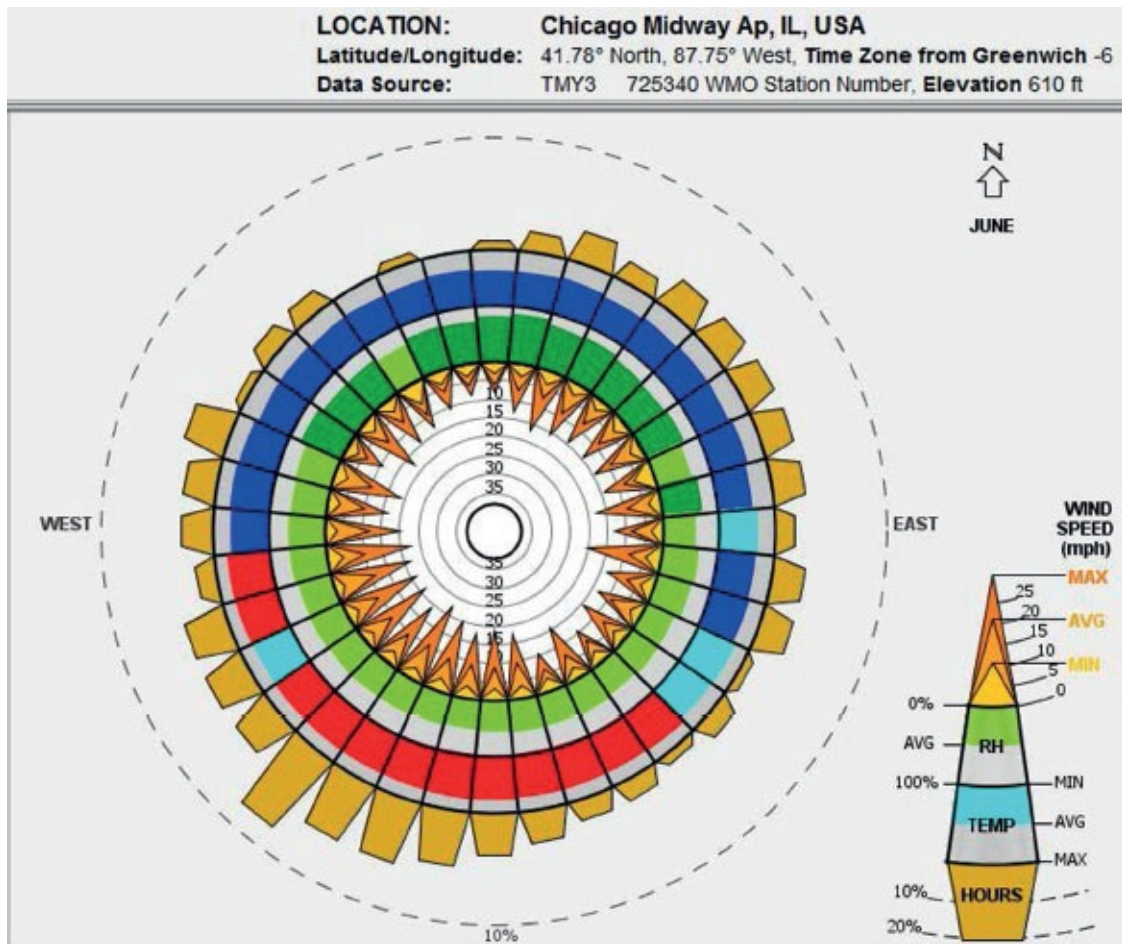


Figure 4.8

A wind rose for Chicago, IL, as derived from web-based Climate Consultant software tool.

Another important symbol for the meteorological indication of wind was introduced much later: the arrow in the weather forecast maps. According to Nova,¹⁷ this signifier dates back to the early days of the Royal Society in England. Measurement of air pressure using a barometer to describe wind dates back to Robert Boyle in 1665¹⁸ and Robert Hooke (1635–1703). In their treatise “Method for Making a History of the Weather” they summarized the first comprehensive study of weather and introduced the idea to use observation for forecasting.¹⁸ These early forecasting methods already included the recording of atmospheric data, including wind, but also temperature, dew point, cloud cover, and other data. The Royal Society provided a center for gathering and collecting weather data, which led to the first international coordination of meteorological observations and forecasting. Finally, in 1781 (according to Nova), the signature for weather conditions was noted: rain, snow, and storms all were assigned a symbol and noted in the *Ephemerides Societatis Meteorologicae Palatinae*.¹⁹ After a sequence of consecutive maps of weather phenomena and climate observations, Heinrich Wilhelm Brandes introduced the arrow into the weather maps,²⁰ and the little arrows have persisted in depictions and predictions of wind ever since 1820. The American scientist Elias Loomis (1811–1889) later introduced the length of the arrow to indicate the strength of winds when studying hurricanes in the mid-nineteenth century.²⁰ Finally, the English admiral Francis Beaufort (1774–1857) developed a scale in 1806 to measure the force of wind at sea, which was adapted to meteorology in 1873 and to this day carries his name.

The Beaufort scale ranges from the light air designated by wind force 1 to hurricanes designated by wind force 12.²¹

4.7 Personification of Winds

Prior to the scientific understanding of how winds in the Earth's atmosphere develop, mythological figures occupied the Earth and represented the wind phenomena. The wind was depicted as God, the breath of life, and Nova²² states that "there does not seem to be a culture that has not been profoundly touched" by the wind. For the Chinese, it is the

spirit of the world ... in Japanese mythology, it fills the emptiness between sky and earth ... for native Americans, it is a specter that lives in the clouds in the form of a wild white colt; the wind of the Hindu religion Vayu ... is the personification of the cosmic spirit and the word. In ancient Persia, the wind was responsible for cosmic and ethical equilibrium. In the Islamic world, it indicates the four compass points.

He finally quotes Saint Francis as a representative of early Christian, European thought: "All praise be yours, my Lord, through Brothers Wind and Air, and fair and stormy all the weather's mood, by which you cherish all that you have made."²³

4.7.1 Wind Names and their Characters

Although wind representations and forecasting have a long established history, a description of wind as an arrow with a direction and a strength/velocity indicator was introduced only in the nineteenth century. Winds in antiquity were assigned personalities and characters. In ancient Greece, winds were gods and had specific characteristics. Those eight wind deities were depicted in the tower of winds in Athens and were carried over into the ancient Roman civilization. The Latin metaphors and names of the winds carried into contemporary life in Italy, where the major wind characters in the ancient city of Rome are still based on ancient names. The Levante and the Scirocco determine the environmental quality of the inner-city climate of Rome as it relates to the changing patterns of wind streaming up or down the Tiber River and swirling around the seven hills.

Homer mentioned four winds in the *Odyssey*: *Eurus*, *Notos*, *Zephyrus*, and *Boreas*.²⁴ These names in Greek related the winds to the directions they came from. *Notos* (south) came from beyond Egypt, while *Boreas* came from the Black Sea. Vitruvius then translated the Greek names into Latin, and they appear again in the Renaissance in the architectural treatise of Scamozzi²⁵ and in the Tower of the Winds at the Vatican.²⁶

The sometimes so-called 'dark' middle ages also had interpreters of weather and natural science, for example Hildegard of Bingen, who wrote *A Book of the Earths*.²⁷

D'Arcy Wentworth Thompson²⁸ provided an interesting analysis of the Greek winds going back to the wind rose of Aristotle. He claimed that the wind rose of antiquity may not have been equally divided into quarters, but into sections of thirds and thus have been more connected to the solar path and the movement of the sun in the various seasons than to the cardinal directions.



Figure 4.10

The Birth of Venus (Nascita di Venere) by Sandro Botticelli (1485/86), with a personalized wind god blowing at her.

4.7.1.2 Anemoi

The lower Greek and Roman wind gods were named according to their character and cardinal directions. These characters are still dominant in the Roman weather forecast and the Italian language. Boreas/Aquilo represented the vicious North, Notus/Auster came from the South, Eurus/Vulturnus came from the East, and Zephyr/Favonius were the favorite westerly winds that brought food. They were brought to everlasting fame by Renaissance painter Sandro Botticelli (1445–1510) in his painting *The Birth of Venus* bringing flowers and in *La Primavera* bringing rain to fertilize the grounds and plants (in the Uffizi, Florence).³⁰

4.7.1.3 Boreas

Boreas was the northern wind that brought cold weather and winter to Rome and Italy. Between 1578 and 1580 the Bolognese architect Ottaviano Mascherino (1536–1606) constructed the Torre dei Venti³¹ on top of the Vatican library, which contained a large wind rose and an anemometer in the ceiling by Ignazio Danti (1536–1586) as well as a meridian that was used to install and verify the Gregorian calendar. One of the frescoes by Nicolò Circignani (1517–1596)³² depicts Boreas, representing the north winds, with the inscription “Aquilone pandetur omne malum,”³³ indicating that everything bad came from the North: bad weather, bad temper, and bad habits of intruding alien forces (see [Figure 10.4](#)). In the sixteenth century, scientific investigations had already found explanation for the wind phenomena beyond the gods: “in an Aristotelian sense as the result of a battle between the warm and the dry exhalations of the earth and their downward movement, after which they cool down and come into contact with the humid air of the atmosphere.” Wind as a result of different air densities was also scientifically discussed in the sixteenth

century as noted by Alessandro Nova.³⁴

4.7.2 Other Mythological Airy Characters

4.7.2.1 Angels and Spirits

Angels are usually invisible creatures of the sky or the sacred heaven, who help humans comprehend when rational explanations fail.³⁵ Angels are considered spiritual symbols of unexplainable phenomena and messengers of God. The most common depiction of angels in Christian mythology is the archangel depicted in the Annunciation.³⁷ Angels most likely inherited some of Hermes' characteristics. In Greek mythology, Hermes was the god of messengers; later he became the Roman Mercurio with similar attributes. He helped travelers at border crossings, but also held his hand over thieves and merchants. Hermes was depicted usually with a winged helmet and as such was considered a figure of air. The winged helmet must have developed into the wings of the angels in Christian mythology and depictions as in the basilica S. Giovanni in Laterano, Rome, by Borromini (1599–1667).



Figure 4.11

Sculpted angel with ruffled feathered wings in S. Giovanni in Laterano by Francesco Borromini (1599–1667), around 1646.

4.7.2.2 Ariel

Wicked and violent demons have found testimony in a particular great work of the Elizabethan theater, William Shakespeare's *The Tempest*, where Ariel, the spirit, sets in motion the tempest storm as ordered by Prospero, the stranded Duke of Milan.

Prospero: Hast thou, spirit,
perform'd to point the tempest that I bade thee?

Ariel: To every article.

I boarded the king's ship; now on the beak,
Now in the waist, the deck, in every cabin,
I flam'd amazement: sometime I'd divide,
And burn in many places; on the topmast,
The yards and boresprit, would I flame distinctly,
Then meet and join. Jove's lightnings, the precursors
O'th'dreadful thunder-claps, more momentary
And sight-outrunning were not: the fire and cracks
Of sulphurous roaring the most mighty Neptune
Seem to besiege, and make his bold waves tremble,
Yea, his dread trident shake.³⁶

4.8 Condensation and Clouds

Hot air can hold more absolute humidity than cold air. This relationship is exemplified in the psychrometric chart, in which the relative humidity level indicates the capacity of air at a certain temperature to hold moisture (see [Figure 2.12](#)). When the temperature of an air sample drops, for example when it contacts a cold glass surface, the water vapor condenses out of the air and creates small air droplets on the glass surface. The level of humidity has a significant impact on human thermal comfort, especially at elevated temperatures, as noted in respective thermal comfort standards.³⁷ While dry air cannot absorb solar radiation, the humidity in the air, the small dissolved water droplets, can absorb solar radiation. That is one reason why humid air can warm up directly, while dry air in arid climates warms up by heat conduction from solid surfaces that have been warmed up by solar radiation. Therefore, a stone can get warm exposed to sun in winter, while the air remains cold. Humid air in summer does not cool down as much as dry arid air when nights get fairly cold in arid desert climates. Although the overall content of humidity in air is only approximately one percent, this small fraction of air has a major effect on climatic variations.

4.9 Impact on Buildings and Interior Spaces

All major characteristics of climate have a direct influence on the natural ventilation capacity within a building: outside temperature and its diurnal changes, relative humidity, and wind velocity and direction. Solar radiation plays an indirect role as it creates hot spots, which enable or restrict temperature-induced air movement.

Horizontal temperature variations in the earth-atmosphere system give rise to horizontal pressure difference systems that result in air motion (winds). Thermal energy from the solar energy cycle is converted into the kinetic energy of the wind system. Within the

kinetic system, the energy cascades down the ladder of atmospheric scales until it reaches the molecular scale of smaller-size eddies and is finally dissipated as heat when it returns to the thermal portion of the solar energy cycle. The building sits right in-between these different scales and thus connects small-scale eddies with large-scale weather patterns. Ideally, the building interior makes optimal use of these multi-scale processes. The building can act as an obstacle to or facilitator of flow and enhances flow around and within for various outcomes for interior occupant thermal comfort as well as for pedestrian comfort outside of the building. How architects can impact these various flow patterns will be discussed in later sections of this book. The urban microclimate and pedestrian comfort is very well covered by Erell, Pearlmutter and Williamson in their 2011 *Urban Microclimate*.³⁹

4.10 Wind Systems

Large-scale wind systems such as jet streams and hurricanes are based on continental scale temperature differences between cold and hot air masses.

Prevailing winds are very common climate features and need to be considered when developing natural ventilation strategies. They typically change with the season or with major shifts in weather patterns. The mistral in the Mediterranean is a strong wind from the north, crossing the sea into the west coast of Italy away from the southern coast of France. The jet stream in the Midwest of the USA blows from the south for most of the summer, bringing warm and humid air from the Gulf of Mexico. The northwesterly wind in the north of Germany blowing from the North Sea coast usually brings rain from the Azores to the shore.

Regional wind systems are based on topographical features and related temperature difference based on these changes in topographical height. The most commonly known regional wind systems are sea-land breezes and mountain-valley breezes.³⁸ In addition, there are also urban-rural breezes and forest-grassland breezes, which can significantly influence wind direction and velocity and thus should never be ignored.

Every topographical change has an influence on the wind pattern. Moderate changes create moderate shifts in flow pattern and steep topographical changes create eddies or even turbulence.

Table 4.2 Local thermal breezes

Local wind systems	System characteristics, scale of speed and height of thermal layer
Land-Sea (or lake)	During the day, the sea or lake breeze moves from above the water towards the land and reverses at night flowing from land to sea/lake. The daytime circulation has a larger extension than the evening/night circulation. Speed: 2 to 5 m/s (395 to 985 f/m) Height of the thermal layer: 1 to 2 km (0.62 to 1.25 miles)
Mountain-Valley	Valleys produce their own local wind systems; horizontal temperature and pressure differences cause local breezes. By day, the air above the slope warms and cool air sinks into the valley center. Speed of uplift along slope: 2 to 4 m/s (395 to 787 f/m) Height of the thermal layer: 20 to 40 m (65.6 to 131 ft)
Urban-Rural	With weak regional winds, a city can generate ‘country breezes’. Vertical instability aids the three-dimensional circulation. Heat island intensity is related to the size of the city.

Forest-Grassland	Thermal contrast between cool sub-canopy forest interior by day and unshaded surrounding fields or grassland.

Source: T. R. Oke, *Boundary Layer Climates* (London; New York: Methuen, 1987), pp. 167–170, 290

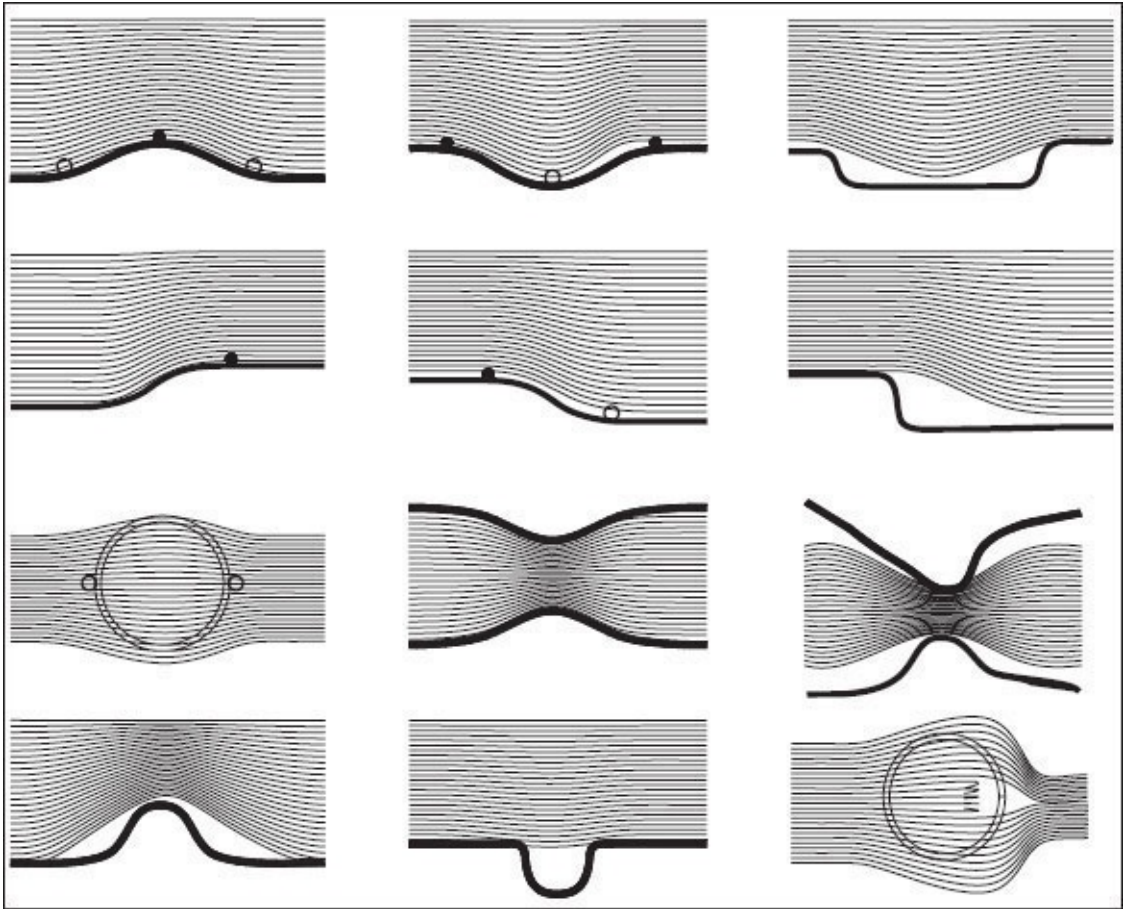


Figure 4.12

Flow pattern around topographic elements and features.

4.11 How Architects Can Influence the Impact of Wind on the Building Ventilation Path

In the context of atmospheric air flow, every building can be considered an obstacle to the local and regional scale of the wind system. The air has to move around the obstacle or through the obstacle, and the shape of the building as well as its orientation and position influences the flow pattern around and through the building. The building builds up resistance against the flow, and this resistance results in the necessary pressure differential to force the flow of air through a building following the designed flow path.

Buildings can also be sources of thermal energy. Dense urban masses can change the wind patterns and temperature scales of the open landscape around them by creating distinct urban climates. Large areas of urban agglomeration influence larger climate/weather patterns. The most commonly known scenario of building-induced weather is the urban heat island (UHI) effect, where a significant difference in temperature between the urban area and the surrounding rural area can be experienced under certain weather conditions.³⁹ Developing pressure differentials in the urban context is more challenging than in the open landscape, as the air flow patterns within the urban street

canyon are less predictable and less constant (see [Section 7.3](#)).

4.12 Information for Architects to Start the Design Process

In order to utilize wind as a ventilation driver, the building shape needs to be designed to build up resistance against the flow, so that a pressure differential can be developed across the designed internal flow path. Openings need to be positioned as inlets and outlets on either side of the flow path between high-pressure zones and negative/low-pressure zones on the leeward side. If stack ventilation is considered, the height of the stack needs to be developed in proportion to the temperature difference within the outside boundary layer.

4.12.1 Macro-Scale Information

Understanding prevailing wind patterns (wind rose)

4.12.2 Regional Scale Information

Understanding and determining terrain/topography/bodies of water

4.12.3 Micro-Scale Information

Understanding and determining:

1. Site topography and trees, etc.
2. Heat islands around the building
3. 'Cool' landscaping around the building
4. Shading around the building
5. Summer-winter distinction / seasonal planting
6. Ground temperature due to materiality
7. Humidity content in air, soil, and wind
8. Positioning the building in the stream of the wind

4.12.4 Final Scale: The Building Scale

Positioning the apertures in the stream of the wind (or creating the pressure difference by positioning the openings).

A major challenge of all of these scales of systems interacting with the building is their dynamic and transient state.

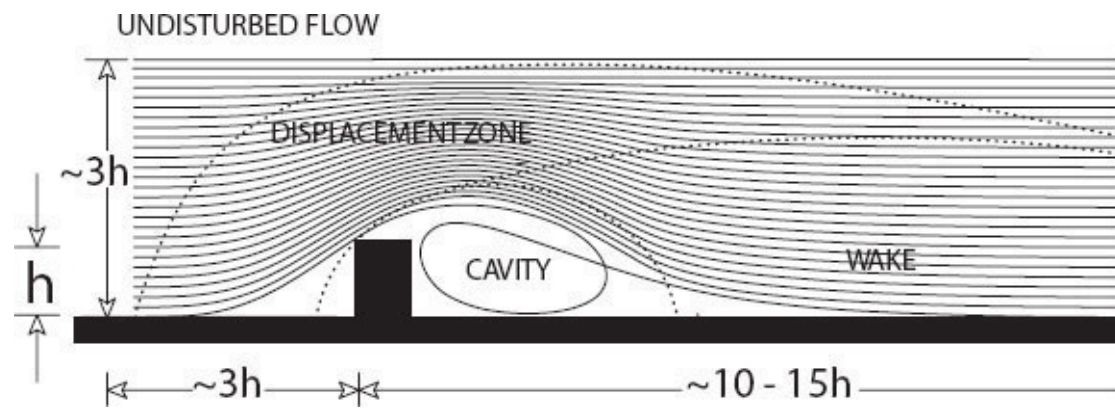


Figure 4.13

Urban flow pattern around buildings.

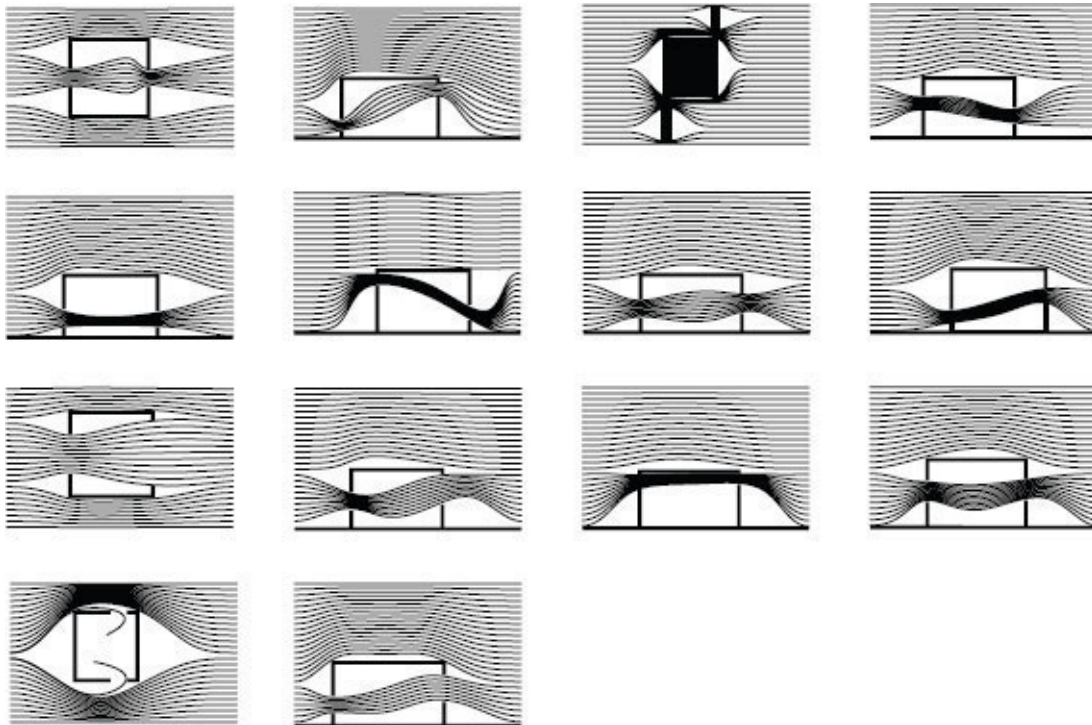


Figure 4.14

Flow pattern around and through buildings.

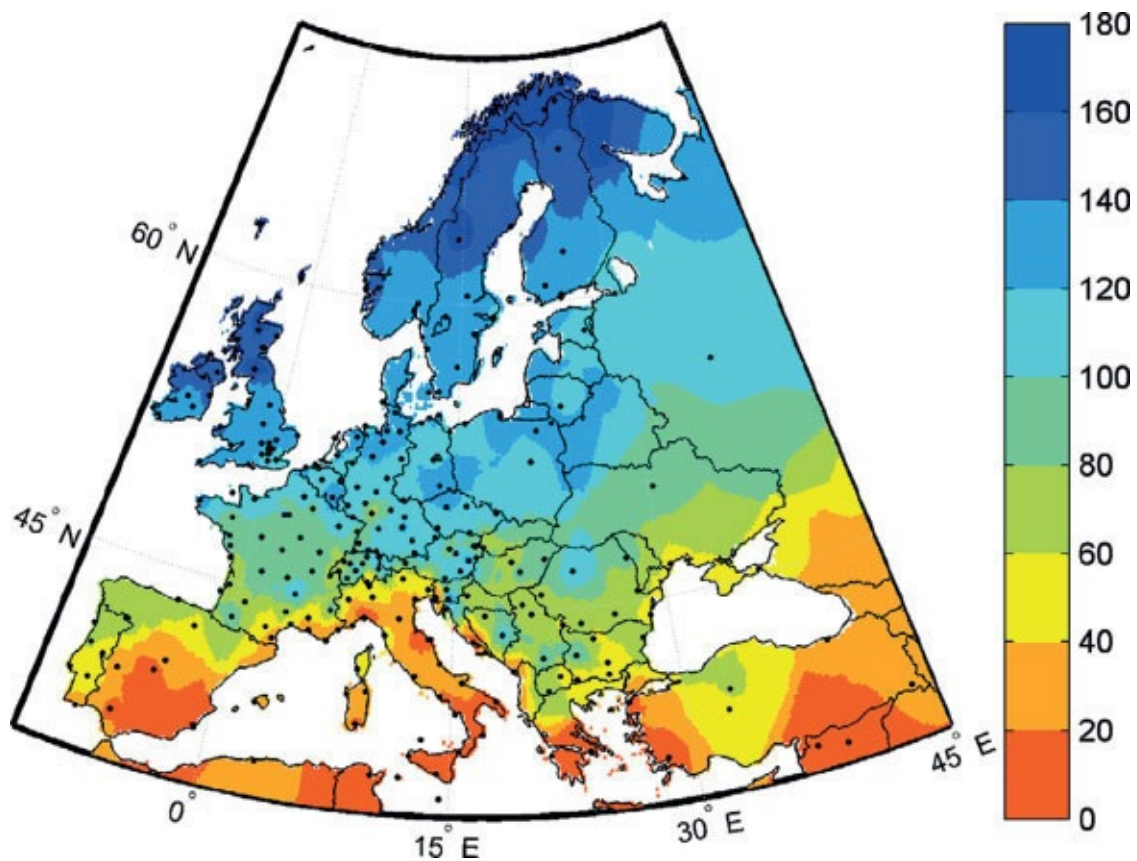


Figure 4.15

Climate zones for natural ventilation: map of mean climatic cooling potential in KWh per night based on Meteonorm data for Europe.

4.13 Climates for Natural Ventilation

Mapping projects in Europe⁴⁰ and the USA⁴¹ have been undertaken to develop indicators for locations with good climate context for implementation of natural ventilation. They will aid architects, engineers, and designers in determining the maximal potential for natural ventilation given the climate conditions of their site. As an example, the above map highlights the potential for nighttime ventilation in Europe.⁴²

Notes

- 1 T. R. Oke, *Boundary Layer Climates* (London; New York: Methuen, 1987), p. 27.
- 2 Ibid., p. 57, Table 2.2.
- 3 Helmut Erich Landsberg, *The Urban Climate* (New York: Academic Press, 1981).
- 4 Evyatar Erell, David Pearlmutter, and T. J. Williamson, *Urban Microclimate: Designing the Spaces between Buildings*, 1st ed. (London; Washington, D.C.: Earthscan, 2011).
- 5 Francis Santamouris, M. Allard, and Alvarez Servando, *Natural Ventilation in Buildings: A Design Handbook* (London: James & James, 1998).
- 6 Istworld, "Natural Ventilation in Urban Areas – Potential Assessment and Optimal Façade Design (URBVENT)," <http://www.ist-world.org/ProjectDetails.aspx?ProjectId=857bad8bd0a3434f983d9faf1c6d2d86&SourceDatabaseId=9cd97ac2e51045e39c2ad6b86dce1ac2> (accessed 5/20/2014).
- 7 T. R. Oke, *Boundary Layer Climates* (London; New York: Methuen, 1987), p. 7.
- 8 *World Maps of Köppen-Geiger Climate Classification*, <http://koeppen-geiger.vu-wien.ac.at/> (accessed 5/20/2014).

- 9 ASHRAE, "Climate Data Center," <https://www.ashrae.org/resources-publications/bookstore/climate-data-center> (accessed 5/20/2014).
- 10 National Renewable Energy Laboratory, *Wind Energy Resource Atlas of the United States*, <http://rredc.nrel.gov/wind/pubs/atlas/> (accessed 5/9/2014).
- 11 Intellicast, "Current Winds," <http://www.intellicast.com/Global/Wind/Current.aspx?region=europ> (accessed 5/8/2014).
- 12 Windfinder, <http://www.windfinder.com> (accessed 5/8/2014).
- 13 See <http://earth.nullschool.net/#current/wind/surface/level/orthographic=-2.34,48.43,280> (accessed 5/8/2014).
- 14 Alessandro Nova, *The Book of the Wind: The Representation of the Invisible* (Montreal: Ithaca, 2011).
- 15 Vitruvius, *The Ten Books on Architecture (De Architectura)*, book I, translation Morris Hicky Morgan (New York: Dover Publications, 1960), p. B.
- 16 "Energy Design Tools," <http://www.energy-design-tools.aud.ucla.edu/> (accessed 5/8/2014).
- 17 Nova, *The Book of the Wind: The Representation of the Invisible* (Montreal: Ithaca, 2011).
- 18 Ibid., p. 186.
- 19 Ibid., p. 187.
- 20 Ibid., p. 191.
- 21 The Beaufort Wind Scale, NOAA, <http://www.spc.noaa.gov/faq/tornado/beaufort.html> (accessed 5/8/2014).
- 22 Nova, *The Book of the Wind: The Representation of the Invisible* (Montreal: Ithaca, 2011), p. 197.
- 23 Ibid.
- 24 Ibid.
- 25 Vincenzo Scamozzi, *L'idea Della Architettura Universale*, 2 vols. (Ridgewood, NJ: Gregg Press, 1964).
- 26 See <http://www.archiviosegretovaticano.va/en/archivio/ambienti/torre-dei-venti/> (accessed 5/8/2014).
- 27 See "The Book of Earths: St. Hildegard's Universe," <http://www.sacred-texts.com/earth/boe/boe29.htm>.
- 28 D'Arcy Wentworth Thompson, "The Greek Winds," *Classical Review*, 32(3/4), 1918, pp. 49–56.
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- 30 See <http://www.polomuseale.firenze.it/> (accessed 5/8/2014).
- 31 See <http://asv.vatican.va/it/arch/torre.htm> (accessed 3/5/2011).
- 32 See http://asv.vatican.va/en/visit/VR_affr/VR.htm (accessed 3/5/2011).
- 33 See http://asv.vatican.va/en/visit/VR_affr/s_mer.htm (accessed 3/5/2011).
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- 38 T. R. Oke, *Boundary Layer Climates* (London; New York: Methuen, 1987), pp. 158–189.
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- 41 J. W. Axley and S. J. Emmerich, "A Method to Assess the Suitability of a Climate for Natural Ventilation of Commercial Buildings," in: *Proceedings of Indoor Air 2002*, Vol. 2 (Monterey, California), pp. 854–859.
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Chapter 5

Inherited Spatial Archetypes for Natural Ventilation

Architectural theory, history, and design have always asked about the origin of form, shape, and space. This chapter will therefore explore the spatial archetypes created over time based on “generative concepts or mind models,” a term coined by Lewcock.¹ Presented here is a genealogy of archetypes for spaces capable of moving air. There are multiple ways of looking at traditions in architecture. Bernard Rudofsky² promoted the approach that the vernacular is the *other*, beyond the artistic creative architect, the *architecture without architects*. Another approach investigates tradition as part of an inclusive architectural development and as archetypal base for architectural thinking in general, as discussed by Aldo Rossi in *The Architecture of the City*.³ This approach has been traced to the writings of Carl G. Jung on archetypes in *Man and His Symbols*⁴ and to Gaston Bachelard in *The Poetics of Space*⁵ and *Air and Dreams: An Essay on the Imagination of Movement*.⁶

These traditions were practiced prior to industrialization and prior to mechanically enhanced environmental controls. Currently, they enjoy a revival and reinvestigation as a source for climate-responsive design, with new publications appearing and with increased research interest addressing traditional building and construction types. This renewed interest parallels the attention of architectural historiography to the global versus a purely Western approach to architecture. For example, in *Vernacular Architecture in the Twenty-First Century* Lewcock⁷ discusses “generative concepts” and analyzes vernacular architecture as mind models for architectural archetypes. He identifies the cave, the covered and open courtyard, and the hearth. Further following Gottfried Semper,⁸ he identifies the plinth as a means against dampness, the roof against rain, and the screen or wall against the wind. Gaston Bachelard’s *The Poetics of Space*⁹ discusses archetypes as basis for memory. Fire and fire exhaust became integrated spatial components of these archetypal formations.

5.1 Shared Ideas as Archetypes

Environmental characteristics have significant impact on the development of spatial language, symbols, and icons, as culture is made manifest through atmospheric and climatic properties, and inscribed into architectural space. Humidity, dryness, heat, cold, and light intensity have left their mark in the built form, roof type, surfaces, and openings of buildings. Buildings are positioned in relation to the direction of the sun, the prevailing winds, and other influences. The need for vision, light, heating, and cooling is always based on the interrelation between the exterior climate and internal needs. Addressing these challenges with limited material resources has led to refined archetypes across

various cultures, climate zones, geographies, and continents.

In the past, anecdotal information based on travel reports¹⁰ often served as the only account of traditional architecture in distant locations. Both vernacular and indigenous architecture can be regarded as only one resource for the development of spatial typological strategies for passive cooling and natural ventilation. However, recently research teams have picked up the challenge to reproduce the spatial environmental strategies of traditional architecture through measurements and simulated models and have developed scientific evidence of their actual operations.

These studies have revealed that the adaptation of vernacular passive natural ventilation strategies into contemporary architecture in current societies is often considered old fashioned or obsolete, which poses a hurdle to a widespread implementation of these strategies. Isaac A. Meir and Susan C. Roaf have reported on this issue relating to the Middle East.¹¹

5.2 The Importance of Inherited Vernacular Strategies for Sustainable Design

Recently, vernacular architecture has enjoyed new attention as an architectural concept that is based on the local climate and terrain condition, nurturing the needs and demands of the user. Multiple recent research projects have pointed out that vernacular or indigenous architecture's approach to passive design strategies is often highlighted as a precedent for environmentally conscious architecture without scientifically quantified proof and without actual understanding of former comfort expectations and building performance. This can obviously lead to severe misunderstandings, if a traditional strategy is evaluated against contemporary comfort and convenience expectations. In addition, traditional building strategies may require unusual control strategies, based on very different parameters and again different comfort acceptance levels.¹²

It is also important to note that traditional buildings may have incorporated more than one strategy to respond to comfort needs of occupants and are not per se meeting contemporary user expectations. Thus, the examples of traditional architecture presented here have been selected based on available literature and personal observation and studies, because they have provided passive cooling potential in the past and might still provide cooling today. However, caution is necessary, because an adaption of these strategies might not be directly possible for contemporary energy-efficient projects due to changes in occupancy patterns, lifestyle, and understanding of convenience as well as comfort.¹³

Bernard Rudofsky¹⁴ directed attention to “architecture without architects” at a time when high modern architecture was entering a time of crisis. He finds many words for the architecture he would like to reveal: “vernacular, anonymous, spontaneous, indigenous, rural ...”

There is much to learn from architecture before it became an expert's art. The untutored builders in space and time ... demonstrate an admirable talent for fitting

their buildings into the natural surroundings. Instead of trying to ‘conquer’ nature, as we do, they welcome vagaries of climate and the challenge of topography.

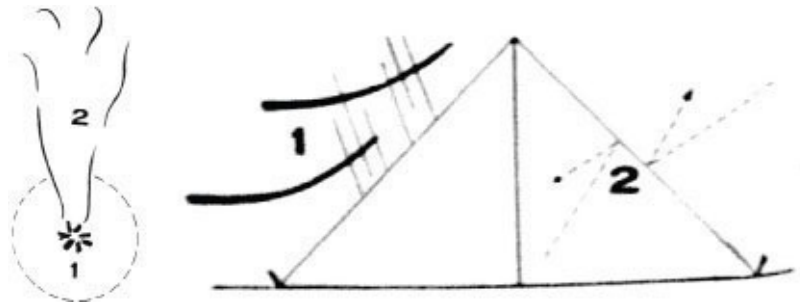


Figure 5.1

Reyner Banham describes two tribes in his *Architecture of the Well-Tempered Environment*, those who would use the found wood to make a fire and those who would build a shelter.

Contrary to Rudofsky’s idea of an anonymous and spontaneous way of building is the interpretation by Ronald Lewcock of vernacular architecture as an archetype, and this also needs to be considered.

In his important history of architecture and the development of environmental controls, Reyner Banham¹⁵ introduces the fable of two tribes encountering a stack of wood. Based on their traditions, one tribe will make a fire and thus stay warm, but will need to find more wood the next day, while the other tribe will build a shelter to be protected from the wind.

Umberto Eco¹⁶ considers spatial types as a syntactic code within the variety of architectural codes. The other codes he reveals are technical codes that have no communicative content (the column just stands up) and semantic codes (the ornament has a religious meaning). The syntax, the spatial type, is thus the conceptual logic which relates the technical codes to the communicative semantic content of an architectural form or element.

5.3 Space Types: Cave, Courtyard, Chimney, Passage/Arcade/Loggia, Basket

Ventilation in traditional architecture has often been a major provider of form, and following these theories of archetypal generic concepts, five different inherited spatial concepts have been identified here.

While the three space types introduced in [Chapter 1](#) (bolted, incorporated, sliding) are based on contemporary compositional principles, spaces can also be classified typologically with respect to their relationship to air movement. Here we distinguish between caves, courtyards, passages/loggia, baskets and chimneys/wind catchers. They can be combined to form contemporary space types ([Chapter 8](#)).

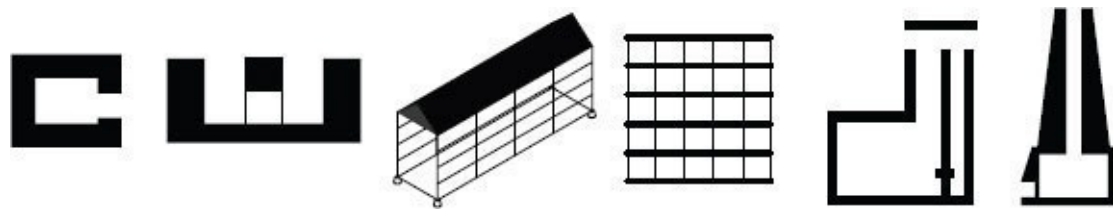


Figure 5.2

These major inherited spatial typologies are analyzed with respect to promotion of air movement: caves, courtyards, passage/loggia, baskets, wind catchers and chimneys (left to right).

5.3.1 Utilizing Temperature-Induced Pressure Differentials: Caves

The cave is a recognized archetypal spatial configuration and has a significant place in Gaston Bachelard's *The Poetics of Space* as the ultimate house and shelter and an image of protected intimacy.

One of the primal ways to shelter from the elements is to occupy an existing cave or to dig into the ground to create a cave for shelter. The cave underground is warmer in winter and cooler in summer because of the great thermal mass and time lag of heat transfer. The first means to utilize the force of air movement for ventilation may well have been the channeling of air through caves following pressure differentials developed by the thermal mass of the cave walls, the difference to the outside temperature, and the height of the cave.

Using caves for cooling or heating comfort and to channel wind by the stack effect is most likely one of the oldest environmental control strategies. Cave dwellings are still fairly common in hot and dry regions of the world, for example in southern Spain, southern Italy, southeastern Anatolia, Kapadokia of Turkey, France, and China. Some historic building types, such as the Harran Houses¹⁷ in southeastern Anatolia,¹⁸ made of square rooms with corbelled domed roof structures, may have followed a cave dwelling. Cave dwellings take advantage of the reasonably stable temperature of rocks or soil into which the cave is carved. A few examples through the centuries and across continents are discussed here.

5.3.1.1 The Kiva of the Anasazi People

In addition to using the ground as a heat sink, some cave dwellers have developed quite sophisticated ventilation mechanisms to channel air into and through the caves. The now unoccupied Anasazi Pueblos in southern Colorado most likely used ventilation shafts behind the fire place to provide space ventilation as well as to supply air for the combustion of the fire. The Anasazi kiva, most likely ceremonial spaces, were ventilated by a separate wind-catching chimney that was connected to the inhabitable cave and also provided heating to the kiva cave.¹⁹

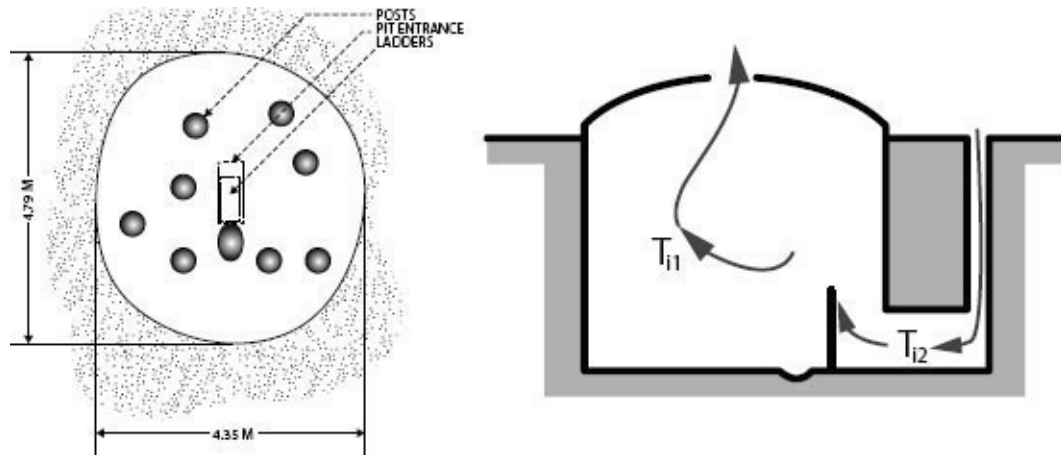


Figure 5.3

Anasazi cave dwellings demonstrated sophisticated ventilation strategies as they were identified to utilize wind catching technologies.

Adil Sharag-Eldin and James Dalton from Kent State¹⁹ examined a potential scenario for an Anasazi kiva. Their team measured a reconstructed kiva in Overton, Nevada, that did not have a ventilation shaft and then modeled a complete kiva with ventilation shaft using energy-modeling software. The results indicate that the round, below-ground spaces, whose function is still not completely understood by archaeologists, may have become rather uncomfortable during heating and needed the ventilation chamber as a means to drive the cooling process. Comfort was assessed based on current comfort understanding. However, the comfort expectations 1,000 years ago, when the kivas were occupied, might have been very different. The adjustments made to the spatial composition were based on a record by anthropologist Walter Fewkes dating back to 1908.²⁰ This archaeologist was puzzled by air shafts that showed no signs of smoke, and called them chimney-like, but not chimneys. The shafts were also too small to be used as entrances. Thus, the simulation conducted by the Kent State team¹⁹ indeed provided a potential interpretation of the spatial layout. If that chimney-like shaft was actually used to introduce fresh air at the level of the occupants above the cave floor, the spatial system might actually make sense as a ventilation shaft.

5.3.1.2 The Corbelled Domes of the Harran Houses in Southeast Anatolia, Turkey

Domed structures are very common in regions in which very little construction timber was available for roof structures, such as in the high plateau desert regions of upper Mesopotamia and the high desert plateau of central Iran. Instead of flat roof structures constructed of timber beams, these mostly residential structures of northern Syria and southeastern Turkey have roof structures that are not vaulted domes, but corbelled domes. They are constructed of spiraling layers of mud bricks with a central opening at the top of the roof to exhaust smoke, quite similar to the tipi tent in North America. The houses are well known for their passive cooling strategies based on their spatial geometries. These strategies are employed in traditional Turkish Harran houses, located in the Harran district of Şanlıurfa province in the southeast part of Turkey. The houses date back multiple centuries, and the origin of the typology is unclear. Domed and conical roofs are common

and unique to traditional architecture in the Middle East as well as throughout the Mediterranean Basin. They employ complex conditioning and energy-efficiency strategies for extremely hot-arid climates with high solar insulations of $\sim 7 \text{ kW h/m}^2 \times \text{day}$. Conical roofed Harran houses are rooted in the regional history and showcase significant low-energy adaptation to the climatic conditions. There is general agreement that Harran houses are warmer in winter and cooler in summer than contemporary modern structures and are typically more energy efficient than flat roofed buildings.

Multiple research teams investigated the relationship between internal climatic conditions and the roof geometry as well as the relationship between the external climatic conditions and the roof geometry. However, few studies examine and tie internal and external conditions simultaneously to the roof type and spatial composition.

The characterization of the interesting internal and external thermal conditions of the Harran houses has fascinated contemporary researchers. The impact of their spatial composition on energy consumption and their thermal performance is still under investigation.²¹



Figure 5.4

The Harran houses in southeastern Turkey near Şanlıurfa. Multiple openings in the mudbrick walls and the top of the corbelled roof channel air in homes, which resemble cool ‘caves.’

Pearlmutter²² compared the solar exposure of a semi-cylindrical and a flat roof experimentally and found that the vaulted roof geometry receives an increase in overall solar exposure ranging from 10 percent in summer to 30 percent in winter. Faghieh and

Bahadori²³ estimated the solar radiation on several domed roofs and determined that domed roofs receive more solar radiation than the flat roofs on an equal base area. Tang *et al.*²⁴ investigated the heat flux through curved (domed and vaulted) roofs in an air-conditioned building compared to that in flat roofed structures to determine the energy efficiency of building types with regard to cooling load. The results show that the heat flux through curved roofs is always higher than through flat roofs when airconditioning is employed. Tang *et al.*²⁵ investigated the effect of vault angle on solar heat gain to improve curved roof performance and found that a roof with a half dome angle of 90 degrees absorbed approximately 30 percent more total radiation daily than a flat roof during the summer months. Gomes *et al.*²⁶ also studied solar incidence based on solar altitude over a hemispherical vault roof and compared these findings to those for a horizontal roof. They determined that when the sun's position nears the zenith, the summer solar performance of a dome is better than that of a flat roof of equivalent base area for northern latitudes. These investigations indicate that incident solar radiation cannot be the cause of the perceived superiority of a domed roof compared to a flat roof. Therefore, the internal thermal conditions related to heat flux and fluid dynamics (stratified air movement as passive cooling strategy) are currently also evaluated in order to calculate, model, and predict the actual performance of vaulted and domed roofs.²⁷

It is interesting to note that the Harran Houses are composed of a cell structure forming a compound that usually consists of a variety of cells on a fairly small footprint of about five by five meters, where each cell is topped by its own individual corbelled domed roof. The corbelled domes are situated on top of the square base, which is about as high as a person. Air is channeled into the space through small paired ventilation openings and warm exhaust is expelled through the top. The thermal mass of the stones as well as the geometry of the roof apparently play a major part in this spatial ventilation strategy.

The origin of these collective cell structures may be manifold and has yet to be determined. Mileto and Vegas²⁸ attribute the spread-out cell structure to Bedouin tents. The cell structures allow for a wide variety of combinations, ranging from single- to multi-dome structures that congregate around two or three sides of a courtyard, with the remaining side closed off by walls. In most cases, many of the daily functions are conducted outside.

The compounds are often oriented from north to south, with the main courtyard facing south to be situated well with the solar radiation (high overhead in summer and lower in winter).

Mileto and Vegas²⁸ present a comprehensive morphological study based on geometry, scale, and complexity. Similarity to the cave archetype is seen in the lack of access to light, with openings for ventilation air flow only, and the reliance on thermal mass for temperature mediation.

The major climatic benefit of the dome, beside the thermal mass and the ventilation effect, is the angle at which the solar radiation impacts the surface of the dome. Although the surface of the dome is larger than the surface of a horizontal roof, the steep angle at

which the radiation hits the surface results in lower heat conduction into the space, which benefits the cooling effect of the thermal stratification. This benefit is also positive at night, when a larger surface can reradiate the heat back out into the clear night sky.

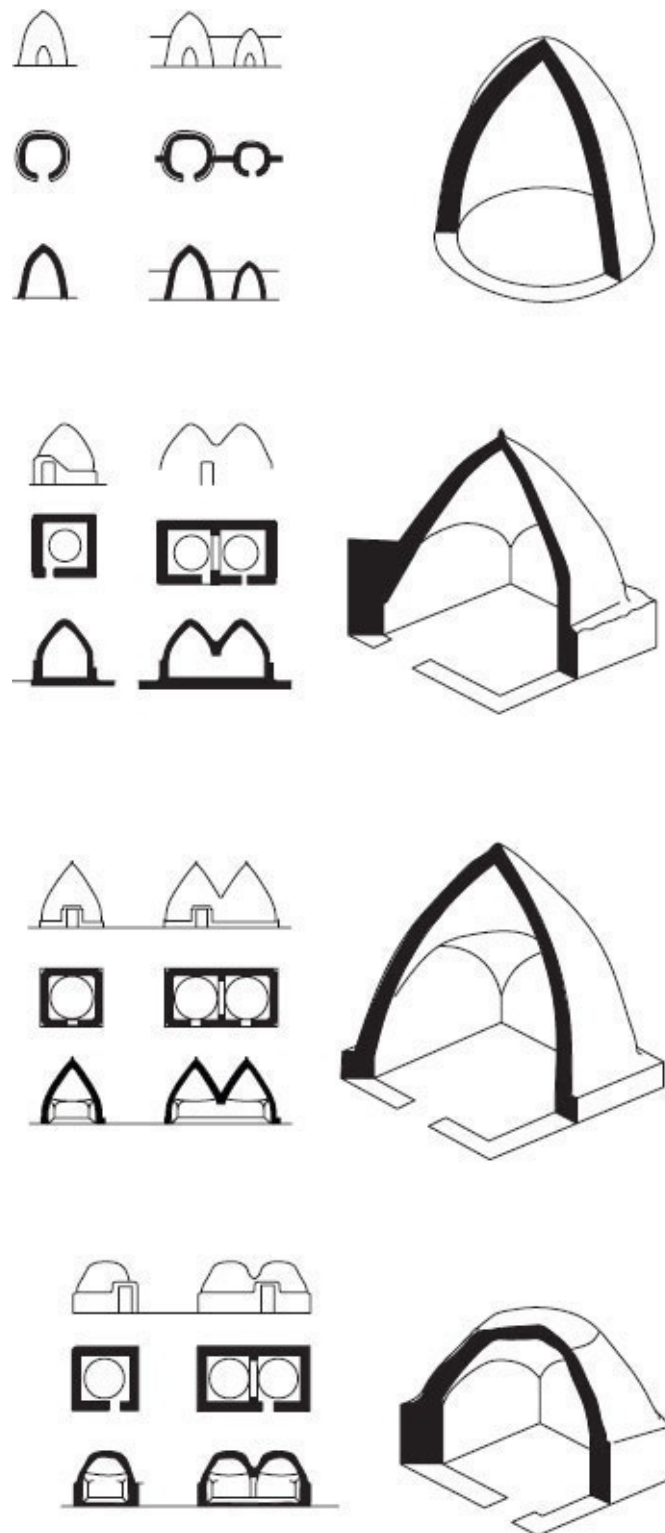


Figure 5.5

Corbelled roofs are a very specific technology utilized mainly in the Middle East in southeast Turkey, Syria, and Iran and show a variety of morphological diversity based on geometry, scale, and complexity.

5.3.1.3 The Aeolian Villas in Costozza, Veneto

Thermal mass played an important part in the ancient cities of Rome, Vicenza, and Naples, and the time lag of thermal conduction facilitates not only complex and elaborate cooling

strategies, but also air exchanges and ventilation in summer. It can be utilized to pull outdoor air through a cool basement, such as in the Villa Rotonda, Villa Emo, or Villa Poiana, by Andrea Palladio. The physics of air has been even more elaborately exploited in the cave system of the Villa da Schio built by Francesco Trento in Costozza during the sixteenth century. Here the villas are connected to caves in the mountain behind the garden where the cold air of the caves ‘pushes’ the warm air out of the inhabited spaces through an elaborate lattice work in the floor.

Here, a very distinct, cave-related ventilation strategy was employed, where cold air was channeled into residential and representational villa spaces (all of which formed a ring around a large, central, fairly dimly lit open hall) from adjacent ‘caves’ through so-called ‘ventiducts,’ which were prominently mentioned by Andrea Palladio (1508–1580) in his four books on architecture.²⁹ Like many Palladian villas, the Villa da Schio uses the constant temperature in a basement or cave to cool the building’s interior.

Used earlier as quarries, these caves were positioned inside the Berici hills behind and above the villas, and thus connecting the cave to the warmer air of the interior of the villa led to the development of a pressure differential and caused the air to move. Here, the ground performs as a wind catcher, or rather a catcher of cooling energy.



Figure 5.6

Palladio’s Villas like Villa Emo shown here, designed by Andrea Palladio in 1559, utilize similar ventilation technologies connecting the living spaces with the cool air of the basements.

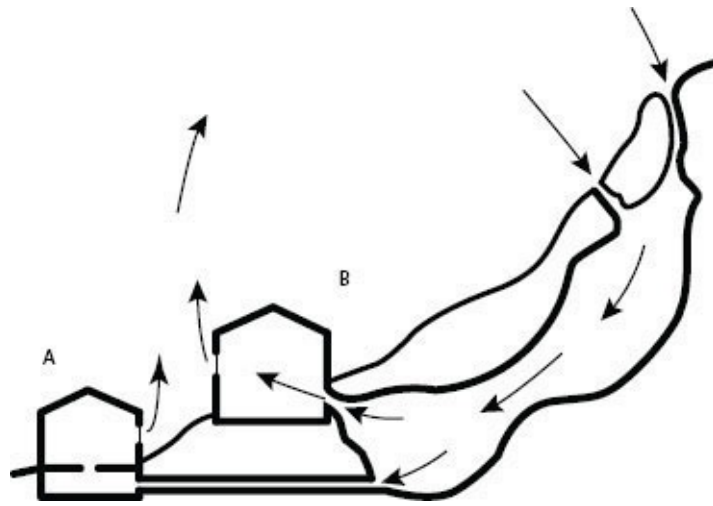


Figure 5.7

The Aeolian Villas in Costozza Veneto are ventilated and cooled through connection with cool cave air inside the Berici Hills.

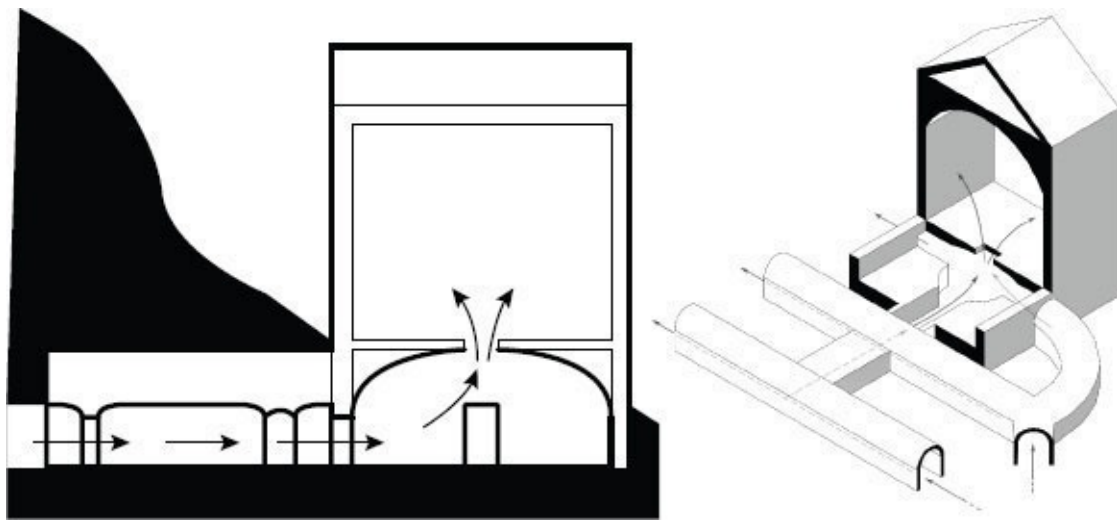


Figure 5.8

Ventiducts direct the cool air from the hill caves directly into the basement of the villa from where the air rises up into the living quarters.

AEOLUS HIC CLAUSOV ENTORUM CARCERER EGNATA EOLIA
 (“Aeolus rules over Aeolia by way of this prison of winds”)³⁰

These lines referring to Greek mythology are inscribed visibly within the *Grotta* and undoubtedly refer to the use of the cool air, with its constant temperature, which was channeled from the quarry into the upper rooms to provide air-conditioning. The grilles through which the air flowed are still visible in the main room. Outside the *villino*, on the roof, stands a figure of Atlas, bowed by the strain of holding up the ceiling of the great cave above him. According to the descriptions left by historical sources, this Atlas probably formed part of the original sculptural decor of the interior of the *Grotta*.³⁰

The yearning for sweet cool relief, in the blazing dog days of summer in the Veneto, inspired a shrewd seventeenth-century abbot to have part of his villa di delizia dug out of the rock of a hill. The better to complete the illusion, he had the walls decorated with woods and ruins and statues of airy divinities.³⁰

Barbara Kenda's compilation of essays³¹ from a symposium in the same Veneto villas provides deep insight into pneumatology, a nearly forgotten concept in Renaissance architecture, which grounded human well-being in air and spiritual breath. This theory provided the background of Renaissance villa concepts, as the pneuma was the vital spirit, which was translated in the heart from the air breathed in through the lungs. Thus the Renaissance architects saw a direct relationship between air, ventilation, and a healthy environment.³²

In order for the cooling system to operate correctly, the cave with its cold air must be located above the villa and the temperature outside has to be higher than in the caves to push the cold air down into the building. Wind and the understanding of physics were an integral part of the development of comfortable architecture and prominently featured in treatises by Palladio,²⁹ Alberti,³³ and Scamozzi.³⁴

Wind channeling devices and orifices became very common in Renaissance and Baroque architecture, as seen in [Figure 5.10](#) in the openings of Borromini's S. Carlino, which connect the crypta to the outside air and create light and air entrances. They were utilized for pleasure and comfort purposes.



Figure 5.9

The ventilation opening in the floor of Villa Trento a Costozza shows elaborate lattice work.



Figure 5.10

Ventilation opening in the crypta of Borromini's S. Carlo alle Quattro Fontane (1638–1641).



Figure 5.11

The Nordic courtyard, recalling the Carelian farmstead, has a much larger width-to-height relationship and lets in solar radiation while protecting from harsh winds, like here in Alvar Aalto's Experimental House in Muuratsalo (1952).

5.3.2 Simultaneously Utilizing Temperature- and Wind-Induced Pressure Differentials: Courtyard

According to Gottfried Semper,³⁵ the archetype of spatial formation is the hearth. The hearth is the central focus of his archetypal dwelling. It creates the basis for the two basic courtyard typologies, the mostly covered courtyard as in the Roman atrium, and the open courtyard as derived from the Hellenistic Greek peristyle. Both were created around the hearth to exhaust the smoke of the fire and to deliver ventilation and combustion air to the hearth and surrounding living quarters. The courtyard is a building typology found in many climate zones, both hot and cold, as it can address multiple climatic effects. Both are still very common space types today, both in urban and in rural contexts. Alvar Aalto's experimental house in Muuratsalo, Finland, designed and built with Elissa Aalto in 1952, focuses on an outdoor courtyard with a central fire pit.

5.3.2.1 Courtyard as Climate Device³⁶

The typological courtyard discussion relates directly to building climate research projects that investigated the tectonic importance of the courtyard for the internal climate. Courtyards are already known in the respective literature as implying “ingenious natural cooling strategies.”³⁷ Vittorio Gregotti states, for example, that “the enclosure not only establishes a specific relationship with a specific place but is a principle by which a human group states its very relationship with nature and the cosmos.”³⁸ He also discusses the question whether the courtyard house is a universal archetype. However, there are opposing opinions about the environmental properties of courtyards. The essay “Courtyards: A Bioclimatic Form?”³⁷ by Raydan *et al.* is important in this discussion. It compares the courtyard house typology in Scandinavia and the Arabic world with respect to their climatic performance, taking the difference in courtyard proportion into account. This climatic study relies on research done by Mänty,³⁹ who analyzed inherited architecture throughout Sweden, Norway, and Switzerland and praised the use of courtyards for their ability to create “pockets of solar gain,”³⁹ thus balancing the harshness of colder northern climates.

Raydan, Ratti, and Steemers’⁴⁰ essay tries to answer the question whether the courtyard is a sun protector or a sun collector by comparing it with isolated low- and high-rise box-shaped blocks. They calculated a number of well-established environmental variables, taking the parameters of the hot-arid climate and the cold Scandinavian northern climate into account, while abstracting the spatial parameters as there is no “universally optimum geometry.”⁴¹ To examine the impact of geometry, the analysis addressed the following parameters: surface-to-volume ratio, shadow density, daylight distribution, and sky view. Neither air flow nor the materiality or openings were considered in the analysis. They concluded that the courtyard implies a “cool island” and that “the climatic advantages of the courtyard form are apparent.”⁴² Although in colder climates the impact of the typology is not as apparent by the tested parameters, it is still detectable.

The potential to improve the environmental performance by adopting court forms in cold climates exists, although this is largely determined by a lower Height to Width ratio than in hot-arid regions, which is not surprising as the latitude of Scandinavia implies also a different sun altitude, therefore different proportions are common sense.

Considering nighttime cooling based on spatial typology,⁴³ they come to the conclusion that “the courtyard becomes a thermal sink that provides coolness to the surrounding rooms with less humidity and a suitable place for tropical plants to grow, creating a pleasant ambience” (see Säynätsalo by Alvar Aalto in [Figures 1.25–1.30](#) in [Chapter 1](#)).⁴⁴

The proportions in relationship to the prevailing wind and the generated air flow are important because the solar gain can be more beneficial when the wind is blocked. Therefore, the enclosed open space exposed to the exterior regional climatic forces has to be proportioned right in order to produce a microclimate favorable for the in-between space. It has to be able to filter the climatic conditions and to reduce their harsh impact on

the interior climate. The key here is that the change of air flow through spatial composition works in favor of climatic interior properties. A more refined study of the air flow patterns in relationship with the prevailing winds would be necessary to unveil the sun-protecting quality of the northern courtyard for cool climates. The solar geometry analysis of Aalto's Säynätsalo provides verification of the theory raised in Mänty's book³⁹ on the value of the northern courtyard (see [Chapter 1](#)). He stated that the courtyard acts as an extension and elongation of the warm outdoor season into the intermediate autumn and spring seasons. Ralph Erskine and Boris Culjat also point this out in their essay on the quality and value of outdoor open public spaces in cooler climates.⁴⁵

Considering the limitations that the climate poses and the undisputable importance of outdoor activity and man's relationship to the natural environment, it becomes necessary to examine and understand the two different types of social space that exist in the urban setting: the outdoor and the indoor. The outdoor spatial type chosen here is 'the courtyard', an urban element with a history as long as the history of urbanization in Sweden.

After an analysis of the relationship of social space, activities, climate, and the courtyard type, Erskine and Culjat conclude: "The conclusion must be, that the outdoor social space has to be located, designed and equipped to extend the outdoor season."⁴⁵ And they also refer to the vernacular for reference:

Scandinavian Farm buildings usually group small-roomed buildings around a central courtyard with an open fireplace in the central dwelling space, which radiates warmth to the surrounding living spaces. The courtyard enclosure acts as a device creating a favourable micro-climate protected from exterior winds. For example in Finland, people and animals live together on a side by side basis and in Carelia animals below and people above thereby benefiting from the release of heat.

They conclude, "We must learn not only to accept seasonal change but also to appreciate its fundamental beauty."⁴⁶

5.3.2.2 The Courtyard House in China

In China, courtyard housing also has a long-standing, inherited tradition; however, in the late twentieth and early twenty-first centuries its existence has been threatened. Similar to trends in the Western world, contemporary approaches to courtyard dwellings have emerged within historical cities, for example in Suzhou. Based on the philosophy of yin and yang and feng shui, living spaces are placed around the Chinese courtyard, which is rather an agglomeration of compounds than a court carved out of a solid volume. Strategically placed openings support the environmental control strategies. Donia Zhang⁴⁷ goes into great detail analyzing the historic and contemporary courtyard house typology in China. She discovered a large array of compositional variation in the arrangement of rooms around the courtyard, all of them using the courtyard as the main circulation space not just for air, but also for its inhabitants. Because of the large geographic spread of Chinese civilization, the courtyard type ranges from very hot and humid to colder climate zones. Zhang noticed a strong and very interesting correlation between the climate zone

and the spatial proportion of the courtyard. Drawing from Knapp,⁴⁸ she points to the difference between the large scale of the courtyards in the northern Chinese climate, allowing the penetration of the sun's radiation for passive solar heating, and the extremely small courtyards situated in the southern Chinese climates.

In order to manipulate the flow path and allow for variation of interior spatial composition, the Chinese courtyard house (similar to the Japanese house) incorporated multiple movable and sliding walls/doors to change, facilitate, or block the internal movement of the air depending on climate situation and needs.

Attention to ventilation is more prominent in southern China's Suzhou than in Beijing, where the construction focuses more on shielding from cold winds and accessing solar radiation, much like the Carelian farmhouse analyzed by Alvar Aalto in Finland.⁴⁹

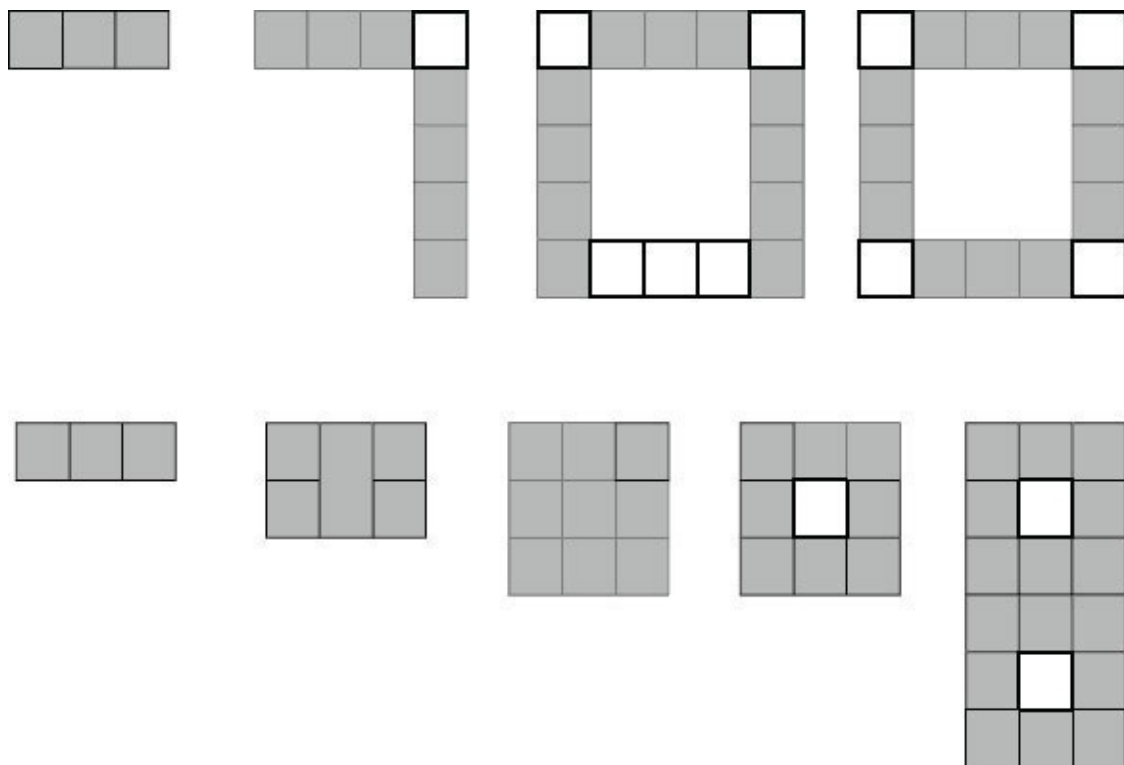


Figure 5.12

Chinese courtyards change significantly in proportion between southern tropical and northern colder locations, as has been analyzed by Knapp in 2005.



Figure 5.13

Muuratsalo Experimental House seen from the outside, which highlights the proportion of the courtyard space.

5.3.2.3 Two-Courtyards Ventilation Strategy

An even more complex scenario is utilized in hot and arid climates with the combination of multiple courtyards for climate control.⁵⁰ Here, a larger courtyard is exposed to solar radiation and heated up, while a second smaller courtyard is shaded, allowing air to move from the cooler to the hotter courtyard, creating a slight breeze through the in-between spaces.

Hassan Fathy⁵¹ discusses in great detail convection-based air movement created by solar radiation and the utilization of this strategy within the courtyard house typology in the hot and arid climate of the Middle Eastern city, where winding streets are fairly narrow and shaded and courtyards are larger and thus exposed to solar radiation throughout the day.

In vernacular architecture, this effect (the stack effect) has been exploited to produce small areas with cool breezes, using the ground heated by the sun as the heat source. As long as a large volume of cooler air is available and is unaffected by heat from the sun, the hotter sun heats the ground, the stronger will be the breeze.

Fathy attributes these movements to the radiation to the clear sky at night and the resulting temperature difference between night air and courtyard air. The courtyard air, heated up by the sun during the afternoon, rises in the early evening into the cooler night sky, which in turn descends into the smaller courtyards and seeps through into the living spaces, cooling them.

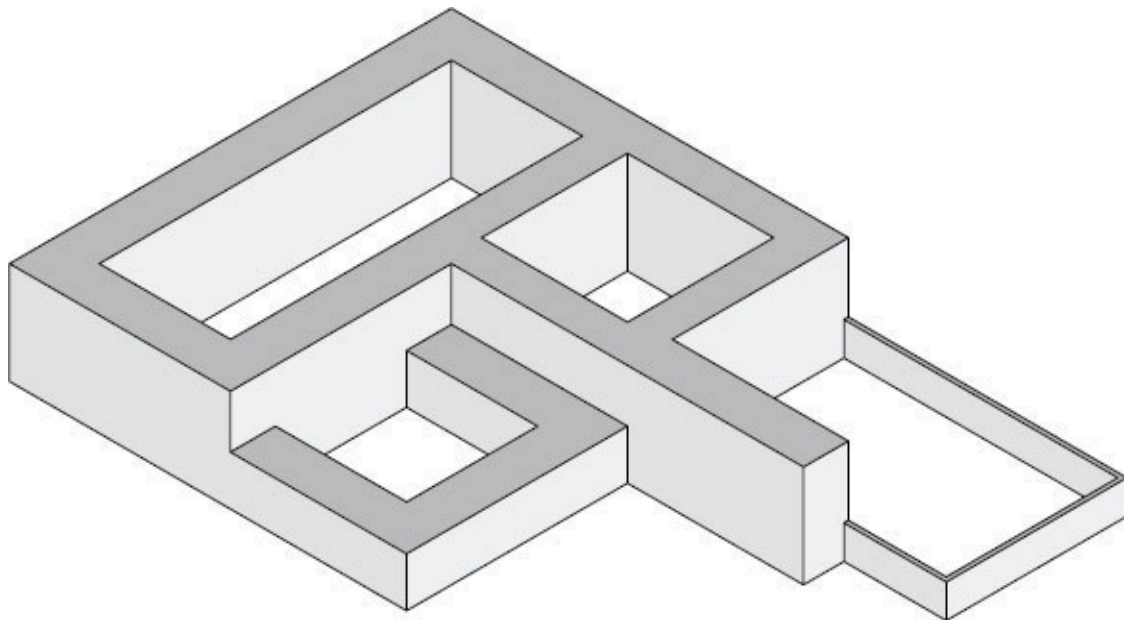


Figure 5.14

The theory that two courtyards operate together has been made popular by Hassan Fathy and is now validated by measurements of Ernest and Ford at the Casa de Pilatos in Sevilla.

Hassan Fathy claims potential temperature drops of 10 to 20 °C (~18 to 36 °F), citing Daniel Dunham,⁵² and declares the courtyard a “reservoir for coolness.” Ernest and Ford⁵³ recently set out to verify this mainly anecdotal claim in the double courtyard of the Casa de Pilatos in Seville, Spain. They performed the necessary field measurements, which verified the convective cooling potential of two connected courtyards in a hot and arid climate. The Casa de Pilatos is a lavish aristocratic urban palace, incorporating two garden courtyards and two internal courtyards that are void of any plantings.

Their conclusion is significant for the evaluation of the impact of multiple transitional spaces on the condition of inhabitable interior space with natural energies:

Free cooling is available because the enthalpy of air in the garden courtyard is much lower than indoor air. In addition adiabatic cooling by evaporation can be incorporated through evaporative cooling to lower the indoor temperature by close to 20 degrees Celsius.⁵⁴

All courtyards across the studied cultures have one major common characteristic: they act as both social spaces and climatic spaces, and this cultural significance guaranteed the survival and revival of this building type.



Figure 5.15

The garden of the Reales Alcázares de Sevilla is connected to smaller shaded courtyards in the interior of the palace.

5.3.3 Horizontal Wind Catchers: Passage, Arcade, Loggia

The analysis of the courtyard typology has already highlighted the importance of in-between spaces – the spaces between inside and outside – in developing a comfortable lived-in spatial configuration and in protecting from some of the environmental forces, while allowing for other environmental forces to flourish by embracing outdoors and indoors at the same time. Another very developed spatial type, developed over centuries, if not millennia, is the passage or covered street, the arcade or covered portico, and the loggia as a covered living room. All three spatial types have in common that one or more sides of their spatial boundaries are open to the outdoors. Covered streets or passages are common in many climates from Jerusalem to Brussels to Helsinki, shading from rain, snow, wind, or the sun. Arcades in Hamburg and Bologna provide covered spaces for passage, but also spaces for trade and commerce. Loggias provided a breezy retreat from the heat of the sun from Rome to Cadiz all around the Mediterranean Sea, the most prominent ones by Michelangelo and Borromini dominating the view of Rome over the Tiber river.



Figure 5.16

The Belvedere, a three bay loggia on the top of Palazzo Falconieri, was added to the palace by Francesco Borromini in 1646.

The great narrator of Roman architecture Pliny the Younger (61 AD–112 AD) described his coastal villa in great detail and certainly did not fail to mention the pleasure encountered in arcade spaces, which were able to catch the breeze and dilute stale air. “Inside the arcade, of course, there is least sunshine when the sun is blazing down on the roof, and as its open windows allow the western breezes to enter and circulate, the atmosphere is never heavy of stale air.”⁵⁵ The current prominence of the double-skin façades can be related back to the arcade as an in-between space, mediating between the inside and the outside of a building.

5.3.4 Wind-Induced Pressure Differentials: Woven Stone Basket

The woven screen or wall is the second important architectural feature mentioned in Gottfried Semper’s theoretical treatise on architecture.⁵⁶ In very warm and humid climates, where protection against cold or cool weather is not desired, and the walls and roofs of a building only need to protect from rain and provide privacy, the wall can become a screen of woven fabric, sometimes of stone and sometimes of vegetative material. This approach created an array of vernacular architectural precedents.

One of the most important archetypes of this spatial strategy is the storage building, which was developed to expose as much as possible of the stored grain to the wind to facilitate drying. This led to the development of a wind-permeable wall, while the foremost aim of the structure was to keep the vital grain safe from pests and intruders. Their spatial structure led to a very interesting connection between these grain storage structures – which are still visible and utilized in Lindoso in Northern Portugal; similar structures called Horreos exist in Galicia, Spain⁵⁷ – and the Hellenistic Greek temple, which also exhibited a semi-open, permeable, yet very refined external wall structure.

Ventilated storage spaces as encountered in the corn cribs and granaries of the Spanish province of Galicia could be considered spatial predecessors of temple archetypes. While the places for the granaries in Lindoso were found in privileged higher positions to take advantage of the winds for ventilation and drying, as Rudofsky points out,⁵⁷ the position of the Acropolis of course also followed ceremonial strategies. Yet, their origin may be similar as well to the origin of woven ornaments, as Semper³⁵ pointed out.

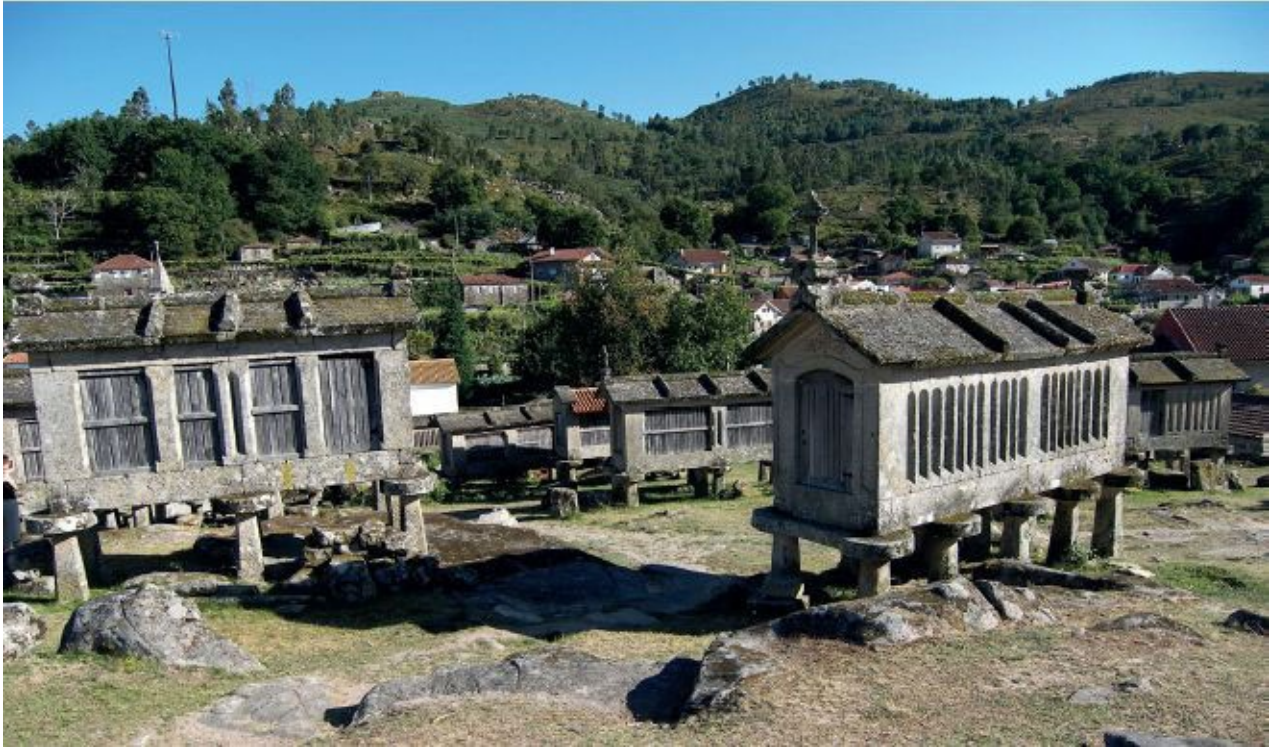


Figure 5.17

The grain storage buildings in Lindoso, northern Portugal, are raised stone ‘baskets’ providing ventilation access to the grain while protecting the grain from intruders.

Gaston Bachelard recalls the poetic dimension of the wind houses in *The Poetics of Space*.⁵

The image of these houses that integrate the wind, aspire to the lightness of air, and bear on the tree of their impossible growth a nest all ready to fly away, may perhaps be rejected by a positive, realistic mind.... it is touched by the attraction of opposites, which lends dynamism to the great archetypes.⁵⁸

And ... the well rooted house likes to have a branch that is sensitive to the wind, or an attic that can hear the rustle of leaves.⁵⁸

The house, as I see it, is a sort of airy structure that moves about the breath of time. It really is open to the wind of another time.⁵⁹

Houses in Bachelard’s poems breathe and ache and move. They are airy creatures. He quotes George Spyridaki: “[a] house that is diaphanous, but it is not of glass. It is more of the nature of vapor. Its walls contract and expand as I desire.”⁶⁰ All these descriptions may hint at interstices in the wall providing ventilation. Bachelard continued his investigation in a complete book on *Air and Dreams* with a full chapter dedicated to winds and storms

as the origin of imagination.⁶

Reyner Banham points to the great California tradition of sleeping porches, which resemble the house of air – the house that breathes. The garden porches have permeable walls and a protective roof, and following the description of the summer cottage of the Gamble family by Greene and Greene at Pasadena in 1908, “the widely projecting roofs over most gables are joined by an elaborate system of external roofed sleeping galleries on the upper floor and terraces at the ground floor level.”⁶¹ The outdoor spaces thus cover about the same amount of area as the enclosed spaces in order to take advantage of the light southern California breeze and to shelter the walls from the direct solar radiation. This house, like most of the Greene and Greene residential design projects, was developed from exquisite timber members and appeared as if woven together just from linear elements as if directly following Gottfried Semper’s textile wall coverings in the “primitive hut.”³⁵

“One may enter almost anywhere for doors and windows are nearly alike,” wrote Charles Greene in an article titled “On California Home Making”⁶² quoted by Esther McCoy, and she continues: “There was no attempt to make the flow of interior and exterior space a single undefined area as is done today” (so not Miesian). Each space had its own identity and was related to all parts of the site development as well as the interior. The interiors had an intimate, sheltered, and darkened atmosphere, cool and comfortable like a cave, which during the day provided an escape from the hot burning rays of the sun and the dry air. During the afternoon or evening, the doors and windows – set in horizontal bands – were swung open to take full advantage of the cool breeze.



Figure 5.18

The Gamble House in Pasadena designed by Greene and Greene in 1908 provides an iconic example of the California garden sleeping porches, raised timber ‘baskets’ open to the ventilation breezes.

5.3.5 Wind-Induced Pressure Differentials: Wind Catcher

The Iranian and Middle Eastern wind catcher is probably the most studied inherited natural ventilation strategy, and it has also been successfully integrated into contemporary built projects.⁶³ The fascination with wind catchers as climate devices is already apparent in Bernard Rudofsky's *Architecture without Architects*,² where he points to the wind catcher in Hyderabad Sind, Pakistan. Sue Roaf with her groundbreaking, but unfortunately unpublished, PhD work⁶⁴ on Iranian wind catchers has become an inspiration for at least one generation of researchers. In spite of the fact that Iran has been fairly difficult to reach for Western researchers during the last 30 years, there are current occupancy surveys and measurements for wind catchers, or badgir, in Iran⁶⁵ and in particular in the city of Yazd.⁶⁶

Wind catchers are essentially spatial devices that channel cooler air from higher surface layers above the roof, where wind speeds are higher than they are closer to the ground, down into the occupied living quarters of the building.

Wind catchers in the past have been part of a larger strategy of passive environmental control features and processes, one of which seems to have been daily and seasonal migration from one room to another, as noted by Roaf.⁶⁷

Recent numerical and quantitative research studies on the relationship of wind catchers to thermal comfort and comfort perception have revealed that the most comfortable summer rooms in houses with wind catchers were actually in the basements.⁶⁶ This information is an indication of the interrelationship of various implemented environmental strategies, including the utilization of thermal mass as a heat sink for cooling purposes.

Wind catchers were implemented not only in traditional buildings in Iran, but also in other parts of the hot and dry as well as hot and humid regions of the Middle East, such as in Dubai, Egypt, and Saudi Arabia, as well as in Iraq. But most of these traditional forms can actually be attributed to Iranians moving about the Persian Gulf and settling in other parts of the region as merchants, bringing their construction tradition with them.

The first and major characteristic of wind catchers is their strong visibility in the urban context. The photo of Hyderabad published by Rudofsky⁶⁸ shows a forest of hundreds of tall, slender structures towering over the city, orienting their shields towards the prevailing wind direction.

Current insight into Iranian wind catchers goes back to a few sources whose authors were actually still able to visit the location in the 1970s: Sue Roaf's unpublished PhD thesis in architecture from the late 1980s and the travel report of geographer Michael Bonine, published as a field report in the late 1970s.⁶⁹ Only recently, with greater mobility in and out of Iran, have researchers been able to conduct occupancy surveys about comfort perception in wind catcher ventilated buildings.¹³ Sue Roaf's account on wind catchers, or badgir, published in "Living with the Desert,"⁶⁷ is based on her field work and reveals many important geometric properties and the immense variety of proportional conditions she encountered in just one city.

The towers of varying height are constructed of mud bricks and divided into a number of chambers with vents opening in various combinations to the prevailing winds. Wind catchers have been built over residential homes of various scales as well as cisterns and more public buildings such as baths. Wind catchers are often connected to a complex system of rooms and courtyards, and all those features together were effectively able to create thermal comfort. However, this most likely does not describe thermal comfort as considered desirable in today's air-conditioned world, but an environment with higher temperature swings that often may have relied on sweating as a cooling strategy for the human body, a strategy that is no longer considered appropriate by current occupants. But according to Sue Roaf's report,⁷⁰ comfort was created through convective evaporative heat loss based on wind velocity and through cooling by evaporating sweat on occupants' skin with the very dry air current. Still, many wind catchers are in use today and are considered comfortable by most of the buildings' occupants.¹³

The operation of a wind catcher is directly related to the fluid dynamics of wind in relationship to obstacles. When wind impacts the wind tower, positive pressure on the windward side is coupled with negative pressure on the opposite, leeward side. A vortex will be created on the leeward side on the back of the massive tower structure. The air on the positive pressure side travels down the chamber shaft of the tower on that side and reaches the base, while air from inside the room gets pulled up by the negative pressure created on the leeward side of the tower. "The performance of a wind-catcher is affected by variables such as height, cross-sectional plan, the orientation of the tower and location of its outlets."⁶⁷

In Yazd, Roaf detected two major types of wind catchers: first, ordinary, functional wind catchers for smaller homes and cisterns, and second, those built by wealthier households and over public buildings such as mosques and baths or caravanserais. Towers over wealthier homes also functioned as signs and decoration. Depending on the size of the house, multiple sections of the home may have had individual wind catchers of different heights and functions. The smaller wind catchers ranged from about 1.2 m (4 ft) to 3 m (10 ft) and were usually divided into two or even eight shafts. Larger wind catchers may rise between 2 and 22 m (6 and 71 ft) with ornate and detailed inlet and outlet vents at the top, sometimes on a diagonal plan, organizing multiple sets of inlet and outlet shafts. Usually wind-catcher openings were oriented on all sides, so that inlet and outlet may actually change, but Roaf also surveyed wind catchers with just one orientation.⁶⁷

With respect to the floor plan, the outer outlet of the shaft was usually positioned at the edge or even corner of a room, sometimes with outlets positioned on multiple floors all the way down to the basement.

It is important to note that in the Yazd houses a complex interaction of various passive cooling devices and architectural features as well as behavioral routines and maybe even clothing options was at play. Iranian desert residences incorporate courtyards, water features, wind catchers, basement rooms, arcades, summer rooms, and winter rooms.

According to Roaf,⁷¹ the Yazdi lifestyle was characterized by internal migration.

Instead of migrating to higher grounds in the mountains, even the smallest homes are laid out for seasonal migration: they have summer living rooms in the center connected to the wind catcher shaft, while the winter room is closer to the solar-exposed façade. Basement rooms in larger buildings had the common function of summer daytime retreats, because they were the best locations owing to their thermal mass and constant temperature between 25 and 28 °C (77 and 82.5 °F). Wind catcher air introduced to basement rooms exhausted stale humid air, even when the introduced air was warmer than internal air. Thus, ventilation does not always have a cooling function in the sense that it reduces air temperature, but it removes heat from occupants' bodies and thus cools the bodies directly and not the internal air.



Figure 5.19

A pair of wind catchers in Yazd, Iran.



Figure 5.20

A highly decorated pair of wind catchers in Yazd, Iran, showing the roof area as occupied space and indicating the relationship of wind catchers to the demonstration of wealth in Yazd.



Figure 5.21

This wind catcher shows the proportional variety still existing in Yazd today.



Figure 5.22

These wind catchers shown from the roof show less detail and fewer ventilation openings.

5.3.6 *Temperature-Induced Pressure Differentials: Chimney*

Most commonly a chimney acts as a spatial device to channel air needed for combustion into fires used inside the building for heating or cooking and to remove smoke developed during the process. Often, the air gets pulled into the combustion chamber through openings in the envelope of the building (such as vents, windows, or cracks). The hot combustion air rises and exhausts through the chimney, which acts as a vertical fluke and often is a dominant feature of the building.

Other examples of chimneys or ventilation shafts are manifold in building types. They may be used to channel wind through a storage space in order to dry grain or hops, like in the oast houses in Kent, England, which were used to dry hops for beer brewing. They had a similar shape to a chimney and were topped with a wind cowl that turned with the wind to provide for the best pressure differential between the front and the back of the opening to allow the warm air to escape. While the wind passes over the top of the chimney, warmer air rises and thus cooler air is pulled from a lower air source.⁷¹

Chimneys have often contributed to the character and appearance of sophisticated palatial or casual rural inherited architecture. Sintra National Palace, for centuries the residence of the Portuguese royal family outside of Lisbon, exposes two enormous conical kitchen chimneys that are visible on drawings of the palace as early as 1509.⁷²

Similar spatial objects can be found in the kitchen of the Cistercian monastery in Alcobaca, Portugal, founded in 1153. Two enormous chimneys constructed in the eighteenth century dominate the space.

Traditional farmsteads in colder Alpine climates have also integrated significant built forms for their kitchen chimneys. In Davos, Switzerland, they even related to the atrium or central hall of the home and thus can be cross-referenced to the courtyard typology. The *Alte Sennhütte* in Davos⁷³ was composed of multiple stacked volumes, leaving the center with the hearth empty, but covering the whole composition with one over-encompassing large roof. The *Sennhütte* thus combines the ventilation strategy of covered courtyard and chimney. The Topkapi palace in Istanbul and its seraglio are also towered by large chimneys. Traditional chimneys obviously serve as key precedents for all stack ventilation used in contemporary natural ventilation cases.



Figure 5.23

The wind cowls of the oast houses in Kent, England, used to dry hops for beer brewing, are able to move with the changing wind direction.

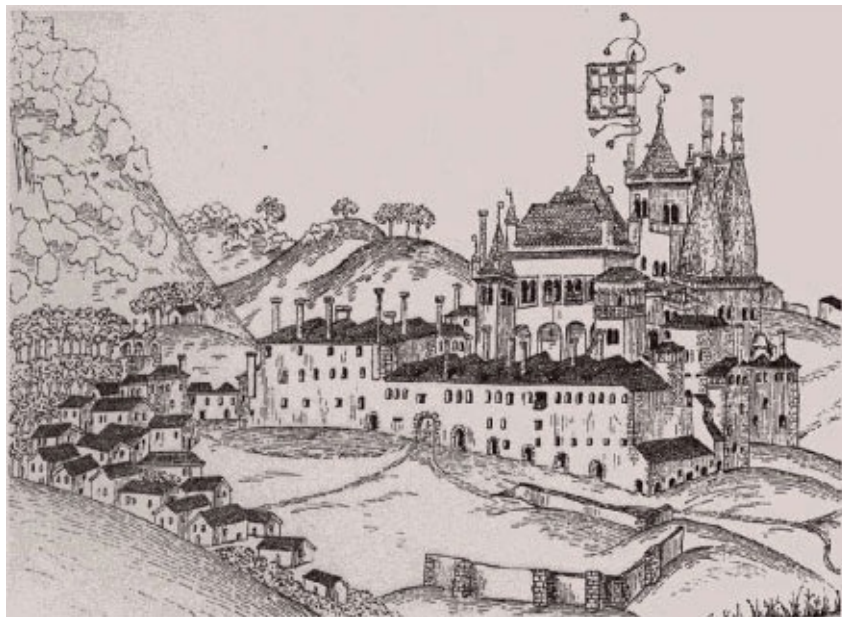


Figure 5.24

The kitchen chimneys dominate the appearance of Sintra National Palace in Sintra, Portugal, already in this early sixteenth-century drawing.



Figure 5.25

The kitchen in the Monastery of Alcobaca incorporates an enormous free-standing chimney over the cooking station.

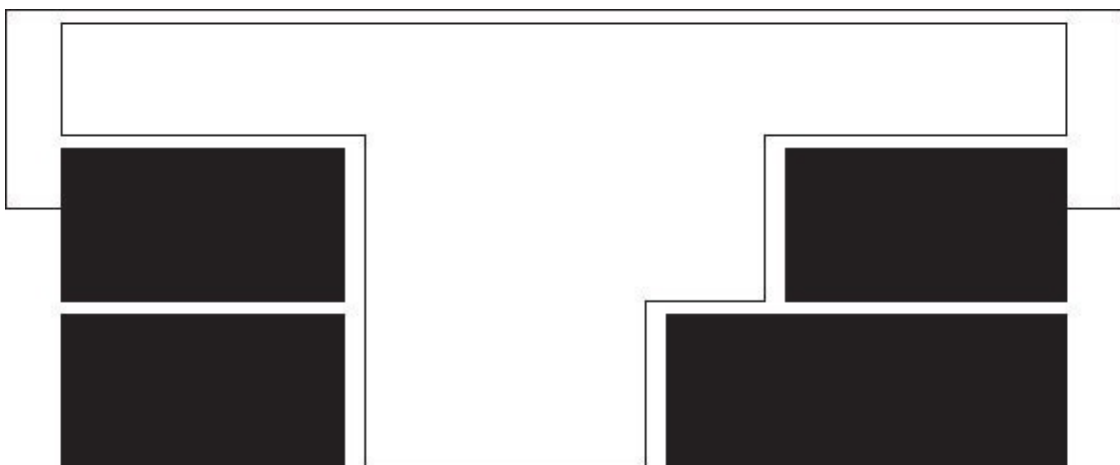


Figure 5.26

Traditional farm houses like the *Sennhütte* in Davos were built around a central furnace and cook top, which resembles an atrium.



Figure 5.27

Chimneys also dominate the exterior appearance of the Serail of the Tokapi Palace in Istanbul.

5.4 Inherited Building Types and Climate

The inherited ventilation typologies described in this chapter can be related to the climate zones in which they are located. Anecdotally, the inhabitants of desert climates developed the largest variety of spatial ventilation types. Cultures in moderate climates were obviously more concerned with keeping warm, followed by the requirement for fresh air, and thus the chimney-atriumcourtyard relationship is dominant in the Mediterranean climate, where both heating and cooling are obvious needs. Strategies in humid climates seemed to induce a lot of wind directly as the major ventilation strategy so that the building envelope remained just a visual privacy barrier. For more information on climate-based design see Saldanha, Hausladen and Liedl's recent publication.⁷⁴ Table 5.1 summarizes the prevailing strategies in the various climate zones.

Table 5.1 Spatial typologies related to major climate zones

Climate zone	Location	Central typological feature
Hot and dry (desert)	Mesa verde, Colorado Acoma pueblo	Cave: nighttime cooling of thermal mass
	Yazd Wind catchers, Iranian plateau	Wind catcher
	New Gourna Hassan Fathy	Wind catcher
	Mardin/Şanlıurfa, Turkey ²	Cave: nighttime cooling of thermal mass
		Nomadic tensile structures
	Tower ventilation in Sanaa, Yemen	Stack ventilation – chimney
	Iranian Sail vaults or domes made from mud-brick and walls made from stone	Stack ventilation – chimney
	Harran Houses	Stack ventilation and cooling
Warm and humid (tropics)	Japanese vernacular	Woven basket
Hot and humid (tropics)	Goa, India	Woven basket
	Hot and humid climate: woven palaces	
Temperate/maritime	Passive solar/solar chimney	Solar-induced chimney
	Chimney, Sintra	Wind-induced chimney
	Oast houses, Kent	Wind-induced chimney
Temperate/continental	The bungalow from India to the Midwest	Woven basket
Cool	Fireplaces and the northern atrium house	Courtyard
Continental (extreme cold and hot seasons)	Bungalow/passive solar	Combination of all strategies
	Earth shelter	Courtyard

5.5 Traditional Vernacular and Contemporary Modern Architecture

A vigorous discourse prevailed all through the Modern Movement in a number of countries on how to relate Modern thought with inherited vernacular traditions. Le Corbusier's travel to the Orient⁷⁵ and Alvar Aalto's references to the Karelian farmstead,⁷⁶ as well as Frank Lloyd Wright's central focus on the hearth in his prairie homes, are just a few indicators that directly relate Modern composition to spatial strategies enhancing air movement. While climate-responsive architecture was not of major concern in the Modern Movement, references to inherited traditions celebrate a revival as part of the environmental, sustainable, or green architecture development. Instead of merely claiming superior performance, many contemporary research teams are currently examining performance-based evidence to verify the actual performance of these inherited concepts for contemporary applications.

More research is necessary to validate many claims about the validity of these inherited concepts in contemporary architecture. The European research project on downdraft cooling supported by the sixth European Union (EU) research framework program⁶³ and current projects funded by the US National Science Foundation within the Emerging Frontier in Research and Innovation (EFRI) program are examples of initial efforts to improve the science for sustainable buildings.⁷⁷

The evolving knowledge base can help to integrate typological knowledge into the design process and refine the place traditional architecture can take within the contemporary discussion on global culture and the development of sustainable architecture for a changing climate in a warming world.⁷⁸ However, what should be clear already is that spatial typologies act as social and climate space, but further analysis of the spatial distribution of heat through air flow in three-dimensional volumetric proportions is still needed.

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Chapter 6

Natural Ventilation and Thermal Comfort

Buildings are designed and constructed to be shelters that protect from uncomfortable or even dangerous climatic and environmental conditions such as rain and snow, high winds, heat and cold, and strong solar radiation. The classical ‘primitive hut’, a roof on four pillars, appears in Laugier’s famous and often cited drawing¹ as a starting point for the basic necessity of shelter. The hearth as a center for buildings appears in Gottfried Semper’s architectural theory² and has been traced as a vital architectural feature, relating monumentality and comfort. But when shelter from the elements is required, designers have to also allow for air to enter the building ideally in a controlled manner for thermal comfort and of course air quality (as noted in [Chapter 3](#)). This chapter will address the major concepts related to thermal comfort in naturally ventilated and hybrid or mixedmode buildings.

Before the advent of mechanical cooling systems, cooling was achieved only by utilizing the storage capacity of latent heat in water or ice through evaporation and convection. Wind moving air over the body resulted in a cooling sensation through evaporation. Evaporative cooling directly facilitates the removal of heat from the human body. Both strategies needed specific spatial design strategies in order to make best use of the existing environmental forces, as has been discussed in the previous chapter.

Thermal comfort as a design criterion, especially during summer, is still a fairly recent design parameter and has only fully developed with the introduction of air-conditioning and mechanical ventilation into the heating, ventilation, and air-conditioning (HVAC) systems of larger buildings. Unfortunately, matching thermal comfort with low energy consumption is often very little considered and understood as a parameter for preliminary design. The results are buildings with energy-consuming, deep plans that come with a tight temperature control set point and that offer neither the opportunity for a continuous flow path through the building nor an option to open a window.



Figure 6.1

The rustic hut as envisioned by Marc Antoine Laugier in his *Essay on Architecture*, written as an architectural rule book in 1753, indicates the primary need for architecture: shelter.

6.1 Standardizing Comfort

Thermal comfort considerations in the USA are guided by ASHRAE standard 55,³ in the UK by CIBSE,⁴ and in Germany by the ISO standard EN ISO 7730.⁵ Other national and international standard bodies are also relevant.

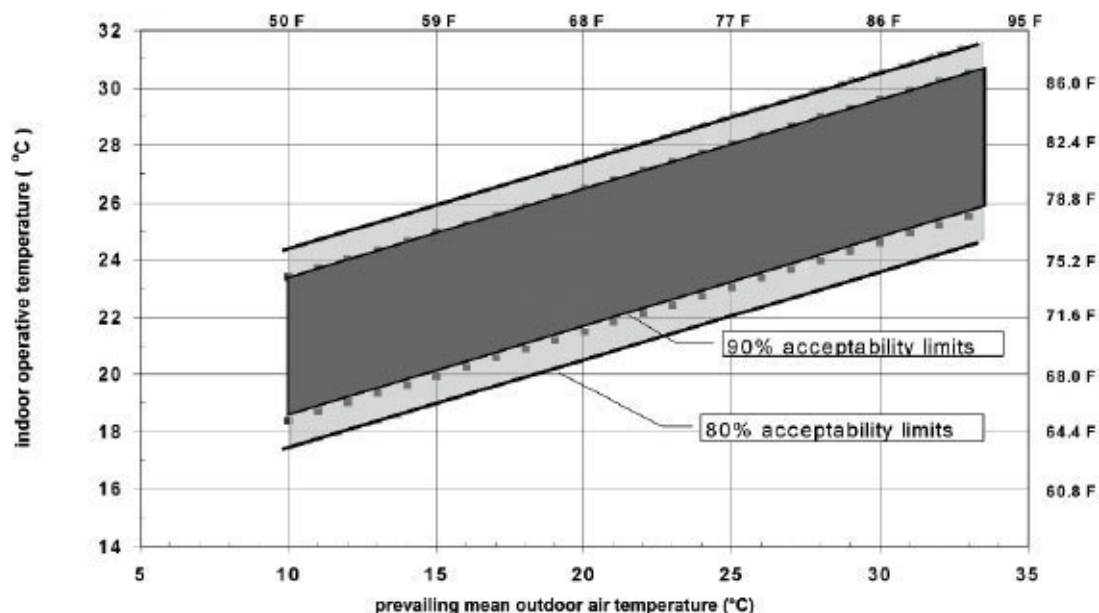
Although ventilation standards and thermal comfort standards are related, they are determined separately. The same applies to illumination standards, which may not be as closely related, but they have a joint source: the sun. In addition, air temperature is not the only criterion determining the quality of thermal comfort, although it is one of the major

influences.

Thermal comfort standards and comfort expectations over the past 50 to 80 years have changed significantly, and the responsibility to provide indoor environmental conditions that meet the required comfort standards has generally been passed from the architects to the building service engineers, with the result that the requirements are mostly met with active mechanical HVAC systems and not necessarily through spatial design. Thermal comfort is rarely taught in the design studio, but is addressed in the environmental forces and systems classes and thus is often considered detached from spatial or visual design concepts and considerations.

Thermal comfort is the condition of mind that expresses satisfaction with the thermal environment, and it is assessed by subjective evaluation (ANSI/ASHRAE Standard 55–2013).³

Table 6.1 The adaptive comfort standard according to ASHRAE 55–2013 FIGURE 5.4.2: Acceptable operative temperature (to) ranges for naturally conditioned spaces



Source: ASHRAE 55–2013 with permission

6.2 Air-Conditioning

Air-conditioning, or artificial weather, was basically invented by Willis Carrier (1876–1950)⁶ in the early twentieth century. It was designed as a means to control air humidity content and as a cooling device, initially for department stores, theaters, and cinemas and later for the post-war American dream home.⁷ Air-conditioning is seemingly controllable, while natural air movement is seemingly not. Air-conditioning has led to a total detachment of occupants from the outdoor environment and its conditions and contributed tremendously to the soaring energy consumption in the United States and other developed and developing nations.

6.3 Comfort Research

Major steps towards the definition of thermal comfort parameters were conducted in climate chambers in the 1960s and 1970s by Ole Fanger's research team. They determined the predicted mean vote or predicted percent dissatisfied (PMV/PPD) model⁸ through studies conducted in tightly controlled climate chambers. Further research⁹ conducted by de Dear and Brager in the USA as well as Nicol and Humphrey in the UK indicated that this model was not suitable enough for thermal comfort understanding in natural ventilation spaces. The PMV/PPD model is not dynamic enough for the environment created in naturally ventilated buildings as it defines a too narrow band of temperatures considered comfortable by users.

6.4 Thermal Comfort Parameter

Thermal comfort is a multi-faceted experience, which is governed by four variables of the thermal environment: air temperature, relative humidity, mean radiant temperature (the temperature of the surrounding surfaces), and air velocity. Clothing as well as activity and the metabolic rate of occupants are personal conditions, which also influence comfort perception. In addition, temperature stratification and temperature difference between head and toes matter. It will be nearly impossible to create an environment that satisfies all occupants. Therefore, the standard requires only a certain percentage of occupants to have a comfortable sensation in order to consider a situation to meet the definition of 'comfortable.'

Surface temperature of adjacent walls is as important, if not more important, than air temperature for an occupant to express thermal comfort. Cooling the air around the occupant is thus only one of multiple means to develop a comfortable thermal environment. [Chapter 10](#) will highlight the relationship between controls, comfort, and natural ventilation.

6.5 Adaptive Comfort Standard for Natural Ventilated Buildings

Gail Brager, Richard de Dear, Fergus Nicol and many of their colleagues¹⁰ in their significant body of work defined the thermal comfort sensation in natural ventilated buildings. Rather than conducting climate chamber investigations, they conducted many field studies of actual buildings and their occupants. These multiple studies resulted in a long debate within ASHRAE's standard committee, resulting in a general agreement on what is now called the adaptive thermal comfort model.¹⁰ This model does not aim for a perfect thermal comfort number, but acknowledges adaptability, changeability, user control, and intuition as well as responses to seasons and weather.¹¹

The adaptive comfort model, as it has now been included in the ASHRAE standard 55–2013,³ is defined as “a model that relates indoor design temperatures or acceptable temperature ranges to outdoor meteorological or climatological parameters.”¹⁰

Changing comfort levels in relation to the exterior climate is a new insight in thermal comfort research, and it is of high value and interest with respect to natural ventilation and

passive cooling concepts. The notion that people need the same temperature level all year round, taking neither seasons nor the exterior climate nor weather conditions into account, has proven to be too narrow a concept.¹²

6.6 Thermal Delight

Lisa Heschong's *Thermal Delight in Architecture*¹³ is an exception in this discourse because it addresses the delight of diverse thermal experiences. While an intuitive approach addresses the design of space either as a geometrical composition or as sensual phenomena, a combination of both is necessary. "Thermal qualities – warm, cool, humid, airy, radiant, cozy – are important parts of our experience of space; they not only influence what we choose to do there but also how we feel about the space."¹⁴

Lisa Heschong also reminds her readers that thermal delight can influence the creation of social communities.¹³ A community is created by sitting around the fireplace and telling each other stories over a cup of hot tea, or by hanging out on the porch swing and producing a light breeze to feel comfortable in the heat of the afternoon. Hanging out on the porch also connected the neighbors in a street, allowed for supervision of kids playing in the front yards, and made the near-home urban environment most likely safer. Unfortunately, the porch as a communal space in the midwestern and southern US household disappeared with air-conditioning. "The words we use to describe such places [such as inglenooks and gazebos] – snug and cozy or airy and refreshing – all imply that these places offer us a sense of thermal well-being."¹⁵

Heschong continues that we usually remember these childhood places fondly. They gave us joy and did not leave us as occupants neutral. The focus on thermal neutrality has eliminated the care for thermal delight she already considered in 1979. Many of her examples relate to heating and warmth, like the Finnish sauna, but she also draws close attention to the Islamic garden for cooling. "Other than the hearth, perhaps the richest example of a thermal place with a profound role in its culture is the Islamic garden, the cool oasis that is the traditional center of the Islamic house."¹⁶ (See [Figure 5.15.](#))



Figure 6.2

Fireplace in Hvitträsk, Kirkkonumi, Finland, designed by Herman Gesellius, Armas Lindgren, and Eliel Saarinen between 1901 and 1903.



Figure 6.3

Inglenook in Hvitträsk, Kirkkonumi, Finland, designed by Herman Gesellius, Armas Lindgren, and Eliel Saarinen between 1901 and 1903.



Figure 6.4

Gazebo in Hvitträsk, Kirkkonumi, Finland, designed by Herman Gesellius, Armas Lindgren, and Eliel Saarinen between 1901 and 1903.



Figure 6.5

Urban courtyard in Şanlıurfa, Turkey, highlights shade, water, and openings for ventilation.

6.7 Relationship of Air Velocity and Comfort

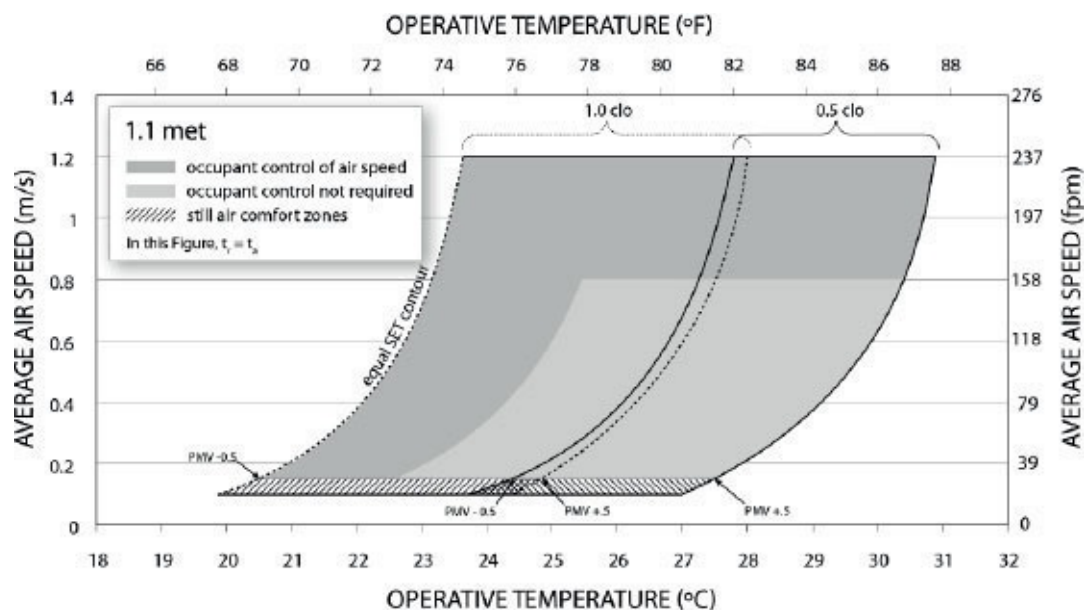
The development of the adaptive comfort model was essential to generate a more standardized model for naturally ventilated buildings, especially in warmer climate zones with higher humidity levels.

There are two parameters that distinguish the adaptive comfort standard from the PMV vote. First of all, elevated air speed increases the acceptance of higher temperatures. This is of course highly important for natural ventilation in buildings, as they usually employ higher air velocities, but also higher temperatures. Air-conditioned buildings are designed to show hardly any perceivable air velocity. Thus the adaptive comfort standard integrates scenarios when indeed the occupants open a window.

Second, the adaptive comfort model, unlike the PMV model, accepts the relationship between outdoor climate and temperatures and desired indoor conditions as dynamic or adaptive and acknowledges that people dress differently depending on whether the weather is nice or not. This provides the model with the opportunity to raise indoor air temperature in summer with rising outdoor temperatures.

This model applies in particular to occupant-controlled, naturally conditioned spaces, in which the outdoor climate can actually affect the indoor conditions and thus the comfort zone. In fact, studies by de Dear and Brager¹⁷ showed that occupants in naturally ventilated buildings were more tolerant of a wider range of temperatures than those in air-conditioned buildings.¹⁸ As a variable standard, the adaptive comfort standard requires the change of indoor comfort conditions with outdoor climate.

Table 6.2 Comfort ventilation w/ higher air speed according to ASHRAE 55–2013
FIGURE 5.3.3A: Acceptable ranges of operative temperature (t_o) and average air speed (V_a) for the 1.0 and 0.5 clo comfort zone presented in Figure 5.3.1.1, at humidity ratio 0.010



Source: ASHRAE 55–2013 with permission

The downside of a tightly controlled indoor environmental condition, for example 72 °F (22 °C) and 50 percent relative humidity, is the energy it takes to keep an indoor environment at such levels, in particular when the outside conditions change rapidly. Adjusting to these changes can consume a significant amount of energy because of variable dynamic and transient outdoor conditions. Adaptation results in a change in behavior based on a reached threshold or tolerance level.

Adaptation is a process over time that adjusts behavior to a condition of dynamic context. Adaptation also requires active control opportunities for the occupants. Buildings with adaptive comfort control operate under the “adaptive principle.” When a change occurs that renders the condition uncomfortable, people generally react in ways that tend to restore their comfort. The adaptive comfort concept is built on surveys conducted in the field and not based on laboratory experiments.

6.8 Thermal Comfort and Metabolism

Thermal comfort is directly related to the human metabolism and the need of the human body to keep a close to constant internal temperature of 37 °C (98.6 °F), which is the stable core body temperature, independent of the activity level of the person.

‘Thermoregulation’¹⁹ is the process directed towards maintaining this stable core temperature. Most body activities require energy and produce excess heat, even thinking. Over time, the heat produced must equal the heat lost to the environment through our skin, otherwise we will develop a fever or suffer from a heat stroke. We thus do not develop a fever when we work out and increase our heart beat rate.

In order to increase heat loss, more blood flows towards the skin to lower the temperature; to minimize heat loss, blood is withdrawn from hands and feet in order to reduce their temperature and to thus reduce heat lost through the skin. That is why in extreme cold conditions, toes, fingers, and ears freeze first, because the body tries to keep the vital functions of the body active. The body just refuses to circulate blood through those outer limbs, and in the worst case lets them die.

6.8.1 Energy of Metabolic Rate

The metabolic rate of occupants indicates the major activity undertaken by the occupants and the energy produced and released by that activity. This energy is important as energy load for the cooling energy needed, but it is also an indication of the rate at which heat is dissipated from the body and influences the air temperature at which occupants experience comfort depending on their activity. The metabolic equivalent of task (MET) is the ratio of metabolic rate when working to the metabolic rate when resting.

One MET is defined as 58.2 W/m^2 (18.5 BTUH/ft^2) and provides a measure of the energy (heat) released by an average person seated at rest. The ‘standard’ person expends energy over a surface area of 1.8 m^2 (19.5 ft^2), so at rest approximately 100 W (341 BTU/h) are released to the surroundings. A standard list of metabolic rates is given in ISO 8996 (2004).²⁰ These rates have been recorded for a steady-state situation, where a seated person always sits and won’t get up.¹⁰ In real-world scenarios, people tend to change their activity and that change also has an impact on their comfort perception, which is difficult to account for and has not yet found a way into the standards, because it would need dynamic control settings, which are difficult to achieve, as will be discussed in [Chapter 10](#). People in a gym give off about five times as much thermal energy as a seated person, which has a direct influence on their thermal comfort. To feel comfortable, the air temperature has to be lower than for a seated person. This comfort setting in a gym can also be achieved by turning on a fan or opening a window and thus increasing air velocity and the removal of heat by evaporation from the skin.

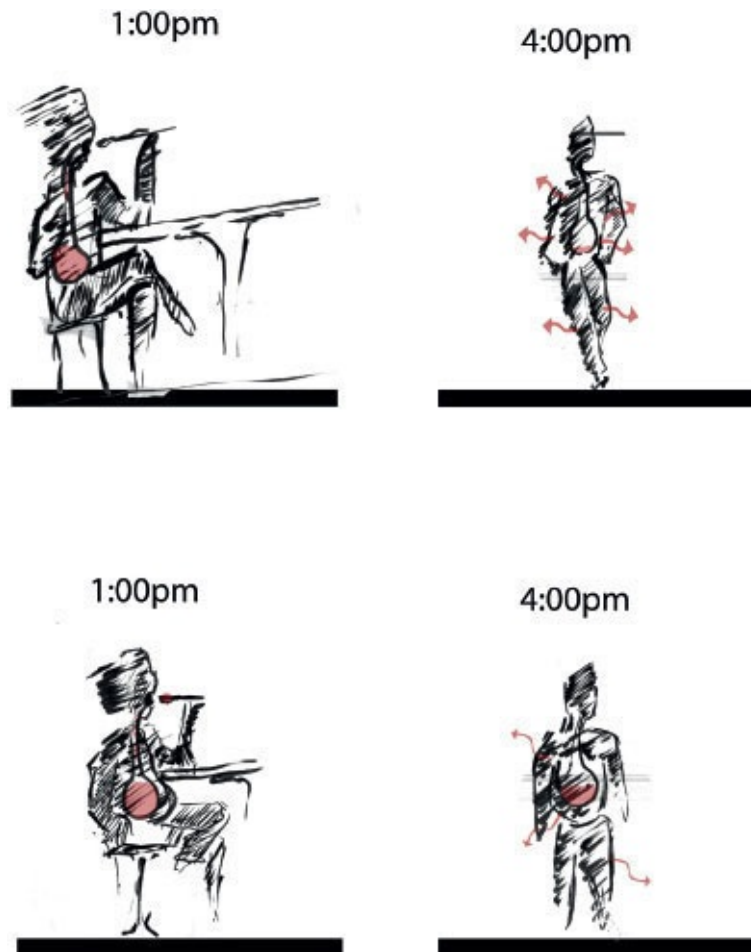


Figure 6.6

Metabolic rate: the human body constantly exchanges thermal energy with its environment.

6.9 Behavior and Comfort

People have certain tolerance levels until they interrupt their activity and create a change to their comfort conditions by putting on a sweater (changing clo – clothing – factor; 1 clo is equal to $0.155 \text{ m}^2 \text{ K/W}$ or $0.88 \text{ °F ft}^2 \text{ h/Btu}$),³ by moving around in the space (changing metabolic rate), by moving into a different room, by moving between different thermal environments, by opening or closing a window, or last but not least by turning up the heat or active cooling.

6.10 Clothing and Comfort

The role of clothing is significant in maintaining thermal comfort. Clothes act like insulation for the heat leaving the body as well as an insulating barrier between the outside condition and the body. Air layers within the clothes are as important as the material of the textiles that make up the clothing. The opportunity to trap humidity in a dry arid climate is similarly important, as is the opportunity for the skin to breathe and thus for sweat to evaporate. The relationship between various textiles and fabrics and thermoregulation and human thermal comfort was studied as early as 1873 by the German public health researcher Max von Pettenkofer in his notable lectures *The Relations of the Air to the Clothes We Wear, the House We Live in, and the Soil We Dwell on*.²¹

It is also common knowledge that people dress differently with the seasons. They wear lighter clothes in summer and heavier, warmer clothes in winter. Depending on cultural and behavioral norms, people adjust their clothing with the seasons or on a day-by-day basis. Basic PMV comfort standards are based on office attire for the conventional office environment.³

The actual equation governing the heat balance of the human body is quite complex and considers all potential changes necessary to keep the body in steady state. The determining factors for the thermal heat balance of the human body are the metabolic rate and the mechanical work done. Here, the convective, evaporative, and radiative heat lost from the clothed body as well as the convective and evaporative heat lost by respiration need to be considered. A significant portion of the metabolic heat rate will also be stored within the body tissue. All heat flows are determined by temperature differences as well as by surface area of the body and multiple other factors related to the quality of the clothing and to specific properties of clothing and the body. Similar relationships and factors exist for convective heat transfer and evaporative heat transfer.

Table 6.3 CLO factor (thermal insulation of clothing)

Working clothing	CLO	m ² K/W
Underpants, shirt, trouser, socks, shoes	0.75	0.115
Underwear with short sleeves and legs, shirt, trousers, jacket, socks, shoes	1.0	0.1555
Underwear with short sleeves and legs, shirt, trousers, jacket, thermojacket, socks, shoes	1.25	0.19
Underwear with short sleeves and legs, shirt, trousers, jacket, thermojacket and trousers, socks, shoes	1.55	0.225
Underwear with short sleeves, trousers, jacket, heavy quilted outer jacket and overalls, socks, shoes, cap, gloves	2	0.31
Underwear with long sleeves and legs, thermojacket and trousers, parka with heavy quilting, overalls with heavy quilting, socks, shoes, cap, gloves	2.55	0.395
Daily wear clothing		
Panties, T-shirt, shorts, light socks, sandals	0.3	0.05
Underpants, shirt with short sleeves, light trousers, light socks, shoes	0.5	0.08
Underwear, shirt, trousers, sock, shoes	0.7	0.11
Panties, petticoat, stockings, dress, shoes	0.7	0.105
Panties, shirt, trousers, jacket, socks, shoes	1	0.155
Panties, stockings, blouse, long skirt, jacket, shoes	1.1	0.17
Underwear with short sleeves and legs, shirt, trousers, vest, jacket, coat, socks, shoes	1.5	0.23

Source: Adapted from F. Humphreys, Michael A. Nicol, and Susan Roaf, *Adaptive Thermal Comfort: Principles and Practice* (London: New York, 2012), p. 101, Table 8.1

The adaptive comfort model is based on field surveys and post-occupancy evaluations and thus on direct answers of occupants to questions of comfort. If an adaptive comfort model is applied to the design of a building, it is expected that the occupants adapt their clothing and behavior to the climate outside.¹⁰

Thus, the comfort temperature is directly related to the clothes occupants wear inside buildings as well as to their activities. Therefore a strategy such as the Japanese “Cool

Biz” campaign²² that allows office workers to dress less formally in summer, together with setting the thermostat slightly higher, provides a laudable reduction in energy consumption. According to press releases from the Japanese ministry of environment, the campaign was a success and it was reinstituted as “Super Cool Biz”²² during the electricity shortage after the 2011 earthquake and tsunami, which shut down all nuclear power plants in Japan and caused a major environmental disaster.

Table 6.4 Metabolic Rates for typical tasks according to ASHRAE 55–2013 Table 5.2.1.2

Activity	Metabolic Rate		
	Met Unit	W/m ²	BTU/hft ²
Resting			
Sleeping	0.7	40	13
Seated, quiet	1.0	60	18
Standing, relaxed	1.2	70	22
Walking (on level surface)			
0.9 m/s, 3.2 km/h, 2.0 mph	2.0	115	37
1.8 m/s, 6.8 km/h, 4.2 mph	3.8	220	70
Office Activities			
Reading, seated	1.0	55	18
Typing	1.1	65	20
Lifting/packing	2.1	120	39
Misc. Occupational Activity			
Cooking	1.6–2.0	95–115	29–37
Light machine work	2.0–2.4	115–140	37–44
Handling 50 kg bags	4.0	235	74
Misc. Leisure Activity			
Dancing, social	2.4–4.4	140–255	44–81
Exercise	3.0–4.0	175–235	55–74
Wrestling, competitive	7.0–8.7	410–505	130–160

Source: ASHRAE 55–2013 with permission

6.11 Outdoor Comfort and Wind

When a body is warm, a cool breeze will provide relief, but when a body is already working hard to keep warm, a cool breeze will feel chilly. The opposite is also valid: warm winds can be wonderful when one needs to warm up, but can create an uncomfortable situation when one would rather cool down. Thus outdoor comfort and the design of comfort through the development of microclimate environments should receive more attention in the future in order to provide improved comfortable outdoor environments. Therefore, increasing attention is focused on outdoor comfort, which is particularly important in urban areas with hot climates, but also in colder environments, where a sunny windless spot can become a haven, the same way a shady spot can become

an oasis in a hot urban environment exposed to direct solar radiation.

This means that outdoor thermal comfort perception is as multi-layered as interior comfort perception. In the outdoors, radiation and convection are even more important for comfort sensation than temperature and humidity alone. This relates to exposure to direct or reflected solar radiation, wind, and the absorption of heat from the human body through wind. This absorption is facilitated by sweating and heat transfer by evaporation. Clothing is the major means to counter external radiation as well as convection.

The body surface temperature can average at approximately 35 °C (95 °F). In order to simplify calculations, the body in space is often estimated as a cylindrical rotational body of a diameter of about 20 cm (0.70 ft). For this body, Erell, Pearlmutter and Williamson state a heat transfer coefficient, which may be estimated by the empirical relation of $8.3 \times \text{velocity}^{0.6}$ with an energy heat flux expressed in W/m².²³ If the air temperature is above the body's surface temperature, the air is adding heat to the body, which can be detrimental for the metabolism unless sweating sets in and heat transfer by evaporation is utilized. More information about this energy balance of a human being in an urban space can be found in *Urban Microclimate* by Erell, Pearlmutter and Williamson.²³

A sweating person is under thermal stress, which can be expressed by the so-called index of thermal stress (ITS) when evaluating the energy balance of a person. According to Erell, Pearlmutter and Williamson, this term was developed by Baruch Givoni²³ and expresses the overall thermal exchange between the body and its surroundings under warm conditions.

The ITS is a measure of the rate at which the human body must give up moisture to the environment in order to maintain thermal equilibrium through several mechanisms of evaporative cooling, particularly through the production of sweat. [...] Thus the value of the ITS is given in terms of equivalent latent heat (in total watts) also considering the cooling efficiency of sweating. For this measure it is important to understand the relative humidity of the air and the evaporative capacity of the air given by the wind speed, vapor pressure and clothing. Sweating is thus most effective in dry and hot climates with a light breeze.²⁴

6.12 Operative Temperature and Comfort

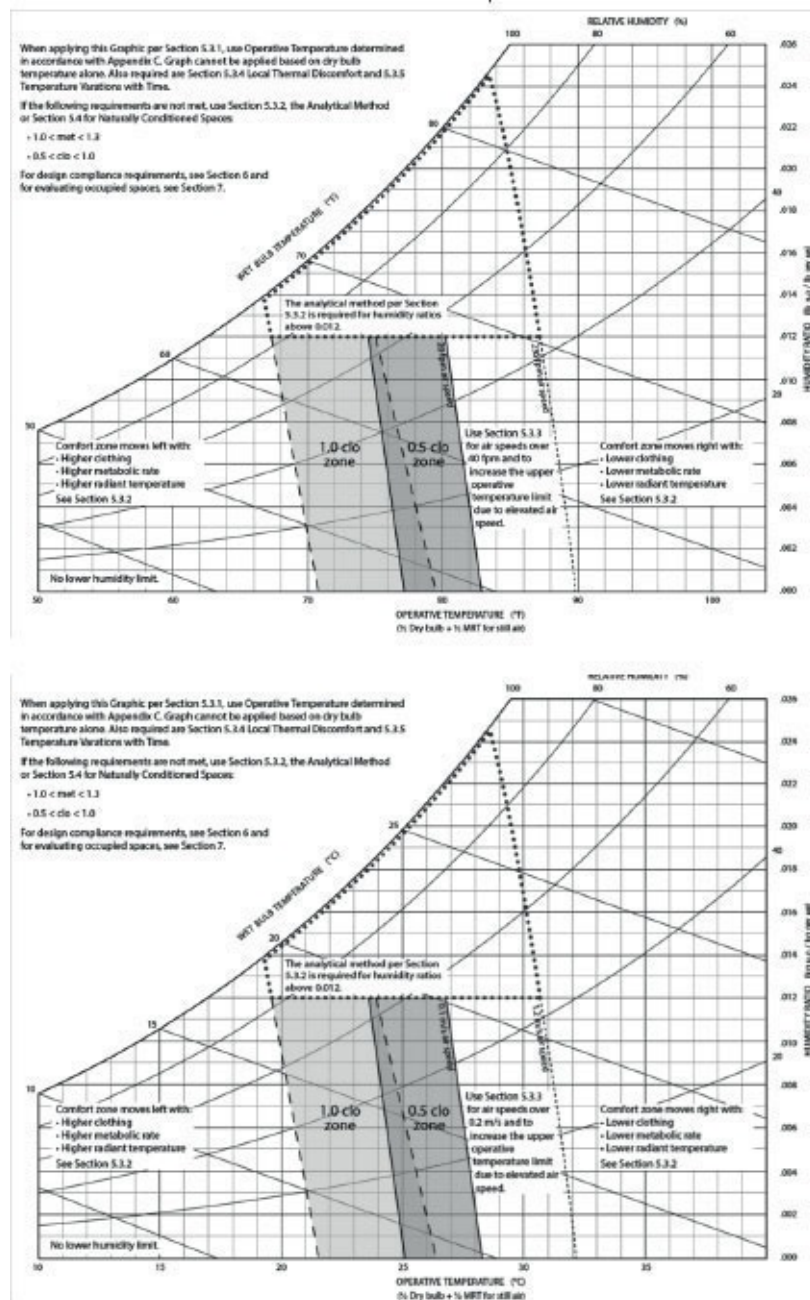
According to the adaptive comfort standard as it is currently understood,¹⁰ the mean comfort temperature can be derived from the respective outdoor temperature. This direct numerical relationship has been developed in multiple comparative field studies and is summarized in the linear graph:

$$T_{\text{comfort}} = 0.53T_{\text{outdoor}} + 13.8$$

The implementation of adaptive comfort conditions might need significant complex control algorithms to operate effectively. More about control strategies is covered in [Chapter 10](#).

Table 6.5 Graphic Comfort Zone Method: Acceptable range of operative temperature (to)

and humidity for spaces that meet the criteria specified in [Section 5.3.1](#) ($1.0 \leq \text{met} < 1.3$; $0.5 < \text{clo} < 1.0$) – (a) I-P and (b) SI according to ASHRAE 55–2013 FIGURE 5.3.1. ASHRAE 55–2013 with permission.



6.13 Ventilation and Humidity

The influence of humidity on human comfort is not clearly defined and in some respects not even clearly known. It is obvious that the potential for thermal comfort in very hot and humid air conditions is significantly reduced because of the lower rate of evaporative heat transfer via sweating. Sweating in many cultures, especially in the Western world, is highly disliked and sometimes even considered a taboo. Although it may create comfort, it suffers from low acceptance rates as a cooling strategy. The requirement to prevent sweating in summer is not a metabolic concern, but a cultural concern. Sweating is the most feasible means of the human body to provide cool comfort to people.

In hot and dry climates, layered long garments are worn to prevent dehydration during

the hot day. Higher air velocity can expel higher air humidity, both in summer and in winter, but in winter care must be taken to protect the structural integrity of the building in order to prevent condensation on walls and colder surfaces. Condensation may cause issues such as mold growth that have detrimental effects on air quality and human health and should be prevented at all costs. Still, the mold itself is not the origin of the problem, but merely a symptom of lack of ventilation, while thorough misunderstandings of condensation at the dew point within the building assembly leads to mold growth.

6.14 The Concept of ‘Coolness’ as a Social Rather than a Health Concern

The United States is the main user of air-conditioning, partly because the climate in parts of the country is not conducive to human comfort as perceived today. Summer temperatures exceeding 100 °F or 38 °C are not perceived as comfortable, even with a cool breeze – in particular in buildings without any means of propelling air movement or keeping cool in a more controlled manner. Mechanical cooling turned into a social status symbol and air-conditioning became a way of life and not merely a necessity, as analyzed by Marsha Ackerman in her comprehensive book *Cool Comfort: America’s Romance with Air Conditioning*.⁷ Henry Miller’s *The Air Conditioned Nightmare*²⁵ repeats the notion that American lifestyle has detached itself from nature. Miller also complained that the complacency created by comfort and convenience was an issue of the new American middle class and their dream of life. This relates directly to issues of productivity and efficiency raised on the North American continent related to the detrimental summer climate as compared to Europe. Better work ethics were related to cool climates, while heat supposedly led to laziness and lack of productivity. Lewis Mumford in *Techniques and Civilization*,²⁶ as quoted by Ackerman, found comfort to be modern man’s greatest achievement, but it puts “disproportionate emphasis on the physical means of living.”²⁷

6.15 Thermal Limits in a Naturally Ventilated Building

With rising concerns regarding energy consumption, climate change, and resource depletion, among other things, the question is: How warm can we allow it to become in a naturally ventilated building and how often should or can we allow it to be warmer and still feel comfortable in order to be less harmful to the environment? This reverses the debate recorded in Ackerman’s thesis about the onset of air-conditioning: How cool does it need to be? Ackerman quotes Huntington, the author of the controversial book *Civilization and Climate*, as stating that “the uniformity of conditions promised by air-conditioning seriously impaired human achievements.”²⁸ The answer is continued research.

6.16 Thermal Pleasure Versus Thermal Boredom: The Concept of Alliesthesia

There is no agreement in thermal comfort research about the need for, usefulness of, or

even desire for increased air movement inside indoor environments. While the mechanical ventilation industry aims at minimizing perceived air movement inside a fully conditioned building, natural ventilation of course requires perceivable air velocity. In addition, the tolerance for higher temperatures increases with air movement. Richard de Dear²⁹ goes as far as to question the whole notion of thermal comfort as a neutral case. He and his research team ask why we should aim for thermal neutrality inside a building when we could pursue thermal pleasure or alliesthesia, as he names it.

The third and most recent shift proposes a new approach to indoor environmental quality, going beyond thermal comfort and reaching for thermal pleasure. Thermal comfort is defined as the state of mind that expresses satisfaction with the surrounding environment (ASHRAE standard 55–2010). The emergent application of thermal alliesthesia to the thermal comfort explored by de Dear (2010) investigates situations in which a peripheral thermal sensation can assume either positive or negative hedonic tone, depending on the state of core temperature in relation to its thermo-neutral set-point.²⁹

The concept of alliesthesia coined by Cabanac (1971) implies the presence of internal signals modifying the conscious sensations aroused from peripheral receptors. For instance accelerations in air speed on skin surface trigger dynamic discharges from the skin's cold thermoreceptors. So, in the warm adaptive comfort zone these turbulence-induced dynamic discharges from exposed skin's cold thermoreceptors elicit small bursts of positive alliesthesia.²⁹

Beyond the physiological issues of skin temperature and sensorial triggers, it may be even more important that natural ventilation and movement of fresh air also have a strong psychological component, which could be explained as simply the joy of and connection with the outdoors or not being enclosed inside a building. This feeling may go along with the smell of earth or flowers, but of course not with the smell of automobile exhausts or idling delivery trucks. Nevertheless, designing for thermal pleasure again becomes a challenge for the architect rather than the issue of thermal comfort, which was pushed into the corner of the building services engineers as it was stuck behind suspended ceilings and in invisible corners of the building and was not part of the architecture, the design of the space.

6.17 Evaluating Thermal Comfort Conditions: The Thermal Comfort Calculator

Air-conditioning and the advent of comfort standards seem to have gone hand in hand. The set point for air temperature seems to have guided the understanding of thermal comfort for the last five decades of the twentieth century. The adaptive comfort model on the other hand acknowledges the effect of many more interacting variables at play around the human body, including the state of the human body itself. Therefore new tools have to be implemented in order to understand which conditions are necessary to provide thermal comfort or even pleasure to occupants. One of these tools has been developed by Richard de Dear at the University of Sydney and can be found at the following link:

<http://web.arch.usyd.edu.au/~rdedear/>.³⁰ It provides output values for a variety of interdependent environmental and body variables. The complexity of this approach may make it look tedious, but the outcome of its application may lead to improved architectural experience and improved comfort. A second tool has just been released by the Center for the Built Environment (CBE), Berkeley, and can be found here:

<http://www.cbe.berkeley.edu/research/thermal-tool.htm>.³¹

Notes

- 1 Marc-Antoine Laugier, *An Essay on Architecture*, Documents and Sources in Architecture (Los Angeles: Hennessey & Ingalls, 1977).
- 2 Gottfried Semper, *The Four Elements of Architecture and Other Writings*, translation Harry Francis Mallgrave and Wolfgang Herrmann (Cambridge, UK; New York: Cambridge University Press, 1989).
- 3 ANSI/ASHRAE Standard 55–2013: *Thermal Environmental Conditions for Human Occupancy* (Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2013).
- 4 CIBSE Guide A, Section 1.3, http://www.arca53.dsl.pipex.com/index_files/thermco2.htm (accessed 5/12/2014).
- 5 ISO 7730: *Ergonomics of the Thermal Environment – Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria* (2005).
- 6 See Willis Carrier, <http://www.williscarrier.com/> (accessed 5/12/2014).
- 7 Marsha Ackermann, *Cool Comfort: America's Romance with Air-Conditioning* (Washington: Smithsonian Institution Press, 2002).
- 8 P. O. Fanger, *Thermal Comfort: Analysis and Applications in Environmental Engineering* (New York: McGraw-Hill, 1972).
- 9 Richard de Dear and G. S. Brager, *Developing an Adaptive Model of Thermal Comfort and Preference*, Final Report ASHRAE RP-884, Macquarie University, Sidney, Australia, Center for the Built Environment Design Research, University of California, Berkeley, 1997.
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Chapter 7

Pressure as Indicator

Generally, air is set in motion by temperature and wind, causing pressure differences between the inside and outside of the building. The pressure is needed to overcome resistance at the inlet opening and all other openings on the air flow path through the geometry of the building. The difference in pressure will cause the flow of air. Temperature-induced pressure differences will be discussed first in [Section 7.1](#), and wind-induced pressure differences will be introduced in [Section 7.2](#). Each ventilation strategy has an impact on the spatial configuration and composition, and this impact will be even more complex when the two strategies are combined. Therefore, before discussing their combined influence, temperature and wind-driven natural ventilation will be discussed separately. For all natural ventilation strategies it is also important to take the external conditions of the driving forces into consideration. We will therefore pay special attention to urban contexts where the outside driving forces are significantly different than in rural environments, as addressed in [Section 7.3](#).

7.1 Temperature-Induced Air Movement

7.1.1 *Stack Ventilation or Thermal Buoyancy Ventilation*

Hot air rises, expands, and becomes lighter (see [Figures 2.9](#) and [2.10](#)). But to what degree does this affect natural ventilation and what conditions are required for buoyancy to facilitate natural ventilation?

It is important to understand the effect of temperature differences on air movement. First of all, temperature difference leads to pressure difference. The pressure difference is a result of the temperature difference between the column of warm air inside the building and the ambient temperature outside of the building as well as of the height of the column of warm air. According to the 1994 Building Research Establishment digest,¹ for each degree of temperature difference between inside and outside, a pressure difference of approximately 0.04 pascals per meter of building height is created. The higher the pressure difference is at the top of the air column, the higher the induced air movement at the bottom of the column and inside the space. This phenomenon of air moving out of the building at the top of the column and moving in at the bottom leads to the development of a neutral plane, where the pressure difference switches.

The ultimate goal of ventilation is to achieve the required air change rate (ACH) in volume (cubic feet or cubic meters) per time step (hour or minute), which requires very specific spatial proportions and design developments in order to prevent old stale air from remaining in the occupied zone and to allow fresh air to enter the occupied zones of a building.

Important for the determination of the flow direction inside a building designed to utilize stack effect ventilation is the position of the neutral pressure level. Fresh air flows

inwards below the neutral plane and stale air flows outwards above the neutral plane. The position is defined by the ratio of the distance between the neutral plane and the center line of the bottom opening to the top opening with respect to the ratio of the temperature difference multiplied by the fraction of the area squared. The position of the neutral plane shifts towards the larger opening proportional to the area of the opening, as can be seen in Figure 7.1.²

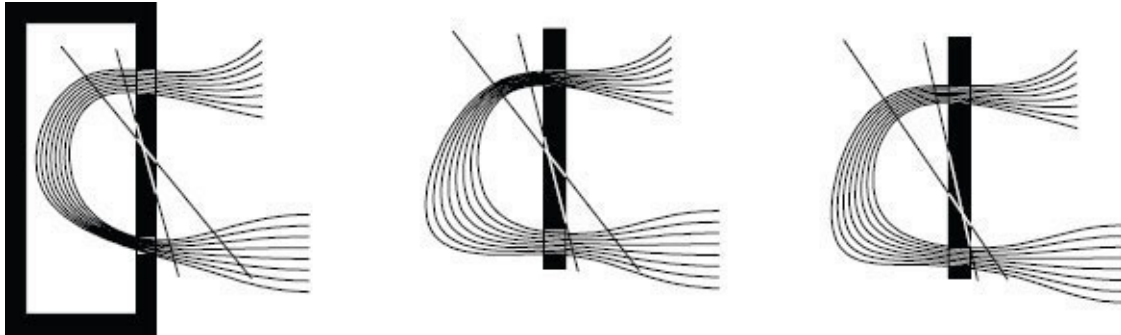


Figure 7.1

Definition of neutral plane: the neutral plane defines the plane in the height of a ventilation stack, where inward pulling air movement forces change to outward moving forces.

There are two different strategies to achieve stack ventilation. The first one assumes homogenous temperatures within the building and requires the interior temperature to be higher than the outside temperature. The second strategy keeps the occupied zones within the building below the outside temperature, for example through nighttime ventilation, and relies solely on the buoyancy effect.

Thus the spatial dimensions have to be set up specifically to create a warm air space with a significant height above the occupied zone of a building so that the stale air flows outwards above occupied spaces and not through occupied spaces. Inlets for fresh air should be positioned below the neutral plane and at a location in the building where outside air is ideally the coolest. The outlet on the other hand should be positioned above the neutral plane at the top of the warm air column, where the space is the warmest. A designer should also make sure that the outlet is well above the neutral plane and that the warm air will not move through occupied areas, which would render them too hot for occupation.



Figure 7.2

Solar chimney: increasing the temperature at the top of the stack increases the pressure differential and thus the air change rate by stack ventilation.

A space that is exposed to solar radiation in order to facilitate the warming up and

consequently the rising of hot air is called a solar chimney. Such a space should not be used for occupancy, except when used for a transitional space such as a staircase. Heat loss through the envelope of the solar chimney requires cautious attention. An atrium can also act as a solar chimney, if the top of the atrium extends beyond the roof line of the building and provides additional solar exposure.

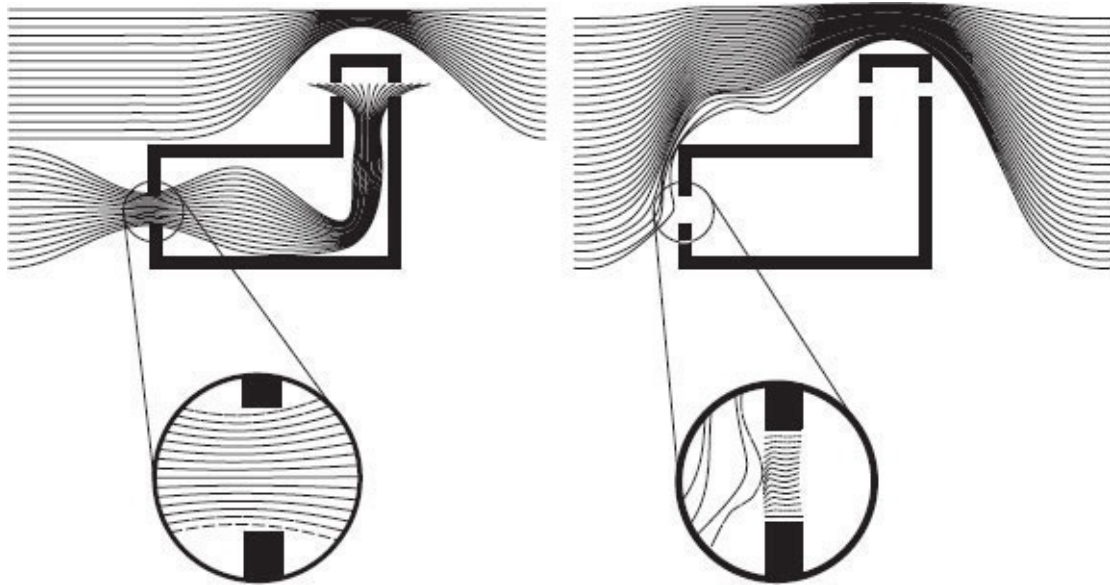


Figure 7.3

The pressure differential active at the inlet has to be strong enough to overcome the friction of air moving against the materials and geometry at the ventilation inlet opening area.

Buoyancy affects all air movement, as there is always a certain combination of wind-induced ventilation and buoyancy ventilation; for simplicity, the strategies are introduced separately first.

User-operated windows can be designed as inlets and outlets for stack ventilation; however, especially at the top of a building, automated vents and louvers may be more appropriate because there is typically only limited access to these locations.

Before starting to design for natural ventilation by stack effect, designers must ensure that they have reduced heat gain as much as possible, utilizing shading, low-energy-consuming equipment, and lighting as well as daylighting. Heat that does not enter the building does not need to be removed. The pressure differential has to be strong enough to overcome the friction working against the flow in the two openings.

7.1.2 Position of Neutral Pressure Level

It is important to understand the position of the neutral pressure level (NPL) in the stack space. Below the NPL, cooler air will flow inwards towards the warmer stack of rising air and above the NPL warm air will flow outwards towards the cooler outside air. The sum of all inflow air volume has to balance the sum of all outflow air volume. The driving force is greatest at the opening furthest away from the NPL. With equal size openings, the NPL is positioned halfway between the two openings and will shift with changing opening size and the distance to the neutral pressure level. The height of the neutral plane can be determined by the ratio of the distance between the inlet and outlet and the pressure at the

inlet and outlet area.³ Air density depends upon temperature.

For each increase of temperature with height, there is a corresponding decrease in pressure. Wind velocity and pressure drop across an opening determine the air flow rate across that opening. Stack pressure equals the pressure losses. Driving stack pressure varies with building height and the temperature difference between indoors and outdoors.

During summer, when outdoor air temperature is warm and close to indoor temperature, the stack pressure differences are going to be rather small, unless the building is very tall, and will be much lower than wind-induced pressure differences. Thus, summer ventilation based on stack ventilation can only be utilized if the upper stack gets really hot, for example through exposure to solar radiation.

For a three-story building with a height of approximately ten meters, the difference between indoor and outdoor temperature should be about 23 °C or 10 Pa. For an eight-story building, it should be approximately 10 °C. These temperature differences rarely occur in summer and thus most stack ventilation strategies are combined with wind pressure in order to operate at the required air exchange rate.⁴

Other rules of thumb⁵ require that the stack outlet be at least half of one story above the ceiling level of the top floor.

A stack terminal device can be added for a wind-buoyancy combined strategy. This device, combined with the air outlet on top of the stack, can respond to the prevailing wind direction and maximize the negative wind-induced pressure. The outlet on the top of the stack should therefore always be positioned on the leeward side of the wind in order to enhance the flow through wind-induced pressure difference.

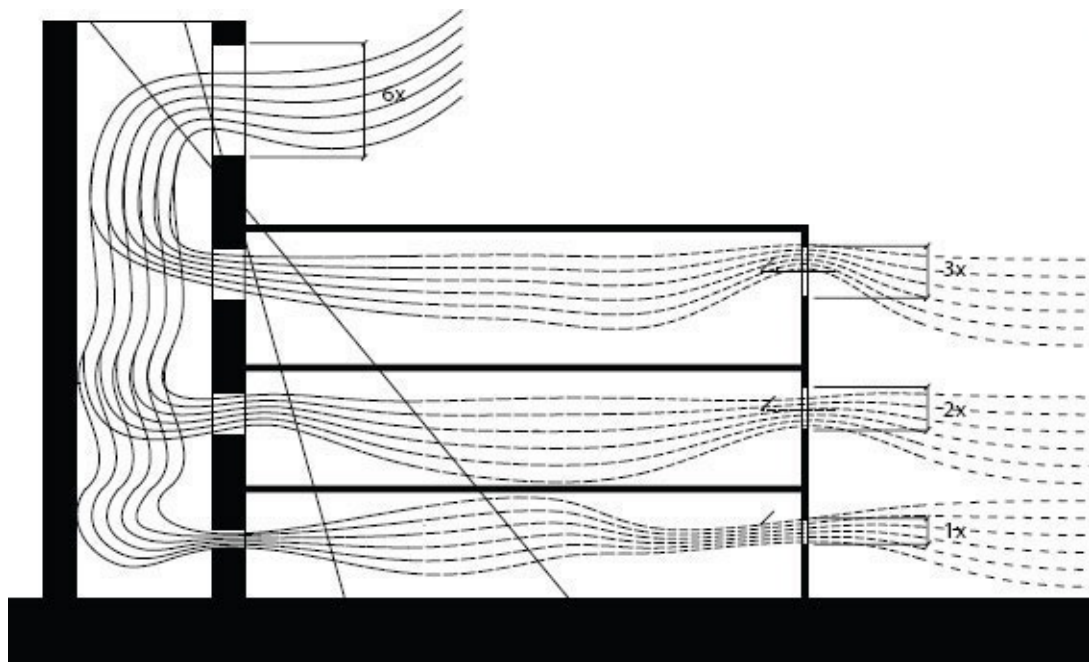


Figure 7.4

The height requirement of the stack is determined by the temperature difference, which can be expected between all inlets combined and the outlet.

Buoyancy-driven natural ventilation systems are the common choice for systems in the

urban context because of the often reduced wind speed in the urban street canyon. In this situation, solarassisted buoyancy can also be an option.

As with all controlled ventilation strategies, it is important that air infiltration be reduced so that leaks do not obstruct the air flow path.

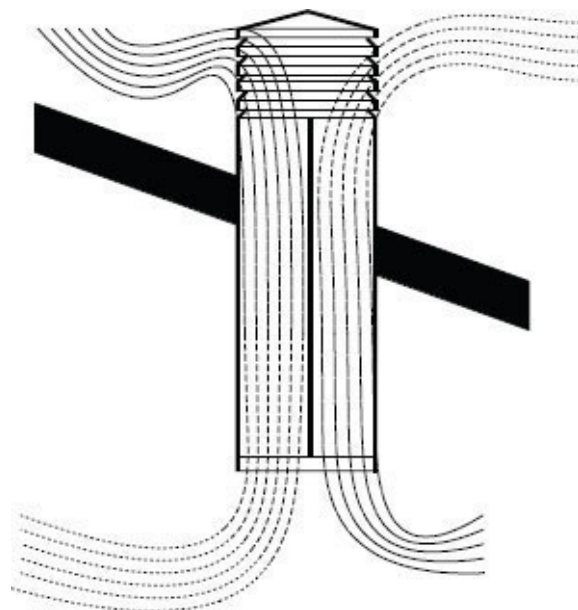


Figure 7.5

Stack terminal devices can be designed just as outlets or as a combined system of wind catcher and stack exhaust.

The Affleck House was simulated (further details in [Chapter 12](#)) to examine how wind enters through the vent in the floor (purple region in [Figure 7.6](#)) and convects through the house before exiting through open windows and doors.

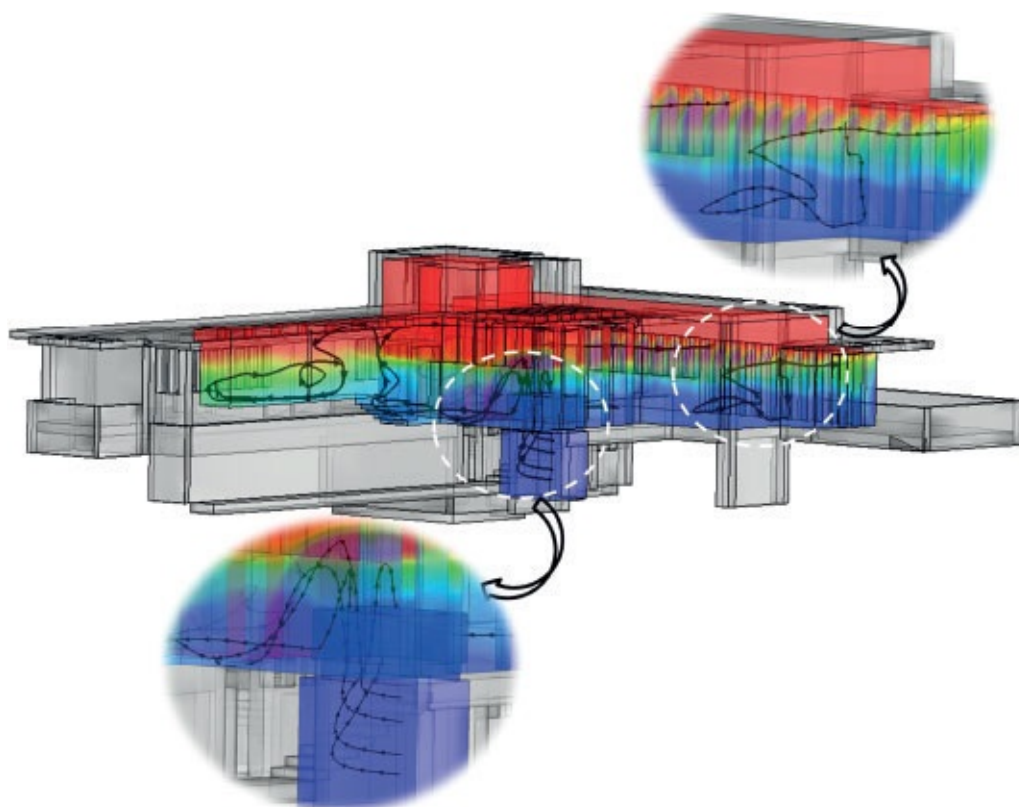


Figure 7.6

Simulation of the Affleck House showing temperature and streamlines. Enlarged views emphasize the wind

drawn into the floor vent and exiting through the windows and doors.

7.1.3 Classification of Stack Ventilation Strategies

Stack ventilation lends itself more to deep-plan spaces and can thus engage more of the full, three-dimensionally composed building than cross-ventilation.⁶ An active group of researchers in the UK around Kevin Lomas developed four main spatial characteristics that distinguish the spatial placement of the inlet and outlet by their position within the floor plan of the building.

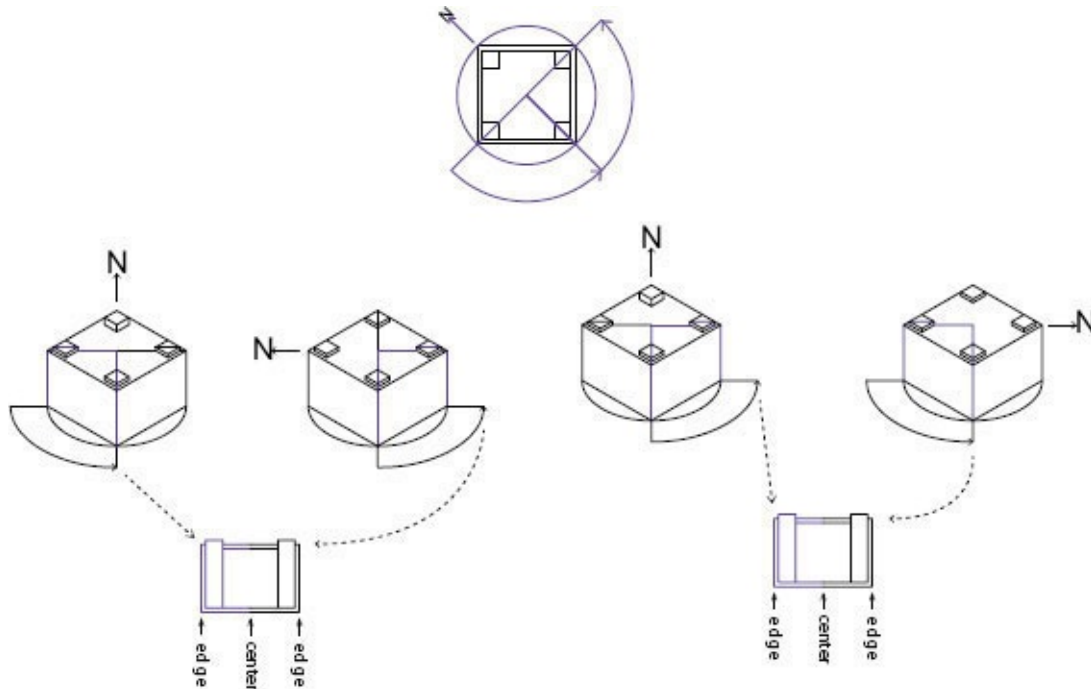


Figure 7.7

The spatial placement for stack ventilation inlet and outlet can follow a variety of combinations, as described by Lomas *et al.*: Edge in – center out / Edge in – edge out / Center in – center out / Center in – edge out.

7.2 Wind-Induced Ventilation

Inside the arcade, of course, there is least sunshine when the sun is blazing down on the roof, and as its open windows allow the western breezes to enter and circulate, the atmosphere is never heavy of stale air.⁷

Pressure difference is created by wind impinging on a building from a certain direction. Positive pressure is created on the windward side, and negative pressure on the wind-opposing side. Wind-driven air flow over a building induces positive (inward-acting) pressures on windward surfaces and negative (outward-acting) pressures on leeward surfaces; thus the building creates a pressure difference across the section that drives cross-ventilation.

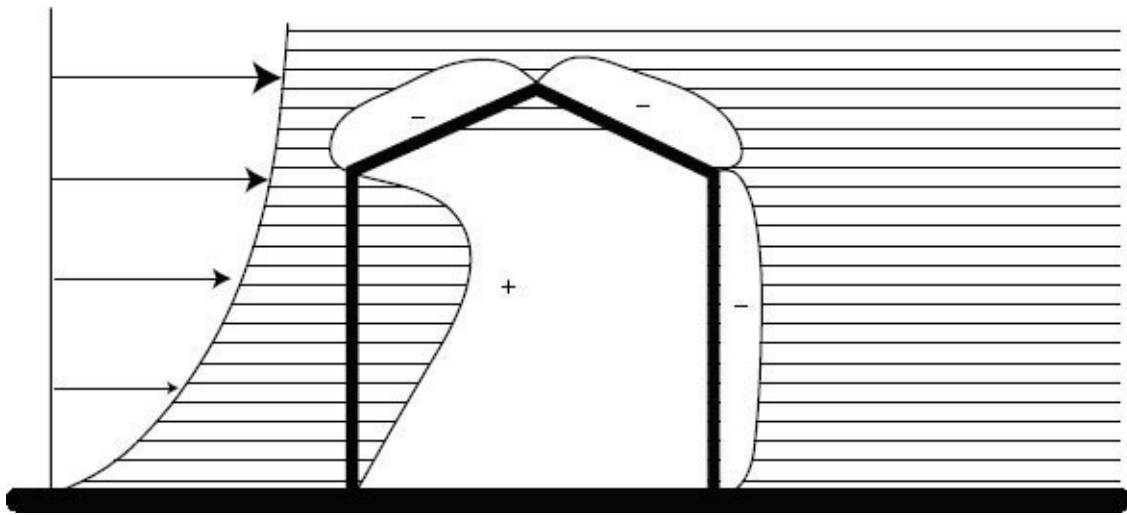


Figure 7.8

Wind pressure distribution around a stand-alone building shows the positive pressure on the windward side and the negative pressure on the leeward side and on surfaces perpendicular to the wind.

Wind pressure on the building depends on the wind direction, its speed, and the shape of the building. According to the 1994 Building Research Establishment (BRE) digest,⁸ the total wind pressure acting across a building is roughly equal to the wind velocity pressure. Wind velocity increases with the height of the building and is reduced in built-up areas because of the urban canyon effect. Only isolated areas allow for the utilization of the full meteorological wind speed measured at an airport weather station. Air enters the building on one side, sweeps the indoor space, and leaves the building on the other side. The ideal wind-driven pressure difference for cross-ventilation is 10 Pa, but wind direction and intensity characteristics are unsteady and can change.⁹

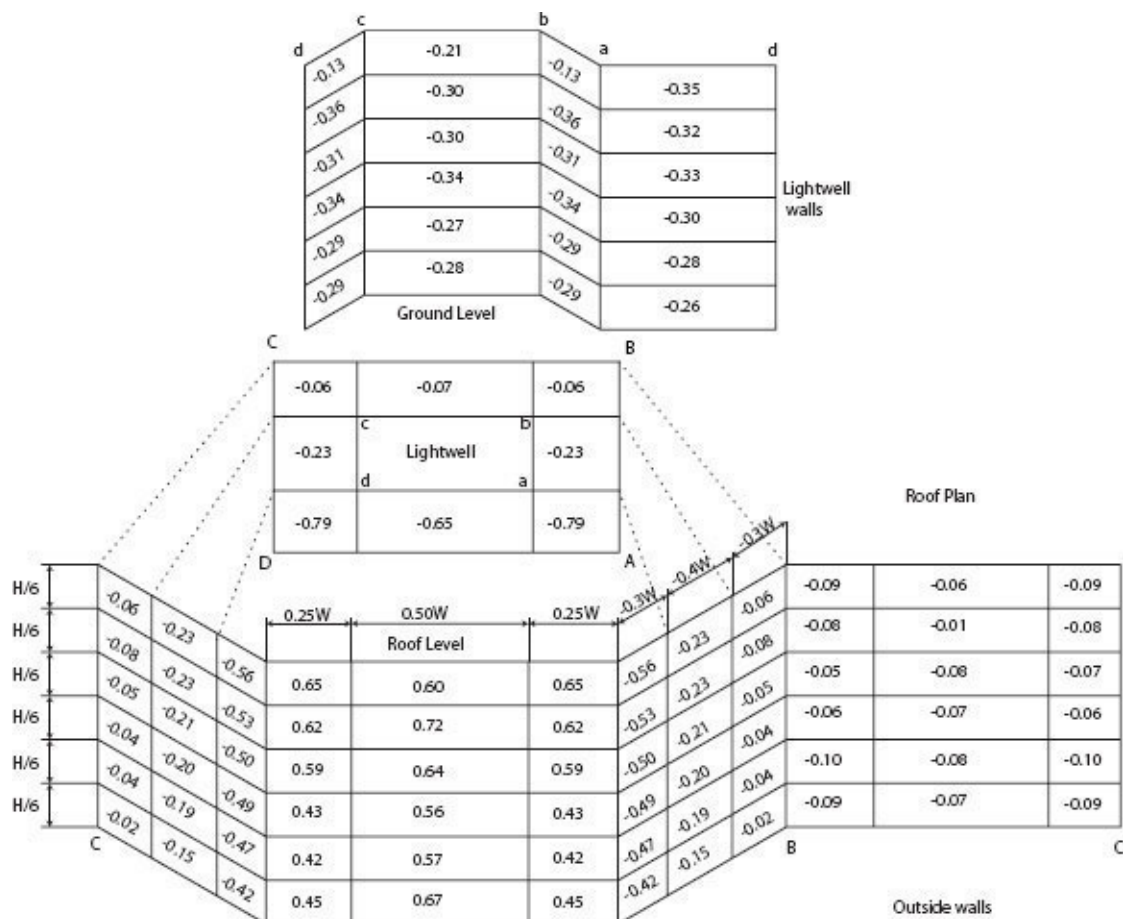


Figure 7.9

An example for a wind coefficient data map on building surfaces depending on height and width of the building. This information is available at a variety of resources (CIBSE, p. 54).

In order for wind-driven ventilation to work effectively, the pull from the negative pressure needs to be able to engage the air inside the full depth of the space to be ventilated; therefore naturally ventilated spaces that rely on wind can only have a certain depth. A basic rule of thumb relates the depth of the space to the height of the space to be ventilated. Most sources suggest a ratio of five times the height for the depth of the space. Thus, increasing the height of the ceiling is of great value to the natural ventilation scheme. In addition, there also should be no or only limited obstructions in the space. If obstructions exist, they need to have openings that resemble the size of the inlet (see a more detailed description of opening sizing in [Chapter 9](#)).

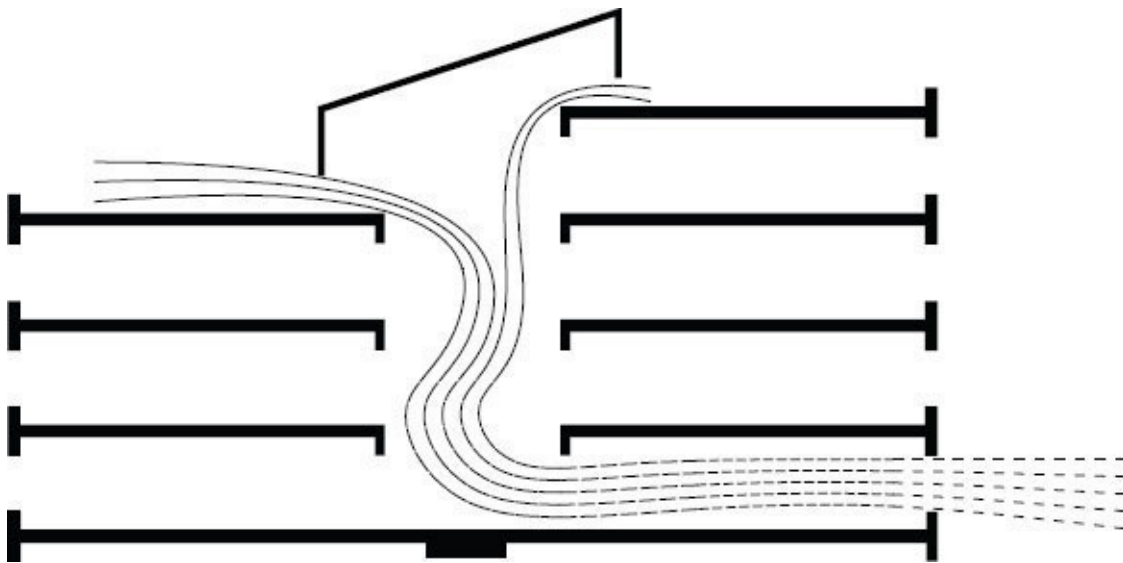


Figure 7.10

Cross-ventilation is often combined with a stack ventilated atrium to increase building depth and coordinate with daylighting and circulation strategies.

Wind as a resource is never steady, either in magnitude or in direction. As a result, the pressure field over the building varies constantly and exact air change rates at all times for wind-induced natural ventilation strategies are hard to predict.

7.2.1 Cross-Ventilation

Cross-ventilation occurs when inlet and outlet are positioned on opposite external walls of the building or space, with a clear flow path designed between them. Wind-induced cross-ventilation can also be combined with a local stack component. With moderate to high internal heat gain, the depth of a ventilation path has to be limited to about five times the height of the room.

The relationship between air velocity, inlet opening (e.g. the window), and depth of space can result in different mixing characteristics. As the CFD simulations indicate (see [Figures 7.11](#) and [7.12](#)), a larger opening creates larger mixing capabilities and recirculation regions above and below the opening, independent of wind velocity. However, for a smaller opening, the wind is directed toward the end of the room and

larger recirculation regions form where used air is not readily exchanged by fresh air.

Flow paths for cross-ventilation strategies need to be properly designed as a spatial continuum. The smallest opening along the path determines the air change rate.

Cross-ventilation can be introduced at a higher level and distributed over multiple inlets into a variety of floors. Double-skin façades can also be used to even out pressure differentials across the façade, as will be further discussed in [Chapter 8](#) using the Kreditanstalt für Wiederaufbau (KfW) case study project.

Cross-ventilation disproportionally mixes incoming air with current room air. This means that the air at the inlet is fresher and cooler than the air closer to the center of the space because air picks up heat and pollutants from occupants and equipment along its path. This is another major reason to restrict the depth of a room.

An atrium or courtyard designed for stack ventilation can act as a ventilation outlet and thus extend the depth of the building while still providing a flow path for cross-ventilation. A stack in an atrium can act as the negative pressure generator that creates a pressure difference across the ventilated space. Thus, both sides along an atrium may be as deep as five times the height of the space and still create proper ventilation and allow in daylight, as long as the atrium is properly designed to promote stack ventilation.

Flow rates will vary with the seasons, and thus strategies have to be evaluated for at least three major scenarios (winter, spring/fall, summer). Designing wind-induced ventilation strategies starts by incorporating wind as a resource to force air flow. This implies an understanding of how wind velocity extends pressure differentials across the façade. It is also important to take the influence of geometry and wind pressure into consideration, especially at the roof level.

7.2.1.1 Basic Proportions and Strategies for Wind-Induced Cross-Ventilation

The air change rate for wind-induced ventilation can be fairly easily found utilizing the computational relationship that the air change rate equals the flow rate with respect to the overall volume of the space with respect to the required time step of one hour. The flow rate is computed based on the air velocity at the inlet and the area of the opening.

With the volumetric flow rate and the flow velocity into the room, the basic spatial proportional rule of thumb for cross-ventilation can be modeled and simulated, where the depth of the room equals five times the height of the room. Once steady state is reached, the volumetric flow rate at the outlet will be equal to the flow rate at the inlet. To verify that the time-dependent simulations have reached steady state conditions, the outlet flow rate is calculated to make sure it is equal to that at the inlet. Three rooms of the same dimensions with different inlet-to-outlet ratios were simulated to test the influence of inlet-to-outlet ratio on air flow rate. The time-dependent computations were conducted for wind-driven scenarios with both low wind velocity ($V = 0.5 \text{ m/s}$) and high wind velocity ($V = 5 \text{ m/s}$). The values for the air change rate are listed in [Table 7.1](#).

Results are shown in [Figures 7.11](#) and [7.12](#) for the different room configurations and wind speeds. Velocity vectors and streamlines are used to help identify the air flow

patterns. The steady state solutions for Room 1–1 (small inlet, large outlet) and Room 1–3 (small inlet, small outlet) are very similar because the inlet windows of these two rooms have the same size. Although the results for Room 1–1 are not shown here (but are included in Detaranto’s 2014 thesis¹⁰), the streamlines and velocity vectors are virtually undistinguishable. There are minor differences at the outlet due to the different outlet opening size. Of course the ACH is identical because the inlet area is the same size. The streamlines and locations of eddies throughout the two rooms are very similar in size and location and tend to follow regions with a temperature gradient. The same pattern can be seen in Room 1–2 (large inlet, small outlet). Obviously the most important factors are the wind velocity and the area of the inlet. With the same opening size, a ten times higher velocity leads to a five times larger air change rate based on a five times larger volumetric flow rate. Table 7.1 also shows that both the air change rate and the volumetric flow rate increase with increasing inlet area.

Table 7.1 Air change rates for cross-ventilation depending on wind velocity, volume, inlet area

Parameters	Room 1-1		Room 1-2		Room 1-3	
Wind velocity V (m/s)	0.5	5	0.5	5	0.5	5
Volume (m ³)	141.64		141.64		141.64	
Inlet area (m ²)	0.945		3.78		0.945	
Outlet area (m ²)	3.78		0.945		0.945	
Volumetric flow rate (m ³ /hr)	1701	17010	6804	68040	1701	17010
ACH	12	120	48	482	12	120

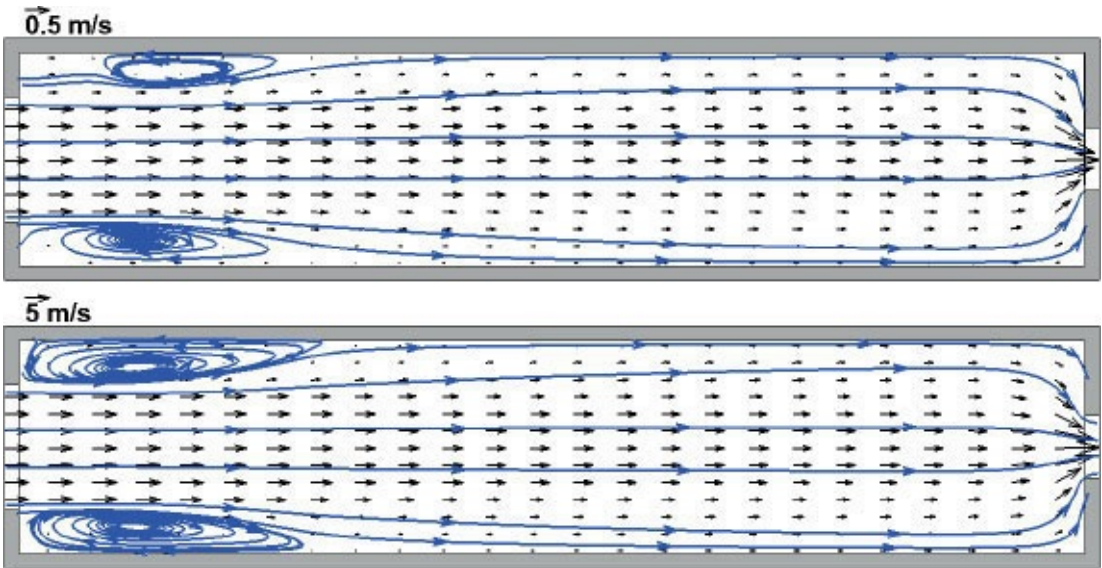


Figure 7.11
Wind-driven flow for cross-ventilation in Room 1–2 for (top) low velocity ($V = 0.5$ m/s) and (bottom) high velocity ($V = 5$ m/s).

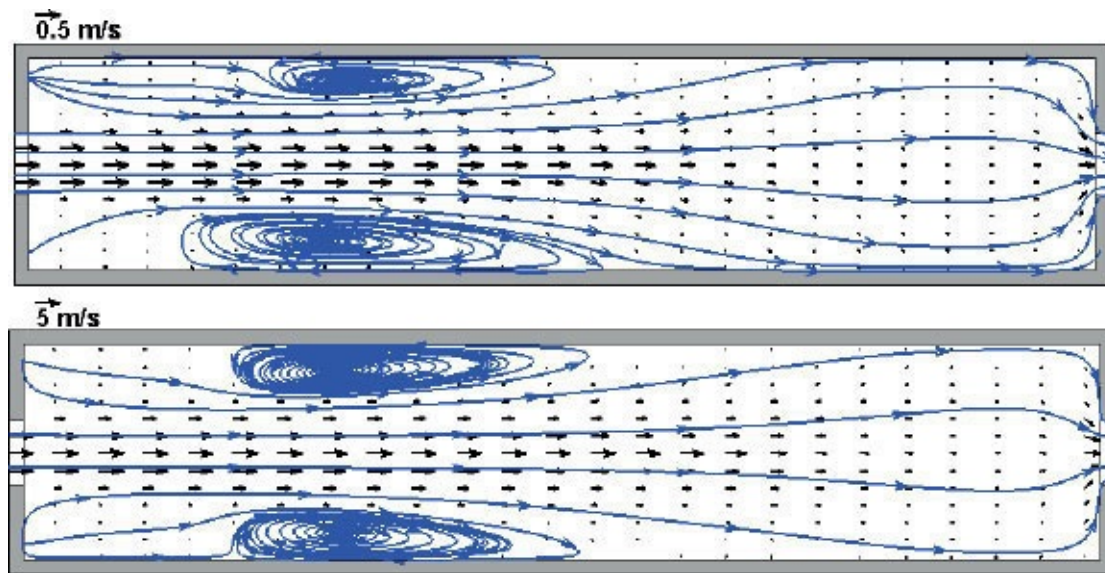


Figure 7.12

Wind-driven flow for cross-ventilation in Room 1–3 for (top) low velocity ($V = 0.5 \text{ m/s}$) and (bottom) high velocity ($V = 5 \text{ m/s}$).

7.2.2 Single-Sided Ventilation

Single-sided ventilation describes a situation when wind enters and leaves through a large opening or through two openings spaced apart on the same side of the building/space. Single-sided ventilation is the most de-central natural ventilation strategy and it can operate independently in different parts of the building. Air exchange occurs by wind turbulence, resulting in air alternating pushing in and exhausting out of the space, depending on the changing pressure difference across the opening and between inside and outside of the space. This will result in a fluctuating pressure and thus pressure and flow direction will be constantly reversing, thus mixing and displacing the exhaust air with fresh, incoming air. Outward openings can enhance single-sided ventilation by engaging the external air stream, which can be further enhanced by a local stack effect within the space. Single-sided ventilation can provide required air change rates for up to a depth of two and a half times the height as long as the space and the opening portion of the window area equal approximately $1/20^{\text{th}}$ of the floor area. Single-sided ventilation is most suitable for cellular room environments, such as offices, while cross-ventilation requires a flow path that spatially connects two sides of the building. Cross-ventilation is more suitable when an open-plan environment is planned.

Single-sided ventilation usually results in lower ventilation rates than cross-ventilation, and it can penetrate only a shorter distance into the space.

With internal heat loads, single-sided ventilation is also achieved by a combination of wind- and buoyancy-driven ventilation. When openings are provided at different heights above each other on the same side of the façade (one more towards the top of the space and one more towards the bottom), wind-driven turbulence combines with temperature- or buoyancy-driven forces in order to exchange air, slightly expanding the depth to which air will be mixed.

Figure 7.13 shows steady-state simulations of velocity vectors and streamlines for

wind-driven flow where the spacing between the openings is the only difference. Room 2–1 has a larger vertical distance between the openings than Room 2–2. A wind speed of 1 m/s was used in the simulations. The ACH shown in [Table 7.3](#) is identical because the rooms have the same volume flow rate. However, Room 2–2 shows that the air recirculated in a region above the upper opening and does not readily mix with the rest of the air in the room. The better mixing strategy would be to have the openings separated by a larger distance, such as in Room 2–1.

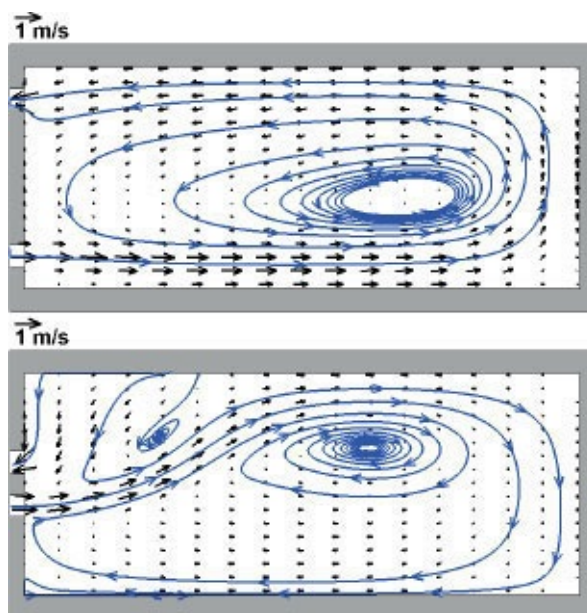


Figure 7.13

Wind-driven flow ($V = 1.0$ m/s) for single-sided ventilation in (top) Room 2–1 and (bottom) Room 2–2.

Both cross- and single-sided ventilation strategies are discussed further in [Chapter 12](#) in relation to modeling techniques and the effects of wind versus buoyancy dominated flows.

Table 7.2 Air change rates for single-sided ventilation based on wind velocity for Rooms 2.1 and 2.2

Parameters	Rooms 2–1 and 2–2
Wind velocity V (m/s)	1.0
Volume (m^3)	760
Inlet area (m^2)	0.6
Outlet area (m^2)	0.6
Volumetric flow rate (m^3/hr)	2160
ACH	31

7.3 Wind Patterns in the Urban Climate Context

7.3.1 Population in Urban Areas

According to the United Nations, “the world is undergoing the largest wave of urban growth in history.”¹¹ In 2013, more than half of the world’s population lived in urban areas. Urban areas are defined by a heightened level of population and building density,

which affects the inner urban climate as well as human indoor and outdoor comfort and well-being. Thus the potential for natural ventilation needs to be specifically explored in dense cities.



Figure 7.14

Aerial view of a very dense urban environment in a residential quarter of Mumbai, India.

The influences are manifold and there is a continuous feedback loop between the interior and exterior climatic conditions. The spatial proportion of the open to the built-up space strongly determines the wind pattern and its strength inside the city. Most buildings act as an obstacle to the major wind flow patterns, not only reducing the possibility for natural ventilation in the urban context, but also increasing the temperature difference between inside and outside conditions, causing the so-called urban heat island (UHI) effect. Buildings are thus both sources and consumers of thermal energy in the urban landscape.

7.3.2 Urban Patterns and the Modern Movement

The layout of the city was the subject of a major architectural debate in the early twentieth century. The dense urban working-class neighborhoods of the industrialized late nineteenth-century metropolitan cities had created environments more or less unsuitable and severely unhealthy for human occupation. Tuberculosis and other respiratory diseases were major issues and the outcry for a new urban environment was born: the Modern Movement, *das Neue Bauen*, or Modernism. Mainly European in origin, the proponents of CIAM (Congrès Internationaux d'Architecture Moderne) met between 1928 and 1959 to

discuss and spread the major architecture principles of the Modern Movement. The congress was initiated by Le Corbusier. Its most influential manifesto was *The Athens Charter*,¹² developed in 1933 and mainly addressing urban and social issues. *The Athens Charter* led to concepts and new urban plans for cities with less tightly spaced buildings and more open and green areas. The report of the third CIAM congress says: “The inhuman character of large cities was evident to all from the outset and the need to transform their structure entirely agreed upon.”

The motto *Licht Luft Sonne* (“Light, Air, Sun”) was already coined in the late eighteenth century by the early group of social utopians including the French Charles Fourier,¹³ the British Robert Owen,¹⁴ and the German Franz Heinrich Ziegenhagen.¹⁵ They all connected the development of utopian social or socialistic ideals with a new way of living and a new urban city layout. Ziegenhagen¹⁶ in particular related social and human health to a reconnection of city dwellers to nature and the natural elements. He considered access to sunlight and pure air as the basis for good living conditions. This parameter led to various architectural forms of lower density on the ground and improved access to sun, light, and air.

The relationship between urban layout and fresh air was also part of the Garden City movement, which originated in England as a response to the dense working-class neighborhoods of English mill towns such as Manchester where health issues were also major concerns. Ebenezer Howard’s “Garden City” proposal¹⁷ is known for its iconic three magnets: town, country, and town and country. The third magnet, town and country, is the ideal garden city for Howard. It would take the best from the country (pure air) and the best from the town (social opportunity), while avoiding the worst of the town (foul air) and the worst of the country (lack of public spirit), and combine them into a new urban fabric: the garden city.

But CIAM realized that the single family or the semi-detached houses proposed by the English Garden City movement were not the answer to the issues of urban settlements on the whole, because they would spread out the city too far. High-rise dwellings needed to be studied in order to determine their impact on dwelling and whether they would be able to deliver “not the dissemination of the elements of the city, but rather ... the aeration of the city.” Therefore, the *immeuble villa*¹⁸ was conceived by Le Corbusier in 1922, in a couple of speculative drawings, which lifted the single family house up into the air.¹⁹

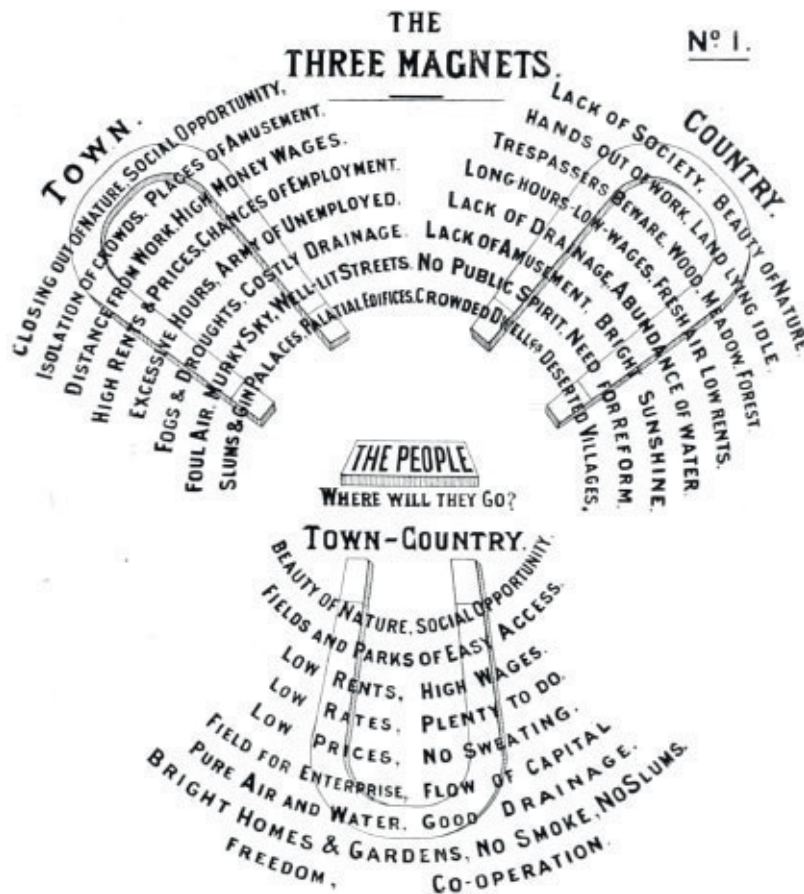


Figure 7.15

Ebenezer Howard (1850–1928) described the benefits of the Garden City in this diagram of three magnets, where the Garden City provides the best of both worlds: fresh air and social opportunity.

Le Corbusier’s La Ville Radieuse, or Radiant City,²⁰ became one of the most prominent examples of the new ideal, and the 1957 Hansaviertel in Berlin may be one of its best built examples. He again proclaimed that air, sound, and light were the elements of the new city, the Radiant City.²¹ The Athens Charter mourned the disappearance of “urban lungs” and related high population densities to a permanent state of disease and discomfort (Observation 9). While Ziegenhagen still applied operable windows to his utopian colony residential quarters, Le Corbusier’s answer to “doctors and the fitters of heating and cooling systems “unfortunately was: “exact air prepared in thermal power stations, disinfected, dustfree, given a suitable degree of humidity, pure and ready.”²² Observation 12 of the Athens Charter postulated that “the air, whose quality is assured by the presence of vegetation, should be pure and free from both inert dust particles and noxious gases” and declared sun, vegetation, and space as the three raw materials of urbanism.

CIAM also noted in Observations 13 and 14 that the most densely populated districts were located in the least favored zones, while the well-to-do lived in the areas with abundant sunshine and pleasing views, sheltered from hostile winds. Observation 16 promoted the separation from traffic and habitation to avoid the noxious gases in the exhausts.

Requirement 23 stated:

We must seek simultaneously the finest views, the most healthful air (taking account of winds and fogs), the most favorable slopes, and, we must make use of existing

verdant areas and determine a maximum population density. To introduce the sun is the new and most imperative duty of the architect.

CIAM thus promoted a radically different way of designing, zoning, and operating the urban environment after the rise of vehicular traffic and the overpopulation of cities during the second half of the nineteenth and the first two decades of the twentieth century had already caused detrimental chaotic urban conditions.



Figure 7.16

Le Corbusier's iconic model for the Radiant City (Ville Radieuse) incorporates the observations of CIAM's Charter of Athens and reduces the urban density while proposing higher buildings.

Yet, the massive reconstruction of the European cities and arising social issues led to a serious backlash against the new urban models in the 1960s. In the 1970s, the European city was reinvented conceptually, for example during the reconstruction of Berlin after 1990, named Critical Reconstruction.²³ Still, in most developing nations, urban density was a necessity rather than a choice. In the developing world, density and high-rise development seem to have become economic necessities. Urban density is thus crucial not only to understand wind patterns but also to develop solutions for sustainable city solutions.

7.3.3 Urban Meteorology

This section covers the aerodynamic characters of cities as described in multiple scientific sources within the field of urban meteorology and urban morphometry.²⁴

Wind in general is a highly variable and irregular physical phenomenon, even more so in the urban context, where wind is generally reduced compared to wind over the open landscape, and the direction of wind can be significantly altered. In addition, wind patterns specific only to urban areas have to be considered. Every urban spatial planning process shapes the wind and energy flows within the area, as in turn it is shaped and influenced by these flows.

Urban climatic conditions are complex and subject to scientific research all across the

globe. For example, the urban heat island (UHI),²⁵ analyzed as early as the 1940s by Helmut Landsberg, affects surface temperature depending on material, color, and reflectivity and vice versa. Beyond temperature, the urban wind patterns are crucial to pedestrian comfort as well as building ventilation, air quality, and energy use.

The layer of air in which the effects of the solid surface can be felt is called the boundary layer.²⁶

7.3.4 Urban Typology

In order to understand the basic relationship between urban spaces and their potential for natural ventilation, the spaces have to be evaluated based on their street canyon proportion and the relationship to wind direction and other climate aspects, such as diurnal temperature swings, which are important for nighttime ventilation. Errel, Pearlmutter, and Williamson²⁷ developed impressive databases for street canyon proportions and resulting wind patterns. In order to visualize these proportional relationships, [Figures 7.17 to 7.19](#) show the major street canyon proportions of select cities to correlate the findings by Grimmond and Oke as well as Errel, Pearlmutter, and Williamson with actual urban landscapes.

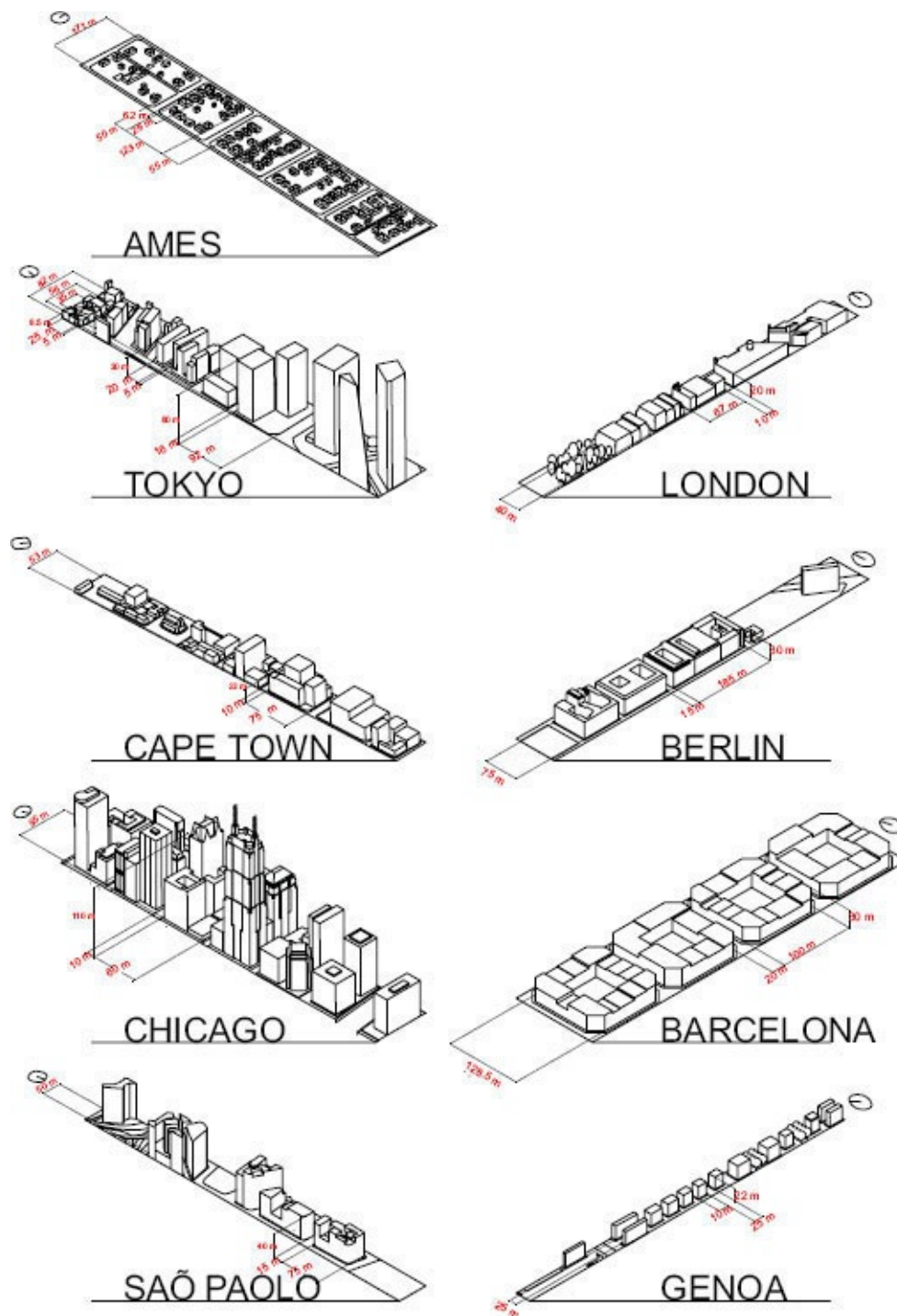


Figure 7.17

Based on Grimmond and Oke's urban morphometry, we analyzed the urban proportion of eight global cities (Ames, Iowa, Tokyo, London, Cape Town, Berlin, Chicago, Barcelona, Sao Paolo, and Genoa) and found that all of them had a very similar street canyon proportion in spite of diverse height and width of blocks.

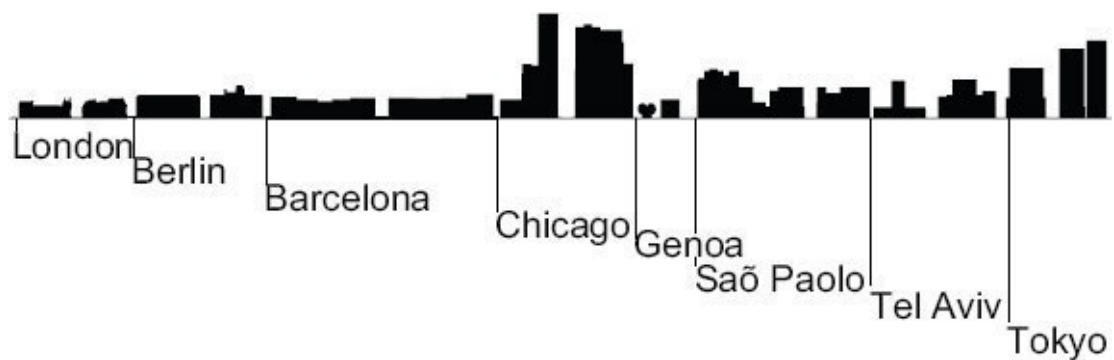


Figure 7.18

Urban Canyon sectional diagrams highlighting the diversity of section.



Figure 7.19

Urban Canyon figure ground comparison and plan dimensions.

Table 7.3 Calculated urban morphometry ratios for various cities (based on Grimmond and Oke²⁴)

City	Block face width 1 (BFW1) in meters	Block face width 2 (BFW2) in meters	Street canyon width 1 (SCW1) in meters	Street canyon width 2 (SCW2) in meters	Building height (BH) in meters	BH/SCW 1
Barcelona	137	128.5	10	10	30	3.00
Berlin	82	55	10	10	27	2.70
London	56	38	17	10	20	2.00
Genoa	18	18	12	12	22	1.83
Sao Paulo	65	30	15	15	40	2.67
Chicago	50	83	17	17	100	5.88
Tokyo	25	35	5	5	8.5	1.70
Cape Town	75	53	10	10	23	2.30
Ames	101	88	28	23	6.5	0.23

7.3.5 Wind and the Urban Street Canyon

The major parameter of the urban climate is the spatial distribution of buildings, indicated by the spatial proportions between height, width, and length of the so-called height-to-width aspect ratio of the street canyon. In addition, the distribution of open green areas and of bodies of water within the urban fabric need to be evaluated. As CIAM's Athens's Charter²⁸ already noted, green areas act as the lung of the city and improve the health of city dwellers.

The urban boundary layer is defined as the portion of air that shows the effects of the solid surfaces over which the air flows. Although wind flow caused by pressure difference usually progresses horizontally, within the urban boundary layer this pattern changes. The flow changes relative to the property of the surface and is affected by obstructive objects in its way. Sharp-edge obstacles, such as rectilinear buildings, cause a separation of the air flow, while rounder objects allow the air to adhere to the surface.

The approach direction of air movement is only partially of importance when investigating the flow around an isolated object or building. The pattern will still be very similar; only the velocity of air impinging on the surface will change depending on the angle at which the building is impinged by the wind.

Once several bluff bodies are moved close together, the urban area is formed, and thus the three distinct air flow zones identified earlier will begin to overlap and merge, creating the specific urban street canyon with air flow patterns very different from those in the open field. In this scenario, the air flow within the street canyon relates mainly to the flow direction of the wind above the urban canopy layer. According to Erell and Pearlmutter,²⁷ three wind regimes have been identified as flow patterns across urban canyons: perpendicular to the street canyon, parallel to the street canyon, and at an odd angle to the street canyon. All three are characterized by specific secondary flows within the canyon and the complexity of air flow in each is characterized in terms of speed, direction, and turbulence.

The most complex scenario related to building ventilation is the flow pattern that develops when the wind blows perpendicular to the street canyon. In this case, the air within the street canyon develops vortices similar to cork screws and these flow patterns constantly alternate the inlet and outlet function of ventilation openings within the street façade. The strength and extent of the vortex in the canyon depends on wind direction and street proportions.

7.3.6 Obstacles to Flow / Flow Around Building

The flow of air around an obstacle is defined by the shape of the object. The laminar flow of air is separated by sharp-edged objects, the so-called bluff bodies, while the air flow adheres to rounder objects such as valleys and hills. Most urban construction can be considered bluff bodies. Generally speaking, the flow is separated by the object, and three different zones around the building can be identified: the displacement zone, the cavity, and the wake. Very close to the building the flow will reverse and turn around on itself into small circular patterns of air movement, also called eddies.²⁹

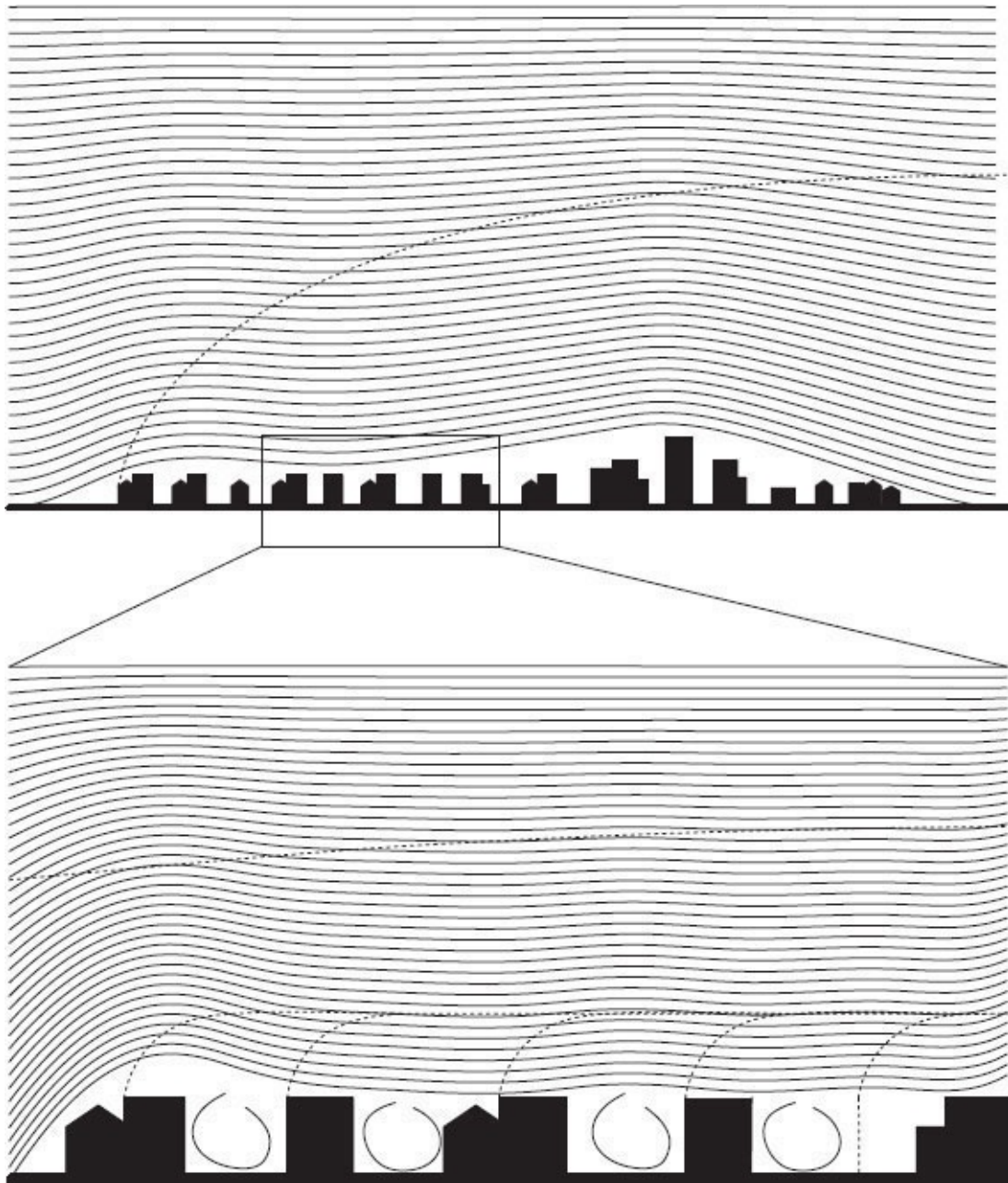


Figure 7.20

Schematic section of the urban atmosphere, differentiating between the urban boundary layer (UBL) and the urban canopy layer (UCL) with roughness sub-layer and mixed layer as transition zones in between.

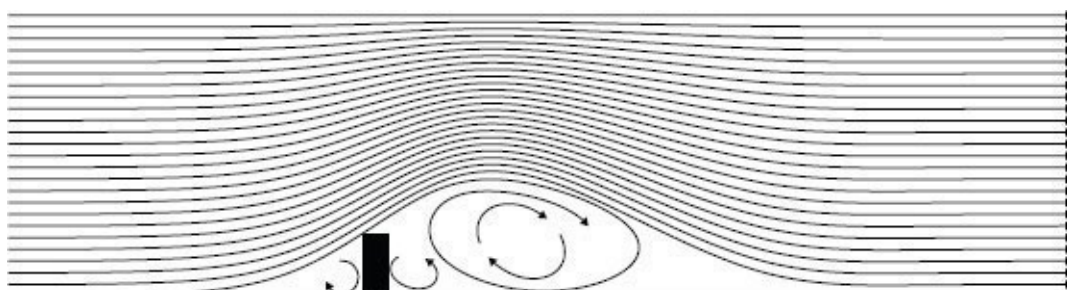


Figure 7.21

The distinct zones developed by air flowing around an obstacle: the displacement zone, the cavity zone, and the wake.

When air flows parallel to the ground and hits an object, four zones are created: the first zone is the zone where the air approaches the building (on the side facing the wind), the second is the zone above the roof, and the third is the zone called the ‘wake,’ which is a

zone downwind. The in-between zone forms the cavity zone. The height above the building at which the air flow remains undisturbed is roughly estimated to be three times the height of the building. If urban elements are spaced wide apart, each building will create these zones, as will large trees. Within the closer vicinity of a building, smaller scale flow patterns will form, which can create rather high wind speeds.

Turbulence structures will form behind the building, where the pressure difference between the low pressure wake zone (around leeward and side faces) and the general flow is strongest. Turbulence will also form in front of the building, where the flow starts to separate. Large masses of buildings can thus have a strong influence on the air flow around their edges, impacting outdoor comfort, but also on ventilation inlets, which might be positioned at those edges with turbulent flows.

These flow patterns overlap when buildings are closer together and thus create distinctly different sets of flows that can be identified by their character and roughly determined by the street canyon aspect ratio. Considering wind in the urban canyon, one can distinguish the difference between wind flow parallel with the street canyon or perpendicular with the canyon.

When the wind flows parallel to the street canyon, the wind inside the street canyon develops in the same direction. When wind approaches perpendicular to the street canyon direction, the air starts to develop a variety of vortices within the canyon that interface with the upper layer flow only at certain moments.

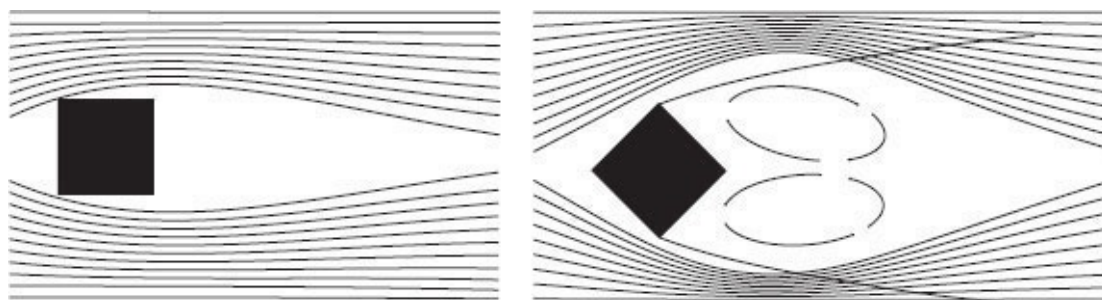


Figure 7.22

Flow around sharp edge objects creates turbulence.

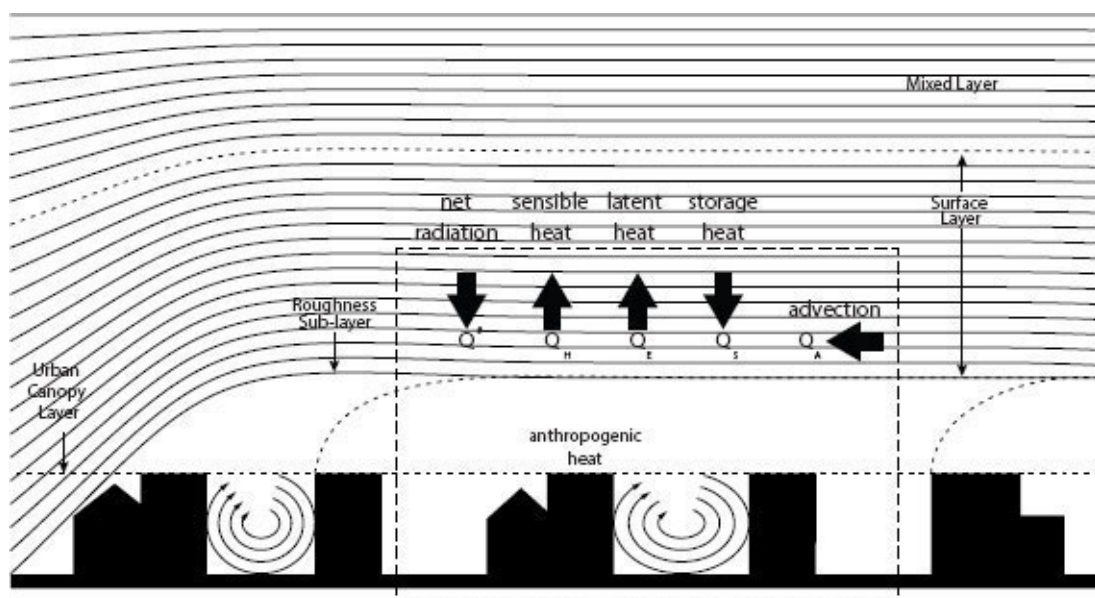


Figure 7.23

Urban surface energy balance and exchange of heat between urban zone and the atmospheric surface layer above.

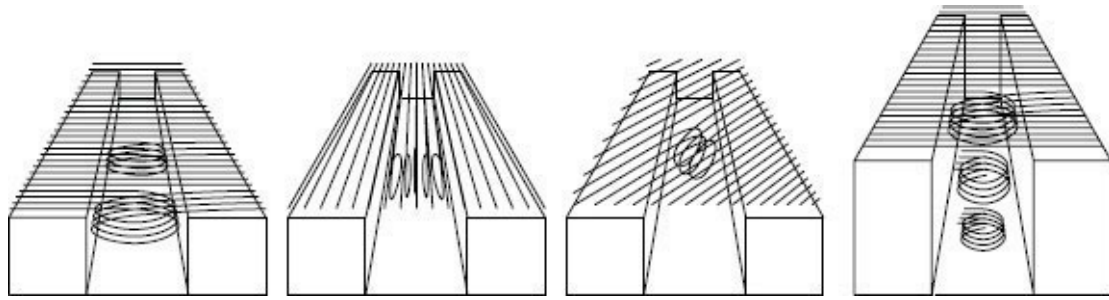


Figure 7.24

Street canyon wind patterns change significantly with the geometric relationship of primary wind flow to street direction.

7.3.6.1 Isolated Roughness Flow

When the spacing between buildings is relatively large, that is, the H/W ratio is less than 0.3–0.5, the flow fields of consecutive buildings do not interact. Thus these urban areas can be considered as isolated buildings.²⁷

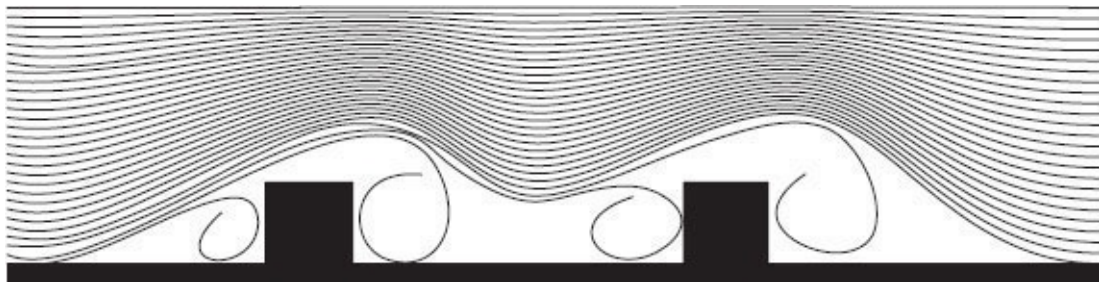


Figure 7.25

Isolated roughness flow occurs in urban areas with buildings spaced far apart (H/W ratio less than 0.3–0.5).

7.3.6.2 Wake Interference in the Urban Canyon

When buildings are closer together, for example with an aspect ratio between 0.5 and 0.65, secondary flows are generated within the canyon space, where the downward flow of the cavity eddy is reinforced by the deflection down the windward face of the next building downstream.²⁷ Thus, the bolster and lee eddy work together to increase turbulence. Despite the more turbulent circulation, average wind speeds are generally lower than when buildings are spaced further apart.

7.3.6.3 Skimming Flow Regime

When successive building blocks are tightly spaced, for example when the H/W ratio is greater than 0.65, the canyon may be considered sheltered from the direct impact of winds perpendicular to its axis.²⁷

Urban microclimate is strongly influenced by the inner urban proportional relationship between built-up areas and open areas such as lakes and parks. These flows are determined by inner urban breezes induced by local temperature differences.

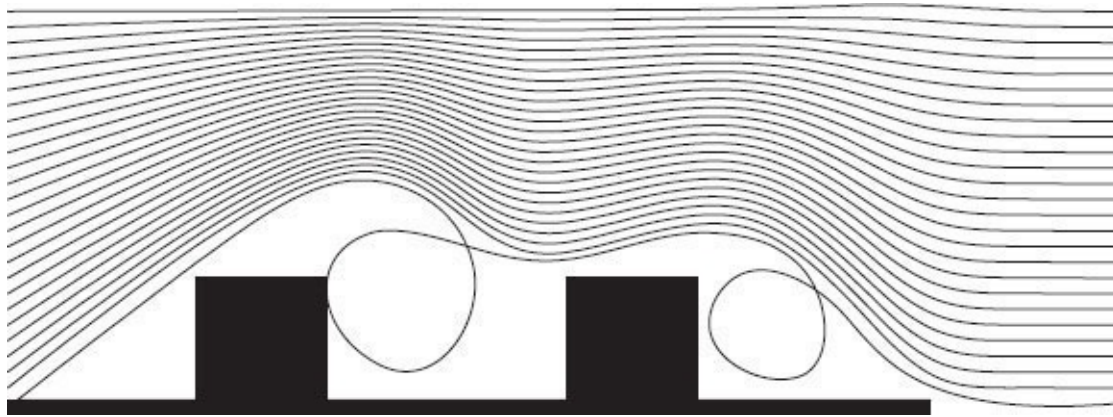


Figure 7.26

Wake interference flow in the urban canyon occurs with aspect ratios between 0.5 and 0.65 where the zone behind the building interferes with the zone in front of the next building to create fairly turbulent mixing situations.

Inner canyon air flow is also influenced by solar radiation, which reaches into the street canyon and heats it up. These patterns overlap with wind-induced patterns and influence air movement relevant for ventilation as well as urban air quality.

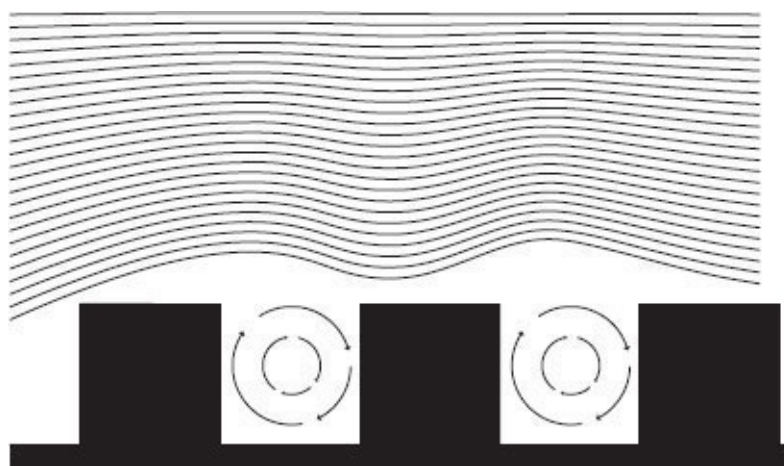


Figure 7.27

Skimming flow regime occurs when the buildings are closer together and the primary wind flow skims across the canyon and the bulk of the fresh air flow does not enter the street canyon.

Urban flow pattern is mainly characterized by turbulence around buildings, and inlets and outlets will change their function depending on the specific flow regime. Another issue influencing the capacity to naturally ventilate is the fact that air speeds are generally lower within the urban area than over the open landscape.

7.3.6.4 Flow Fields above the City

The urban fabric also influences the flow field and the temperature distribution above the city.³⁰ The most obvious and commonly known phenomenon is related to hot air rising and the bubble of hazed, warmer air hovering above each major urban agglomeration.

7.3.7 Influence of Urban Climatology on Urban Planning and Architectural Design

A variety of wind velocity profiles can be identified over various distinct terrain conditions and in particular over urban conditions. Ideally, for urban sites site-specific

climate data should be used, and these are often hard to obtain owing to the uncertainty of the inner canyon turbulence, unless the site has its own weather station.

For example, because of the shifting patterns of air movement inside the street canyons, the vents in the urban context need to be designed both as inlets and as outlets in order to account for different wind directions and the reversal of the flow in the canyon.

7.3.7.1 Climatic Cooling Potential (CCP)

Major parameters in the urban environment influencing the potential for natural ventilation are

- Reduced wind speed
- Increased temperature
- Variability and uncertainty of air flow patterns and directions.

This is of particular importance for nighttime ventilation in warm or hot climates with increased night temperatures in the urban context. For this scenario, Erell, Pearlmutter, and Williamson developed a calculation methodology to evaluate the cooling potential called climatic cooling potential (CCP).³¹

7.3.7.2 Thermal Influence on Urban Air Flow

If one side of the street canyon is exposed to solar radiation and wind is weak, buoyancy forces interfere with the wind-induced street canyon vortex and most will likely split the vortex. If strong solar heating on the canyon walls or floors warms the canyon in the direction of the wind, the vortex in the street canyon will separate and two outward flows on either canyon wall will be created. On the other hand, solar heating of the leeward wall will reinforce the corkscrew-like street vortex. The effect of thermal buoyancy caused by solar radiation diminishes with stronger wind across the street canyon.³¹

7.3.7.3 Interaction of Air Flow in the Urban Boundary Layer (The City) with other Factors

Wind speed in the Earth's atmospheric (or planetary) boundary layer usually increases with height above surface. With an urban roughness layer, the starting point of the vertical profile is moved upwards away from grade level, because the surface of the ground provides a frictional drag owing to the roughness of the surface. Smooth surfaces create less friction than rougher surfaces, similar to other movements, for example those of cars. The urban surface is rougher than any other surface on the planet Earth, except for high mountain ranges, which indeed also create their own specific climate.

7.3.7.4 Boundary Layer Roughness Length

Aerodynamic resistance plays an important role in this overall evaluation of the urban boundary layer. Velocity and turbulence thus relate directly to the roughness of the boundary layer over which the air is flowing. Francis Allard³² defines the roughness height as an

aerodynamic characteristic of the ground surface. For an identical geostrophic (velocity) and an identical height above the ground, the average velocity will decrease for an increasing roughness of the ground. The roughness height is thus a function of the nature of the ground and the geometry of existing obstacles.

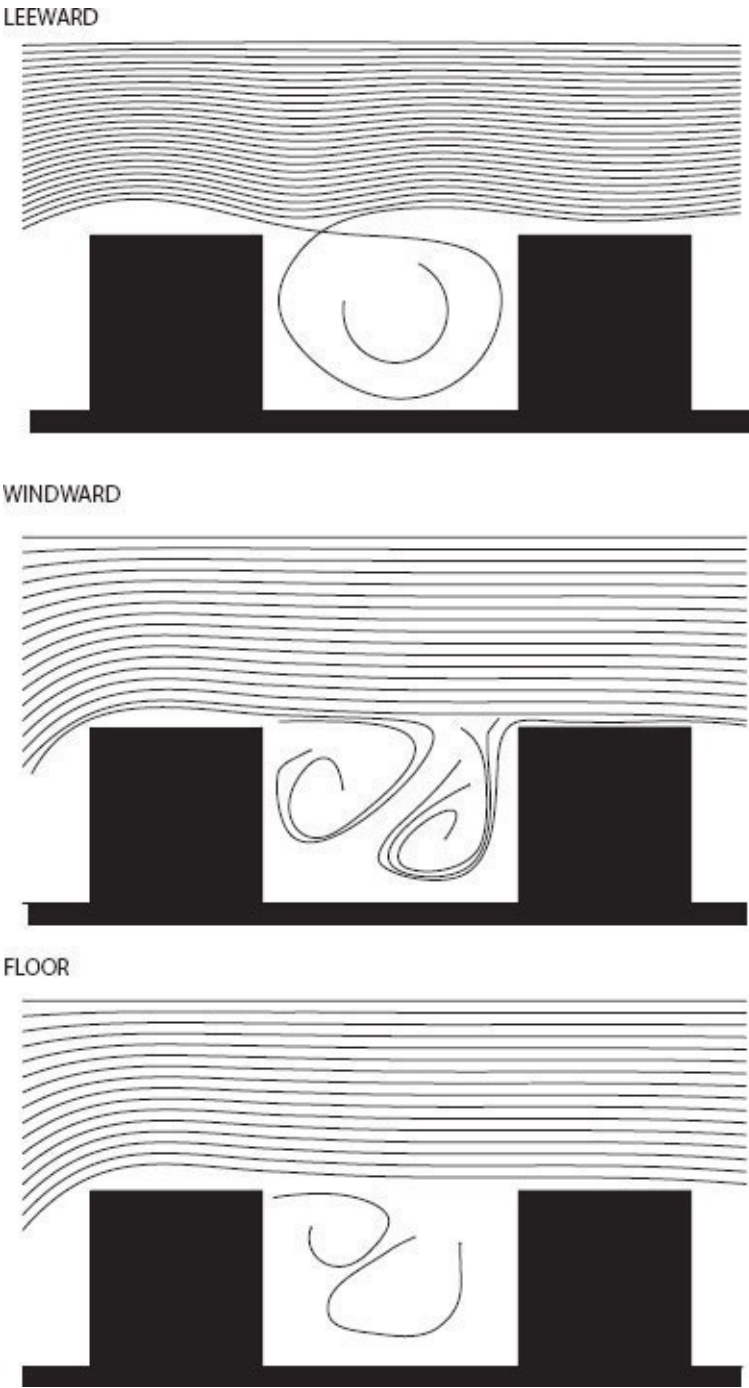


Figure 7.28

Solar radiation entering the street canyon significantly impacts the canyon flow. Top: solar radiation hits the leeward side; middle: solar radiation hits the windward side; bottom: solar radiation hits the floor of the canyon.

Table 7.4 Roughness length of various surface types

Type of surface	Roughness length (or height) (in m)	Roughness class
Sea, loose sand, snow	0.0002 (U-dependent)	I
Concrete, flat desert, tidal flat	0.0002–0.0005	I
Flat snow field	0.0001–0.0007	

Rough ice field	0.001–0.012	
Fallow ground	0.001–0.004	II
Short grass and moss	0.008–0.03	III
Long grass and heather	0.02–0.06	IV
Low mature agricultural crops	0.04–0.09	IV
High mature crops (grains)	0.12–0.18	V
Continuous bushland	0.35–0.45	V
Mature pine forest	0.8–1.6	VII
Dense low buildings (suburb)	0.4–0.7	VII
Regularly built large town	0.7–1.5	VIII
Tropical forest	1.7–2.3	IX
High rise (from Allard, p. 62)	4.00	IX

Source: Adapted from Jon Wieringa, “Representative Roughness Parameters for Homogeneous Terrain,” *Boundary-Layer Meteorology*, 63(4), 1993, p. 348, Table VIII; and Christian Ghiaus and Francis Allard (eds), *Natural Ventilation in the Urban Environment* (London: James & James, 2005), p. 62

In the urban context, pollution distribution and noise attenuation are also influenced by the roughness height of the urban context.

In general, the wind speed increases with distance from the ground and so does the boundary layer influenced by the roughness class. The zero-plane displacement depends on the roughness length of the boundary layer.

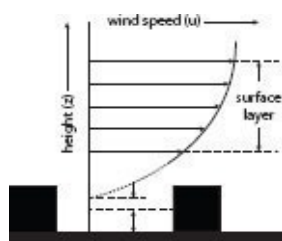


Figure 7.29

Depending on the roughness of the urban environment, the vertical profile of wind velocity above terrain is shifted upwards significantly, reducing the wind velocity available to urban ventilation strategies.

7.3.7.5 Zero-Plane Displacement

The zero-plane thus shifts upwards with the density of the urban environment based on the roughness length. This is called zero-plane displacement,³³ which in many cases is approximately equal to two-thirds of the average height of roughness elements. The zero-plane displacement literally indicates the shift of wind speed curve upwards relative to the open field. Thus, there is an overlay between the air flow pattern in the canyon and the flow field above the urban area, which influences the upper third of the street canyon.

Various sources provide experimental data for this shift and the various patterns, but almost all go back to the Davenport roughness classification tables,³⁴ which were last updated by Wieringa in 1991 and 1993.³⁵

Table 7.5 Terrain categories and homogenous fetch requirements

Terrain Category	Proportion	Description
Smooth turbulent flow		Occurs over flat surfaces without any obstacles which are prominent enough to produce any wakes
Semi-smooth turbulent flow	$x/H > 15$	Occurs over surfaces with isolated obstacles which are sufficiently far apart that the individual wakes dissipate in the interspaces between the obstacles
Wake interference flow	$x/H \sim 10$	Occurs when obstacle interspaces are equal to or slightly less than typical wake length (5 to 15 obstacle heights)
Skimming flow	$x/H < 5$	Occurs when the surface is so closely covered with obstacles that the flow in the interspace between the obstacles has a flow regime quite separate from the bulk flow above ($D < \text{or equal } 3 H$)

Source: Adapted from Jon Wieringa, “Representative Roughness Parameters for Homogeneous Terrain,” *Boundary-Layer Meteorology*, 63(4), 1993, p. 327,

7.3.7.6 Urban Pollutants

Major research on wind in the urban context has recently focused on the dispersion of pollutants created mainly by vehicular traffic, but also by industrial operations. Understanding the dispersion of pollutants can be extremely valuable with respect to the position of air inlets and outlets. Unfortunately, the current state of research is far from reliably predicting specific distribution patterns of air pollutants.³⁶

7.3.8 Urban Geometry

Urban geometry also has an effect on roughness, in particular when the urban surface is heterogeneous. In general, density and spacing of urban objects are the major factors in determining the relationship of these objects to external wind forces.

The building height is the major parameter required to determine how the wind might flow in an urban area. Other important parameters are frontal area densities and plan area density. A convenient and often used rule of thumb says that the vertical displacement of wind intensity may be approximated as one-tenth of the canopy height as approximately two-thirds of *the height of the building*.

7.3.9 Urban Morphometry

The term ‘urban morphometry’ can be traced back to Grimmond and Oke.²⁴ Roughness elements in the urban context can be buildings as well as trees. With decreasing height of buildings, the influence of trees becomes larger, and with increasing building height, the influence of trees on urban wind decreases.

Table 7.6 Typical roughness and other aerodynamic properties of homogenous zones in urban areas, ordered by height and density. The columns show z_H as element height (in meters), z_d as zero plane displacement plane (in meters), z_0 as surface roughness length (in meters), g_{aM} as aerodynamic conductance (in mm/s), and C_D as drag coefficient ($\times 10^{-2}$)

Urban surface form	z_H	z_d	z_0	g_{aM}	C_D
Low height and density	5–8	2–4	0.3–0.8	30–50	0.6–1.0
Residential – one or two story single houses, gardens, small trees, mixed houses and small shops, warehouse, light industrial, few trees					
Medium height and density	7–14	3.5–8.0	0.7–1.5	45–75	0.9–1.5
Residential – two and three story large and closely spaced, semi-detached and row houses, large trees; less than five-story blocks of flats with open surroundings; mixed houses with shops, light industry, schools, churches					
Tall and high density	11–20	7–15	0.8–1.5	50–80	1.0–1.6
Residential – loosely spaced, less than six-story row and block buildings or major facilities (factory, university), town center					
High-rise	> 20	> 12	> 2.0	> 90	> 1.9
Urban core or suburban nodes with multi-story tower blocks in dense urban surroundings; major institutional complexes					

Source: Adapted from C. S. B. Grimmond and T. R. Oke, “Aerodynamic Properties of Urban Areas Derived from Analysis of Surface Form,” *Journal of Applied Meteorology*, 38(9), 1999, Table 6, p. 1281, Figure 7 and Figure 8

Roughness increases with density so that wind velocity in the street canyon decreases, while its patterns become more volatile and turbulent. Depending on the research reference and research group and depending on whether the research might have been conducted by field experiment or computational models, three or four categories of urban flow are detected.

7.3.10 Airport Wind Data and Energy Modeling Tools

Wind data obtained from airport weather stations often provide the basis for climate files, which are inserted into building energy modeling software tools, and may very well provide an unrealistic context for ventilation design within the denser urban context. Reduced wind velocity will usually lead to larger ventilation openings to ensure the same amount of volume flow rate in the urban context. Some tools, like MIT Coolvent (<http://coolvent.mit.edu/>), already address the different environments for natural ventilation.

Table 7.7 Typical non-dimensional roughness properties of homogenous zones in urban areas, ordered by urban density and flow regime

Urban surface density – flow regime	UTZ (urban terrain zone)			
Low density – isolated flow	0.05–0.40	0.08–0.30	0.35–0.50	0.06–0.10
Buildings and trees are small and widely spaced				
Medium density – wake interference flow	0.3–0.5	0.55–0.7	0.55–0.7	0.08–0.10
Two- to four-story buildings and mature trees, elements of various heights occupy more than 30% surface area and create semi-closed spaces (street canyons, courtyards)				
High density – skimming flow	0.5–0.8	0.65–2.00	0.60–0.85	0.07–0.12
Buildings and trees of similar height closely packed, narrow street canyons				
High rise – chaotic and mixed flow	> 0.4	> 1	0.50–0.70	0.10–0.20
Scattered or clustered tall towers of different heights jutting up from dense urban surroundings				

Table 7.8 Available urban energy models

Model	Description	Date
Canyon Air Temperature Model (CAT)	CAT is a parametric model that predicts site-specific air temperature in an urban street canyon for extended periods on the basis of data from a reference station in the region. In addition to a rudimentary description of the two sites, it requires only time-series of meteorological parameters measured at standard stations as input, which serve as descriptors of the constantly evolving meso-scale weather.	2006
Town Energy Budget Model ³⁷ (TEB)	An urban surface scheme for atmospheric meso-scale models is presented. A generalization of local canyon geometry is defined instead of the usual bare soil formulation currently used to represent cities in atmospheric models. This allows refinement of the radiative budgets as well as momentum, turbulent heat, and ground fluxes. The scheme is aimed to be as general as possible in order to represent any city in the world, for any time or weather condition (heat island cooling by night, urban wake, water evaporation after rainfall and snow effects).	2000
Ali-Toudert Dortmund ³⁸	This method combines the urban canyon model TEB with the thermal energy modelling software TRNSYS 16.1 to evaluate the interaction between interior and exterior urban climates.	2010

7.3.11 Modeling the Urban Energy Balance

Modeling the urban energy balance and the effect of the urban form on wind and natural ventilation is complex, and various computational models have been developed, each with its own advantages and disadvantages.

Notes

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Chapter 8

Spatial Strategies / Space-Induced Air Movement

8.1 Developing the Flow Path

Natural ventilation needs a carefully crafted flow path through the building, which develops the correct pressure differential across the building between inlet and outlet in order to remove exhaust air and ventilate at the required rate for air quality and cooling purposes. The *CIBSE Applications Manual AM10* (2005),¹ one of the most comprehensive guidelines to date on natural ventilation, confirms that the first design consideration for natural ventilation is to plan the flow path through the building and design for the flow pattern and strategy. The CIBSE manual states necessary design considerations: understanding heat gain, narrow plan or courtyards, noise and pollution level outdoors, occupancy adaptation to weather conditions with choice of clothing, and tight temperature and humidity control.²

Unfortunately, drawing a few arrows onto a sectional diagram is not sufficient.

First of all, the form of the building has to match the strategy. The orientation of the building as well as the depth of the floor plate and the sectional layout all have to balance the outside forces and the internal needs. For cross-ventilation, the orientation of the windward façade has a significant impact on the flow direction within the building and the degree of mixing with fresh air, which is the major requirement for wind-driven ventilation strategies.

The collaborative engineering and architecture design team needs to ensure that the strategy chosen can provide the needed air flow rates at the naturally provided pressures. Because of the dynamic nature of the outside conditions, the design team will have to consider a variety of conditions and scenarios to develop a flow path and a ventilation strategy. The team should look at a high cooling summer mode, heating winter mode, and most likely also a spring and fall mode, as wind direction and temperatures can significantly vary in these shoulder seasons. The 2005 CIBSE manual¹ further notes that

the magnitude and pattern of natural air movement depends on strength and direction of the natural driving forces and the resistance of the flow path, thus the design team has to develop a dynamic interaction between flow path (space) and force (pressure differential).

High temperature differences and stronger winds will make for stronger driving forces in winter when the cooling capacity of natural ventilation is only needed in buildings with very high internal gains. Thus, in most cases fresh air intake can be reduced to the minimum needed for indoor air quality. Spring and fall are the best seasons for natural ventilation because weather conditions for cooling are very good, but the driving forces

will often be reduced because the temperature difference between inside and outside is significantly lower. Wind speed is also much lower in most locations. In peak summer situations, the outside conditions may reach higher temperatures than indoors conditions, which would be detrimental for wind- and temperature-driven ventilation strategies. The stack effect may even get reversed and introduce air at temperatures that exceed comfort level. This would warm up the internal spaces instead of cooling them. In such locations, only hybrid or mixed-mode systems will be able to achieve thermal comfort, for example in combination with chilled beams or radiant cooled surfaces. Similar to the winter scenario, air supply in hot summers should be reduced to the minimum air quality requirements in order to balance additional energy use and uncomfortable situations.

The following case study projects highlight specific design strategies and their context and parameters. It should also be noted that natural ventilation strategies can be combined and different parts of a building can be ventilated using different strategies. Some larger projects can also incorporate hybrid ventilation strategies, which allow for ventilation to be switched seasonally to mechanical ventilation.

Ventilation needs to be designed in section and plan combined, ideally as a volumetric composition, because air is not an object moving in space, but is space itself, expanding and contracting, mixing and displacing.

8.1.1 Path 1: Cross-Ventilation

Cross-ventilation is the typical flow path strategy for office or apartment buildings with shallow plans, where floors are separated vertically, and where a flow path can be established horizontally between the windward and the leeward side of the building. This demand on the building form has a direct relationship to the situation of the building in its urban or landscape context. The building form and orientation need to support the creation of a pressure differential and resistance against the flow. In addition, the requirement on cross-ventilation strategies to develop a spatial continuum can lead to limitations/restrictions of the spatial layout for the building circulation and location of apartment and office buildings. This often leads to open floor plans in order to avoid obstruction of the flow path and provide the required flow rate. Moreover, economics of space are also in effect, as most often the cross-ventilation flow path calls for two apartments to flank a staircase in order to open the cross path on both sides of the stair space. In order to add a third or even fourth unit to the one staircase, the ventilation path has to cross the circulation path. Multiple architects during the Modern Movement have developed spatial strategies to overcome this dilemma. The most prominent case is the sectional layout of the Unité d'Habitation in Marseille by Le Corbusier, built in 1945, which used only three stair towers for 337 apartments on 12 floors, and only one central circulation corridor on every third floor. The so-called split level section enables a combined cross-stack ventilation path across the central corridor. A similar system had already been used almost 20 years earlier by Hans Scharoun in Breslau (1929) in the Ledigenheim (Bachelor hostel). Many variations of this spatial strategy followed during the 1950s and 1960s, one of which is the Bakema tower³ at the Hansaviertel in Berlin (1957).

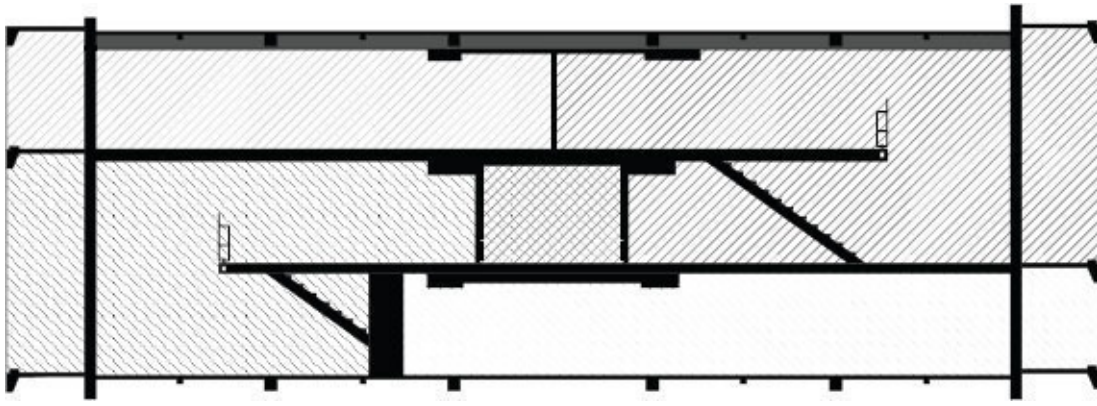


Figure 8.1

Le Corbusier's Unité d'Habitation developed the most iconic sectional diagram for a split-level apartment circulation layout overlapping with a circulation corridor.

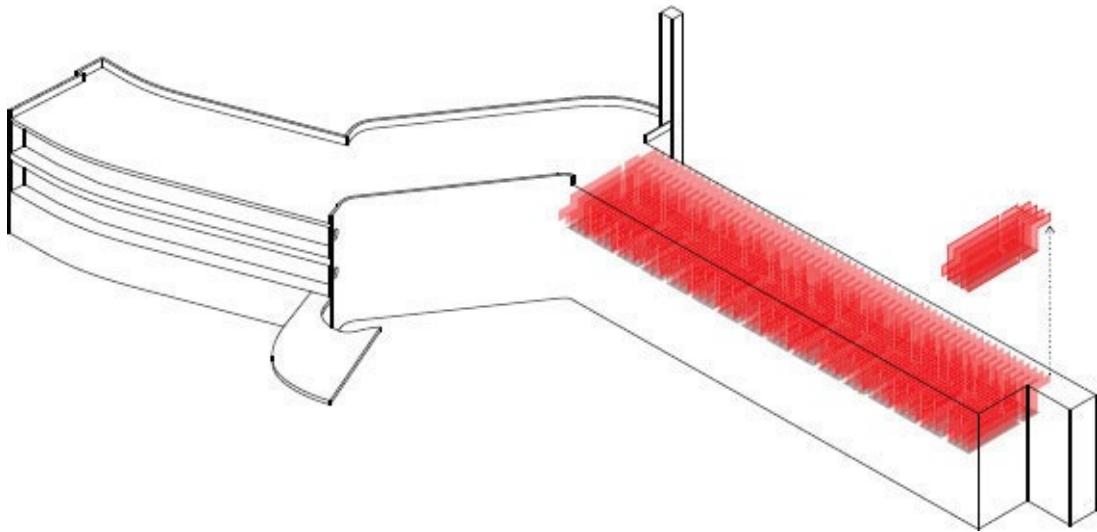


Figure 8.2

Hans Scharoun's Ledigenheim (home for singles) developed an even more compact sectional layout for a cross-ventilation path overlapping with a circulation corridor.

This spatially complex layout also supports a daylight scheme for the apartments and improves overall environmental quality. Yet these projects were structurally complex and in some jurisdictions, such as Berlin, Germany, alterations were required to meet fire egress requirements.

The two selected case studies highlighted in the following section approach the requirement to develop a continuous flow path with spatial design innovation as part of the same pioneering development. They aimed to overcome issues of building depth and façade access for inlets or outlets in an innovative way.

8.1.1.1 *Casa ad Appartamenti Giuliani Frigerio, Como, by Giuseppe Terragni (1939–1940)*

This apartment building is Giuseppe Terragni's last built project in Como⁴ before he enlisted in the military during World War II and died at a young age in 1943.⁵ The central staircase serves three apartments in a split level configuration on four floors, which allows the central apartment to be cross-ventilated above the corridor, which leads to one of the corner apartments. This configuration developed a complex interlocking and overlapping

of volumes and frames, which has been thoroughly analyzed as an architectural composition by Peter Eisenman.^{6,7} For example, the façade composition on the southeast does not necessarily reveal the split level configuration because of the clever composition and layout of windows in bathrooms and kitchens. Yet, the actual performance benefit of the split level configuration revealed itself during a site visit in 2012. The split level allows three apartments to be accessed from one stairwell, while all three receive natural cross-ventilation.



Figure 8.3

Casa Giuliani in Como by Giuseppe Terragni: southern street façade as the building appears in 2012.

When the building was constructed in 1939 to 1940, the building appeared to have been standing fairly remotely in the vicinity of Lago di Como. This site situation has been altered and to contemporary visitors the building hardly reveals itself, because it is now mostly surrounded by very close neighbors and embedded in a tight urban grid. This new context obviously also changed the ventilation context and most likely reduced the ventilation potential.



Figure 8.4

Casa Giuliani in Como by Giuseppe Terragni: interior view of the corridor beneath the ventilation window, 2012.



Figure 8.5

Casa Giuliani in Como by Giuseppe Terragni: eastern street façade with the windows of the corridor visible beneath the kitchen ventilation window, 2012.

Case study design data

Design intention:

The design reveals efficient space planning to achieve an economic apartment layout while providing daylight and cross-ventilation to all spaces in each apartment, including bathrooms and kitchens. The trade-off is that the elevator is situated at the midway point between the three apartments and thus none of the apartments is wheelchair accessible.

Ventilation strategy:

Natural ventilation strategy and mechanical integration: cross-ventilation combined with radiant heating in winter Spatial design strategy (flow path) plan/section analysis: split level composition Façade strategies (apertures): operable windows

Project data:

Year of completion: 1940

Height/building type: Apartment building (15 m / 49' 11")

Stories: Four

Function: Housing

Structure: Reinforced concrete frames with infill masonry brick

Plan depth: Approx. 18 m / 59', which is approximately five times the floor to ceiling height

Climatic data:

Location: Viale Fratelli Rosselli 24, Como, Italy

Geographic position: 45.8167° N, 9.0833° E

Elevation: 300 m / 985 ft

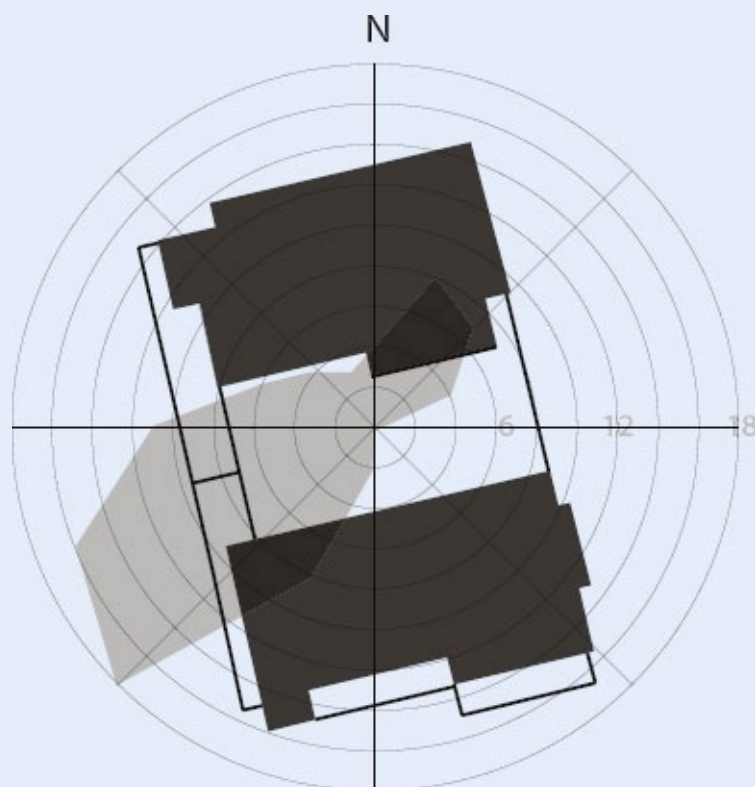


Figure 8.6

Wind rose for Como, Italy, showing the prevailing wind directions throughout the year (in m/s).

Climate classification: Temperate climate of northern Italy, Koeppen Geiger (KG) climate classification: Cfb (warm temperate, fully humid, warm summers). Lugano/Agno has a mild, humid, temperate climate with warm summers and no dry

season.

Prevailing wind direction: The wind typically blows either from the north or from the south, which has a significant influence on the valley of Lago di Como, which runs north to south into the Alps; Como is located at the southern tip of the lake.

Average wind speed: 5 mph (8 km/h) year round

Mean daytime temperature during summer: The warm season lasts from June 7 to September 6 with an average daily high temperature above 75 °F / 24 °C. The hottest day of the year is July 30, with an average high of 83 °F / 28.5 °C and low of 63 °F / 17 °C.

Mean daytime temperature during winter: The cold season lasts from November 19 to February 28 with an average daily high temperature below 51 °F / 10.5 °C. The coldest day of the year is January 7, with an average low of 31 °F / 0.5 °C and high of 44 °F / 6.5 °C. Heating degree days 65 °F/18 °C:⁸ 4804/2700 Cooling degree days 78 °F/25 °C:⁹ 114/45

Day-night difference during hottest months: approximately 20 °F / 7 °C

Mean annual precipitation: Warm season rain occurs mostly during thunderstorms at the foot of the Alps, while cold season precipitation occurs as moderate rain or snow.

Average relative humidity: Dew points vary with highest about 65 °F / 18.5 °C and thus just slightly on the muggy side, most of the year comfortable and dry in winter.

Highest relative humidity and length of humid season: N/A

Energy data: N/A

Time of year natural ventilation can be utilized: Year round, heating-dominated climate. For efficiency in winter, preheating of ventilation air would be ideal, but is not utilized.

Saved heating and cooling energy: N/A

Typical annual energy consumption: N/A

Considerations, obstacles, issues, etc.: Heating-dominated climate, site context has changed.

Project team:

Giuseppe Terragni (1939–1940)

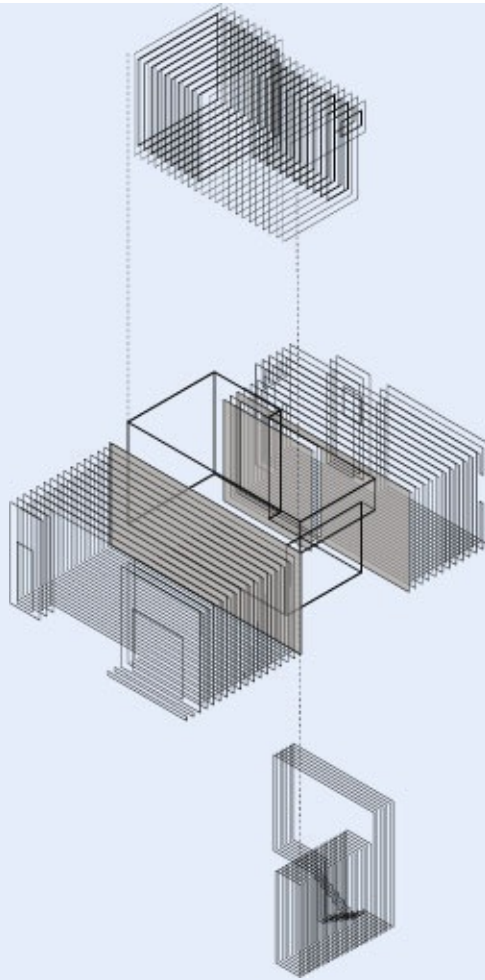


Figure 8.7

Section through the central apartment of Casa Giuliani showing the location of the kitchen window above the corridor.

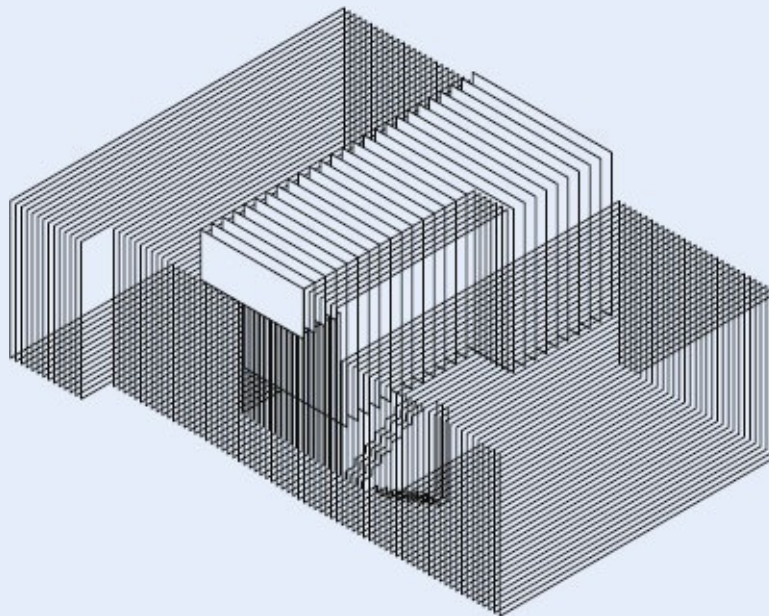


Figure 8.8

Spatial composition of apartments at Casa Giuliani developing the flow path.

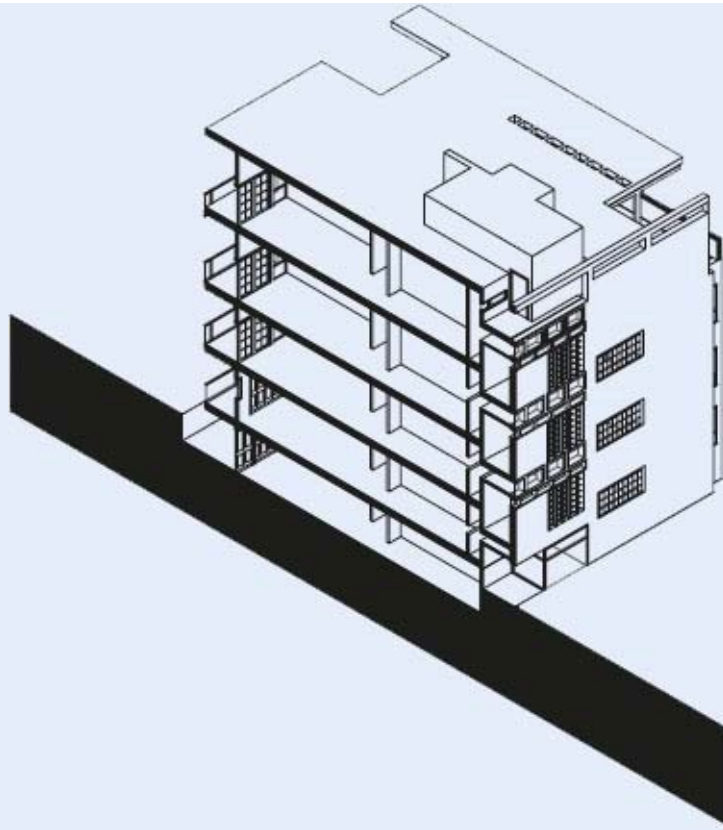


Figure 8.9

Volumetric composition creating the flow path within Casa Giuliani.

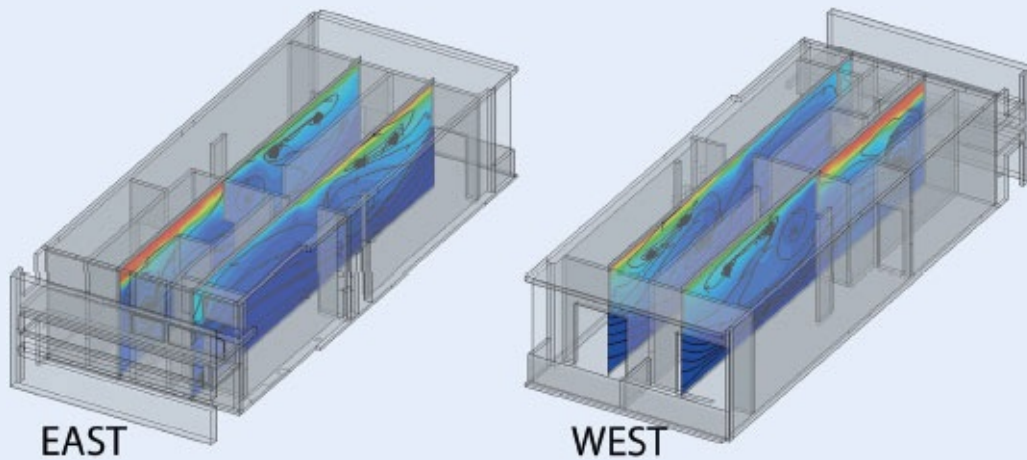


Figure 8.10

CFD simulations of flow path through the central apartment seen from inlet side (ambient temperature 24 °C, wind speed 5 mph).

8.1.1.2 Kanchanjunga Apartment Building by Charles Correa (1970–1983)

Mumbai, India, is located on a peninsula with a large curving bay opening to the Arabian Sea on the west side. The site of the Kanchanjunga Apartment Building has a view of the bay on the west as well as to the harbor on the east side.

In Mumbai, a building has to be oriented east-west to catch prevailing sea breezes and to open up the best views of the city. Unfortunately, these are also the directions of the hot sun and the heavy monsoon rains. The old bungalows solved these problems by wrapping a protective layer of verandas around the main living areas,

thus providing the occupants with two lines of defense against the elements.¹⁰

Case study design data

Design intention:

Drawing from Le Corbusier's Unité scheme, Charles Correa developed double height garden terraces, which aided the channeling of light and air, but also shielded the inner spaces from strong solar radiation and driving monsoon rains.

Ventilation strategy:

Natural ventilation strategy and mechanical integration: Original cross-ventilation, but AC window units installed post completion in selected apartments.

Spatial design strategy (flow path) plan/section and analysis: Complex split level composition with multiple space heights. The apartments always have one double height terrace and a lower section stacked one on top of the other.

Façade strategies (apertures): Operable windows and deep recessed terraces

Project data:

Year of completion: 1970–1983

Height/building type: 84 m / 275 ft, residential high-rise tower

Stories: 32 luxury apartments, with 3 to 6 bedrooms each, on 26 stories

Function: Apartments

Structure: Reinforced concrete structure with a central core and 6.3 m / 20.6 ft cantilevers for the terraces

Plan depth: 21 m / 69 ft in both directions



Figure 8.11

Kanchanjunga Apartment Building by Charles Correa in Mumbai, India: view of the tower as it sits in the cityscape.



Figure 8.12

Kanchanjunga Apartment Building by Charles Correa in Mumbai, India: different two-story split-level apartments are composed as interlocking volumes forming one cubic tower.

Climatic data:

Location: 72 Peddar Road, Tadeo, Mumbai, India

Geographic position: Latitude: 19° 11' 8.124" N; longitude: 72° 51' 0.3514" E

Climate classification: Hot and humid tropical. Tropical savannah climate with dry winters, Aw (equatorial, winters dry)

Prevailing wind direction: Predominantly westerly and southwesterly winds

Average wind speed: Highest average wind speed is 9 mph (14.4 km/h) in July; lowest average wind speed is 4 mph (6.5 km/h) in winter; the highest wind speed can be experienced during the rainy season.

Mean daytime temperature summer: The warmest time in Mumbai is in October/November.

Mean daytime temperature winter: The coolest time of the year is from June to September, monsoon season.



Figure 8.13

Kanchanjunga Apartment Building by Charles Correa in Mumbai, India: the corners of the apartments are large double height loggias to modulate the incoming air flow from the breeze of the Arabian Sea.

Heating degree days 65F/18C: 0

Cooling degree days 76F/24C: 2294/1256

Day-night difference during hottest months: The warm season lasts from October 13 to November 26 with an average daily high temperature above 92 °F / 33.5 °C. The hottest day of the year is October 31, with an average high of 93 °F / 34 °C and low of 76 °F / 24 °C.

The cold season lasts from June 25 to September 17 with an average daily high temperature below 87 °F / 30.5 °F. The coldest day of the year is January 30, with an average low of 66 °F / 19 °C and high of 87 °F / 30.5 °C.¹¹

Mean annual precipitation: February has the least clouds, while June, July, and August have around 80 percent to 90 percent of cloud cover. July is also the rainiest month with precipitation on 89 percent of the days.

Average relative humidity: N/A

Highest relative humidity and length of humid season: The highest relative humidity occurs in July with 95 percent. The humid monsoon season lasts from June through September. Highest dew points will be around 79 °F / 26 °C, which feels rather uncomfortable and muggy.

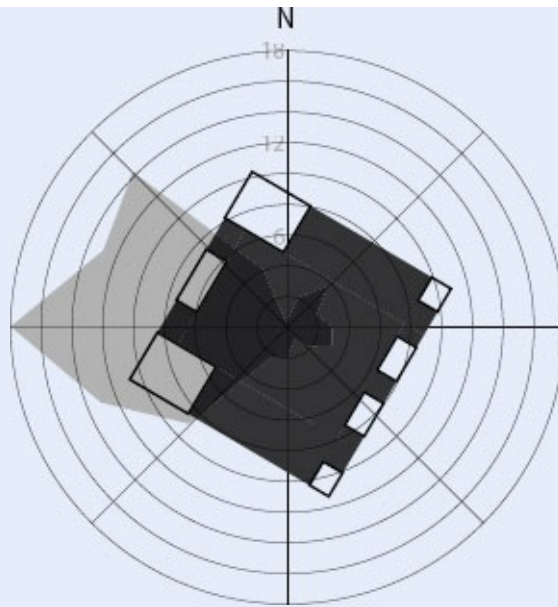


Figure 8.14

Wind rose for Mumbai, India, showing the prevailing wind directions over the year (in m/s) overlaid with the site plan of the Kanchanjunga Apartment Building.

Energy data:

N/A. Energy data is not available due to the time of construction. The building is also not monitored.

Time of year natural ventilation can be utilized: The building was constructed for natural ventilation all year round, but considering the high humidity level in summer, June through September should probably be excluded from natural ventilation considerations in this climate.

Saved heating and cooling energy: N/A

Typical annual energy consumption: N/A

Considerations, obstacles, issues, etc.: Summer heat, high relative humidity combined with high temperatures and heavy monsoon rain.

Project team:

Charles Correa Associates, Mumbai, India

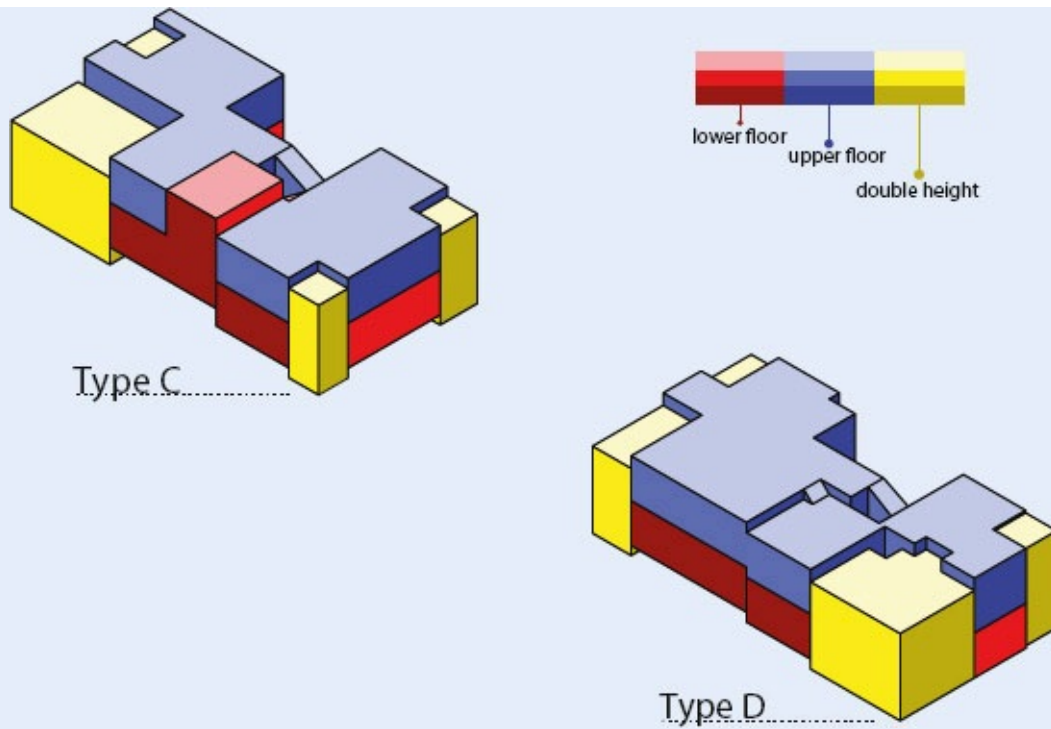


Figure 8.15

Volumetric composition creating the flow path for cross-ventilation at Kanchanjunga Apartment Building.

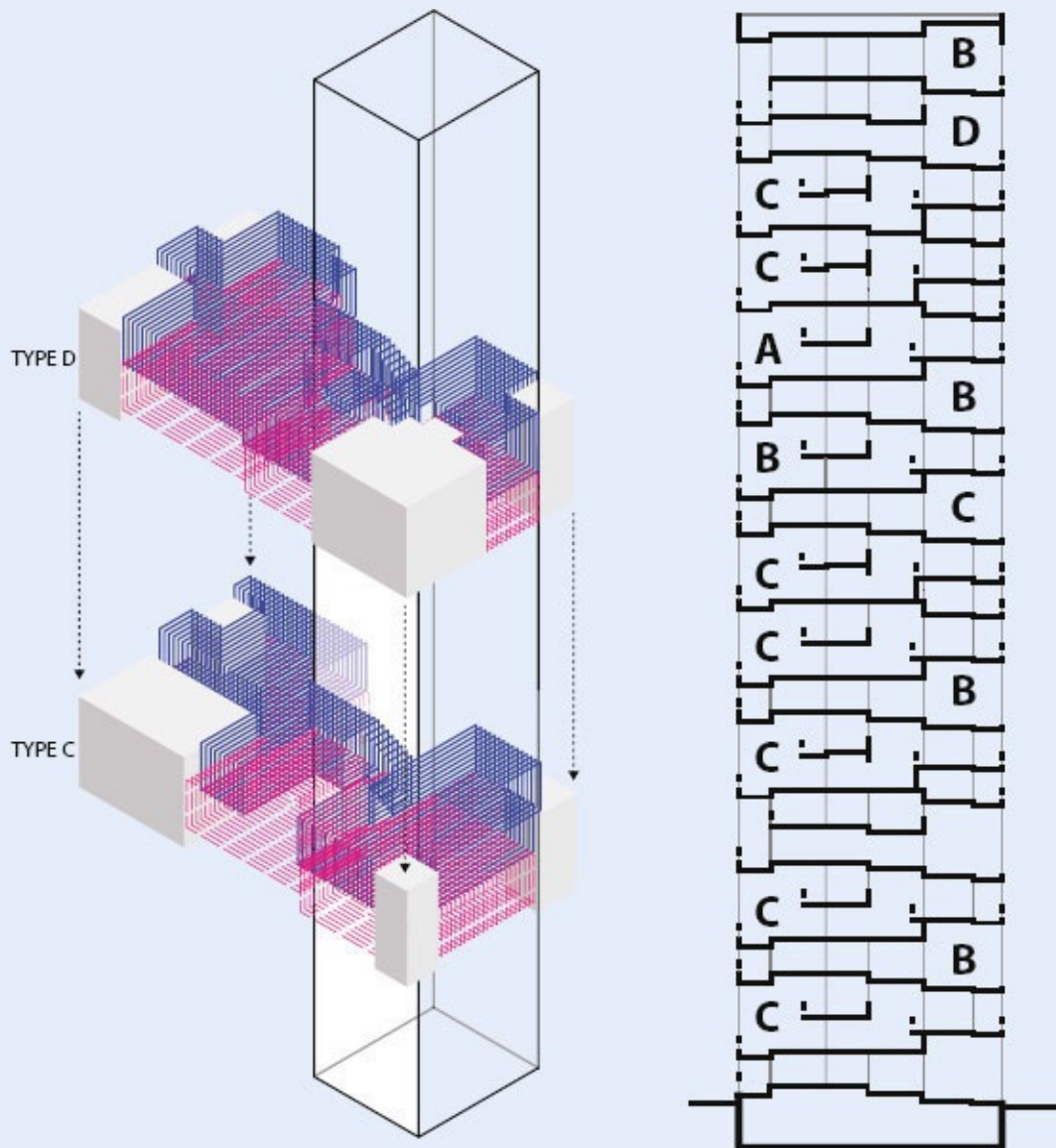


Figure 8.16

Spatial composition of Kanchanjunga Apartment Building developing the flow path.

8.1.2 Path 2: Single-Sided (Comfort) Ventilation

Single-sided ventilation is less effective than cross-ventilation in comparable situations and only serves a fairly narrow zone close to the façade. Single-sided ventilation often combines wind- and temperature-induced air flow and uses the same opening as the inlet and outlet. More effective combined stack ventilation utilizes two openings on one side of the space (a high and a low opening) in order to facilitate the stack in the space. This locally limited strategy can be combined with other strategies. The Anglo-Saxon sash window (see Figure 9.3) provides the potential to combine an upper and lower opening beautifully. But single-sided ventilation serves far less space as it is only effective in building zones close to the inlet/outlet opening unless it is connected to other, larger scale strategies, for example an atrium stack or cross-ventilation, as in the case study project highlighted here.

8.1.2.1 Commerzbank by Sir Norman Foster

The Commerzbank building in Frankfurt, Germany, by Norman Foster's design team was one of the first high-rise office towers to rely heavily on natural ventilation in a mixed-mode situation. It is considered Europe's first ecological office tower, moving away from the homogenous glass box. The tower rises from a plinth which is integrated into the block structure of the historical Frankfurt city grid. The tower is not completely surrounded by other towers of similar height, but is rather a singular entity in a context of lower blocks. The design intention for the tower is based on interconnected 'Winter Gardens' linked to a central atrium, which spirals up the tower to become the visual and social focus for four-story clusters of offices. The tower is set back from the street and is based on a triangular plan with a central atrium connecting all tower floors. A glass ceiling above the lobby visually connects the tower to the entrance. Sky gardens and office spaces are composed in a spiraling configuration. Thus, two office segments always face one sky garden. Outward-facing offices are naturally ventilated through a double-skin façade, while the inward-facing offices are ventilated driven by the stack flow inside the atrium and out through the sky garden. Four sections are separated vertically by a diaphragm glass ceiling, which manages the stack flow and keeps it from becoming a 'storm.' In addition, it provides smoke containment and restricts the spread of fire in case of an emergency. The structural system supports these major spatial compositions with six mega-columns in the corners of the building and three atrium columns supporting eight-story vierendeel girders, which support the office sections.



Figure 8.17

Commerzbank Tower as it appears above the street canyon of Frankfurt/Main.



Figure 8.18

View up the interior courtyard of Commerzbank Tower showing one of the horizontal glass screens, which create the boundary between the multiple sky gardens.

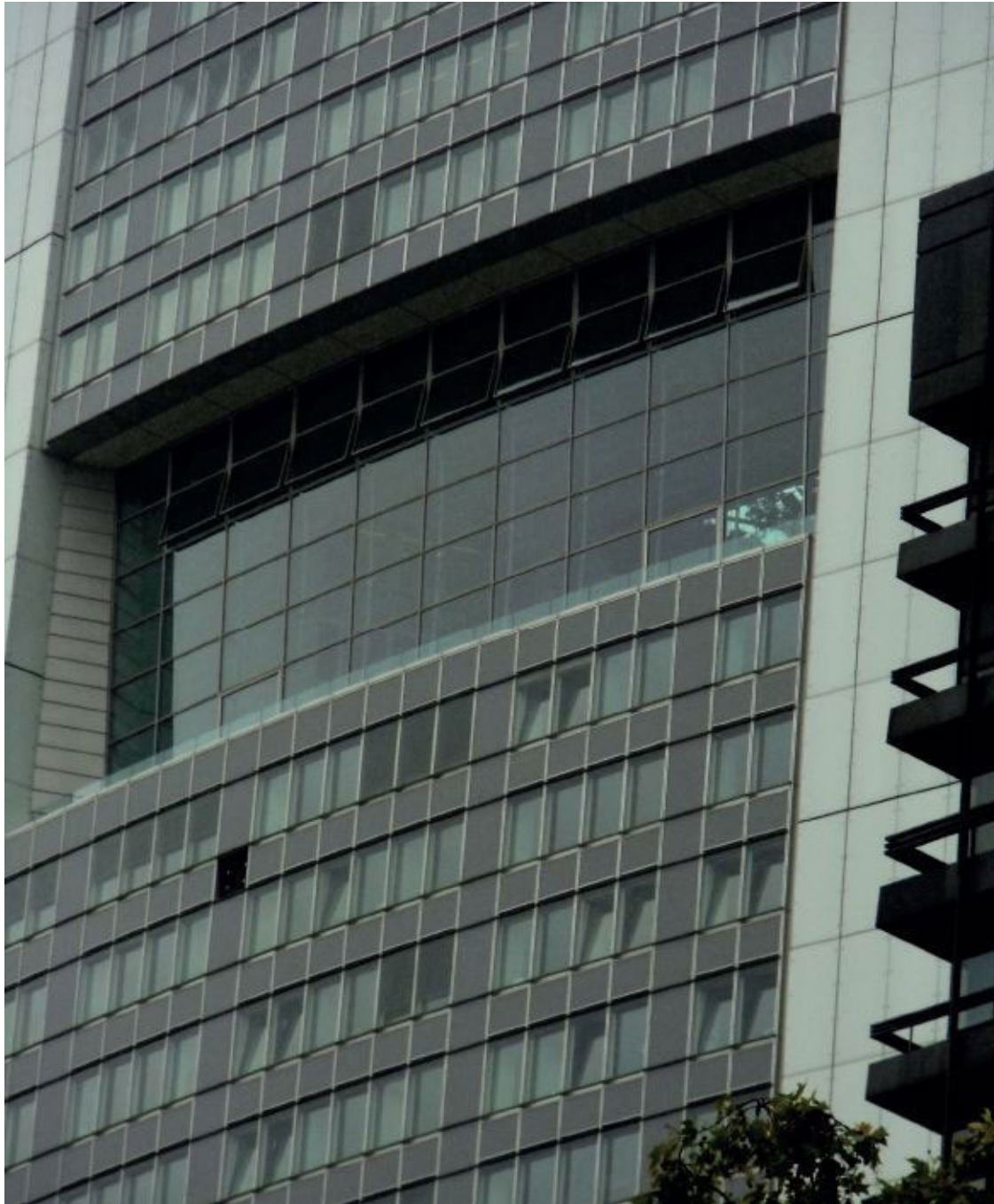


Figure 8.19

Close-up view of the Commerzbank façade showing the double-skin façade and the recessed volume of the sky garden.

Case study design data

Design intention:

The natural ventilation strategy engages a macro- and a micro-level. The central atrium and sky gardens combine large-scale stack and cross-ventilation in three stacked 12-floor ‘villages,’ and because of the spiraling composition, the layout allows for ventilation with all major wind directions, as there is always a windward sky garden. Depending on the direction, stack ventilation can also be reversed to wind

flow pushing down through the atrium and out through the lower floor sky garden.¹²

The overall length of flow path across the atrium and sky garden is approximately 48 m / 157.5 ft, and the individual office depth and height for single-sided ventilation is 16.5 m / 54 ft. This reinforces the rule of thumb given in [Section 7.2](#).

Ventilation strategy:

Natural ventilation strategy and mechanical integration: Natural ventilation chimney creates negative pressure to pull air through and up the building and the sky gardens. In addition, the building can be ventilated and cooled with a complementary changeover system that switches between natural and mechanical ventilation on a seasonal or even daily basis to combat high summer temperatures and cold temperatures in winter, and to operate the building in case of too high winds, which would cause discomfort in the atrium/sky gardens.

Spatial design strategy (flow path) plan/section and analysis: Triangular in plan, three 'petals' and one 'stem.' Façade strategies (apertures): Every office has operable windows and relies on natural daylighting.

Project data:

Year of completion: 1997

Height/building type: Top: 298 m (978 ft); main tower: 259 m (850 ft); commercial building

Stories: 56

Function: Commercial office tower; 120,736 m² / 85,500 m² in the tower (1.3 mio ft² / 920,315 ft²).

Structure: Reinforced concrete, steel frame

Plan depth: 16.5 m / 54 ft

Climatic data:

Location: Frankfurt, Germany

Geographic position: 50.1106° N; 8.6742°E

KG climate classification: Oceanic climate, Cfb / warm temperate, fully humid, warm summers

Prevailing wind direction: SSW

Average wind speed: 8 mph / 12.85 km/h

Mean daytime temperature summer: 18.3 °C / 65 °F

Mean daytime temperature winter: 1.83 °C / 35 °F

Heating degree days: five year average, 15.5 °C / 60 °F base: 2232/4050

Day-night difference during hottest months: 17.73 °C / 64 °F

Mean annual precipitation: 621 mm / 24.4 in Average relative humidity: 50.9 percent

Highest relative humidity and length of humid season: July 16, 75 percent

Energy data:

The building is powered completely by renewable energy as of January 1, 2008. Reference energy data was measured in 2008.

Time of year natural ventilation can be utilized: 85 percent of year (vs. 60 percent time of year anticipation).

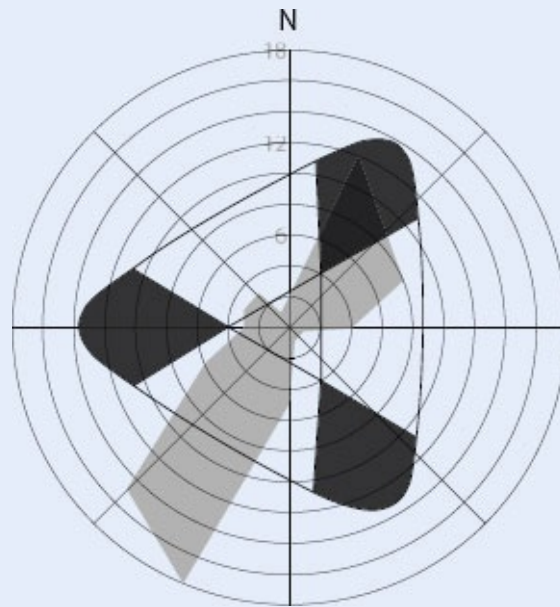


Figure 8.20

Wind rose diagram for Frankfurt/Main (in m/s) showing how the volume of the Commerzbank tower sits within the prevailing winds.

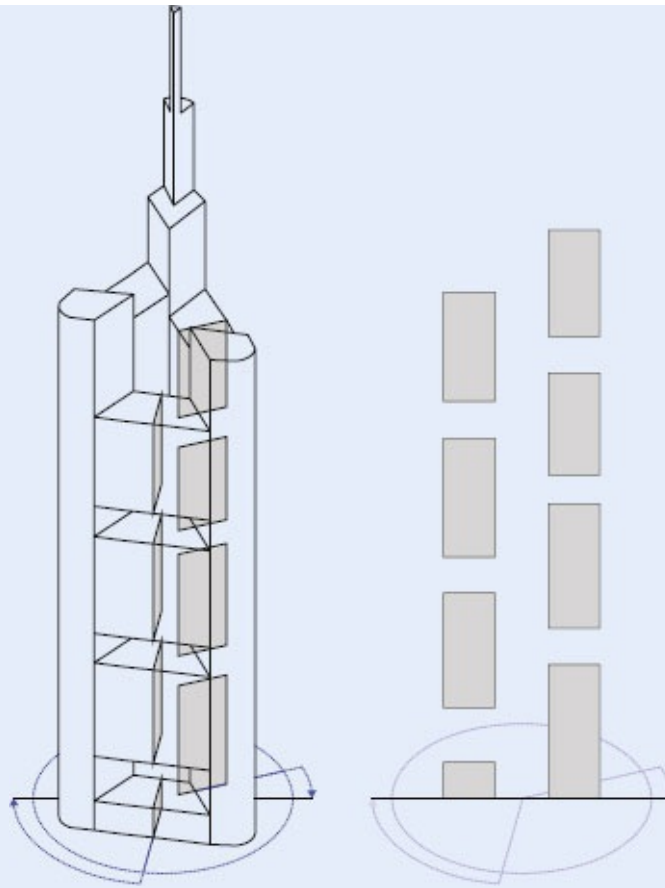


Figure 8.21

Section through the Commerzbank tower showing the diagonally connected interlocking composition of the sky gardens connecting the inner flow path of the building.

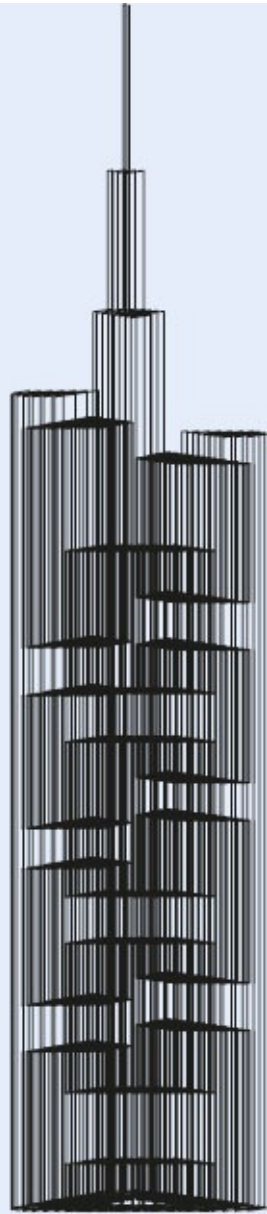


Figure 8.22

Volumetric composition of office section and sky gardens, which facilitate the overall ventilation path, while each office individually is connected to the flow path through single-sided ventilation strategy.

Saved heating and cooling energy: 63 percent compared to a fully air-conditioned German office building (measured) and 38 percent compared to a fully air-conditioned office building built to EnEV 2007, the German Energy Conservation Ordinance (measured)¹³

Typical annual energy consumption: Approximately 50 percent of traditional office buildings

Considerations, obstacles, issues, etc.: High winds can lead to switch-over to mechanical ventilation. Fire and smoke prevention lead to horizontal glass barriers, but these also aid in the ventilation strategy

Project team:

Structural engineer: Ove Arup and Partners/Krebs and Kiefer

Quantity surveyor: Davis Langdon and Everest

M+E engineer: Roger Preston & Partners/RP&K Sozietat GmbH/Perrerson and Ahrens

Landscape architect: Sommerland & Partners

Lighting engineer: Lichtdesign¹⁴

8.1.3 Path 3: Stack Effect Ventilation

Other than the first two flow path strategies, stack ventilation most often uses the whole building to develop the flow path in order to achieve the high temperature differential necessary to develop the stack driving force for the air exchange rate. Flow paths are often designed as central communal spaces, such as atria or staircases, in order to integrate and enhance the stack. For appropriate stack design it is important for architects to understand the concept of the neutral plane. Below the neutral plane, the air flows inwards, and above the neutral plane, the air flows outwards. This can become problematic when occupied spaces are situated above the neutral plane and warmer air flows out through openings above the neutral plane, passing through occupied spaces. This is an often encountered mistake in designing stack effect ventilation.¹⁵

This situation requires that close attention be given to the roof and the top of the stack shaft during the design phase. Most ideal are spatial strategies where the top of the stack expands over the roof of the building to provide additional height in order to lift the neutral plane above the occupied spaces. Strictly temperature-induced ventilation is rare. It is most likely that wind will work in conjunction with the stack effect at the inlet as well as at the outlet. In fact, there are multiple cases where the exhaust of the stale warm air at the top of the stack is assisted by the negative pressure produced by a wind-enhancing device, using the Venturi effect or merely by opening the exhaust towards the leeward side of the stack.

Multiple iconic contemporary buildings utilize stack effect ventilation and often combine the stack with the public and/or circulation space. One of the most published buildings using and promoting stack ventilation is the Eastgate shopping center in Harare, Zimbabwe, by Mick Pearce Architects.¹⁶ In the published description, Mick Pearce refers to the termite mound as inspiration. According to his description, the termites use a very refined system of stack vents to provide a constant temperature inside their nest and to exhaust stale and warmer air, which rises through the vents. The Eastgate center, he claims, operates using a similar strategy of concrete stack vents that pull air up and ventilated concrete floors to pull fresh air into the office spaces.¹⁷

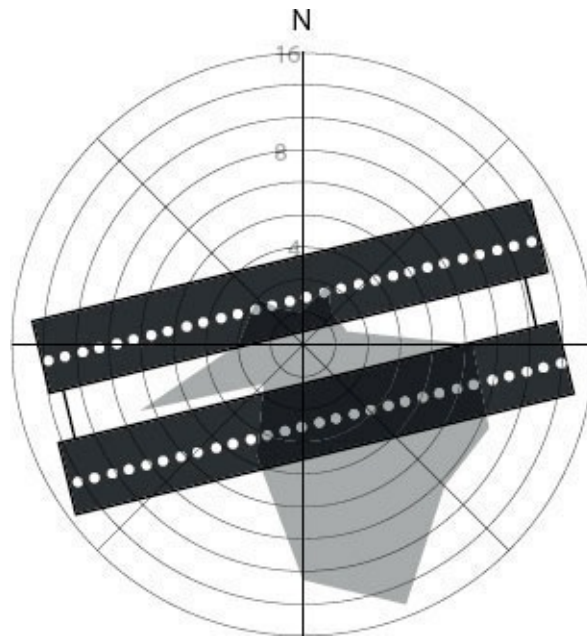


Figure 8.23

Wind rose diagram for Harare, Zimbabwe, showing how the volume of the Eastgate shopping center sits perpendicular to the prevailing winds (in m/s).

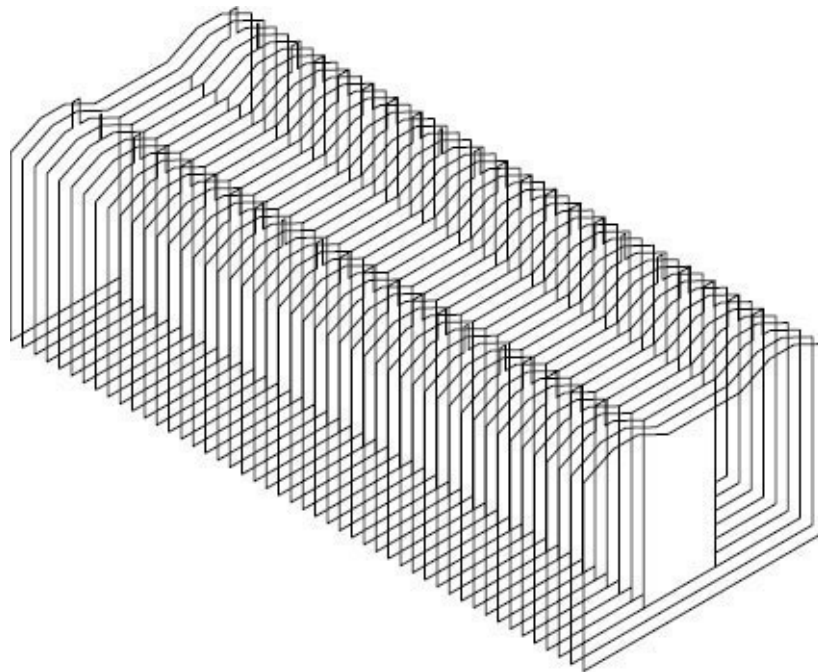


Figure 8.24

Volumetric spatial composition of Eastgate shopping center.

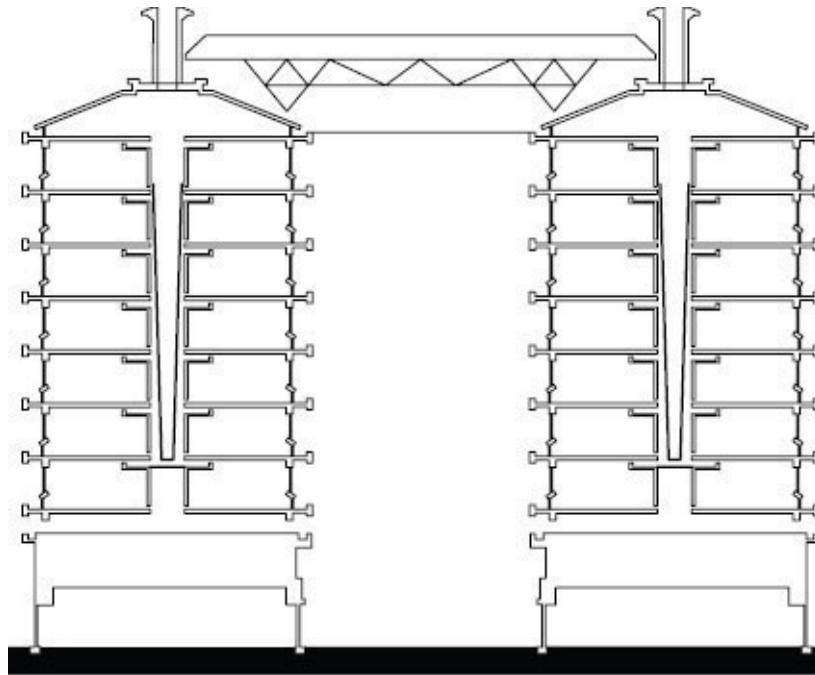


Figure 8.25

Section through Eastgate shopping center in Harare, Zimbabwe, showing the two central ventilation stacks as well as the courtyard, which reduces the flow path depth and adds daylighting capacity to each floor.

8.1.3.1 *Judson University in Elgin, Illinois, near Chicago*

The Harm A. Weber Academic Center at Judson University, by Alan Short and Associates, is among the first contemporary large-scale buildings in the American Midwest to exploit natural ventilation in the extremes of the Midwestern climate. The building exploits the use of stack ventilation through specifically designed shafts, which terminate in multiple towers above the building. The building is composed as an assemblage of three very distinct formal and functional parts. The major volume is the cube of the library/studio, which centers itself on a day-lit atrium, which also provides one of the stacks for stack ventilation. The bowtie contains classroom spaces, which are typically mechanically ventilated, and the office slab is ventilated by the stack spaces left between the bowtie and the slab as well as shafts that are integrated into the façade layer. Library and studio spaces as well as offices incorporate operable windows in addition to stack-induced air flow.

Beneficial for the building strategy was the overlapping approach of day-lighting and ventilation strategies, which also resulted in well day-lit spaces and provided significant electricity savings.



Figure 8.26

South façade of the Harm A. Weber Academic Center at Judson University in Elgin, Illinois, highlighting the photovoltaic array on the top of the ventilation stacks warming the upper level of the stack to increase the pressure difference between inlet and outlet.



Figure 8.27

Interior courtyard of the Harm A. Weber Center at Judson University doubling up as ventilation flow path and daylighting device.



Figure 8.28

Ventilation exhaust device on the roof of Harm A. Weber Center at Judson University, adding an iconic feature behind the photovoltaic array.

Case study data

Design intention:

The design team, Alan Short and Associates from the UK, aimed to develop a natural ventilation strategy for a deepplan building in the continental warm humid climate of the American Midwest. The goal was to operate the building with natural ventilation for a significant period of the year.

Ventilation strategy:

Natural ventilation strategy and mechanical integration: Integrating stack ventilation, cross-ventilation, and mechanical ventilation into a hybrid system

Spatial design strategy (flow path) plan/section and analysis: Multiple: narrow plan for cross-ventilation, shafts and atrium for stack ventilation, exhaust towers exposed above roof

Façade strategies (apertures): Large inlet vent at the back of the building for IEQ and cooling, operable ventilation for personal comfort, roof exhausts for stack ventilation

Project data:

Year of completion: 2007

Building type/height: Academic building / 21 m / 69 ft

Stories: Four

Function: Mixed-use educational building with offices, classrooms, library and design studios

Structure: Main structural material is concrete in walls, floors, and ceilings for thermal mass as a major component for the natural ventilation strategy. The exterior wall is made of stick frame extensions to include the vent stacks and the daylighting splay windows as well as shading of the window glass.

Plan depth: Overall: 32 m / 105 ft with a 7 m / 33 ft atrium in the center

Climatic data:

Location: Elgin, Illinois, USA

Geographic position: 42° 2' N; 88° 17' W

Climate classification: Climate/context: climate zone Köppen Dfa (snow, fully humid, hot summers).¹⁸ Humid continental climate (Köppen climate classification Dfa) with hot, humid summers and cool to cold winters.

Prevailing wind direction: South/southwest and all other westerly directions; least probable are winds from the east. Between 8 and 14 mph / 12.85 and 22.5 km/h.

Average wind speed: Wind speed is highest in winter with an average of about 12 mph / 19.5 km/h and lowest in the warmest month of July with 8 mph / 12.85 km/h. This is one reason why stack ventilation was used as the major driver for the natural ventilation flow path.

Mean daytime high temperature summer: Between 73 and 84 °F / 22.75 °C; maximum 91 °F / 32.75 °C

Mean daytime temperature winter: Between 15 and 24 °F / -9.4 and -4.4 °C

The warm season lasts from May 25 to September 21 with an average daily high temperature above 73 °F / 22.75 °C. The hottest day of the year is July 24, with an average high of 84 °F / 29 °C and low of 65 °F / 18.3 °C. The cold season lasts from December 1 to March 3 with an average daily high temperature below 40 °F / 4.4 °C. The coldest day of the year is January 20, with an average low of 15 °F / -9.4 °C and high of 29 °F / -1.5 °C.

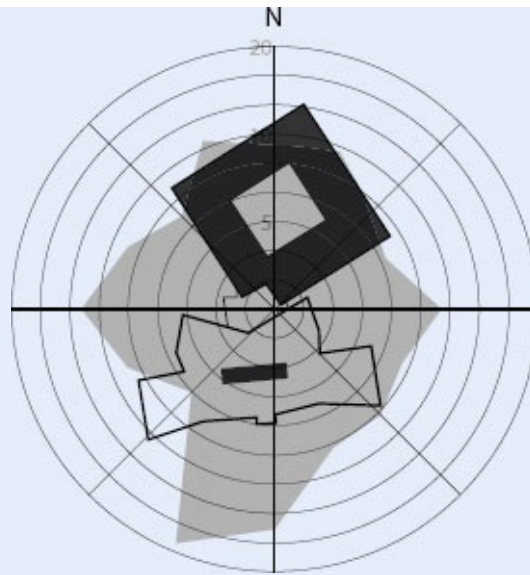


Figure 8.29

Wind rose diagram for Elgin, Illinois, showing how the volume of the Harm A. Weber Center sits perpendicular to a pretty diverse distribution of prevailing winds for both summer and winter (in m/s).

Heating degree days 65F/18C: 7480/4138

Cooling degree days 78F/25C: 360/182

Day-night difference during hottest months: 20 °F / 12 °C maximum

Mean annual precipitation: Mainly thunderstorms in summer and light snow in winter

Average relative humidity: Between 47 percent and 95 percent in summer

Highest relative humidity and length of humid season: July and August can be humid and muggy

Energy data:

Time of year natural ventilation can be utilized: Shoulder seasons of spring and fall, mild summer and mild winter days

Saved heating and cooling energy: 18.3 percent savings over base code 42.6 percent natural gas

Typical annual energy consumption: 7423.3 MBtu / 2175 MWh¹⁹

Considerations, obstacles, issues, etc.: Window screens are needed for the Midwest to protect against bugs and mosquitoes, which doubles the inlet size.

Project team:

Architect: Short & Associates Architect

Architect of record: Burnidge Cassell & Associates

Landscape architect: SlaineCampbell

Energy consultant: Institute of Energy & Sustainable Development

Mechanical, electrical & structural engineer: KJWW Engineers, Des Moines, Iowa²⁰

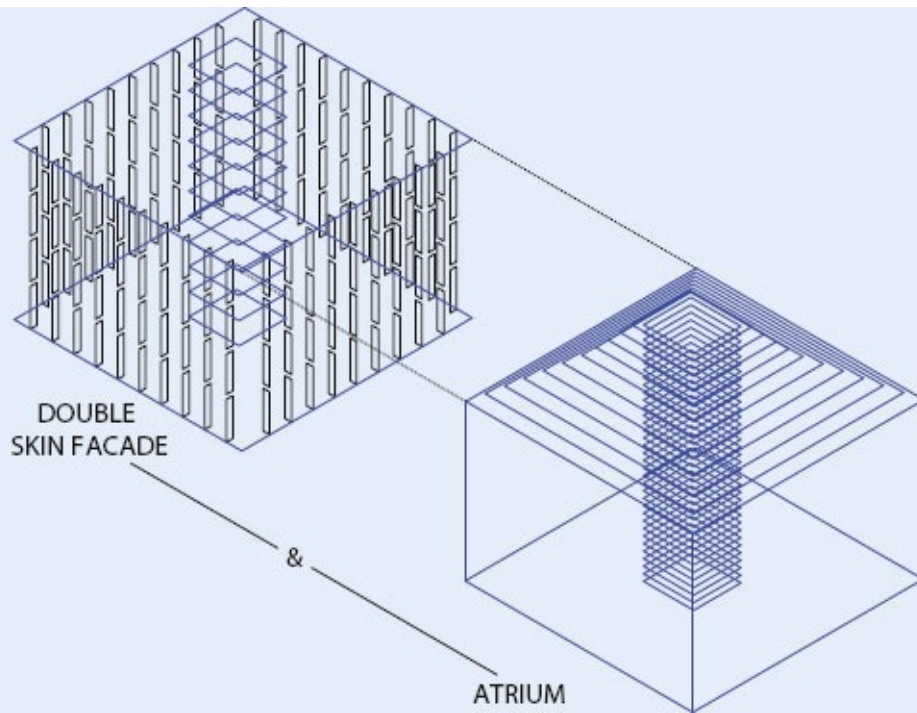


Figure 8.30

Flow path diagram of the library building showing the spatial compositional relationship between the stack vents inside the double-skin façade and the internal covered atrium at the Harm A. Weber Center of Judson University.

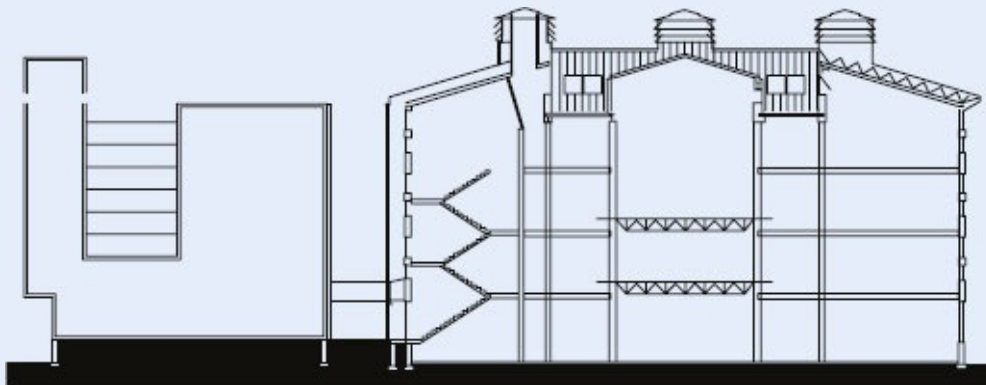


Figure 8.31

Section through the Harm A. Weber Center highlighting the vertical stack spaces in between the actual volumes of the building composition.

8.1.4 Path 4: Solar Chimneys

Solar chimneys are a specific variation of the stack effect employed by conventional chimneys and utilized for centuries to exhaust combustion air and smoke from fireplaces. In the case of the solar chimney, the top of the stack is additionally heated through glass or sheet metal by the sun's radiation in order to increase the air temperature on the top of the stack to raise the differential between the inlet and the outlet of the stack temperature and thus the pressure differential. Paradoxically, this is particularly useful in warm or even hot climates because stack ventilation only works when the inner temperature at the top of the stack is above the outdoor temperature. Otherwise, the outside warm air would flow into the building. The air in the solar chimney always has to be warmer than the outside air.

One known case of solar chimney enhanced stack ventilation is the Building Research

Establishment's (BRE) Environmental Building in Garston, Watford, UK, designed by Feilden Clegg Architects and Arup's as engineers.²¹ In this project, glazed façade shafts extend above the roof to form metal clad chimneys, which are topped by a 'hat' to assist wind enhancement of the flow. The glass façade of the ventilation shafts and the shiny metal chimneys create an iconic elevation with a rhythm of stack chimneys at every axis of the building.

Solar-enhanced ventilation has also been introduced into the Sidwell Friends School by Kieran Timberlake²² as a means to facilitate natural ventilation in their classrooms in case the wind-induced cross-ventilation is not sufficient for proper air change rates.

To ensure adequate ventilation on very hot and still days, fan-assisted ventilation may be considered.

Stack ventilation follows the same rules of thumb as cross-ventilation; thus the distance between the inlet and outlet should not be more than five times the floor to ceiling height. The stack outlet needs to be at least half of one story level above the last ceiling of the top floor.²³ If possible, the exhaust outlet should be placed onto the leeward or negative pressure side of the chimney away from the side on which the wind impinges on the chimney.

In comparative research studies²⁴ the effectiveness of solar versus nonsolar chimney ventilation has been studied, and Alfonso and Oliveira report an increase in efficiency of 10 to 22 percent. The efficiency is higher in warmer months and generally in warmer climates. Solar chimneys should also be insulated the same way as passive solar collecting spaces in order to direct all gathered solar energy to warm up the air and not conduct back out into the atmosphere or into the interior space. They also studied the design parameters of the chimney section and chimney height and came to the conclusion that "for satisfying the needed average flow rate: the average flow rate changes linearly with chimney section; for a given solar collection area, it is better to have a larger chimney width and a smaller height."²⁵

The influence of wind on solar stack ventilation is random and in most cases can be ignored in order to compute the appropriate air change rates.²⁶

8.1.4.1 The Charles de Gaulle School

The Charles de Gaulle School, completed in 2007/08 in Damascus, Syria, by the French team Lion Architects, is a very recent example of solar chimney ventilation in a hot and dry climate. Engineering was conducted by Transsolar KlimaEngineering, from Germany. The building itself is a cluster of two- to three-story classroom buildings, with a solar chimney extending about one floor up into the sky above the upper classroom ceiling. As solar chimneys do not serve any other function than ventilation, their area can be fairly small and only needs to fulfill the outlet area and height requirements to increase the stack. Important to note is the careful design of the building section and the integration of a vegetation microclimate design in the courtyard, which enables the cooling of the fresh intake air over the floor of the courtyard before it enters on the shaded side of the building.

The proportions of the building follow exactly the rules of thumb for cross- and stack ventilation with even less than five times the floor to ceiling height as space depth and a stack that extends about one floor high over the top of the roof. The overall site plan reveals a very intricate integration of inside and outside classrooms and break spaces for this airy school building.



Figure 8.32

Lycée Charles de Gaulle in Damascus, Syria: overview of the composition of building and courtyard spaces.



Figure 8.33

Lycée Charles de Gaulle in Damascus, Syria: detail of solar chimney.



Figure 8.34

Lycée Charles de Gaulle in Damascus, Syria: courtyard with trees.

Case study data

Design intention:

Utilize stack ventilation in hot and arid climate of Damascus, Syria

Ventilation strategy:

Solar chimney.

Natural ventilation strategy and mechanical integration: No active cooling

Spatial design strategy (flow path) plan/section and analysis: Chimney height is equal to one floor

Façade strategies (apertures): Ventilation inlets are situated in cool, vegetation-enhanced courtyard

Project data:

Design: 2006

Year of completion: 2007/08

Height/building type: School building

Stories: Two, with one additional story for the solar chimney

Function: School, classroom buildings

Structure: The walls are double-block for their thermal properties: solid concrete on the inside and concrete breeze-blocks on the outside, separated by an air pocket

Plan depth: 15 m / 49 ft approximately

Site size: Ground floor area: 4,995 m² / 53,766 ft² – Total site area: 10,000 m² /

107,640 ft²

Climatic data:²⁷

Location: Damascus, Syria (West Asia) Geographic position: 33° 30' 47" N; 36° 17' 31"E

Elevation: 680 m / 2231 ft

KG climate classification: BWh hot arid desert; winters are mild with precipitation, sometimes snow.

Prevailing wind direction: The wind is most often out of the southwest (24 percent of the time), south (13 percent of the time), and west (11 percent of the time).

Average wind speed: Between 10 and 20 mph (16 and 32 km/h)

Mean daytime temperature summer: 26 °C / 79 °F; average high in July/August is 36 °C / 97 °F; record high 45 °C / 113 °F.

Mean daytime temperature winter: 6 to 12 °C / 43 to 53.6 °F

Heating degree days 65F/18C: 2769/1520

Cooling degree days: 825/440

Day-night difference during hottest months: 20 °C / 40 °F

Mean annual precipitation: 25 mm / 1 inch in winter; none in July/August

Average relative humidity: Can range between 15 percent and 90 percent in August, with dew points between 41 and 65 °F / 5 and 18 °C.

Highest relative humidity and length of humid season: Varied

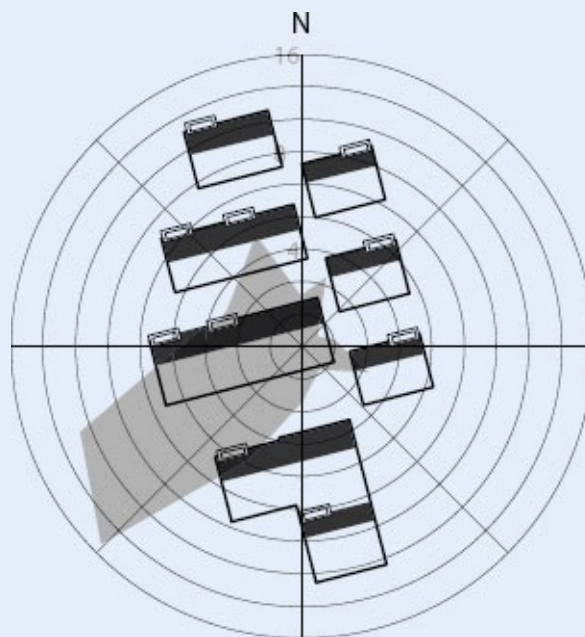


Figure 8.35

Wind rose for Damascus (Beirut, Lebanon) showing the prevailing westerly winds of the region (in m/s).

Project team:

Architect: Ateliers Lion Associés, Dagher Hanna & Partners, Paris, France

Climate engineer: Transsolar KlimaEngineering

Client: French Ministry of Foreign Affairs

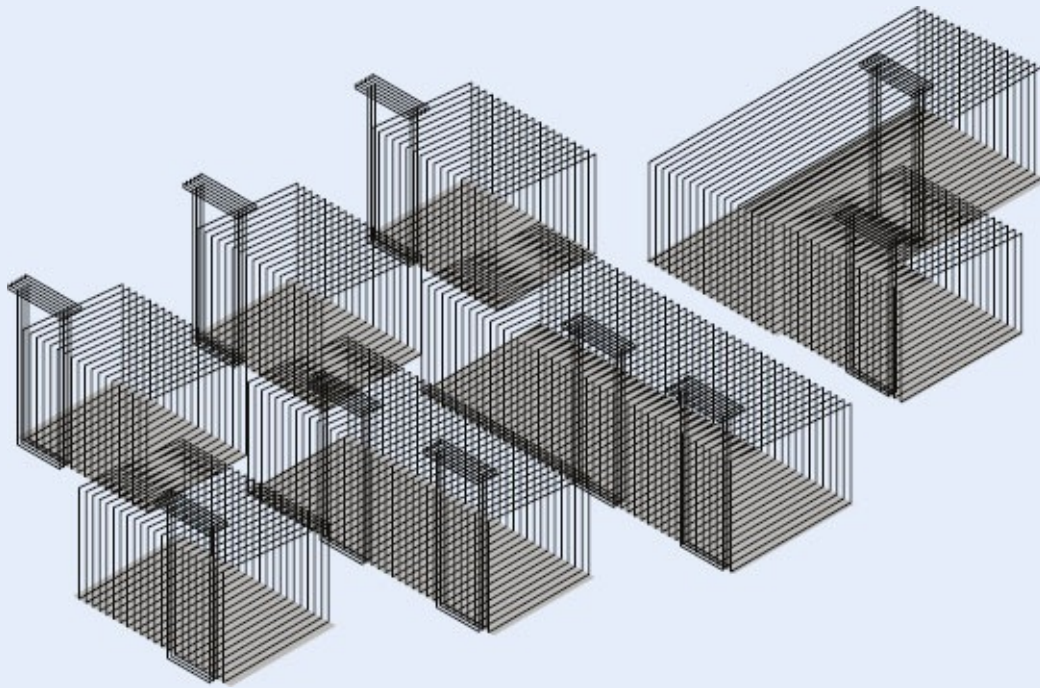


Figure 8.36

Volumetric diagram highlighting the flow path and spatial composition of Lycée Charles de Gaulle in Damascus.

8.1.5 Path 5: Wind Towers – Passive and Hybrid Downdraft Cooling

Wind towers similar to those developed centuries ago in Iran/Persia and the Middle East are recently experiencing a strong revival. Research and innovation is mainly driven by a group of innovative architects and engineers from Italy and the UK led by Brian Ford, who started to explore this strategy in the 1990s as an alternative to air-conditioned deep-plan buildings and who created design data based on a large European research project (Passive and Hybrid Downdraft Cooling, PHDC).²⁶

8.1.5.1 Habitat Research and Development Center (HRDC) by Nina Maritz Architects, Katatura, Windhoek, Namibia

Nina Maritz designed the HRDC with the ambition “to be the centre of excellence in housing research and development by applying new methods and ideas of science and technology for the sustainable development of the Namibian housing sector,”²⁷ and the center was developed with the mission “to promote the use of local, indigenous building materials and designs, to engage multi-disciplinary teams in basic research, and to adapt existing knowledge and applied research to achieve a holistic approach to problem solving in the field of housing and related issues.”²⁸

The center has been developed with a holistic profile and architecture concept. Whenever possible reclaimed material was used, for example reclaimed pavers and

cement block at about a third of the price of new ones. The building is spread out over the site for the various program parts, and each section is towered by a wind catcher, six all together, to pull in air from the wind flow above the building into the lower sections of the building. If possible, requirements for cross-ventilation space dimensions ask for operable windows.

Case study data

Design intent:

This building is located in the southern hemisphere and therefore the main solar orientation is to the north. To mitigate the prevailing wind direction and the solar exposure, the building's main axis is oriented about 25 degrees east of north. This orientation shelters the building from the low-angle December (summer) sun on the southeast and southwest side of the building. The wind catchers are supplemented by occupant-controlled lower-level operable windows as well as clerestory windows for daylighting.

Ventilations strategy:

Natural ventilation strategy and mechanical integration: Wind catcher towers only for cooling

Spatial design strategy (flow path) plan/section and analysis: Open plan combined with wind catchers

Façade strategies (apertures): Wind catchers for cooling combined with operable windows for comfort ventilation



Figure 8.37

Habitat Research and Development Center (HRDC) in Windhoek, Namibia: the center with its wind towers in the landscape. Stack ventilation windows are also visible at the top of the building.



Figure 8.38

HRDC in Windhoek, Namibia: one of the wind towers as seen from the exterior passageways.



Figure 8.39

HRDC in Windhoek, Namibia: the top of the wind tower is covered by a sheet metal roof, which helps to induce the Venturi effect and increases the air velocity at the top of the tower.

Project data:

Year of completion: 2004

Height/building type: 5 m for the building plus additional 3 m / 9.84 ft for the tower;
mixed use

Stories: Two to three

Function: Research center, offices, public spaces

Structure: Recycled and found materials such as stones, sheet metal, steel beams, used car tires, brick, and willows

Plan depth: Between 11 and 19 m / 36 and 62 ft

Building size: 2196 m² / 23,640 ft²

Climatic data:

Location: Katatura township, Windhoek, Namibia

Geographic position: 22.5231° S, 17.0603°E

Climate classification: Windhoek is situated in a semi-arid climatic region (Köppen: BSh).

Prevailing wind direction: Northwest (May through September), east/northeast (February, March April, November) and south (October/January), depending on season

Average wind speed: Very constant wind speed around 8/9 mph / 12.85–14.5 km/h

Mean daytime temperature summer: Maximum 32 to 34 °C / 90 to 93 °F

Mean daytime temperature winter: 4 to 6 °C / 39 to 43 °F

Heating degree days 65 °F/18 °C: 926/496

Cooling degree days 78 °F/25 °C: 633/334

Day-night difference during hottest months: Daily temperature swings 20 °C / 36 °F

Mean annual precipitation: Median rainfall 12 to 14 in / 305–356 mm

Average relative humidity: Humidity average 10 to 20 percent

Highest relative humidity and length of humid season: None

Energy data:

Time of year natural ventilation can be utilized: Year round

Saved heating and cooling energy: N/A

Typical annual energy consumption: N/A

Considerations, obstacles, issues, etc.: None

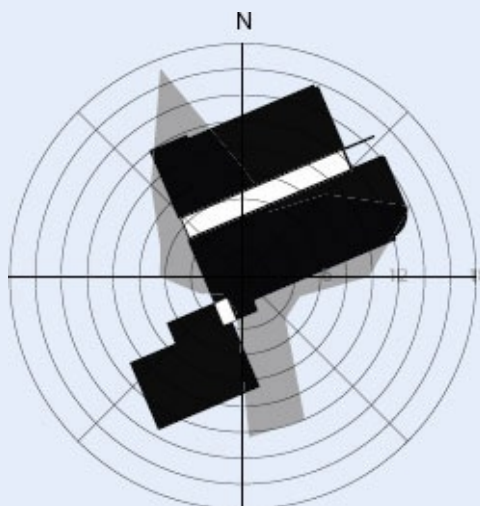


Figure 8.40

Wind rose for Windhoek, Namibia, showing the prevailing winds in the location (in m/s).

Project team:

Nina Maritz Architects

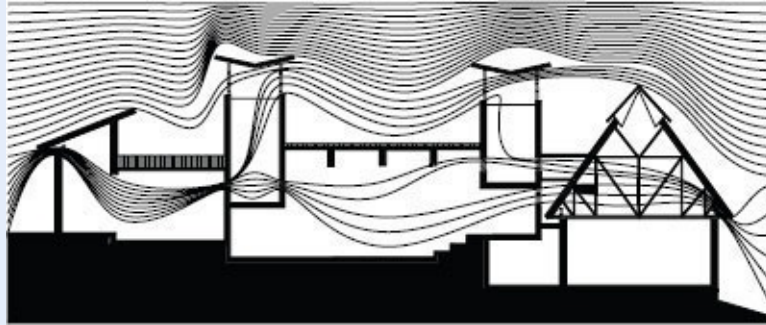


Figure 8.41

Section through the main space of the HRDC showing the interaction of cross-ventilation and wind catcher ventilation.

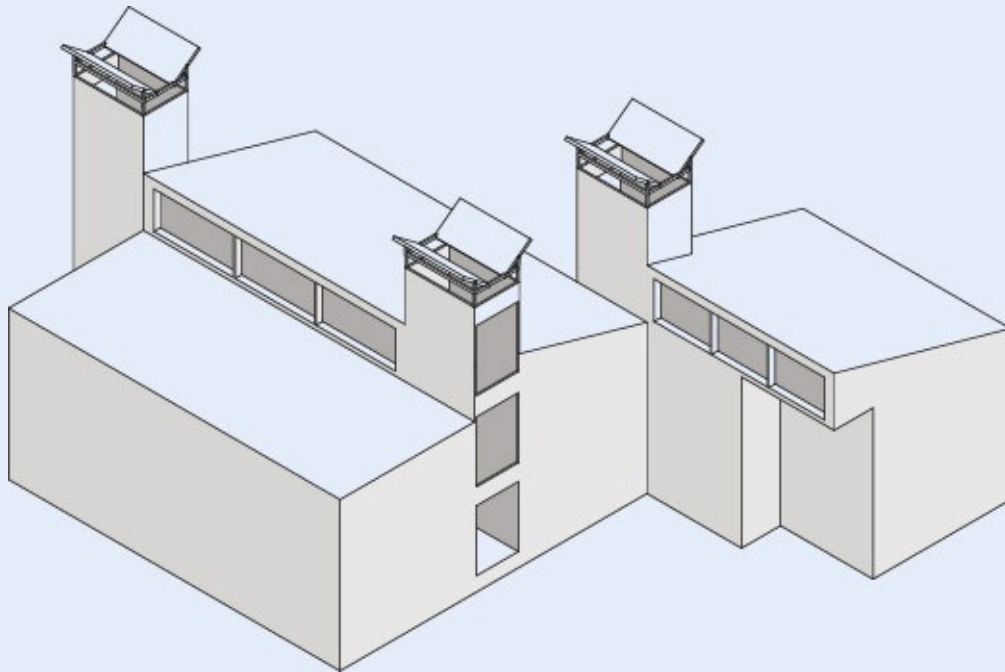


Figure 8.42

Axonometric view of the overall spatial composition of the HRDC.

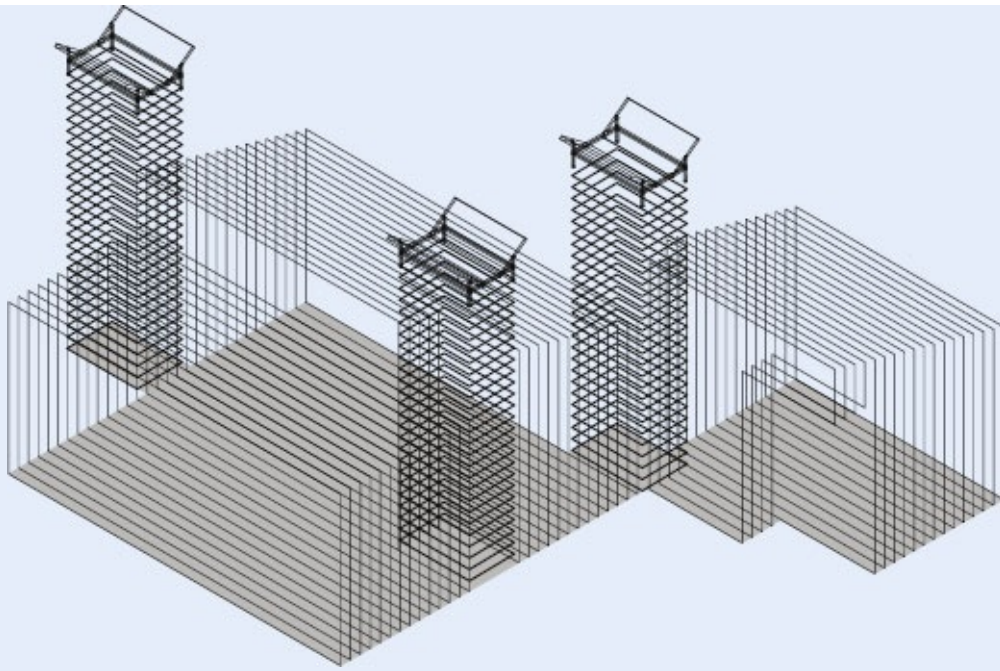


Figure 8.43

Volumetric flow path diagrams showing the spatial composition of the wind towers, which are integrated into the main spatial volume as an edge in – edge out flow path composition (see [Figure 7.7](#)).

8.1.6 Path 6: Combined Strategies

Most often natural ventilation strategies in larger scale buildings combine multiple flow path strategies and most often also multiple ventilation strategies. Often combinations are based on different identified zones in the building.

8.1.6.1 Freie Universität Berlin Library

The Free University Berlin was founded in 1948 in the Western sector of Berlin, Germany. Twenty years later, a new building was designed in the suburb of Dahlem by Candilis, Josic, Woods, and Schiedhelm based on their winning competition entry of 1963. The building was not constructed until 1967, and was finally completed in 1973. The iconic yet confusing clustered layout of streets and courtyards carried the social optimism of the time. However, the materials, assemblies and construction techniques were prone to dilapidation and failure and thus a major overhaul had to take place in the 1990s, which also included the insertion of a new major library complex into one of the courtyards. All of this work was conducted by Sir Norman Foster and Partners between 1997 and 2004. The new philological library, also called ‘The Brain,’ consists of multiple levels of reading areas and shelves covered by a large, free-carrying roof made of steel trusses and covered by inner and outer layers of skin, which facilitate heating, natural ventilation, and cooling of the inner, open-plan library space.²⁹

Case study data

Design intention:

Hybrid system where the outer skin acts as buffer and ventilation duct; thermal mass is used to balance the temperature swings.

Ventilation strategy:

Natural ventilation strategy and mechanical integration: Cross-ventilation only for the library section through ventilation skin

Spatial design strategy (flow path) plan/section and analysis: Open plan

Façade strategies (apertures): Multiple operable windows.

Project data:

Year of completion: 2005

Height/building type: 19 m / 62 ft

Stories: Four floors enclosed in a bubble-like, free-standing structure

Function: Library

Structure: A covering shell of white fiberglass fabric panels and translucent ETFE (Ethylene tetrafluoroethylene) elements spans $64 \times 55 \times 19$ m ($210 \times 180 \times 62$ ft). It is a double-layered skin with a MERO²⁸ wide-span steel structure painted in bright yellow.²⁹

Plan depth: 6290 m^2 / $67,705 \text{ ft}^2$



Figure 8.44

Philological library of the Freie Universität Berlin: interior view of the building skin.



Figure 8.45

Philological library of the Freie Universität Berlin: interior view of the ventilation openings in the building skin.



Figure 8.46

Philological library of the Freie Universität Berlin: exterior view of the all-encompassing building skin.

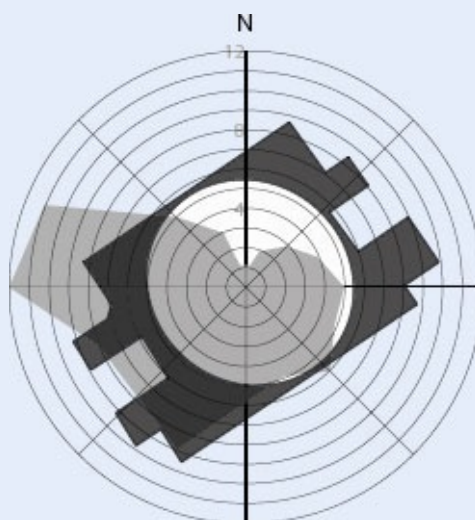


Figure 8.47

Wind rose for Berlin, Germany, showing the prevailing westerly wind of the location (in m/s).

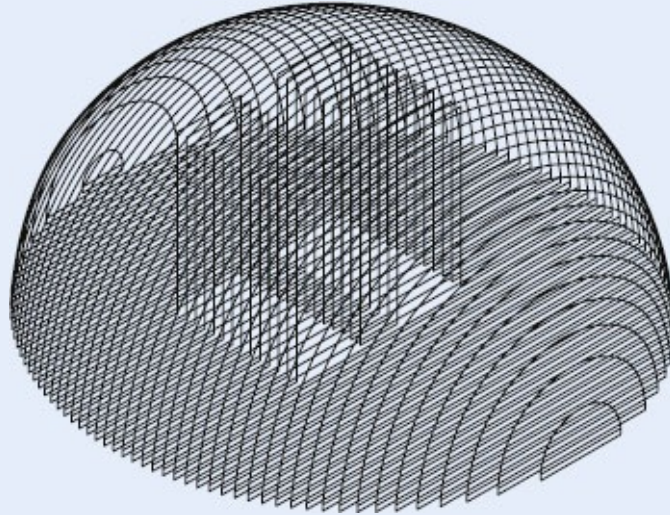


Figure 8.48

Volumetric diagram highlighting the flow path and spatial composition of the Philological library at the Freie Universität Berlin.



Figure 8.49

Sectional diagram of the Philological library at the Freie Universität Berlin showing the relationship of skin, core, and ventilation flow path in between.

Climatic data:

Location: Berlin, Germany

Geographic position: Latitude: 52° 28'N; longitude: 13° 18'E

KG climate classification: Berlin lies on the edge between the temperate Oceanic Cfb climate of Western Europe and the humid continental climate Dfb of Poland and Western Russia.

Prevailing wind direction: The wind is most often out of the west (28 percent), southwest (12 percent), east (11 percent), south (11 percent), and northwest (10 percent).

Average wind speed: 7 to 10 mph / 11.25 to 16 km/h

Mean daytime temperature summer: 19 °C / 66 °F

Mean daytime temperature winter: 2 °C / 35.6 °F

Heating degree days 65F/18C: 6261/3438

Cooling degree days 78F/25C: 44/6 (basically no cooling needed)

Day-night difference during hottest months: 16 °F / 10 °C

Mean annual precipitation: 20 mm / 0.86 in

Average relative humidity: N/A

Highest relative humidity and length of humid season: N/A

Energy data:

Time of year natural ventilation can be utilized: Year round

Saved heating and cooling energy: N/A

Typical annual energy consumption: N/A

Considerations, obstacles, issues, etc.: Security is a major concern for libraries. Berlin has a heating-dominated climate, therefore preheating the ventilation air and heat exchange was essential for the ventilation strategy.

Project team:

Architect: Foster and Partners

Structural engineer: Pichler Ingenieure

M+E engineer: Schmidt Reuter Partners / PIN Ingenieure

8.2 Connecting the Inner Flow Path to the Outer Condition

8.2.1 KfW Westarkade, Frankfurt, Germany, by Sauerbruch Hutton

Case study data

Design intention:

Kreditanstalt für Wiederaufbau (KfW) Westarkade³⁰ adds a tower on a plinth to an existing agglomeration of bank office buildings of various heights. A ring of double-skin façade surrounds a single ring of offices, which circle around the circulation and infrastructure core. Corridors meet the façade at three points to enable nighttime cross-ventilation and core activation. Wind is used as the driving force to provide fresh ventilation air, while stack pressure difference is utilized to exhaust the stale and warm air through shafts in the core of the building. The double-skin façade is closed off between the floors in order to prevent an unwanted stack effect in the double-skin façade. The double-skin façade merely supports the distribution of pressure around the whole ring of offices, so that all outer office windows act as ventilation inlets. This facilitates consistent fresh air input across all offices and makes the offices

independent from each other within the ventilation regime. The saw-tooth façade highlights the difference between light-admitting surfaces, which are fixed, and air-admitting openings, which are colored and alternate with acoustic panels. The air intake panels are much more slender than the daylight windows.

Ventilation strategy:

Natural ventilation strategy and mechanical integration: Mixed-mode/complementary/concurrent; wind-driven cross-ventilation combined with stack-driven shaft ventilation Spatial design strategy (flow path) plan/section and analysis: The streamlined, drop-shaped tower sits on a three- to four-story plinth and is integrated into an assemblage of other buildings of various heights.

Façade strategies (apertures): Double-skin façade with operable windows in both layers to enable multiple opening combinations to facilitate a variety of flow path strategies

Project data:³¹

Year of completion: 2010

Height/building type: 56 m / 184 ft, office

Stories: 14

Function: Offices total 22,300 m² / 240,035 ft²

Structure: Composite / glass façade

Plan depth: 6.3 m / 20.6 ft from core and 26 m / 85.3 ft total



Figure 8.50

KfW Westarkade Frankfurt, Germany: exterior view of the tower from the west.

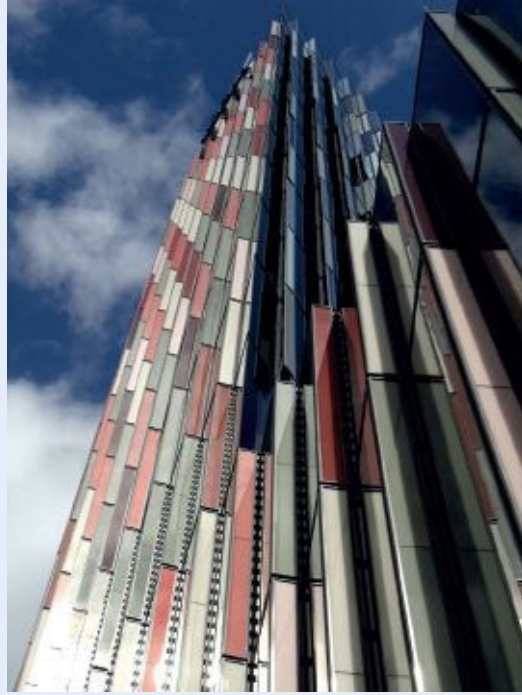


Figure 8.51

KfW Westarkade Frankfurt, Germany: view up the tower edge with ventilation wings open.



Figure 8.52

KfW Westarkade Frankfurt, Germany: detailed view of the building envelope with ventilation windows open.

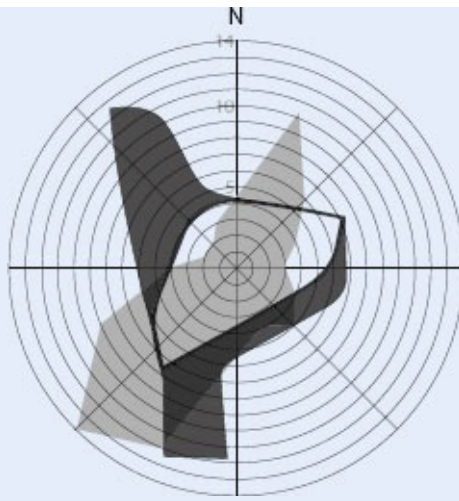


Figure 8.53

Wind rose for Frankfurt, Germany, showing how the shape of the tower is located within the prevailing westerly wind of the location (in m/s).

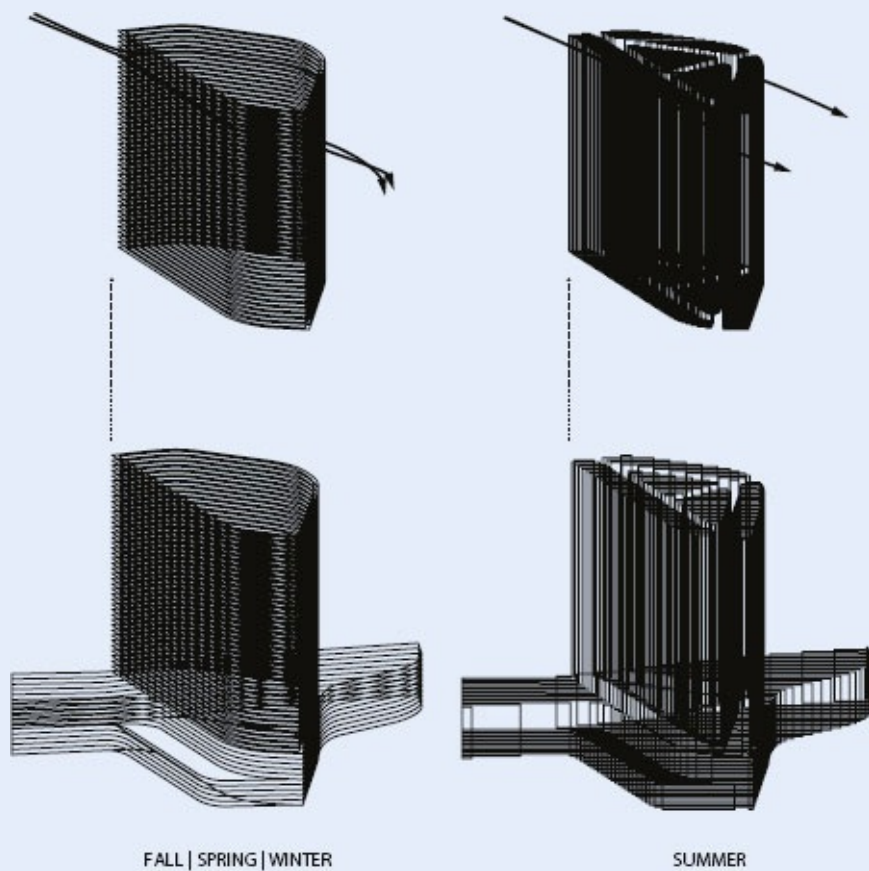


Figure 8.54

Volumetric diagram highlighting the flow path and spatial composition of the KfW Westarkade building in Frankfurt.

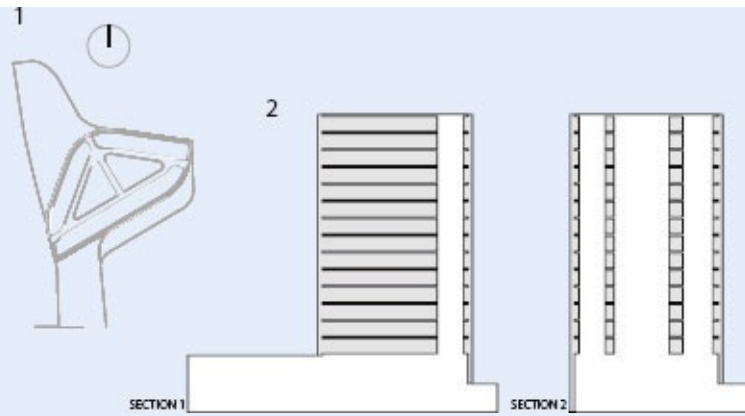


Figure 8.55

Section diagram highlighting the seasonally changing flow path for natural ventilation in the KfW Westarkade Frankfurt.

Climatic data:

Location: Frankfurt, Germany

Geographic position: latitude: 50° 7' N; longitude: 8° 41' E

KG climate classification: Warm temperate with fairly mild weather and good natural ventilation potential. Oceanic climate, Cfb/warm temperate, fully humid, warm summers.

Prevailing wind direction: SSW

Average wind speed: 8 mph / 12.85 km/h

Mean daytime temperature summer: 18.3 °C / 65 °F

Mean daytime temperature winter: 1.83 °C / 35 °F

Heating degree days: Five-year average, 60 °F/15.5 °C base: 4050/2232

Day-night difference during hottest months: 17.73 °C / 32 °F

Mean annual precipitation: 621 mm / 24.4 in

Average relative humidity: 53 percent

Highest relative humidity and length of humid season: July 16, 75 percent

Energy data:

Time of year natural ventilation can be utilized: Eight months of the year

Saved heating and cooling energy: 84 percent compared to fully air-conditioned German office buildings

Typical annual energy consumption: Estimated at 50 kWh/m² / 15,850 BTU/ft²

Considerations, obstacles, issues, etc.: Continuous spaces are always in conflict with fire protection measures. Therefore the continuous cavity ring of the double-skin façade can be subdivided into three zones in synch with the three fire protection zones inside the building.

Project team:

Architect: Sauerbruch Hutton

Associate architect: architekten Theiss Planungsgesellschaft mbH

Structural engineer: Werner Sobek Group

Energy concept: Transsolar KlimaEngineering

MEP engineer: Reuter Rührgartner GmbH: Zibell, Willner & Partner

Main contractor: ARGE Züblin, Bögl

8.2.2 San Francisco Federal Building by Morphosis

Case study data

Design intention:

San Francisco provides perfect conditions for natural ventilation because of its fairly mild temperatures and constant ocean breezes. The Federal Building combines an elongated tower with a slender floor plan and a base plaza. The plan provides good conditions for floor-by-floor cross-ventilation utilizing operable, out-swinging, top-hung windows combined with a multi-layered shading system necessary because of its orientation. The positioning of the tower into the prevailing wind coming from the northwest conflicts here with the low-angle solar radiation. This leads to the exposure of the elongated west and east façades to the low-angle morning and evening sun, which can cause significant solar heat gain, which does not facilitate low energy ventilation. Due to federal security concerns, the bottom five floors are not designed with operable windows and are thus fully air-conditioned. This zoning requirement was then supplemented by the programming for the building. The base contains a conference center, fitness center, and daycare center. The narrow floor plan is complemented by an open floor plan with intersections of closed volumes for more enclosed spaces such as bathrooms and meeting rooms. A gap of half a meter above these volumes permits air to flow across the spaces. Ceilings are exposed concrete, cast with a wavy underside to enhance daylighting through reflection, but also to expose a larger area of mass to the ventilation air for nighttime cooling.

Ventilation strategy:

Natural ventilation strategy and mechanical integration: Mixed-mode based on zones. Mechanical ventilation is used in parts of the building that are not connected to the perimeter open plan. In addition, mechanical ventilation can be supplemented and trickle vents are added above baseboard heaters to warm incoming ventilation air during the cold season.

Spatial design strategy (flow path) plan/section and analysis: Open plan combined with enclosed volumes; bottom five floors sealed for security reasons

Façade strategies (apertures): Operable, top-hung windows with shading screen and

additional trickle vents for cooler seasons



Figure 8.56

Federal Building San Francisco, California, USA: exterior view of the tower from the northeast.



Figure 8.57

Federal Building San Francisco, California, USA: exterior view of the tower slab from the southeast showing the solar shading screen.



Figure 8.58

Federal Building San Francisco, California, USA: detailed view of the building envelope from the northwest.

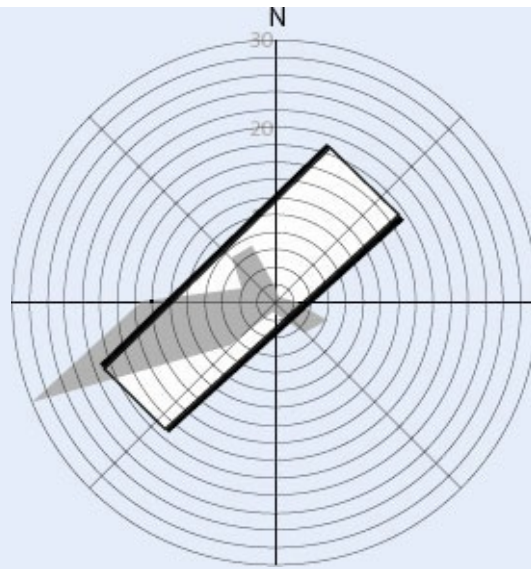


Figure 8.59

Wind rose for San Francisco, California, USA, showing how the shape of the tower is located within the prevailing westerly wind of the location (in m/s)

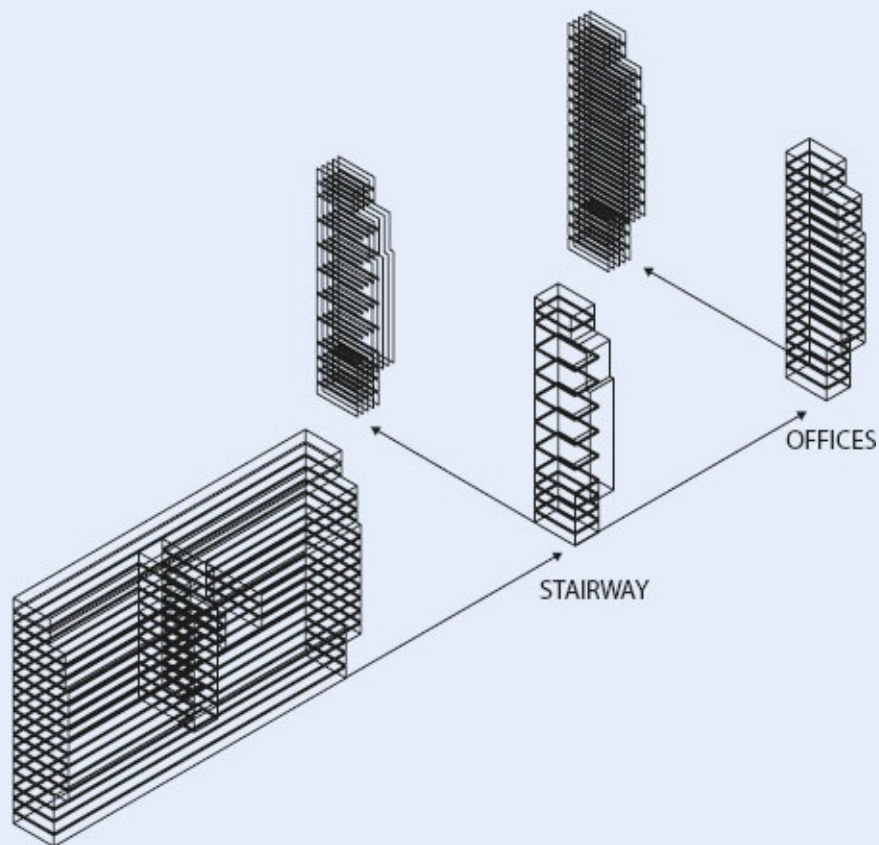


Figure 8.60

Volumetric diagram highlighting the flow path and spatial composition of the Federal Building in San Francisco, California.

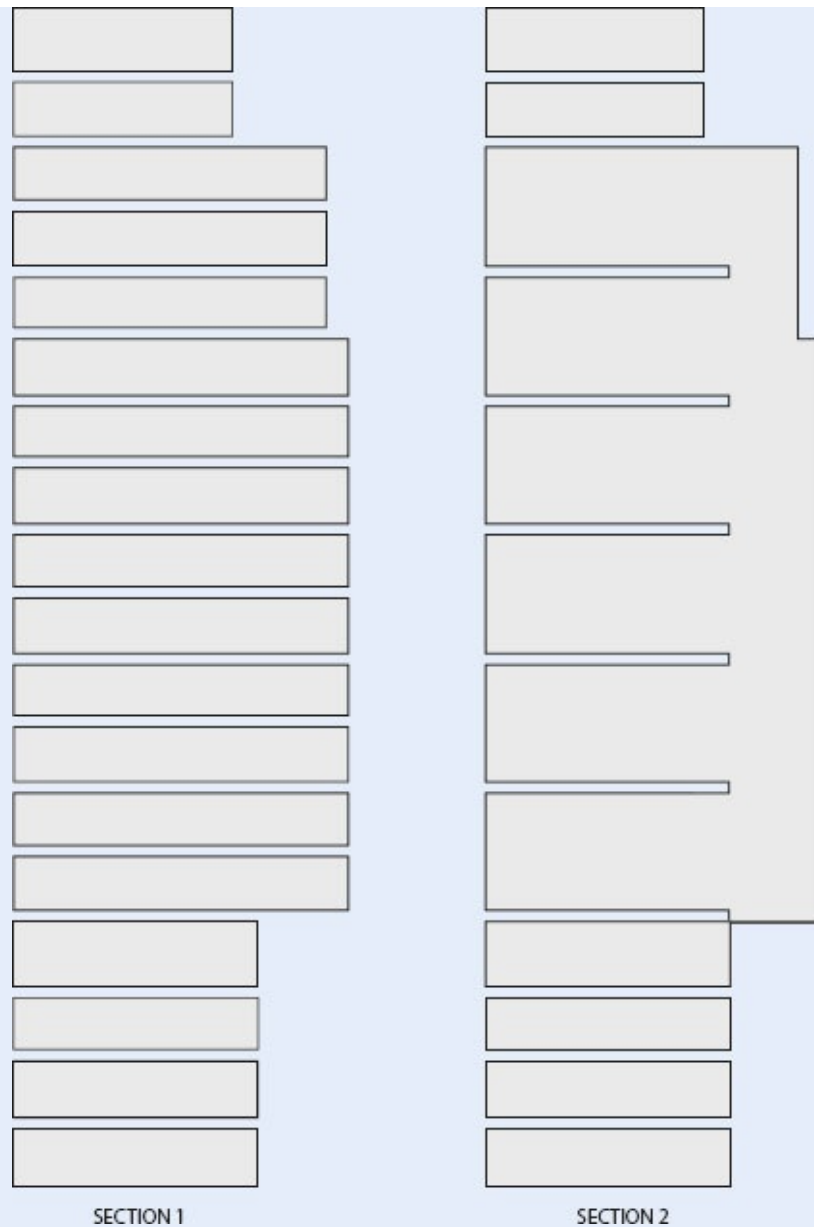


Figure 8.61

Section highlighting the flow path of the natural ventilation flow of the Federal Building San Francisco, California.

Project data:³²

Year of completion: 2007

Height/building type: 71 m / 233 ft / federal administration

Stories: 18

Function: Offices and conference spaces

Structure: Concrete

Plan depth: 19 m / 62.3 ft between façades

Climatic data:

Location: San Francisco, Northern California, USA

Geographic position: Latitude: 37° 47' N; longitude 122° 26' W

Climate classification: Temperate

Prevailing wind direction: West

Average wind speed: 9.5 mph / 15.5 km/h

Mean daytime temperature summer (July, August, September): 23 °C / 73.4 °F

Mean daytime temperature winter (December, January, February): 14 °C / 57.2 °F

Heating degree days 65F/18C: 2719/1510

Cooling degree days: 31/17 (basically no cooling needed)

Day-night difference during hottest months: 10 °C / 18 °F

Mean annual precipitation: 500 mm / 19.68 in

Average relative humidity: 60 percent during hottest and coldest month

Highest relative humidity and length of humid season: Maximum 75 percent in February during cold season

Energy data:

Time of year natural ventilation can be utilized: 21 percent of the building's usable area is naturally ventilated 100 percent of the time.

Saved heating and cooling energy: 55 percent compared to a conventional air-conditioned building of the same size and typology (estimate) and about 15 percent compared to California Title 24 Energy Code.²⁹

Typical annual energy consumption: Unpublished

Considerations, obstacles, issues, etc.: Additional heat gain due to orientation might not always be offset by natural ventilation.

Project team:

Owner/developer: US General Services Administration

Design architect: Morphosis

Associate architect: Smith Group

Structural engineer: Arup

MEP engineer: Arup

Project manager: Hunt Construction Group

Main contractor: Dick Corporation; Morganti General Contractors

Other consultants: Lawrence Berkeley National Laboratory (Natural Ventilation Modeling); curtain wall: Design & Consulting, Inc.

Notes

- 1 CIBSE, *Natural Ventilation in Non-domestic Buildings*, CIBSE Applications Manual (London: CIBSE, Carbon Trust, 2005), pp. 8–10.
- 2 Ibid.
- 3 See “Das Bakema-Van Den Broek-Punkthochhaus,” <http://www.acamedia.info/arts/architecture/bartning7.htm> (accessed 5/13/2014).
- 4 See http://www.architetturadelmoderno.it/scheda_nodo.php?id=72&lang=_eng (accessed 5/13/2014).
- 5 Bruno Zevi and Giuseppe Terragni, *Giuseppe Terragni*, 1st ed., Serie Di Architettura (Bologna: Zanichelli, 1980).
- 6 Peter D. Eisenman, “From Object to Relationship II: Giuseppe Terragni, Casa Giuliani Frigerio,” *Perspecta* (Yale University), 13/14, 1971, pp. 36–65.
- 7 Peter Terragni, Giuseppe Eisenman, and Manfredo Tafuri, *Giuseppe Terragni: Transformations, Decompositions, Critiques* (New York: Monacelli Press, 2003).
- 8 Heating degree days (HDD) are defined as a measurement to reflect the demand for heating energy against a baseline indoor temperature for a specific location and average daily outside temperature. Ten HDD reflect an average temperature difference of 10 °F or 10K between a desired indoor temperature of 18 °C / 65 °F and the outdoor temperature of a particular day. Adding all HDD for a year provides a measurement for the severity of winter.
- 9 Cooling degree days (CDD) are defined as a measurement to reflect the demand for cooling energy against a baseline indoor temperature for a specific location and average daily outside temperature. Ten CDD reflect an average temperature difference of 10 °F or 10K between a desired indoor temperature of 25 °C / 78 °F and the outdoor temperature of a particular day. Adding all CDD for a year provides a measurement for the severity of winter.
- 10 See “Charles Correa Associates,” <http://www.charlescorrea.net/> (accessed 5/13/2014).
- 11 See <http://weatherspark.com/averages/33910/Mumbai-Bombay-Maharashtra-India> (accessed 5/13/2014).
- 12 Antony Salib and Ruba Wood, *Natural Ventilation in High-Rise Office Buildings*, CTBUH Technical Guides (New York: Routledge, 2013), pp. 33–41.
- 13 Various web sources were consulted for this case study project (all accessed 5/13/2014): <http://www.fosterandpartners.com/projects/commerzbank-headquarters/>, <http://www.degreedays.net/#generate>, http://sustainability2009.commerzbank.com/reports/commerzbank/annual/2009/nb/English/703025/co_sub_2_sub_-accounting-energy-use.html.
- 14 CIBSE, *Natural Ventilation in Non-domestic Buildings*, CIBSE Applications Manual (London: CIBSE, Carbon Trust, 2005), pp. 11–13.
- 15 See <http://www.mickpearce.com/about/pressmedia/> (accessed 5/13/2014).
- 16 See <http://www.mickpearce.com/works/office-public-buildings/eastgate-development-harare/> (accessed 5/13/2014).
- 17 M. Kottke, J. Grieser, C. Beck, B. Rudolf, and F. Rubel, “World Map of the Köppen-Geiger Climate Classification Updated,” *Meteorol. Z.*, 15, 2006, pp. 259–263, doi:10.1127/0941-2948/2006/0130.
- 18 Keelan P. Kaiser, David M. Ogoli, and Malcolm Cook, “Harm A. Weber Academic Center, Post-occupancy Building Performance and Comfort Perceptions,” *ARCC Journal of Architectural Research*, 6(2), 2009.
- 19 “The Environmental Building” (BRE), <http://projects.bre.co.uk/envbuild/>.
- 20 “Green Building” (Sidwell Friends School), http://www.sidwell.edu/middle_school/ms-green-building/index.aspx.
- 21 CIBSE, *Natural Ventilation in Non-domestic Buildings*, CIBSE Applications Manual (London: CIBSE, Carbon Trust, 2005), p. 17.
- 22 Clito Afonso and A. Oliveira, “Solar Chimneys: Simulation and Experiment,” *Energy and Buildings*, 32(1), 2000, pp. 71–79.
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- 26 “Habitat Development and Research Center,” cndstudio2012.files.wordpress.com/2012/10/hrdc.pdf.
- 27 Foster + Partners, <http://www.fosterandpartners.com/projects/free-university/> (accessed 5/13/2014).
- 28 “Mero Construction systems”, *Mero Structures*, <http://www.mero-structures.com/construction-systems-2.html> (accessed 05/18/2014).
- 29 “The Free University Still Embodies the Social and Architectural Dynamic of the 1960s,” *Architects’ Journal*, 9/15/2005.
- 30 Antony Wood and Ruba Salib, *Guide to Natural Ventilation in High-Rise Office Buildings* (New York: Routledge, 2012).
- 31 Ibid., pp. 122–123.
- 32 Antony Wood and Ruba Salib, *Guide to Natural Ventilation in High-Rise Office Buildings* (New York: Routledge, 2012), pp. 104–111.

Chapter 9

Façade as Filter: From Windows to Curtain Walls to Adaptive and Smart Skins

The building envelope is the crucial filter and membrane for ventilation, supplying and exhausting air through its openings. In order to develop a functioning natural ventilation strategy, these inlets and outlets have to be properly placed and sized to provide the required ventilation rate, while the remaining parts of the façade should ideally be fully sealed in order to control the flow and to prevent infiltration negatively influencing the flow rate.

The building envelope also plays a significant role in controlling the exchange of thermal energy between inside comfort and outside climatic conditions. This exchange can only be prevented by vacuum insulation, which is still a very costly endeavor. Thus, the construction and sealing of the building envelope has to be conducted with utmost care to prevent the creation of thermal bridges. Air infiltration may result in uncontrolled air exchange rates, which can lead to reduced pressure differences elsewhere. High temperature differences inside the building envelope assembly can also lead to harmful and destructive condensation. This in turn can lead to mold growth and thus health hazards.

Inlets and outlets for natural ventilation, which connect the ventilation flow path to the external environmental forces, are a crucial factor in the design of spaces for natural ventilation. The most common element or device to enable this connection is the operable window. The vertical window is mainly needed for wind-driven ventilation flows, while the window opening in the roof can also work together with buoyancy effects for ventilation.

9.1 Window Ventilation in Different Regions and Climates

The Old English word for window ‘vindauga’ means wind-eye, from Old Norse *vindr* ‘wind’ + *auga* ‘eye,’ the eye for the wind, which combines the two major functions for openings in buildings: letting in light and air and allowing the view to venture out. The word, along with many others, was presumably introduced to the Anglo-Saxon language by Danish settlers mainly in the ninth, tenth, and eleventh centuries. The modern Danish word for ‘window’ is *vindue*, pronounced not very differently from its English counterpart.¹

Very different styles of windows developed in different parts of the world, depending on climate, available materials, customs, and other requirements such as cultural norms and privacy requests. Often the aspects of physics were intuitively integrated based on physical needs for view and air change rates versus heat and security.

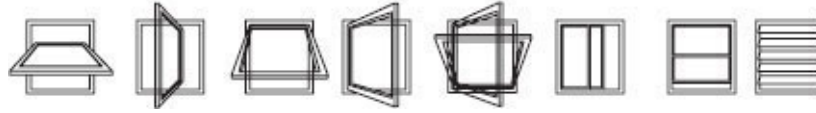


Figure 9.1

Different opening styles for windows directly influence the ventilation inlet flow direction of the flow path inside the building. From left to right: horizontal pivot, vertical pivot, top hung, side hung, tilt and turn, vertical sliding, horizontal sliding, louvers.

Operable windows can be user controlled or automated (see [Chapter 10](#)). Over centuries, different opening mechanism have been developed, which lend themselves to a different climate and different ventilation strategies.

9.1.1 French Doors

Side-hung casement windows are traditional in France, where they open inwards as two panes (French windows/doors). In the Netherlands or Northern Germany they open outwards, which is often explained by the fact that they can be closed by the wind and the wind presses them tight to the frame. These windows often provide better protection against driving rain as they close tightly against the direction of the rain.



Figure 9.2a

French windows, as seen here from the exterior of a typical house in the Paris region, reach from close to the floor to close to the ceiling, are split in the middle, and are side hung and usually open inward.

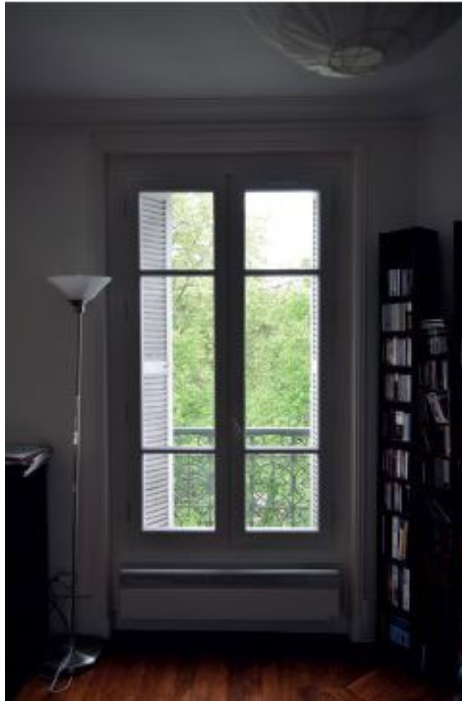


Figure 9.2b

An interior view of a French window.

9.1.2 English Sash Windows

English sash windows slide in a vertical direction; usually two frames, sometimes even three frames, slide over each other to create openings of multiple scales on the top and bottom. Sash windows can allow for small and large air flow rates, but are prone to infiltration as they are difficult to manufacture airtight, similarly to other sliding windows. The advantage of sash windows is that they do not protrude out into the space when opened.



Figure 9.3

English sash windows are double hung, horizontally split and slide up and down, allowing gradual changes in the opening size, and do not protrude into the occupied space; thus they do not redirect the flow.

9.1.3 Hopper Windows

Hopper windows often combine an operable window frame with a closed sealed glass pane. This is a common practice in the Nordic countries and highlights the distinctively different sizing requirement for daylighting, solar gain, and natural ventilation.



Figure 9.4

Hopper windows are small window flaps opening outwards, as here in the Iowa Interlock House.

9.1.4 Northern European Box Windows

Northern European box windows basically combine two layers of side-hung windows, which trap an air space between them for improved insulation in winter. These two layers of glass also greatly improve the acoustic separation of inside and outside.



Figure 9.5

Northern European box windows can open inwards or outwards and are composed of two sets of four windows, which enclose an air space in between (photo taken in Tallinn, Estonia).



Figure 9.6

This Roman window at Palazzo Cenci, the ISU College of Design studio in Piazza delle Cinque Scole, Rome, Italy, includes three layers: an outer layer, which acts as a shading device, but also as a ventilation louver, the actual window with glass, and an inner layer, which can seclude the window from the inside for total privacy.

9.1.5 Multifunctional Roman Windows

Multifunctional Roman windows are an even more complex development. They combine two side-hung frames with glass combined on the interior with two solid wooden shutters that create complete darkness and privacy and an external layer made of a set of louvered shutters, which can provide shading of the glass from the exterior as well as ventilation inlets when the glass panes are opened.



Figure 9.7

The ventilation opening in Alvar Aalto's own house window, which he designed with his first wife and partner Aino Aalto, separates the ventilation function clearly from the view window.

9.1.6 Ventilation Windows

When ventilation requirements and requirements for view windows are even further apart, such as in the Nordic countries, the vertical ventilation opening is so small that it does not even contain glass. An example is seen in the ventilation openings in Aalto's own house in Helsinki, Finland. This design removes the infiltration issues by using gaskets and seals within the large view window, while still providing ample daylight through the large pane of glass. The view window is sealed shut, and the assembly only contains one small vertical ventilation flap.

9.1.7 Laueferli in Davos

Another strategy to separate the vent window from the view window was developed in traditional farm houses of the Davos Alps in Switzerland, where just one small pane of

glass is movable, while the others are stationary and sealed.

9.1.8 Pivot Windows

Pivot windows are hung at the center axis of the operable frame. They have been fairly common in industrial applications, factory buildings, and greenhouses, and have been made famous by the Bauhaus building in Dessau, 1925–26, by Walter Gropius (1883–1969).

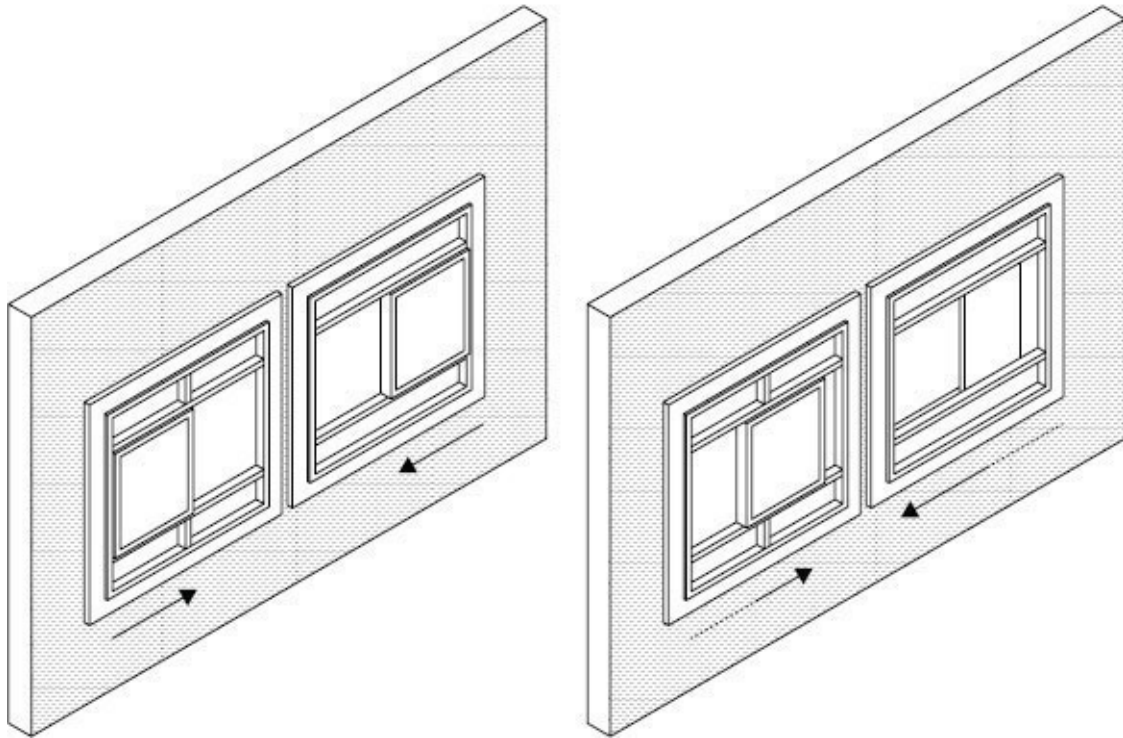


Figure 9.8

The so-called Laeufferli in Davos describes a fairly small ventilation slider, which is integrated in a larger composition, which was brought to attention by Andres Giedion⁷ in his book on the Davos Alphuette.



Figure 9.9

Walter Gropius' famous glass façade at the Bauhaus building in Germany from 1926 connects a series of pivot windows through a mechanical opening mechanism.

9.1.9 Wing Walls

The prevailing wind direction may not match the orientation requirements for windows and/or for the entire building. Wing walls can help to channel the required air flow into the opening. The opening frame of a window and/or its shutters can act as wing walls. Carefully placed façade elements can serve a similar function.

9.1.10 Ventilation Holes

In Chinese traditional residential architecture, emblems applied to the building as part of the structural features of the house were common. Good fortune, longevity, and wealth and privilege were some of the wishes embedded in the building fabric. A ventilation opening captured by Knapp in Meixian, Guangdong, for example takes the shape of a bottle gourd. The bottle gourd represents longevity and magic. The origin of this relationship is not clear, but it might lead back to the ‘Li Tiegui,’ one of the eight immortals of the Daoist life philosophy, whose emblem is a gourd, the magic vapors from which are said to be capable of trapping evil, according to Knapp’s comprehensive analysis of Chinese house typologies.²

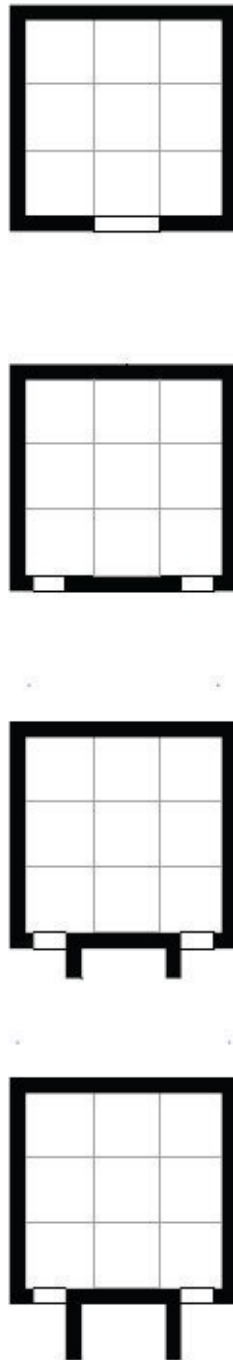


Figure 9.10

Wing walls can direct the air flow patterns and influence the way fresh air mixes with stale air in interior space.

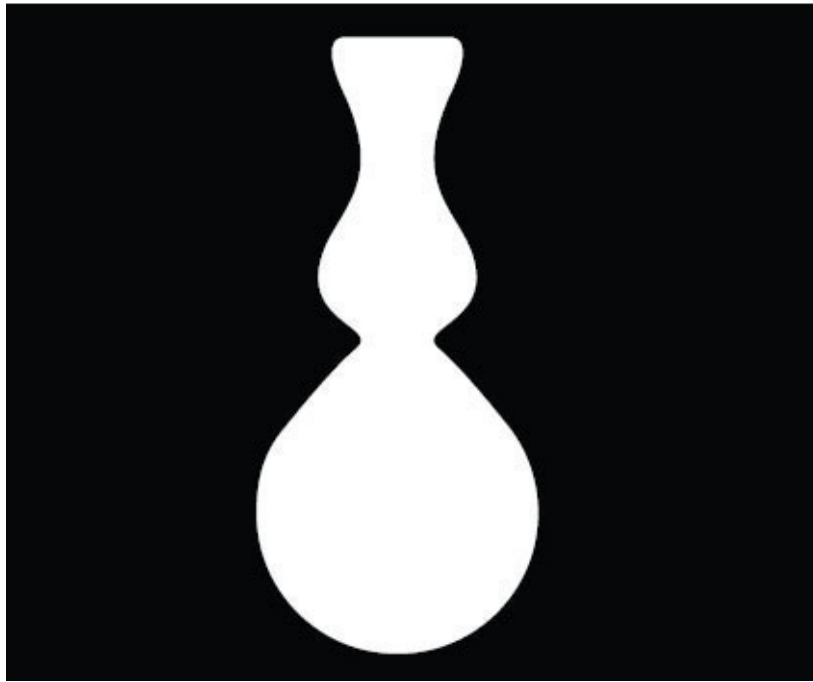


Figure 9.11

Ventilation hole from Meixian, China, shaped like a gourd.

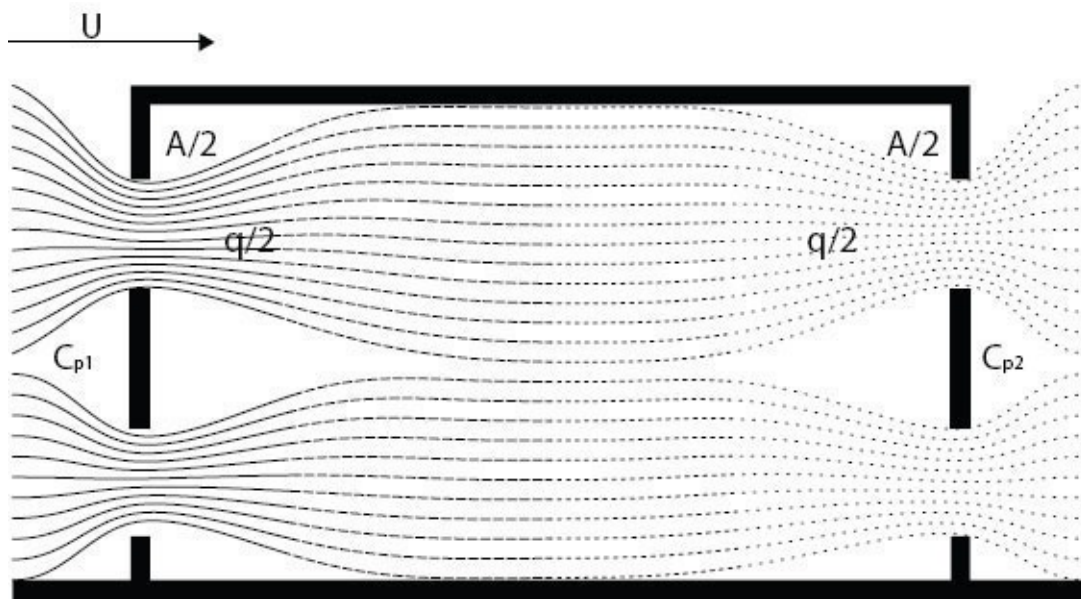


Figure 9.12

The size of opening directly influences the air flow rate in relation to wind velocity.

9.2 Proportional Rules for Window Openings and Distribution

Many parameters are used to determine the positioning of ventilation openings in the form of inlets and outlets in the building envelope. The most important of all are the geometry of the building and the position of the building on the site or within the street canyon. The proportion of the street canyon determines the force of the ventilation air at air inlets and outlets. These parameters also determine the quality of air at this important boundary condition. The position of the window in the height of the room and height above ground as well as its orientation are as important as the operation mechanism of the window itself

and the direction in which they open. In most cases, the scalability of the opening size provides control opportunities to manipulate the incoming air change rate and the air velocity.

The orientation of windows in the wind direction directly determines the flow direction of the air movement inside the space and thus the mixing capacity of the air stream.

It is often overlooked that precise prediction for air change rates can only be obtained for fairly flat façades. Elements attached to the outside of the façade can significantly alter the air flow pattern as well as the air velocity at the inlet and outlet. Such obstacles along the façade influencing the ventilation rate inside a building include solar shading, overhangs, balconies, bay windows, and other elements, such as awnings as shading devices, or bug screens. These devices create more complex and turbulent wind patterns at the inlet (as well as the outlet) and make the evaluation of a ventilation strategy even more challenging.

The report for the European UrbVent (2005) project³ thus stated that urban façades are too complex to allow for a precise prediction of ventilation rates and may even require studies in wind tunnels. Only simple geometries are predictable enough to develop generalized recommended guidelines for opening sizes.

In general, research has shown that multiple small openings can create a more homogenous air flow regime than a single local opening, even if the size of the one large opening equals the sum of the small sized openings.⁴ If designed correctly, balconies and overhangs can in some cases even increase air flow rates.⁵ But overhangs can trap warm air in front of the window, which means that air warmer than desired and necessary may penetrate the inlet and counteract cooling efforts. In addition, window screens and louvers significantly reduce air flow rates and in general require a doubling of the inlet area.

All of these additions to the building exterior jeopardize the precision at which the pressure coefficient and thus the rate and direction of wind entering the inlet can be predicted. But some rules can still be established.

Required ventilation openings can be roughly sized by estimating the heat that needs to be removed and the temperature difference between supply air and the desired room air (ΔT). This information will provide the required air flow rate. Air flow rate requirements and available wind speed can then be used to size the required opening. First, the uncertainty of wind distribution over the ventilation inlet/outlet has to be considered. In general, inlets should have the same size as outlets in order to allow a homogenous flow rate across the building.

There are various scaling rules of thumb for the different air flow requirements and strategies, but they all share a basic requirement for a continuous flow rate: all openings along the flow path should be designed at roughly the same size and the smallest opening determines the overall flow rate.

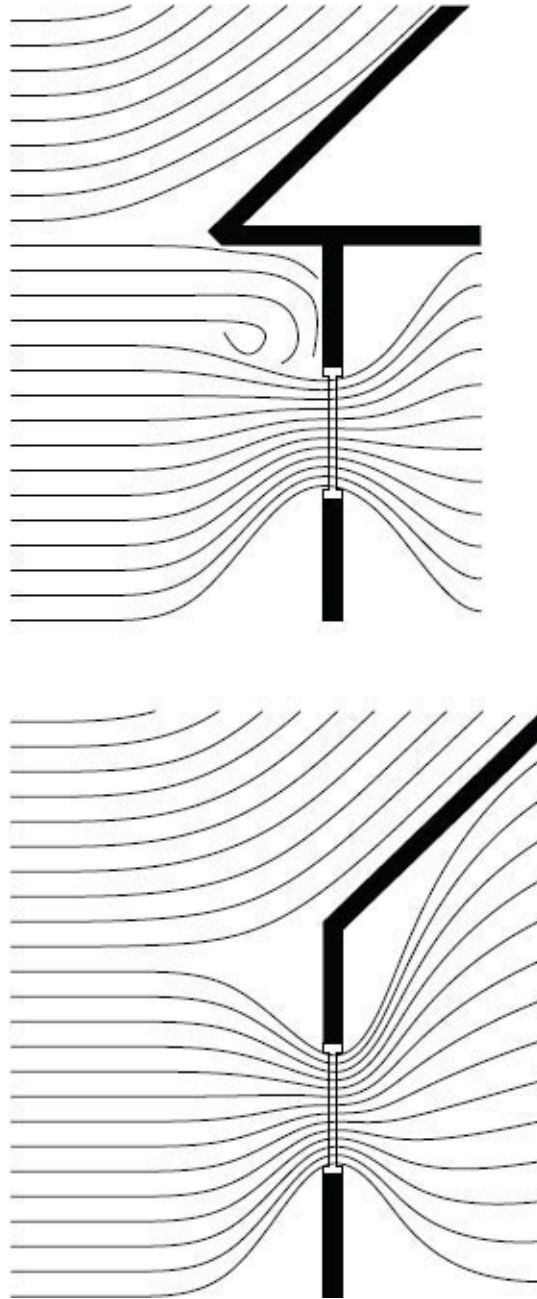


Figure 9.13

Overhangs trap hot and humid air in front of ventilation openings and should be avoided in hot and humid climates. Movable shading devices will be more beneficial.

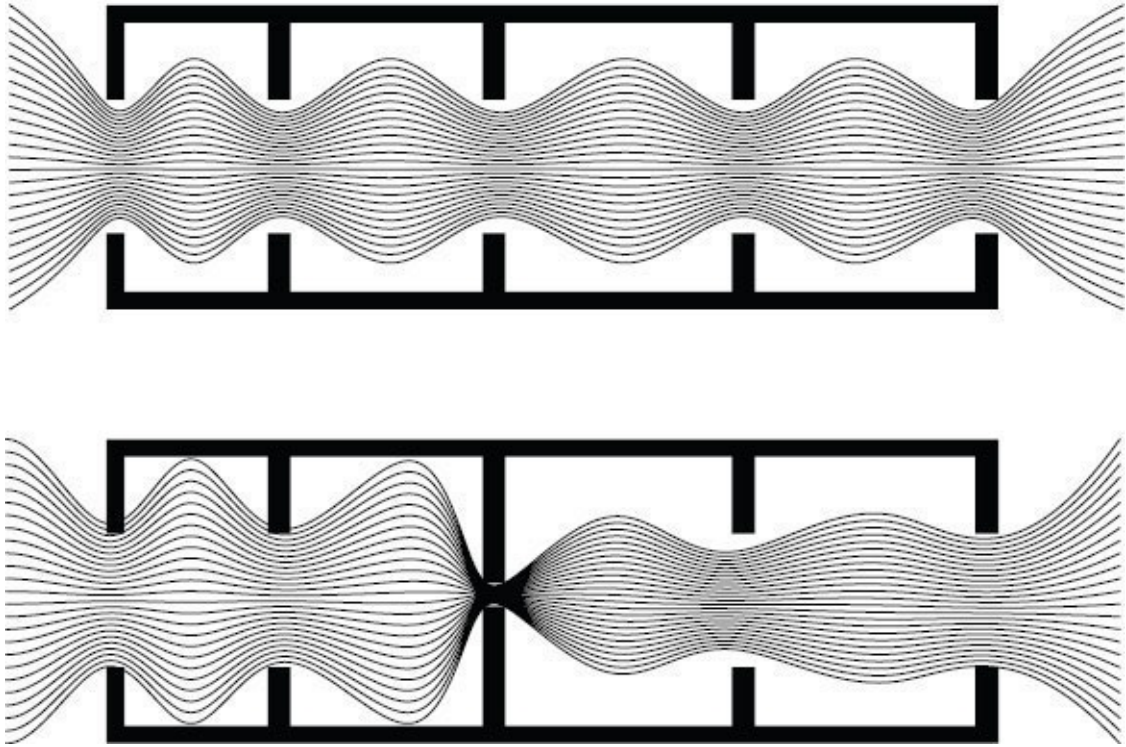


Figure 9.14

The smallest opening determines the overall air flow rate.

9.3 Façade Proportions and Window Ventilation Strategies

From an architectural perspective, the window is the most prominent compositional element in the building façade. Over the centuries it has developed multiple cultural values and functions. Louis Kahn (1901–1974) built a home for Mrs. Esherick in Chestnut Hill, Philadelphia, Pennsylvania in 1961 (already discussed in [Chapter 1](#)). In the Esherick House the windows are incorporated in a spatial strategy which combines cross- and stack ventilation. When a connecting double height space is incorporated in an all-encompassing volume, spatial continuity is achieved in a compact vertical and horizontal volumetric composition. Warm air rises by convection, enabling the stack effect owing to the high spatial volume. The higher the spaces, the further away the exhaust air is allowed to move from the comfort space of the inhabitants, and it gathers at the ceiling, where it can be exhausted. Wind can assist the stack effect.

This compositional strategy of ordering space and air is intentionally designed for natural ventilation, and the façade includes wooden shutters to modify the flow. These shutters also contribute to the compositional complexity of the façade, as they are set back in the volumetric surface. Thus the volume of the wall shades the surface of the shutter, while at the same time air velocity is increased by the bottleneck effect of the inlet points. To reduce heat gain, the sealed glass surfaces are shaded with exterior blinds.

Kahn's architecture has often been described as a spatial composition of volumes divided between server and served spaces. This analytical view indicates a distinction between the spaces with a controlled environment and those helping to enhance and control this environment. In the Esherick House, these distinct boundaries are not valid. Server and served space are one and the same, because the spaces of the house are

designed to enhance natural ventilation. The spatial composition explores the connection of two single spaces and one double height space incorporated within a compact volume, which in itself is subject to a complex geometric composition. In this house, structure, space, light, and vents are intertwined in the same volumetric composition, enhancing immaterial movements of air and light. The spatial envelope in the Esherick House mediates the flow of light and air in a very distinct way by changing the relationship between inside and outside.

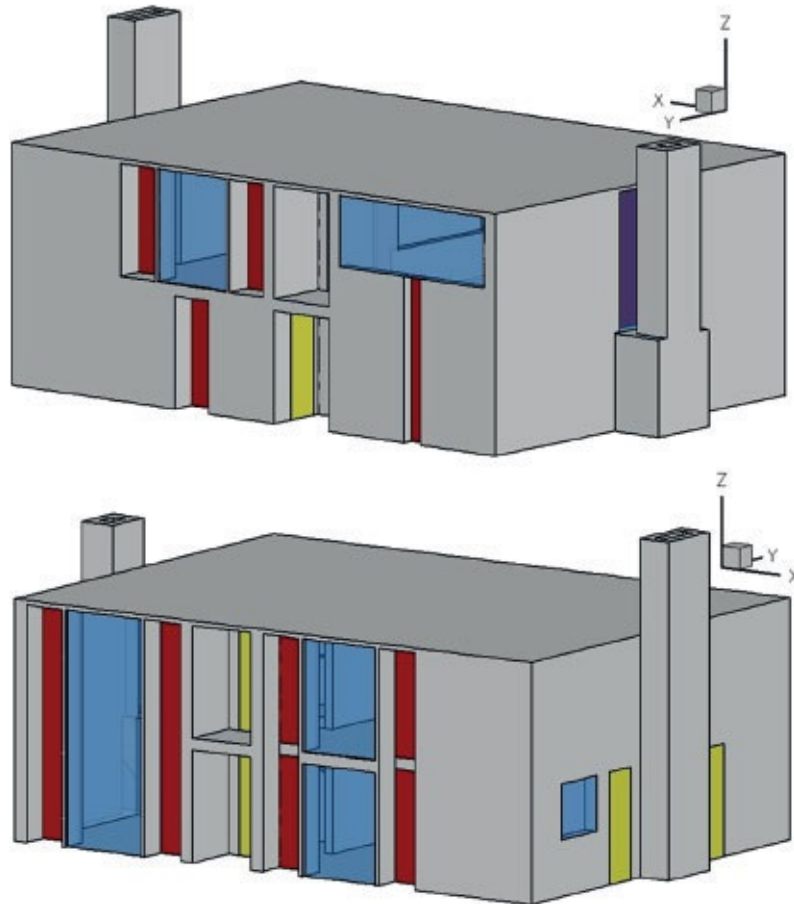


Figure 9.15

Esherick House façade with highlighted ventilation shutters.

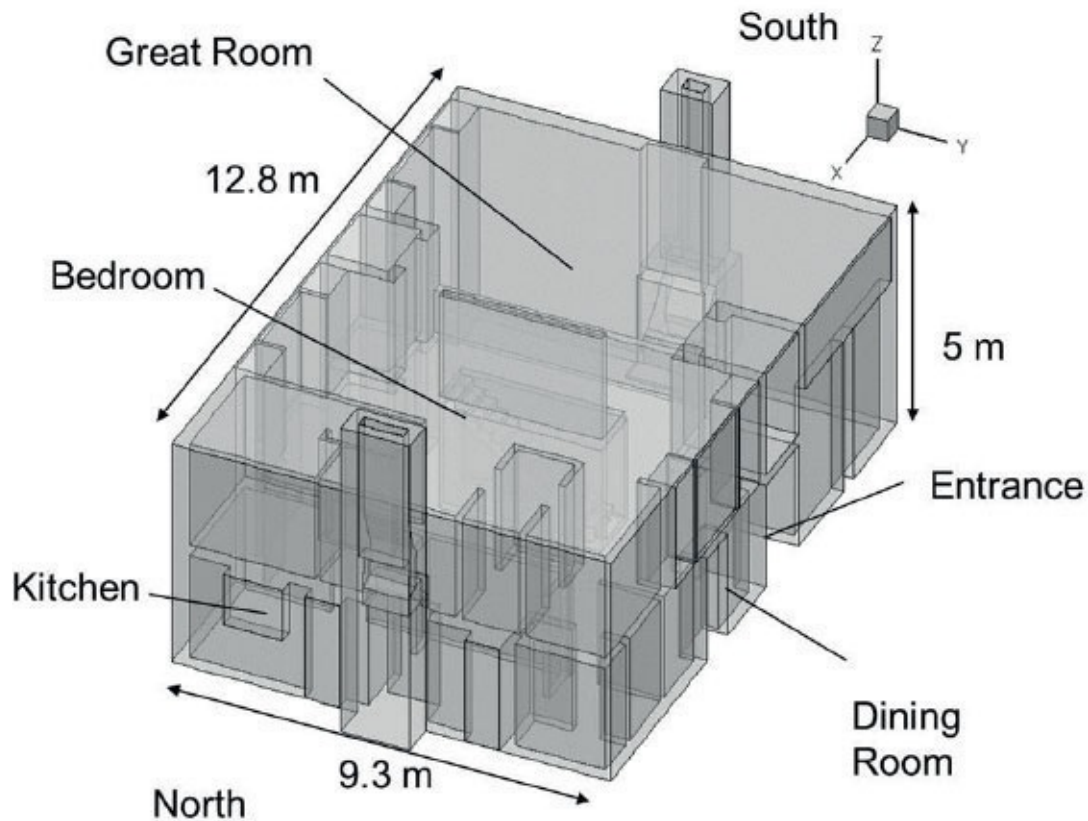


Figure 9.16

The spatial composition of the Esherick House juxtaposes a double height space with two single stories.

This example highlights the relationship between air flow and geometric proportions. Elements need to be determined by volumetric proportions, not by planar composition and numbers alone. Thus, for an analysis of air flow in the Esherick House the understanding of space needs to go beyond the obvious, established reading of the geometric composition of the house extensively described as complex planar geometry. Rykwert⁶ for example noted that the building is designed as a cubic volumetric composition of 9×9 (+1) modules with vertical proportions of $1 \times 2 \times 1$ and 2×2 modules.

Another architectural feature utilized to manipulate air movement in space is the size and placement of openings. A change in relationship between inlet and outlet openings has a tremendous impact on the velocity of air, allowing the manipulation of flow. In the Esherick House, openings for air and openings for light are designed not as one but as separate entities, which also enhances the changing relationship between interior and exterior, as shown in a related computational fluid dynamics (CFD) analysis of flow patterns inside the building.⁷

As Buttiker⁸ noted, closing the wooden shutters that act as ventilation openings hides the view to the garden and leads to a withdrawal into an inner world. In this scenario, only the clerestory window high up provides daylight and views to the sky. Opening the ventilation door relates the occupant back to the exterior view, offering the view of the garden, the weather, and the changing seasons. This situation enables the interior to be part of the greater flow of air. The house can thus be seen as a physical obstacle that distorts the laminar flow into unpredictable turbulence and eddies through and around the building.

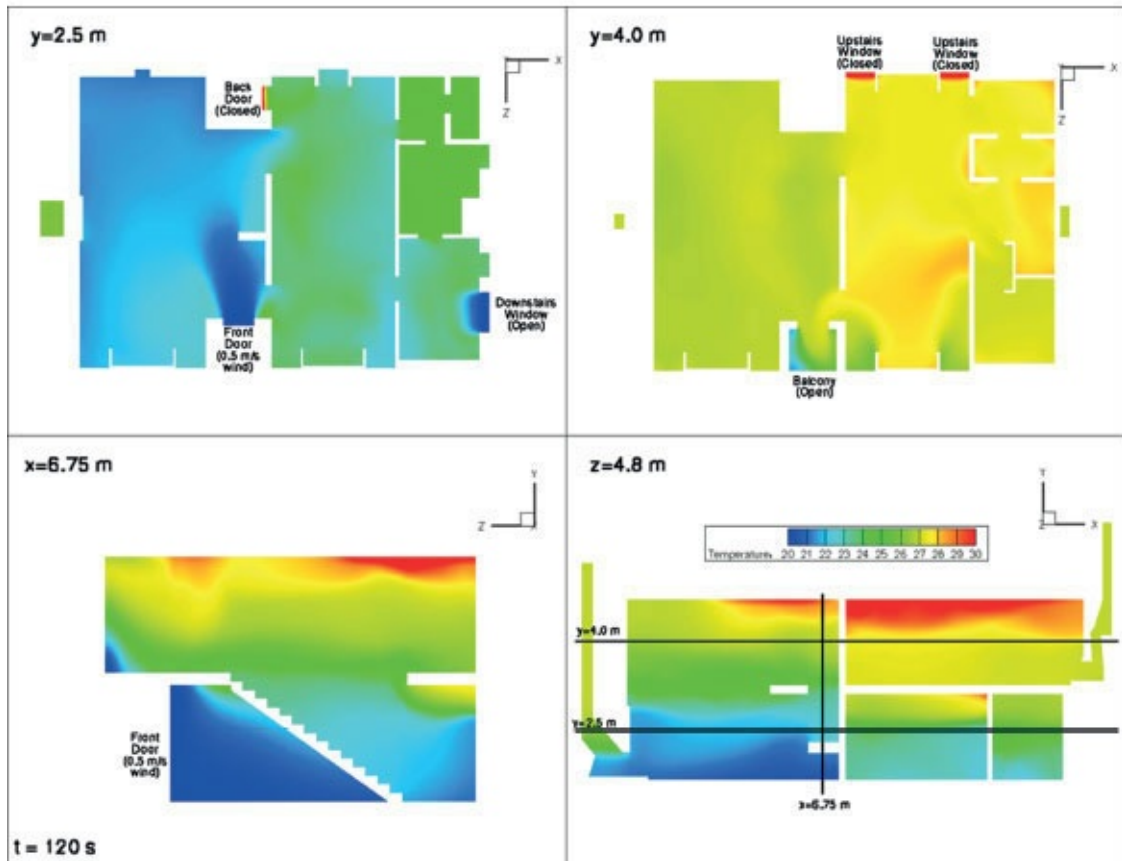


Figure 9.17

The CFD analysis of the Esherick House highlights the importance of the height of the space for cooling purposes.

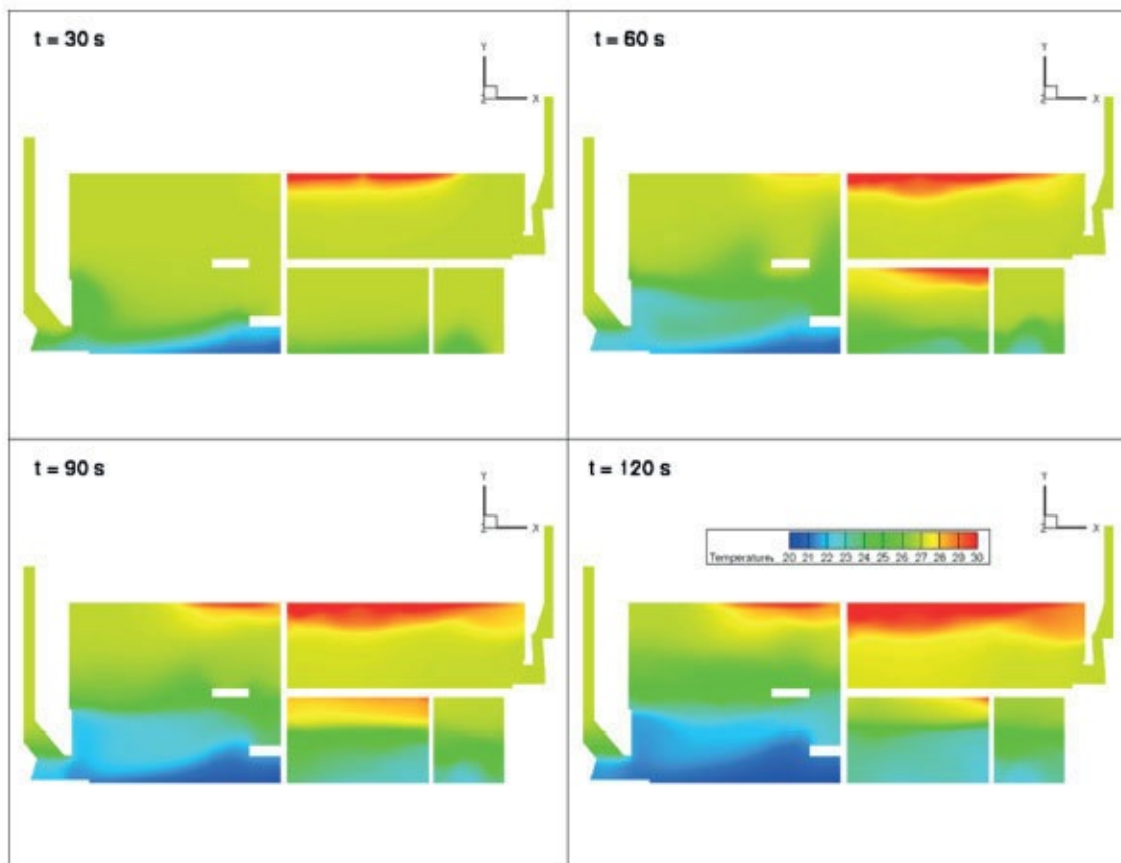


Figure 9.18

CFD analysis of the Esherick House: four time steps of cooling case.

9.4 Benefits of Double-Skin Façades in the Context of Natural Ventilation

Double-skin façades ensure noise insulation and security as well as reduced external wind velocity at the inlet. This strategy benefits high-rise buildings or buildings in the vicinity of windy coast lines, for example in a port location such as the current development in the HafenCity, Hamburg.⁹ Double-skin façades are best suited for urban environments, high-rise buildings, and coastal locations and can also be used as a retrofit. Shading devices can be integrated without danger of damage, because they can be introduced into the cavity between the two façade layers.

When designing double-skin façades, the stack height within the façade requires careful consideration to determine whether it can or cannot contribute to the ventilation strategy.



Figure 9.19

Double-skin façade in the Unilever Building in HafenCity Hamburg, Germany, where the single outer layer of plastic film clearly serves the purpose of slowing down the wind velocity at this windy location in the middle of the port at the Elbe river.

One of the first double-skin façades designed in the twentieth century is most likely the double-glass window in Alvar Aalto's Paimio sanatorium in Finland. The two panes of glass acted as ventilation inlet in order to reduce the velocity of air and to pre-warm the air, and avoid draught for the occupant in the custom-designed patient room (see [Figure 3.5, Chapter 3](#)).

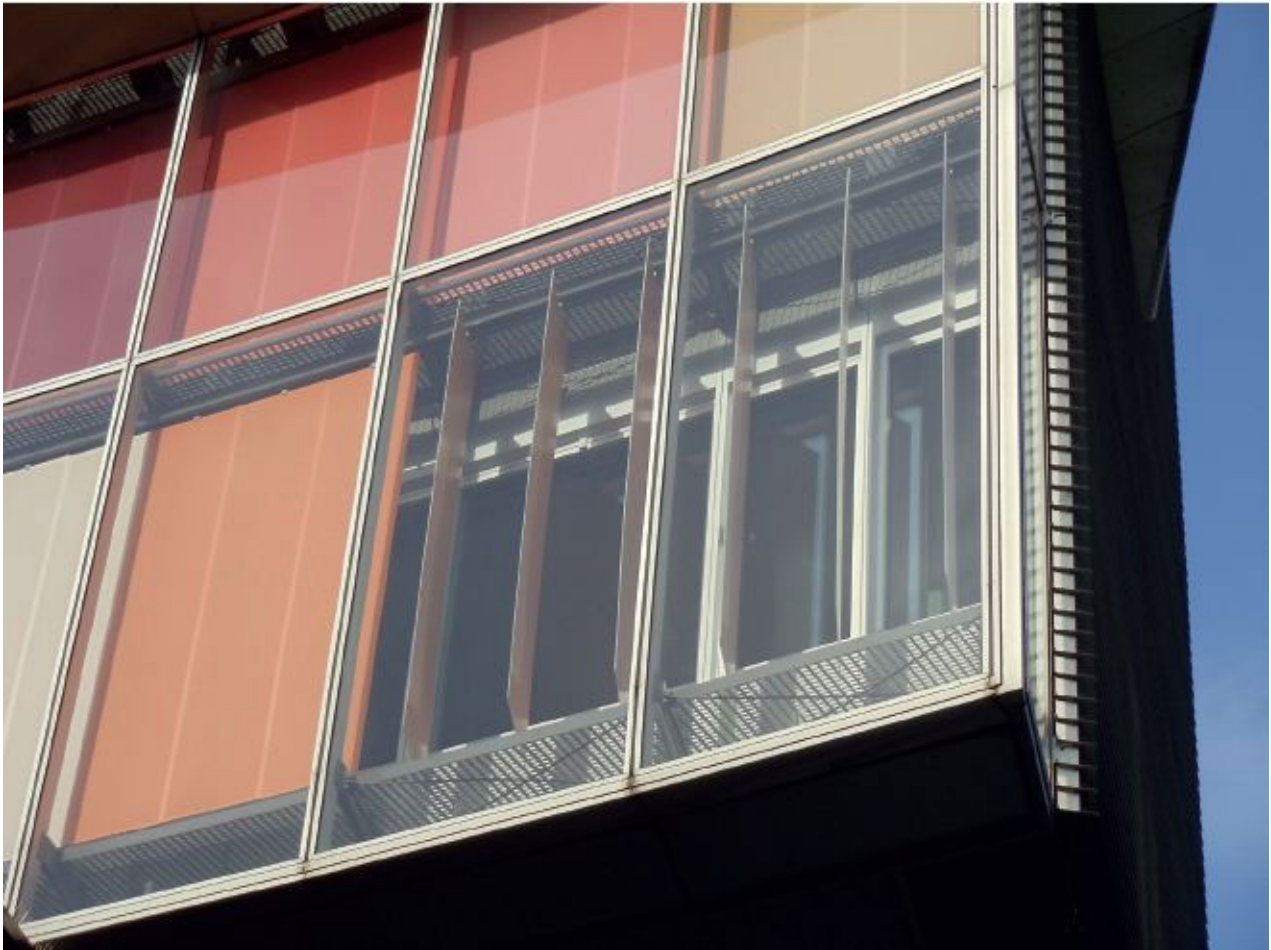


Figure 9.20

The double glass façade of the GSW building in Berlin facilitates the cross-ventilation by providing a stack.

9.5 Innovations: Adaptive and Smart Skins for Air and Light

Adjustability, interactivity, and adaptability to changing demands and conditions around a ventilation opening has been a goal both in recent high-tech and in historical low-tech approaches. In some examples, even the direction in which the ventilation window opens matters. The air flow pattern changes depending on whether the window opens towards the interior or towards the exterior. Thus, it is only a short step to consider the whole façade as a potential ventilation opening, offering flexible variations to let air in or to block it, and to even channel or modify the air flow direction and its speed. Current research and development directions are manifold. For example, research teams are

examining materials that can react to environmental changes in order to alter the composition of the façade, such as bi-metal strip façades that can react to solar radiation, temperature, and/or wind. Yet, contemporary developments are often representational and artistic representations rather than functional, showcasing the turbulence of the wind across the façade instead of utilizing them. Kinetic architecture often uses wind as a motor, motivator, or actuator for a visual representation of wind, but these devices very rarely act as ventilation elements at inlet or outlet locations.

The ‘Tower of the Wind’ by Toyo Ito in Tokyo is a sculpture visualizing wind and sound carried by wind, and most air bubbles, such as the water pavilion by the Dutch firm NOX, are architecture made of air, but usually not naturally ventilated spaces.

Innovative research in this area is conducted by, for example, CASE, the Center for Architecture Science and Ecology, a joint research program by the Rensselaer Polytechnic Institute (RPI) and the architecture firm Skidmore Owings Merrill (SOM).¹⁰

Latest CFD simulation research on façade design and composition draws from experiences of kinetic movement of marine mammals such as whales. Counterintuitively to common thought, rough edges on their flippers seem to reduce turbulence around them and increase the animals’ ability to speed up in water. According to simulations at the Technical University (TU) Delft,¹¹ manipulation of the surface roughness of the façade through kinetic adaptation enhances the air flow related characteristics of the building. High-rise buildings could change pressure differentials in the façade to influence the air velocity through the building. This theoretical project was presented in a research paper, which stated, “roughness elements located on the building envelope are (considered) able to modify the velocity field close to the façade; this modification has an effect on the natural ventilation and, primarily, on the heat exchange due to the wind convection.”¹¹

Most discussions on the relationship between a building and its air flow environment considered the large-scale level of the building itself, where the form and position of the building divides the flow and creates a pressure differential around the building. This novel adaptive concept, presented in a theoretical aerodynamics research project, suggested the manipulation of the building’s surface roughness at the level of the openings, such as with balconies, overhangs, recesses, or even at the level of the material and the surface texture.

As Lingnarolo and his team write:

External roughness elements, which are able to change orientation, can strongly modify the velocity field, for example, by making a more uniform pattern on the facade or canalizing the airflow and moving it in different zones. These external elements should be able to move and adjust themselves assuming different apertures and directions in different areas of the building façade according to the wind characteristic and the current needs (e.g. cooling energy demand).¹¹

They continue that

the aerodynamic and hydrodynamic characteristics of a smooth body are not

necessarily better than the ones of a rough body, as it could be naturally expected based on normally anticipated physical phenomenon. Surface roughness does indeed increase the friction between the flow and body, but it has also a positive influence on other phenomena.¹¹

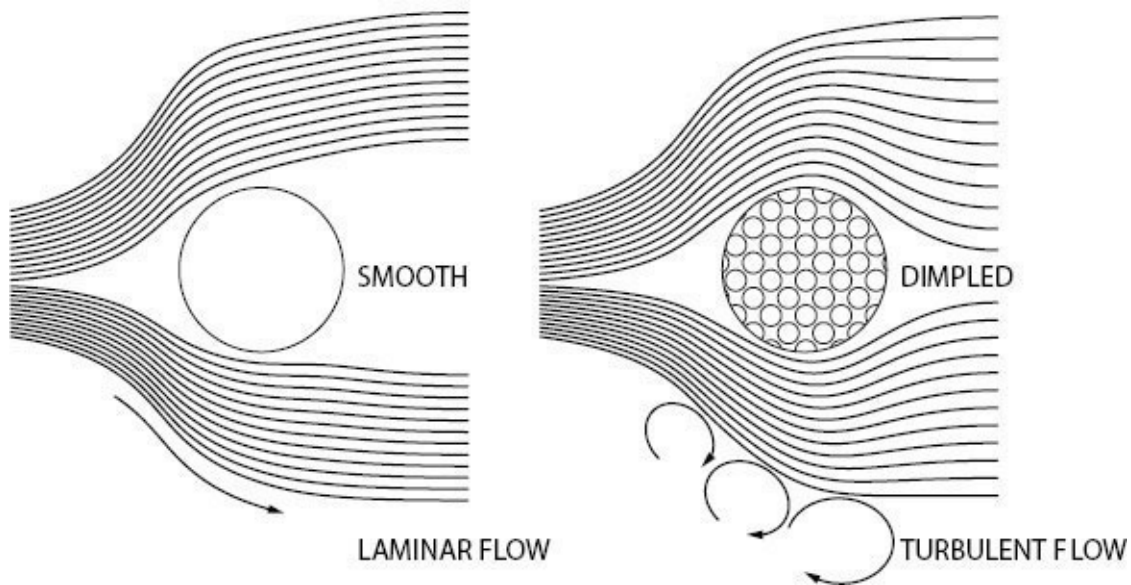


Figure 9.21

The texture of a golf ball facilitates its movement through air by reducing the resistance of air against its flow.

There are other examples of rough surfaces increasing speed in some objects, such as golf balls.

The dimples on the surface of a golf ball cause the air flow on the upstream side of the ball to transit from laminar to turbulent. The turbulent boundary layer is able to remain attached to the surface of the ball much longer than a laminar boundary and so creates a narrower, low pressure, wake and hence less pressure drag. The reduction in pressure drag causes the ball to travel further.¹¹

The change in roughness on a building's surface can reduce drag around the building and reduce the flow velocity around high-rise buildings, which may create significant advantages in natural ventilation for high-rise buildings.

Balconies, for example, reduce the wind pressure across the flow path, as reported in the TU Delft project,¹¹ which investigated the application of the concept to a high-rise structure. Usually, the upper floors experience too high wind velocities for any natural ventilation strategy, which is often counteracted with a double façade. In this case, horizontal balcony-type façade elements as well as high fin-type elements were studied, and although the pressure field did not decrease significantly, the velocity field did decrease, which would have a significant impact on the capacity to conduct natural ventilation by opening windows.



Figure 9.22

Balconies or other elements on the outside of the façade act as roughness elements and can significantly alter the air velocity around a building.

9.6 Roof Ventilators, Coils, and Wind Catchers

Chimneys are a very common feature in historical buildings and sometimes even take over the complete formal appearance of the building, as in Sintra Palace (see [Figure 5.24](#)). The most important parameters for roof-integrated ventilation elements are their height and shape, which should be designed to enhance and even increase the flow rate over or through the device. The shape variety of historical wind catchers has been thoroughly studied by Sue Roaf,¹² who revealed a large array of options that also relate and showcase social status and cultural values (see [Chapter 5](#)).



Figure 9.23

This wind cowl at Nottingham Jubilee Campus is a good example of purposely designed devices enhancing natural ventilation.

Contemporary guidance can be found in the draught cooling sourcebook by Brian Ford *et al.*¹³ In order to keep elements small, internal and external heat gain should be kept as low as possible.

9.7 Roof Elements to Enhance Air Flow by the Venturi Effect

High over the skyline of Berlin towers the signature roofline of the GSW building by Sauerbruch and Hutton, headquarter of a communal housing association with a winged roof to enhance the stack ventilation in the double-skin façade on the western side of the high-rise building.¹⁴



Figure 9.24

The roof wing on the top of the GSW building in Berlin, Germany, increases the air velocity above the building and thus facilitates the ventilation drive in the stack façade on the west.

9.8 Louvers

Louvers for natural ventilation do not differ much in their exterior appearance from louvers used as air intakes in active ventilation systems. They can be very useful façade ventilation elements when large air change rates are required, for example for night ventilation. They also offer protection against rain and intruders, can integrate screens against all kinds of insects, and can even include filters against pollen.

9.9 Trickle Ventilation and Ventilation Skins

Trickle vents are purposefully designed devices that allow for constant air change rates, and a variety of systems is available on the market. They close when it rains, they filter against dust, and they can also attenuate noise.



Figure 9.25

A trickle vent acts like this fine meshed shading screen, which lets in air at a constant rate, but a very low velocity.



Figure 9.26

Window panes in historical palaces and villas in Goa, India, made from oyster shells filter light as well as air.

Such a breathing skin can be seen in the palaces of Goa, made from translucent hand-size oyster shells with gaps between the shells for air penetration. They represent a specific typology of trickle vents for a climate, in which temperatures never require heating. Here, glass adds unwanted heat gain and is not a necessity so that other forms of closure and closing mechanisms should be reinvented. In these historic residences of Goa, India, the oyster shells were used to filter the harsh daylight and provide continuous trickle ventilation.

Pietro della Valle, a seventeenth-century Italian traveler to Goa, the Portuguese colony on the Indian subcontinent, describes

the buildings of the city [of Goa] are good, large and convenient, contriv'd for the most part for the benefit of the wind and fresh Air, which is very necessary in regard of the great heats, and also for reception of the great Rains of the three months of Pansecal, which are June, July and August.¹⁵

Other architectural features of these buildings were high steep roofs, verandas, galleries, and porches, which also contributed to the ventilation and cooling for the interior.

The historical precedent given by the Goa palaces and the colonial architecture of Mumbai with its façades of movable and permeable elements were revived by Studio Mumbai in the Palmyra House and Utsav House (architects: Studio Mumbai; location: Satirje, Maharashtra, India; principal architect: Bijoy Jain; project team: Roy Katz, Jeevaram Suthar, Pandurang Malekar, Mangesh Mhatre; structural engineer: Dwijen

Bhatt).¹⁶ Studio Mumbai is a cooperative of architects and craftspeople founded by Bijoy Jain in Mumbai. This team combines design and craft of most of the components that go into their projects. This process allows for the designers to bring back traditional knowledge and typologies and avoid the use of mass-produced window products that are not well suited for the Indian climate. Both projects also show the traditional spatial composition needed for protection against rain and for air to flow through the very lightly constructed building.

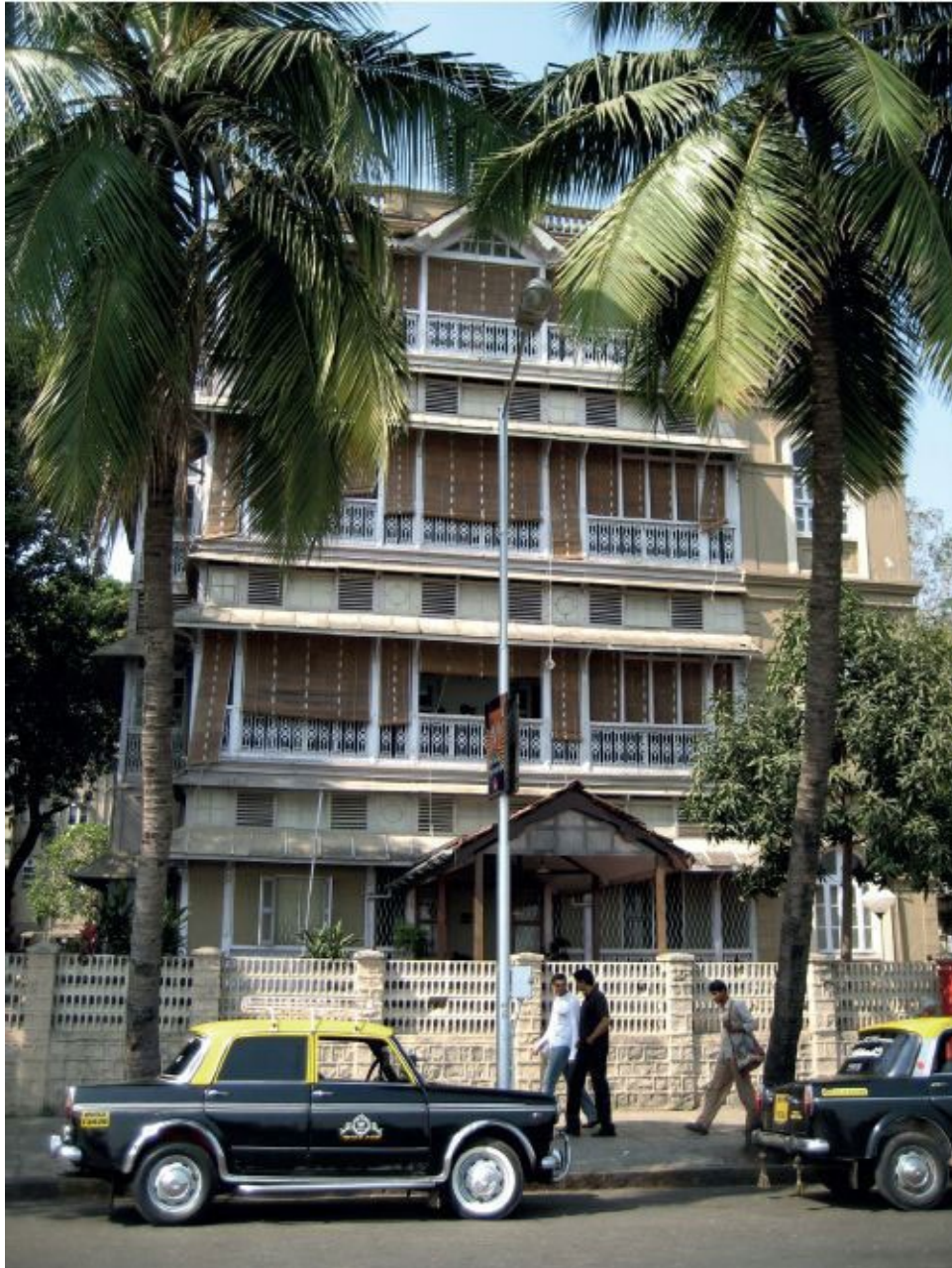


Figure 9.27

This street façade in Mumbai, India, completely made up of ventilation openings filters light as well as air.



Figure 9.28

A Mashrabia is a screen which does not allow a view into the interior of the building, but permits filtered light and air inside, as seen in this street façade in Mumbai, India.

Notes

- 1 “What Is the Origin of the Word Window?” *The Free Dictionary*, <http://www.thefreedictionary.com/window> (accessed 5/14/2014).
- 2 Ronald G. Knapp, *Chinese Houses: The Architectural Heritage of a Nation* (Singapore: Tuttle, 2005), p. 89.
- 3 C. Ghiaus, F. Allard, M. Santamouris, C. Georgakis, and F. Nicol, “Urban Environment Influence on Natural Ventilation Potential,” *Building and Environment*, 41(4), 2006, pp. 395–406.
- 4 M. Santamouris and Peter Wouters, *Building Ventilation: The State of the Art* (Sterling, VA: Routledge, 2006).
- 5 *Ibid.*, p. 224.
- 6 Joseph Rykwert, *Louis Kahn* (New York: Harry N. Abrams, 2001), pp. 53–54.
- 7 U. Passe, P. Stoakes, and F. Battaglia, “Interdisciplinary Research into the Fluid Dynamics of Natural Ventilation Flows,” in: *Healthy Buildings 2009: Proceedings of the 9th International Healthy Buildings Conference and Exhibition* (Syracuse, NY, USA), paper no. 226.
- 8 Urs Butiker, *Louis I. Kahn: Light and Space* (New York: Birkhaeuser, 1994), pp. 90–95.
- 9 *Hafencity Hamburg*, <http://www.hafencity.com/en/home.html> (accessed 5/14/2014).
- 10 Center for Architectural Science and Ecology, <http://www.arch.rpi.edu/2012/05/case/>.
- 11 Lorenzo Lignarolo, Charlotte Lelieveld, and Patrick Teuffel. “Shape Morphing Wind-Responsive Facade Systems Realized with Smart Materials,” in: *Adaptive Architecture Conference* (2011), pp. 3–5.
- 12 Elisabeth Beazley and Michael Harverson, *Living with the Desert: Working Buildings of the Iranian Plateau* (Warminster, UK: Aris and Phillips, 1982).
- 13 Brian Schiano-Phan, Rosa Francis, and Elizabeth Ford, *The Architecture & Engineering of Draught Cooling*:

A Design Sourcebook (PHDC Press, 2010).

- 14 Antony Salib and Ruba Wood, *Natural Ventilation in High-Rise Office Buildings*, CTBUH Technical Guides (New York: Routledge, 2013), p. 64.
- 15 Pietro Havers, G. Della Valle, and Edward Grey, *The Travels of Pietro Della Valle in India: From the Old English Translation of 1664*, translation G. Havers, 2 Vols (London: Printed for the Hakluyt Society, 1892).
- 16 Studio Mumbai, <http://www.studiomumbai.com/> (accessed 01/17/2015).

Chapter 10

Control of Natural Ventilation

10.1 Senses, Sensors, and their Controls

Wind chimes are mobile structures that indicate wind direction and air motion on front porches and back yards are common vernacular objects in many cultures. The American artist Alexander Calder (1898–1976) raised suspended, air-driven objects to a delicate art form. Jean Paul Sartre commented on Calder’s mobile sculptures in 1947¹: “They feed on air, they breathe, they borrow life from the vague life of atmosphere.”

Sensing wind as air movement is closely connected to the forecasting of weather and has a long-standing tradition in meteorology and atmospheric science.



Figure 10.1

Alexander Calder (1898–1976): Vertical Foliage. 1941. Sheet metal, wire, and paint, 157.5 × 167.6 × 142.2 cm.

The term *weatherlessness building* was coined by H. G. Wells in his 1933 novel *The Shape of Things to Come*. The sharp analysis by Ackermann² in her thesis indicated that Utopia had a homogenous, never changing, indifferent climate that would counteract the effects of weather on social movements of people, on behavior and clothing habits. She also analyzed the American fairs of the 1930s and 1940s as exhibitions for the heroic future of America, which advertised a new American society relieved of its weather constraints.³

This attitude and desire changed the building fabric in the USA to this day. Air-conditioning demanded closed windows, and because the only control was the human occupant, the windows were sealed. In the current twenty-first century, sensors for all impulses and senses are available and building control systems can be more receptive to switches between active mechanical systems and natural ventilation. In addition, a debate is needed about who should be in charge of the climate controls inside a building. The user can take more control.

10.1.1 Sensing Air Movement

Air is moving constantly, even if we as humans cannot always detect its movement with our most sensitive sensor, the skin. The major stimulus for sensation of air motion is its temperature as well as the velocity of its motion.

The most common way to sense air motion and the direction in which air is moving is known by every child. You take your finger and wet it with your tongue and hold it into the air. The direction of the wind can be felt on the side of the finger, which is now cooled by evaporation. This experiment (as already noted by Pettenkofer⁴) does not work as well in moist and humid air as it does in drier weather conditions.

Pettenkofer also already took note of the threshold of sensitivity of the human body to the sensation of air movement.⁵

The air in this room appears still, and yet it is in thousand-fold movement and ceaseless restlessness; but happily our nerves are not aware of this, just as a shortsighted person may deny the existence of some object, till his eyes get the assistance of a glass. Whoever of you would be able to feel or see all the movements of air in this room, would probably not be able to stand it. A correct idea may be formed about it by the action of smelling substances. If, for instance, an escape of gas were to take place in a remote corner of this room, you would become aware of it almost immediately all over the room. Our nerves are happily so organized, that they begin to feel the motion of the air only when it amounts to 31/4 feet per second.

10.1.2 Sensors for Air Motion

The wind direction has been determined since antiquity using a wind vane, a technique still in use today.

Anemometers are the instruments to measure wind and air movements. Wind velocity is usually measured by a cup anemometer, rotating cups mounted on a cross, first designed by Leon Battista Alberti (1404–1472). These rotating cups measure the wind speed according to the speed of rotation.

Measuring low speed air velocity and direction is a very awkward task, and because of the wind's volatility, reliable data are difficult to obtain. Some instruments measure actual air speed, others measure pressure, but as the two are related, one piece of information can be obtained from the other. Hot wire anemometers use a very thin hot wire to detect the velocity of air. Wind flowing over the hot wire has a cooling effect, and because every metal has a resistance related to its temperature, this information can be converted into wind speed. Hot wire anemometers are extremely sensitive and can be used to measure complex turbulent flows.

Unfortunately, the simultaneous measurement of air direction and velocity is very complicated and demands costly ultrasonic sensors that measure the time of sonic pulses between two transducers.



Figure 10.2

The wind vane and cup anemometer as part of the weather station at Iowa State University's energy efficiency research laboratory: the Interlock House.

10.1.2.1 The Tower of the Winds, Vatican

While the ancient Greek Tower of the Winds in Athens did not actually measure wind, but time, as described by Vitruvius,⁶ the Torre dei Venti in the Vatican provided the Vatican with one of the first sophisticated weather stations to measure wind direction. Ottaviano Mascherino (1536–1606) constructed the Torre dei Venti on top of the Vatican library. It contained a large wind rose and anemometer in the ceiling designed by Ignazio Danti (1536–1586) as well as the meridian that was used to install the Gregorian calendar.⁷ Through a complex mechanical mechanism, the movement of the weather vane was translated onto a rotating hand that moved across a painted wind rose created by Nicolo Circignani (c. 1517/1524–after 1596) with the allegories of the four seasons connecting time and wind. The whole ceiling was taken up by this gigantic wind clock, which was connected to the wind vane by clogged gears.⁸

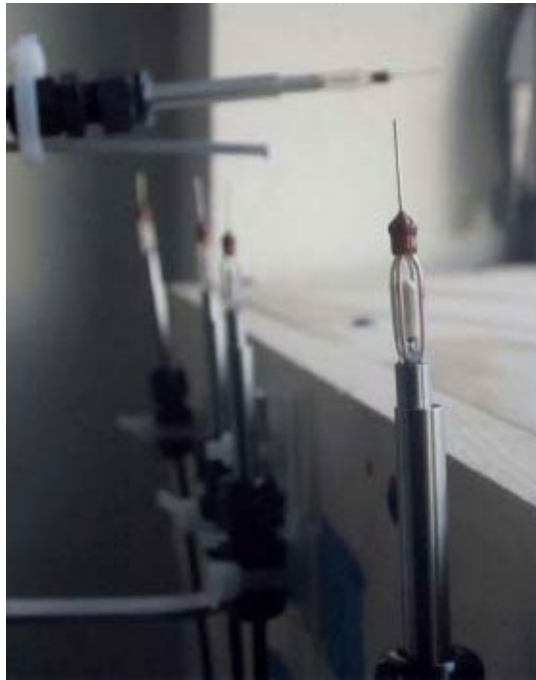


Figure 10.3

A hot wire anemometer detects wind velocity and directions.

10.1.2.2 Age of Air

Ideally the flow path for the fresh, incoming air should be directed so that the fresh air reaches the heads of the occupants first before being diluted with the ‘older’ room air, and exhaust air should leave the room as directly as possible before it is mixed with the incoming fresh air. In order to extract toxic pollutants in research labs, exhaust hoods are placed right at the source. The same strategy is most often used in kitchens large and small to exhaust fumes when cooking. One measurement to control the functioning of a ventilation strategy is the evaluation of the ‘age of air.’ Ideally, the air entering the room reaches all occupants at the same time, which is usually not possible, for example when one person sits next to the window and another closer to the interior of the building. In order to measure the age of air, that is, the time it takes for the air inside a space to change with the required air change rate, the air entering a room can be marked with a tracer gas, which allows measuring the concentration and distribution of this gas in certain locations. The time it takes from the insertion of the tracer gas into the air to the measurement location is defined as the age of the air. The measurement of the age of air is important to determine the capability of the ventilation strategy in terms of mixing and/or diluting or displacing the room air with fresh, incoming air.



Figure 10.4

The wind vane in the Sala Meridiana of the Torre dei Venti situated on the top of the Secret Archive of the Vatican connects to a ceiling fresco and an interior wind dial.

A term used by air quality experts to evaluate a strategy is the ‘air change efficiency.’ This term indicates the time it takes to replace air in a room. According to Roulet,⁹ the efficiency tells us how the fresh air is distributed in a given space. For displacement or piston-type ventilation, where the room air is displaced from below with 100 percent fresh air, the efficiency is equal to one. In other words, all fresh air entering a space moves through the space to the outlet at the same time. With full mixing, the efficiency will be 50 percent, and when dead zones remain, in which the air is allowed to age, the efficiency will be even more reduced. Inefficient air flow paths create short cuts, which means that the fresh air intake and exhaust are too close together so that fresh air can leave right away without affecting exchange, thus ‘wasting’ the air. Twenty-five percent efficiency would then be considered a poor performance, because that would indicate that ten percent of the air at the exhaust is older than three times the time it took the earliest air to exit.

Smoke tests are used to qualitatively (visually) determine the direction from which air enters or leaves a space.



Figure 10.5

Wind direction can be detected with a smoke pen, as shown here during an experiment at the Iowa NSF EPSCoR community lab, the Interlock House, originally constructed as Iowa State University's 2009 entry for the U.S. DOE Solar Decathlon competition.

How can designers evaluate the age of air in their design strategy when deciding on a flow path and opening strategy?

10.1.3 Actuators

An actuator is comparable to a motor that sets a device in motion. They can be operated by electrical energy or by hydraulic or pneumatic pressure and convert that energy into motion, driving the opening element. Windows and vents operate on hinges, push-pull pistons, chains, gears, motors, hydraulics, levers, and multiple other means.¹⁰ Control strategies need to consider the activation mechanism as well as the weight of the window or vent. Push, pull, flip, and rotation are the major movements. Operation of actuators is automated by a control algorithm, which can be challenging to program. Ideally, an actuator should serve only one vent or window, but often multiple windows are linked and controlled jointly by one actuator.



Figure 10.6

The windows in the Bauhaus lined up in a band are all operated by one joint actuator.

10.1.4 Controls

Because of the dynamic nature of the external resources for natural ventilation, control mechanisms are necessary in most cases. They can range from manual control, which usually means that the occupant gets up and opens or closes the window, to complete automated controls, and every stage of override in between. Often controls also need to be installed to enable other functions of the building: inlets and outlets need to be closed when driving rain is expected, when winds are so high that building components can be harmed, and when it gets too cold or too hot. Control strategies for natural ventilation also include the operation of elements that reduce or increase heat gain depending on the season. Solar blinds need to be pulled or drawn to reduce heat gain. Many research studies show the importance of proper and complex controls, while most thermostats only use temperature as an indicator.¹¹ But temperature may not always be enough to account for all variables. Occupancy control through motion sensor or CO₂ levels only provides one indicator (increase in occupancy). It does not necessarily tell anything about the actual air quality.

The interaction of operation choices with external forces such as rain, hail, snow, and high winds has to be programmed.

Control strategies are complex scenarios even if, at this point, most systems only

operate in an on/off mode, which means that the actuators are programmed to either open or close the vent individually or to open or close a bank of vents at the same time.

The placement of the sensors that control the actuators is another highly important decision to be made. A sensor driving a ventilation system should never be placed into a hot spot or direct sunlight. If no good placement for a sensor can be found, the control strategy can also rely on a schedule or an occupancy sensor to activate the vents.

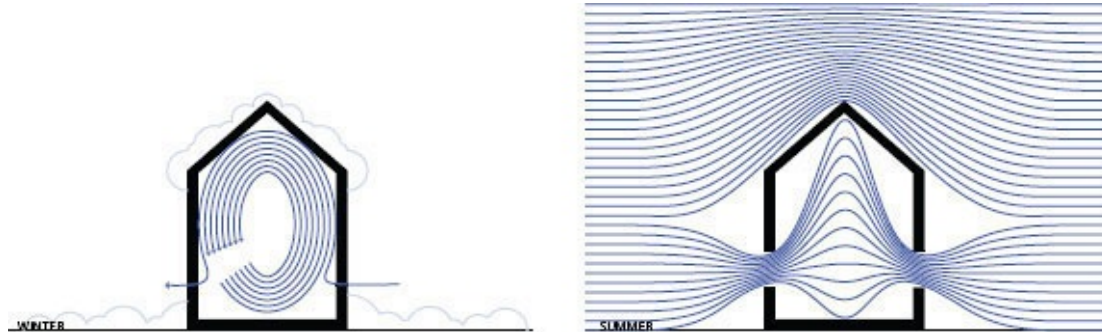


Figure 10.7

The control algorithms for summer and winter ventilation need adjustment for different opening sizes.

Currently, most controls are connected to more or less automated building management systems (BMS), which can operate vents and dampers. Downdraughts in vent stacks, which indicate a reversal of the stack flow, can be identified by temperature sensors within the stack or atrium.

10.1.4.1 Occupants and Controls

Buildings that open or close vents or blinds without input from occupants can be a nightmare for the users. Users in buildings with automated controls may feel like Charlie Chaplin in *Modern Times* or Jacques Tati in *Playtime*, where machines or buildings take over the controls from the occupants. The ‘uncontrollable’ control system can be the worst annoyance for occupants and architects alike. Achieving usability of building systems is rarely a successful endeavor. However, neither can the completely manually operated building fulfill all needs. Today, usually compromises in the form of automated control systems that can always be overridden by occupants are the best systems available, but many issues still need to be addressed to improve the balance between occupant desire, tolerance, and air quality and energy use on the other hand.

Occupants have a certain level of tolerance to discomfort and often ‘good enough’ is satisfactory before a change is requested, either by getting up and opening or closing a window or by changing a thermostat setting, or even by calling maintenance, which obviously demands higher discomfort and is connected to real perceived dissatisfaction with the given situation. Usually, occupants choose the easiest path to address discomfort: they will choose the simplest, most convenient, and most accessible solution to their discomfort, as noted in the CIBSE manual.¹² In hybrid mode, the user will switch to automated mode when the operable window is too far away and very rarely will an occupant act in anticipation of a change in their environmental condition; thus they will only close the window once it already has become cold.

Automated control strategies, which are often perceived as capricious, can make occupants angry, as noted by the CIBSE manual,¹² mainly because of the interruption the action causes in their daily routine and often because moving parts for vents and blinds tend to be noisy and interrupt the current ongoing activity. Research has also shown that occupants will make changes to reduce discomfort, but will not turn things back again, once the discomfort has discontinued, which will leave windows open, lights on, or blinds down for longer than necessary, not to mention other mishaps.

10.1.4.2 Predictive Controls

The famous hockey player Wayne Gretsky once said, “I skate to where the puck is going to be, not where it has been.”¹³ In order to best balance human thermal comfort and energy efficiency, it can be beneficial to skate to where the puck is going to be, which means that the control strategy for a building should anticipate future changes. The set points for the heating and cooling of a building are determined by several factors, including natural and engineered factors. Anticipation of the sign, magnitude, and future trend of natural heating and cooling would provide some clue about where, left to itself, the “puck is going to be.” This information, along with interior data, can be used to suggest adjustments to aid in passive heating or cooling.

Mathematically we can describe the indoor heating rate of a building in a simplistic way by:

$$\frac{\partial T_i}{\partial t} = H + \alpha \frac{\partial T_o}{\partial t} + \beta \frac{\partial R}{\partial t} + \gamma \frac{\partial W}{\partial t}$$

where $\frac{\partial T_i}{\partial t}$ is the rate of change of indoor air temperature with time, H is the engineered rate of heat applied (or extracted), $\frac{\partial T_o}{\partial t}$ is the rate of change of outside temperature, $\frac{\partial R_o}{\partial t}$ is the rate of change of external radiative heating, and $\frac{\partial W}{\partial t}$ is the rate of change of wind speed. α , β , and γ are constants relating to the response time (thermal mass) of the building to changes, in outside air temperature, radiative heat loss or gain, and wind-driven change of building heat loss or gain. These constants can be determined experimentally.

In a simple control scenario, we want to keep the indoor temperature constant: $\frac{\partial T_i}{\partial t} = 0$. This leads to an expression for the rate of heat that needs to be applied to keep the temperature constant.

$$H = -\alpha \frac{\partial T_o}{\partial t} - \beta \frac{\partial R}{\partial t} - \gamma \frac{\partial W}{\partial t}$$

In reactive mode, the engineered response adds or takes away heat in reaction to changes in T_i . In anticipatory mode, T_i will remain constant because H will match the anticipated (forecasted) changes in T_o , R , and W . In principle, this leads to better regulation of indoor temperature (presumably greater comfort), and in some cases will prevent overshooting of the engineered response to changing indoor temperature when external factors were about to reverse the natural heating rates. Implementing this strategy requires measurement of

the unknown constants and access to a forecast of outside temperature, radiant heat, and windspeed over the time horizon dictated by the measured constants.

Novel developments in computation algorithms give rise to new control opportunities, called model predictive controls (MPC), which can base their control strategies on occupancy schedules and weather forecast and thus can anticipate a needed change. They drive the controls of a building's thermal condition based not only on temperature set points, but also on anticipated dynamic changes; for example, their control strategies are driven based on weather or occupancy forecasts so that changes do not occur only when the trigger has been reached, but occur prior to this point so that the uncomfortable situation is actually avoided completely.¹⁴ MPC strategies take uncertainty and dynamic conditions into account and can “evaluate a tradeoff between energy savings and thermal comfort.”¹⁵ Unfortunately, these are decisions that users often cannot make for themselves without additional information which also has an effect, such as utility costs or weather forecast.

In natural ventilation cases, MPC works well when coupled with thermal mass; for example, when a really hot day is expected the next day, the air change rate for night ventilation can be increased to cool down the mass of the building more than usual in order to create an even larger heat sink for the daytime heat gain. MPC will also prevent the active cooling from kicking in at the end of a hot day for just an hour or so, when the night conditions will allow for heat removal without additional energy consumption.

10.1.4.3 Airtightness and Infiltration

The creation of an airtight building envelope is an often underestimated contributor to a good natural ventilation strategy. Buildings with high infiltration rates can often not build up the pressure differential needed for the demanded exchange rate. In addition, they can divert air away from the designed flow path. High levels of infiltration may also lead to higher energy consumption in order to condition the cool or warm air seeping into the occupied spaces. Infiltration can also cause draught, condensation, and mold growth within the building envelope, which in turn affects air quality.



Figure 10.8

A commercially available blower door test kit was used to test the airtightness of the Iowa NSF EPSCoR Interlock House.

A common method to test the airtightness of a building envelope and its systems is the so-called *blower door test*, where one opening in the building is equipped with an exhaust fan that pulls out air at a certain pressure and measures the rate of replacement. Most commonly, the air change rate through infiltration is measured at a constant pressure of 50 Pa produced by an exhaust fan. All other windows need to be closed. In such a scenario, the air change can be measured and compared with the figures for other buildings for efficiency. If the ACH stays under 0.6 ACH at 50 Pa, PassivHaus Standard is achieved.¹⁶

An airtight building is thus a construction-based control strategy to obtain well-performing natural ventilation flow regimes and precise air change rates.

10.1.4.4 User Interaction and Overriding Controls

According to many research studies, user satisfaction is one major advantage of natural ventilation because users are in control of most natural ventilation building control strategies, or at least in most cases there is an override strategy so that users can directly react to a draught, chill, or overheating. Low-tech natural ventilation systems, especially in the residential context, are usually user controlled. Most important for occupant-driven control is that the occupants are well informed about the control strategies necessary to keep them comfortable. If energy efficiency is a common goal, occupants will also need to know how their actions will relate to higher energy bills. It has been recorded in research case studies¹⁷ that occupants are actually quite considerate with energy and operate

mechanical systems sparingly, if they have the choice, especially if they have to pay the bills themselves. This interaction becomes even more critical in hybrid situations, when users can also interact with the active system for an advanced hybrid mode situation.

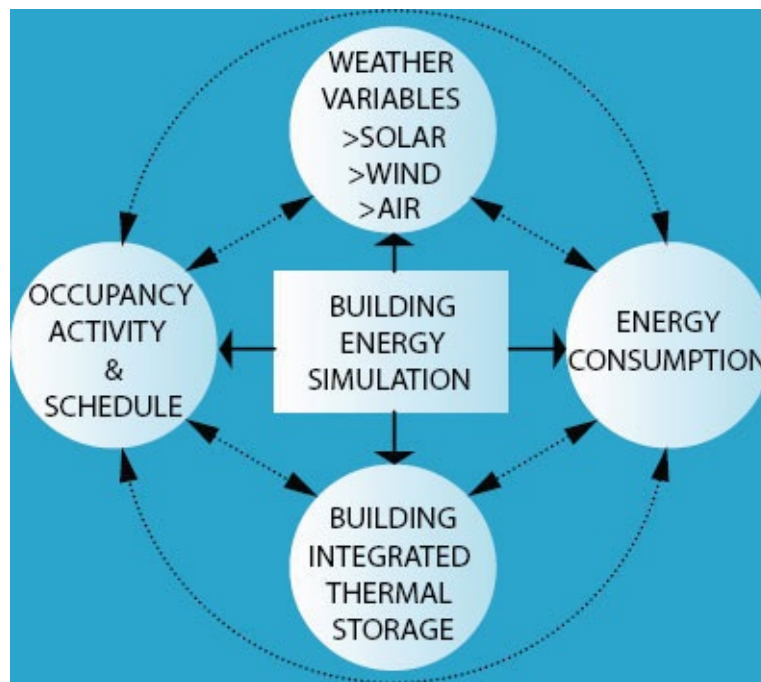


Figure 10.9

Advanced control systems need to adjust for the interaction and feedback loop between complex parameters.

10.2 Distinct Natural Ventilation Strategies

Reyner Banham's¹⁸ famous parable of the two savage tribes is an appropriate introduction to this section, which will cover nighttime ventilation and thermal mass (see Figure 5.1). The tribes arrive at "an evening-campsite and find it well supplied with fallen timber." The timber could either be used as a wind-break, which Banham calls the structural solution, or burned for a fire, which he calls the power-operated solution. "An ideal tribe of noble rationalists would consider the amount of wood available and make an estimate of the probable weather for the night – wet, windy, or cold, and dispose of its timber resources accordingly." Most real tribes would do none of that, he says, but would either build a fire or build a structure, depending on the knowledge passed down from their ancestors. Because most pre-technological societies had very limited combustible materials available (especially prior to the extraction of oil), their architecture was dominated by heavy, massive constructions to mitigate the external climate. The only civilization that developed based on the power-operative mode is the modern North American civilization, which still constructs very lightweight structures to this day and conditions them with the support of abundant energy.

10.2.1 Cooling the Structure: Nighttime Ventilation

Entering a massive stone building in Rome during the summer will be a memory for ever; here, the thick stone walls radiate the cool temperature of the winter and the heat of the summer never penetrates the full depth of the material.

Nighttime ventilation is a very common and successful natural cooling strategy, which includes the activation of thermal mass in a building. Cooling the mass in the building down to a temperature below comfort zone temperature during cool summer nights provides a heat sink for the thermal energy gathered during the day. Usually, natural ventilation is the driving force and large volumes of air flush the building through two or more large openings. Nighttime ventilation takes advantage of high thermal mass inside the building and low outside air temperatures. During the time when the building is not occupied at night, the cooler air is flushed into the interior and directed over the mass surface to cool it down, so that it becomes a heat sink during the day. The advantages of nighttime ventilation are that:

- The building fabric is cooler during the day, which influences thermal comfort owing to the mean radiant temperature effect on the occupants' bodies.
- Internal peak temperatures will be reduced, because first the fabric of the building (its thermal mass) will store the thermal energy of internal gains as well as potential solar gains.
- Peak temperatures are shifted to the later times of the day and internal peaks are shifted in comparison to external peaks.
- Reduced internal air temperature is achieved throughout the day, thus reducing or even eliminating the need for active mechanical cooling.

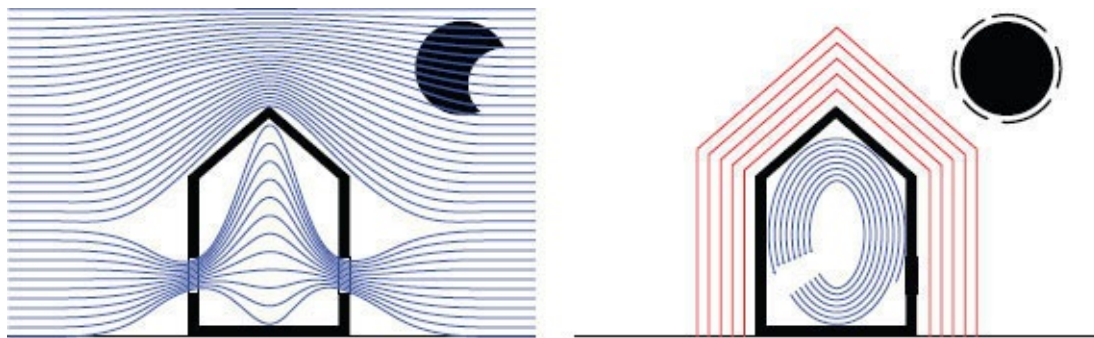


Figure 10.10

Night flush ventilation cools down the thermal mass of the building interior with cool night air and demands the closure of windows during the day.

The quantitative calculation method is fairly simple. The heat capacity of the thermal mass needs to be determined as well as the hourly temperature difference in order to calculate the overall thermal mass required for natural ventilation.¹⁹

Temperature swing and time lag of thermal energy storage are the key factors to be included in the quantification of nighttime cooling.

10.2.1.1 Nighttime Ventilation Case Study: The Paul Wunderlich Haus

In the Paul Wunderlich Haus in Eberswalde, Germany, designed by GAP,²⁰ one of the most sustainable buildings currently existing in Germany, nighttime ventilation is utilized. This building is a very good example of current best practice of energy-efficient construction. The most important feature of the building is a highly insulated building

envelope, with a 40 percent window to wall ratio and triple-pane glazing reducing heat gains in summer and heat losses in winter. The building combines active ventilation and thermal active surfaces with night flush ventilation for cooling, at a time when the building is unoccupied. The energy concept is well integrated into the architectural concept and layout of the four building parts on site. Natural ventilation is coupled well with daylighting strategies in the offices as well as in the major conference room for the county council.

The climate in Eberswalde is temperate and thus cool nights in summer are most common. Humidity levels in summer are also moderate. Thus night air can be used most of the summer to cool large parts of the building to an agreeable daily comfort range without any added mechanical cooling.

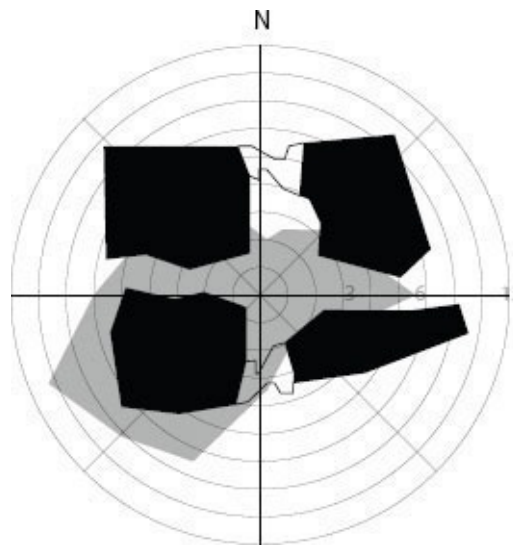


Figure 10.11

The Paul Wunderlich Haus in Eberswalde, Germany, as it sits inside the prevailing wind direction, utilizes operable windows for cross-ventilation and night flush cooling. (In m/s.)

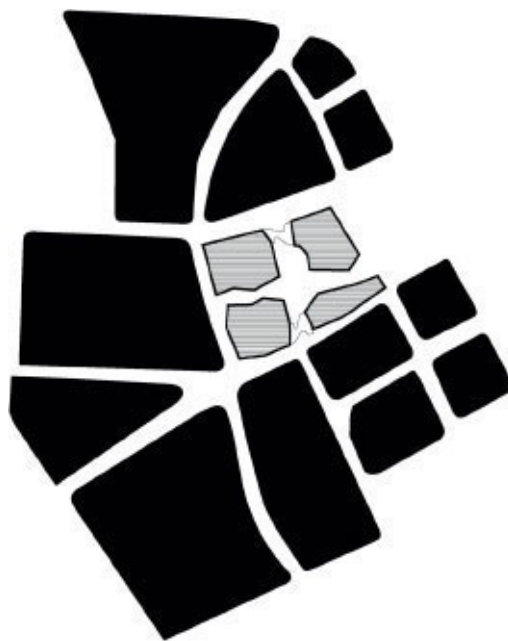


Figure 10.12

Site plan of the Paul Wunderlich Haus in Eberswalde, Germany.

The building complex is composed of four separate parts, each with fairly similar layouts of offices around a combined zone surrounding a courtyard. The assembly hall is day-lit from above. Every office has operable windows, and there is a controlled air change rate with combined heat recovery ventilation.



Figure 10.13

The courtyard between the four buildings connected to form the Paul Wunderlich Haus.

One invisible feature of the construction is the extreme airtight building envelope and exposed concrete slabs for night flush cooling. Phase change materials are also added to store latent heat.

Ground coupled heat pumps are added through energy piles in the ground for summer cooling and winter heating through heat exchange.

The night flush strategy can be identified as direct night ventilation,²¹ where the natural flow of air cools the mass of the building. The high heat capacity of the mass allows the building fabric to absorb the heat gains during the day, which will prevent the air from warming up. Air will only start warming once the mass has warmed. Three years of monitoring the energy balance of the building revealed that ventilation provided close to 50 percent of the cooling energy.¹⁹

The long-term monitoring also revealed another interesting challenge that resonates with other responses to night cooled buildings: the morning temperatures were sometimes considered too chilly by occupants and thus the full cooling potential of the thermal mass was not utilized.

Cooling capacity beyond natural night flush cooling is mainly used for server rooms and high occupancy loads.

Limitations for night flush ventilation cooling strategies are warm nights as experienced in urban centers, because of the heat island effect and lower wind speed in the urban canyon. Eberswalde on the other hand is a small town with plenty of potential to cool down at night. Nighttime cooling-potential maps are being developed (see [Figure 4.15](#)).



Figure 10.14

The entrance space to the Paul Wunderlich Haus.

10.2.1.2 Materials for Thermal Mass in Nighttime Cooling

The most common materials used as thermal mass obviously are heavy weight structural materials in the building interior, which have a high heat capacity and store a large amount of thermal energy without creating a temperature increase in the volume of air in the room. Exposed concrete slabs and walls are thus often encountered in buildings designed with nighttime cooling concepts. A new development in recent years is the use of so-called ‘phase change materials’ (PCM) as temporary thermal energy storage integrated in the building.

10.3 Limitations of Natural Ventilations

Limitations to the application of natural ventilation can be grouped in multiple categories. The first challenges are based on the lack of available natural resources in the urban or rural environment. Others are related to the interior requirements for natural ventilation and open connection to the outdoors.

10.3.1 Climatic Limitations

High summer temperatures above the adaptive comfort zone threshold can limit the cooling effect of outside air for cross- and single-sided ventilation. In locations with high outdoor summer temperatures, nighttime ventilation may be the only option for wind-induced air movement. In such a scenario, daytime ventilation should be reduced to the minimum required by IEQ standards.

Lack of sufficient diurnal temperature swing can severely reduce the opportunity for

night ventilation using thermal mass. In some locations, night temperatures only drop in the early morning and thus the time to cool down the necessary mass before occupants arrive back in the morning may be too short. High humidity levels are often considered an obstacle, but they only seem to be detrimental in climate scenarios in which wind velocity is very low.

Extreme cold winter temperatures require preheating of ventilation air in order to save heating energy, which can be achieved passively through doubleskin façades. This strategy has already been used by Alvar Aalto at Paimio sanatorium (see [Chapter 3](#)) and is now adapted with ventilated sunspaces, Trombe walls, or transpired heat collecting façades, which has been tested at the new National Renewable Energy Laboratory (NREL) office building in Golden, Colorado.²² Active preheating of ventilation air can be accomplished with air-to-air heat exchangers. Night ventilation in winter should be avoided, and the building envelope should be extremely airtight.

Low external wind velocity cannot be increased inside of a building, and thus opportunities for cross-ventilation strategies in the dense urban context can be very limited. Therefore, stack ventilation or wind catcher strategies have seen increasing applications in dense urban contexts.

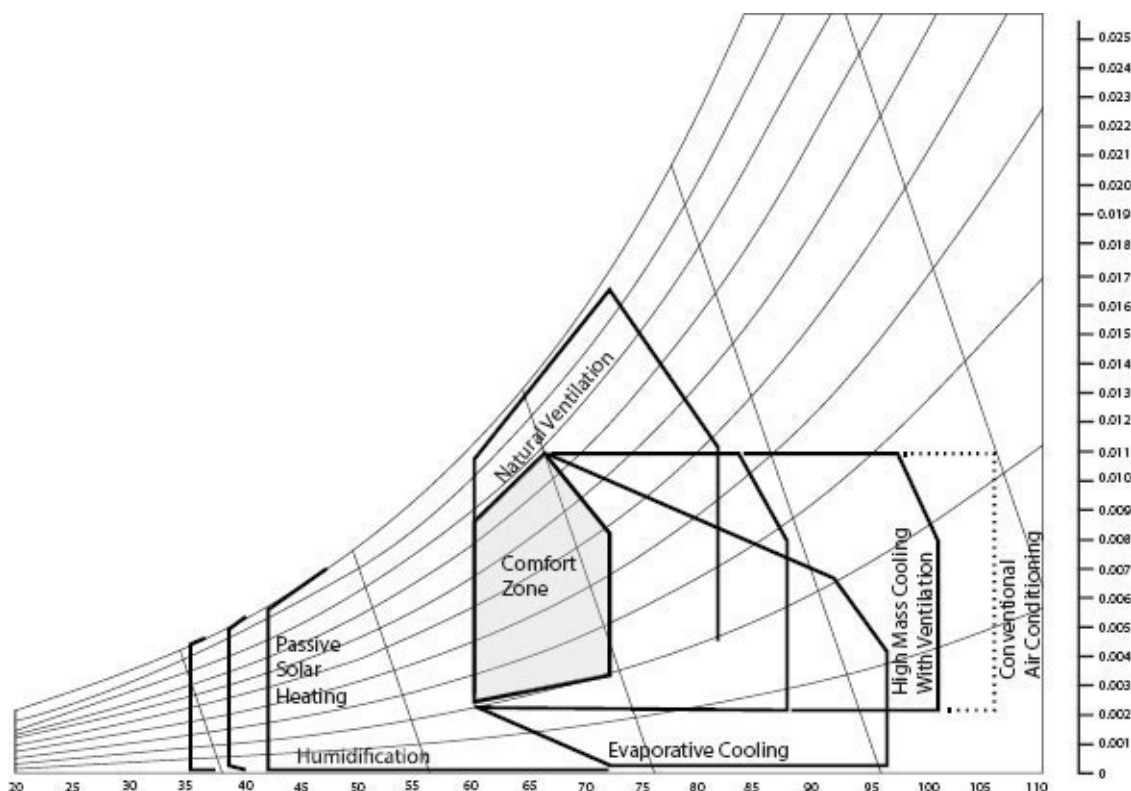


Figure 10.15

The bioclimatic chart showing the climatic limitations for natural ventilation strategies.¹⁹

10.3.2 Acoustic Challenges

The second group of challenges for natural ventilation strategies is related to outside threats resulting from the much more intense interconnectivity between indoor and outdoor air. Those challenges can derive from outside driving rain or snow, mosquitoes or other insects, and outside noise.

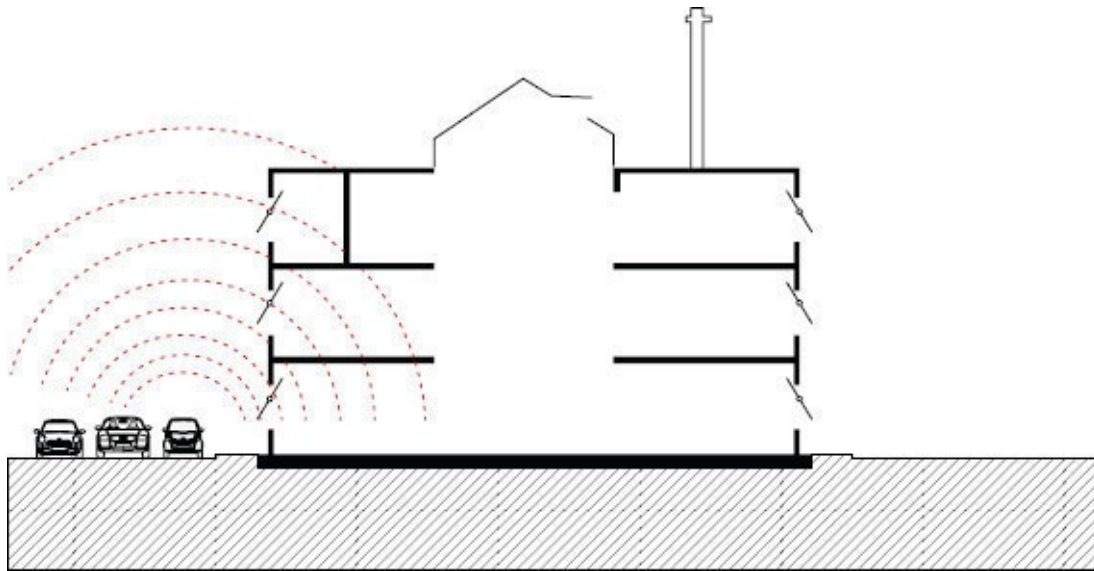


Figure 10.16

Acoustic buffering is necessary when the ventilation inlet is situated close to streets with high traffic or other sources of disturbing noise.

High levels of thermal mass in the form of open concrete ceilings or floors can also lower the acoustic quality of a building. Acoustic attenuation should therefore be an integral part of any natural ventilation strategy. This can come in the form of wall and ceiling panels or furniture. Acoustic challenges related to the required space connectivity across the building can be counteracted by the layout of functions, the placement of inlets and outlets, heavy sound-proofed windows, buffering materials, and landscaping in the vicinity of the air intake and exhaust.

10.3.3 Issues with Noise and Pollution

Obviously outside noise and pollution are major concerns in the urban context as well as in specific locations with detrimental outside conditions when integrating natural ventilation strategies into a building. Thus, operable windows and vents should always be placed strategically. But when occupants are afraid of intruders, they will not leave windows open, so perceived security concerns can also lead to reduced ventilation effectiveness.

Pollution should be reduced at the source, which is often easier said than done. Non-VOC paint and carpets, less glue, less formaldehyde, non-smoking policies, localized exhaust strategies, and other strategies are policies to reduce interior-based pollution. Reduced car exhaust can be achieved through speed limits or the promotion of electric cars. On a larger scale, urban planning and zoning strategies can limit polluting industries to certain areas of the city or distribute them on the wind-opposite side of the city.



Figure 10.17

The vents at the Judson University Harm A. Weber Academic Center are directed towards the north side and the parking lot.

Building zoning strategies can also help prevent local pollution. For example, a loading dock should not be located next to the ventilation inlets. Ventilation inlets should not be located next to a parking lot. Unfortunately, louvers and vents are often considered aesthetically unattractive and are thus banned from the ‘front’ façade.

10.3.4 Issues of Risk and Life Safety for Open-Plan Spaces and Stack Atria

Open-plan architecture needed for a continuous flow path through a building can pose severe safety and fire risks as well as transport noise and sound across buildings and thus impair quality of life, safety, privacy, and environmental quality. Vertical stacks are great to promote air change rates, but they also promote the spread of fire and smoke. Vertical fire and smoke spread in particular needs to be restricted, which poses a conflict in vertically connected spaces needed for stack effect ventilation. Fire and safety risks need to be carefully evaluated during egress planning and modeling. Smoke exhausts as well as movable fire blankets or walls are usually required. Atrium spaces will need to be separated in case of a fire. Thus, movable fire walls are requested in most locations by fire marshals in order to prevent the spread of smoke and fire before granting building permits for naturally ventilated buildings.

Double-skin façades, which continue along the complete height of a building, pose similar risks of fire and smoke spread, and many permit jurisdictions require sealable dampers between every level. In some instances, glass or window sprinkler systems have been installed to prevent fire spread without the inclusion of fire rated glass. Each naturally ventilated building, especially on a larger scale, thus requires a very careful evaluation of the risk of fire and smoke spread and demands a closely integrated design strategy overseen by ventilation engineers, designers, and fire safety experts on the team.



Figure 10.18

Open atrium spaces, for example here in the Unilever House Hamburg by Behnisch & Behnisch, require specific protective elements against fire and smoke.

Operable windows on lower floors certainly create safety and sometimes privacy issues and have not been allowed on the lower five floors of the San Francisco Federal Administration Building; however, they have been acceptable on upper levels.



Figure 10.19

The Federal Building in San Francisco by Morphosis requires operable windows and solar protective screens, but only on upper floors.

10.3.5 Screens, Louvers, and Shades

Any kind of screen for insects, security, or privacy will automatically increase the need for overall opening size. Insect screens provide an interesting problem, as their influence on the air change rate changes with the distance between the screen and the ventilation inlet.

A recent computational research study²³ showed that insect screens have a strong influence on the air flow rate of windward inlet openings, while they have hardly any influence on the leeward outflow rate and thus the opening size.

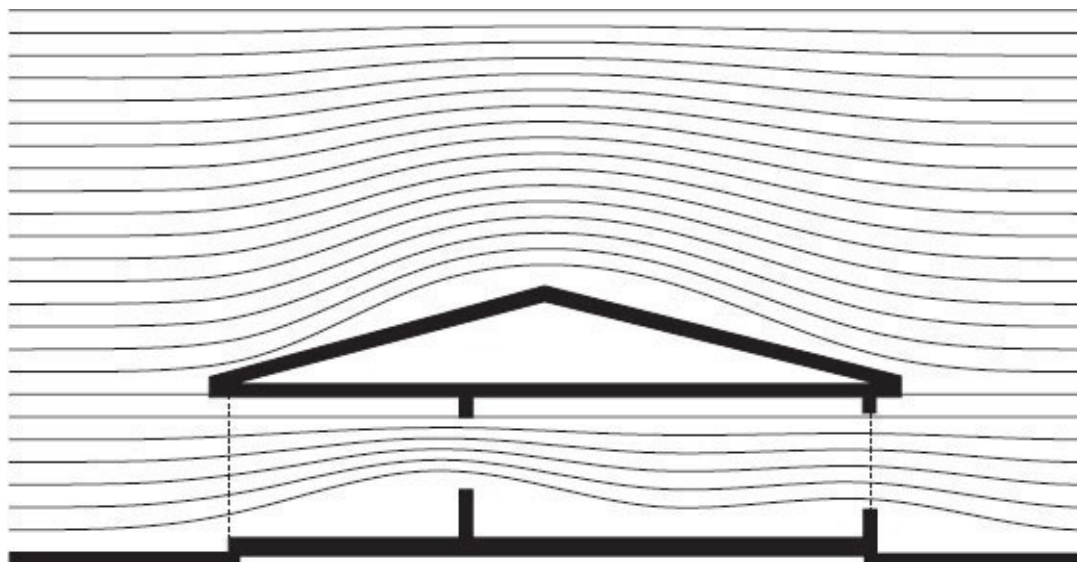


Figure 10.20

The distance between mosquito screen and inlet window as in a Midwestern porch is important to mediate the reduced air flow rate through the screen.

The air intakes for the Judson College Harm A. Weber Library Building are equipped with large areas of insect screens and thus had to be sized significantly larger than necessary without screens.²⁴ In some intake locations, the mesh is folded in a zigzag shape in order to increase the intake area.

Notes

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Making Air Visible – Complex Science Summarized for Architects and Designers

Chapter 11

Overview of Methods for Calculation and Simulation

The most common approaches to study ventilation include small- and full-scale experiments, empirical models, analytical models, multi-zone models, zonal models, and computational fluid dynamics (CFD) models. Experiments are the most costly approach, requiring specialized equipment and resources. Empirical models are developed using conservation equations and experimental data to provide simple relations. On the other hand, analytical models are derived from the same conservation equations but assumptions are used to obtain simplified equations. Alternatively, computational models can be used to calculate velocity, pressure, and heat transfer within a building, as well as help us visualize the air flow patterns. The computational approaches, in order of complexity, include multi-zone models, zonal models, and CFD.

Each of these approaches and methods has its merits and can be used to provide further insight into the complex dynamics of air flow and thermal interactions for natural ventilation applications. The aim of this chapter is to briefly present tools that are used to provide a more comprehensive understanding of air motion. The intention is to help guide the architect and designer with tools that will best meet their needs.

11.1 Experiments and Wind Tunnel Research

Experiments are a necessary tool to help determine the physics of air flow and provide measurements in terms of velocity and pressure. The effect of wind on building ventilation is greatly influenced by the building geometry and layout, as discussed in [Chapter 4](#). Ventilation is also influenced by the proximity of surrounding buildings, especially in heavily populated urban areas. Thus, experiments are constructed to determine the pressure differences that occur around a building. Thermocouples can also be instrumented to measure temperature changes that are complementary to the velocity and pressure measurements.

Small-scale experiments are used to model full-scale buildings; these are more economical and do not require large spaces to perform the experiments. The size of models can range from scales of $1/10^{\text{th}}$ to $1/100^{\text{th}}$ of the full building, or even smaller. In general, the data collected is limited to a small number of measurements and is susceptible to errors. One source of error is the use of probes or other intrusive devices that can disrupt the flow patterns. There is also error with the accuracy of the equipment and repeatability of the measurements. Although there might not be lots of experimental data, the value of the data can be seen in the literature as it is used to develop correlations.

Wind tunnel experiments are used to determine air flow within a naturally ventilated building. The approach is to place a small-scale model of a building in a wind tunnel and measure the air flow and pressure distributions around the building. Such tests can be

performed for a multitude of wind speeds and wind orientations to the building. The drawback is that the dynamics of the air flow within the building is not measured (and the use of CFD will provide such insight; see [Chapter 12](#)). The measurements can be used in the development and validation of other models, discussed in [Sections 11.2](#) and [11.3](#).

Wind tunnel data have an important role in understanding wind loads on building ventilation. The American Society of Civil Engineers has published standards and guidelines that provide best practices to conduct and interpret wind tunnel tests.¹ One of the difficulties with wind tunnel testing is creating a wind profile that represents the ambient air flow along the terrain that captures the boundary layer. The wind velocity profiles u can be written as a power law $u = Ay^n$, and are a function of the vertical direction y from a surface.² The constants A and n depend on the roughness of the terrain. To contrast the differences between terrains, typically values of n are 0.16 for flat open (country) terrain, 0.28 for suburban or wooded areas, and 0.4 for urban areas with high-rise buildings. Refer to [Section 7.3](#) for urban wind patterns.

There is also the issue of turbulence and replicating turbulent scales in a wind tunnel. The use of a mechanism to trip the air flow helps facilitate creating the appropriate turbulent structures that are present in atmospheric flows. Pressure probes affixed to the building provide measurements that are related to the upstream air flow pressure to determine pressure coefficients for a set of conditions (building geometry, wind speed, and wind orientation).

Although full-scale experiments are not common, there are a few studies related to natural ventilation that should be acknowledged. An excellent review of experimental techniques was provided by Hitchin and Wilson.³ Included in the review is a discussion of tracer gas techniques, citing advantages and disadvantages, anemometer techniques to measure air speed, and guidelines for scale-model measurements. One decade later, Cockroft and Robertson⁴ measured velocity for ventilation due to turbulent wind flow through a single opening and developed a simple analytical model to compare with the experiments. An almost full-scale study was performed by Lane-Serff *et al.*⁵ for stack flow in a single enclosure. The impressive study by Katayama *et al.*⁶ began with data collection of wind measurements for cross-ventilation of an existing five-story apartment complex during a three-week period in the summer. They further investigated the cross-ventilation using a 1/300th scaled model in a wind tunnel. While they did find consistency between the on-site measurements and wind tunnel measurements, differences were attributed to the turbulence of the actual wind-building conditions. Dascalaki *et al.*⁷ performed an extensive set of experiments to correlate their single-sided ventilation measurements with existing models. They concluded that discrepancies between the experiments and models were due to the importance of inertia forces relative to gravitational forces and proposed a correction factor. More recently, Carey and Etheridge⁸ investigated ventilation rates using direct wind tunnel modeling for three conditions: wind only, buoyancy only, and a combined wind-buoyancy flow.

It is worth noting that water tunnel tests have been used to study stackdriven ventilation.

The use of water instead of air is to ensure that buoyancy effects are properly captured. As will be discussed in [Section 11.2](#), non-dimensional parameters are used to preserve conditions between small- and full-scale flows, and this is particularly difficult with stack flow. The water tunnel experiments of Linden *et al.*⁹ for a small-scale model were used to compare with a full-scale building. The effects of wind were ignored and therefore results from the water tunnel experiments could be directly related to thermally driven flows, that is, buoyancy. The experiments introduced brine (a salt solution) into fresh water; when the two fluids interacted, the different fluid densities create a gradient identical to convection currents. A major result was that Linden *et al.* demonstrated that thermal stratification is due to the size of the ventilation openings and the thermal source.

The measurements obtained from small-scale experiments can be related to the actual (large-scale) scenarios using non-dimensional parameters that preserve similarity between the two systems. Parameters such as a Reynolds number (Re) or a Grashof number (Gr) can be used to relate velocity and heat transfer effects between two systems; however, care must be taken when selecting variables to non-dimensionalize. For example, the Reynolds number is defined as

$$\text{Re} = \frac{\rho V \ell}{\mu} \quad (11.1)$$

where V is the mean velocity, ℓ is a length scale and the fluid properties are density ρ and dynamic (absolute) viscosity μ .¹⁰ The ratio of the dynamic viscosity to the density is the kinematic viscosity, $\nu = \mu/\rho$. The velocity might characterize the wind speed (forced convection) or the mean flow velocity if buoyancy is dominant (free convection). The length scale could be the height of an opening or the length of a surface. Despite the choice of characteristic parameters, the interpretation of the Reynolds number is that it relates the inertia forces to the viscous forces. The Reynolds number also indicates if a flow is laminar or turbulent. For many flows, the critical Reynolds number for transition from laminar to turbulent flow is estimated between $\text{Re} = 2 \times 10^5$ to 3×10^6 because the transition varies from one problem or geometry to the next.¹⁰ Similarly, the Grashof number is

$$\text{Gr} = \frac{g \beta \Delta T \ell^3}{\nu^2} \quad (11.2)$$

where g is gravity, β is the thermal expansion coefficient that accounts for density and temperature changes (refer to [Section 11.3](#)), and ΔT is a temperature difference between an object (or surface) and ambient conditions.¹¹ The interpretation of the Grashof number is that it measures the ratio of buoyancy forces to viscous forces. The forced and free convection effects can be compared, and a rule of thumb is that when Gr/Re^2 is on the order of unity, both effects are important. If $\text{Gr}/\text{Re}^2 \ll 1$, buoyancy is negligible, and if $\text{Gr}/\text{Re}^2 \gg 1$, buoyancy is dominant.¹¹ To determine if a free convection flow is laminar or turbulent, the Rayleigh number (Ra) is used by combining the Grashof number and Prandtl number, $\text{Pr} = \nu/\alpha$

$$Ra = GrPr = \frac{g\beta\Delta T \ell^3}{\nu\alpha} \quad (11.3)$$

where α is the thermal diffusivity of the fluid. The Rayleigh number has a similar meaning to the Reynolds number. An estimate of when a buoyancy-driven flow might be turbulent is guided by $Ra \approx 10^9$.¹¹

When comparing different systems, defining a consistent set of characteristic parameters is important. A technique known as Buckingham pi theorem^{12, 13} helps maintain similitude and provides an eloquent way to determine the functionality of each variable of interest, such as velocity, pressure, and geometry. With a proper set of non-dimensional parameters, the full-scale system can provide insight into the size requirements of the small-scale model and the required flow conditions. It is important that similitude is maintained, otherwise the small-scale model may not exhibit the proper flow physics, especially when thermal changes are of interest. Although full-scale experiments are possible, they can be costly and require a large, dedicated, controlled environment to reduce error and unwanted conditions in the measurements.

Experiments are a valuable tool to help us understand the behavior of air movement, and pressure and temperature changes that persist in ventilation. The data are also useful to help create reduced models that provide trends and simple estimates for ventilation processes. The next section provides a few examples of how experiments are used to create simpler mathematical models.

11.2 Empirical and Analytical Models

Both empirical and analytical models are qualitative tools to help the architect and engineer determine ventilation performance for different building geometries and thermal conditions. The governing conservation equations for mass and energy (refer to [Section 11.3](#)) are the basis for developing empirical and analytical models. These models often appear to be the same approach, but the primary difference is in the process to reduce the governing equations to simplified forms.

Empirical models have functional forms that include constants and exponents specific to a set of experiments.¹⁴ The simplified models offer a general expression to correlate bulk conditions for velocity and temperature. Single-sided ventilation has received considerable attention, and the experimental work by de Gids and Phaff¹⁵ provides an empirical relationship for an effective velocity through a single opening that includes the velocity associated with stack flow, wind, and turbulence. They noted that the velocity profile depends on the more dominant force due either to wind velocity or to temperature difference. Using a full-scale outdoor experiment, de Gids and Phaff developed an expression for mean velocity U_m due to wind, stack, and turbulence effects based on pressure differences

$$U_m = \sqrt{2(\Delta p_{\text{wind}} + \Delta p_{\text{stack}} + \Delta p_{\text{turb}})/\rho}$$

and the pressure contributions were recast into a relationship of the form

$$U_m = \sqrt{C_1 U_{\text{wind}}^2 + C_2 H \Delta T + C_3} \quad (11.4)$$

where U_{wind} is the velocity from metrological data, H is the height of the opening and ΔT is the temperature difference. The constants were determined by fitting data from dozens of experiments, where the wind constant $C_1 = 0.001$, the buoyancy constant $C_2 = 0.0035$, and the turbulence constant $C_3 = 0.01$. Although this study is frequently referenced in the literature, the use of Equation 11.4 is limited because the constants are specific to the conditions of the experiment and the particular urban environment. More recently, Larsen and Heiselberg¹⁶ developed an empirical relationship that has a very similar form to Equation 11.4. However, they included the incident wind angle $f(\beta)$ and an explicit term for the measured pressure coefficients

$$U_m = \sqrt{C_1 f(\beta) |C_p| U_{\text{wind}}^2 + C_2 H \Delta T + C_3 \Delta C_{p,\text{open}} \Delta T / U_{\text{wind}}^2} \quad (11.5)$$

where $\Delta C_{p,\text{open}}$ is based on the pressure difference at the opening as a function of incident wind angle. For cases where wind-driven effects become dominant, Dascalaki *et al.*⁷ used experiments to develop a correction factor CF that is a function of the Grashof and Reynolds numbers

$$CF = 0.08 \left(\frac{Gr_H}{Re_D^2} \right)^{-0.38} \quad (11.6)$$

where H is the characteristic length corresponding to the opening height and D is the room depth. Thus, the characteristic lengths in Equations 11.1 and 11.2 are replaced with D and H , respectively. It is not within the scope of this book to present the numerous correlations that are in the literature, but there are many useful resources that provide recommendations for basic correlations.¹⁷

The development of analytical models incorporates assumptions that reduce the complicated forms of the partial differential governing equations (Section 11.3). Assumptions such as steady state and symmetry or one-dimensional flow greatly simplify the equations. An advantage of the analytical model is that it is not as restrictive as empirical models. In most cases, the solutions do not require significant computer resources.

One example relevant to natural ventilation is the development of an analytical model using Bernoulli's theory for a buoyancy-driven flow.¹⁸ The relationship provides a means to calculate the volumetric flowrate V as a function of temperature and geometry for single-sided ventilation through two openings:

$$\dot{V} = C_d A \sqrt{g H \Delta T / T} \quad (11.7)$$

where ΔT is the temperature difference between the outdoor (ambient) conditions T_∞ and the indoor temperature, H is the distance between the center of the openings of equal area A , and g is gravity. Equation 11.7 can be applied to single-sided ventilation through one opening such as a door where H is defined as the height of the opening. The contraction coefficient C_d (also known as the discharge coefficient) accounts for losses due to a

pressure drop as the flow travels through a constriction. The coefficient has been determined from experiments for different scenarios,¹⁸ and a value of 0.6 is often used when modeling flow through a doorway.

Another example of an analytical expression is the relation developed by Andersen¹⁹ for cross-ventilation in a room that is presumed fully mixed with a uniform indoor temperature T_{in} and a heat source. The relation for volume flow rate has the same form as Equation 11.7 but with different definitions for A and H . A reduced form of conservation of energy assumes that convection heat transfer Q_{conv} is due to a temperature difference and the bulk fluid motion¹¹

$$Q_{conv} = \rho \dot{V} c_p \Delta T \quad (11.8)$$

where c_p is the constant pressure specific heat. Equations 11.7 and 11.8 are combined with $\Delta T = T_{in} - T_{\infty}$ and the area A is dependent on the complex geometry of the cross-ventilation openings. The volume flow rate is written as

$$\dot{V} = (C_d A)^{2/3} (B/H)^{1/3} \quad (11.9)$$

where H is the vertical distance between the ventilation openings and $B = Q_{conv} g / (\rho c_p T_{\infty})$ is the buoyancy flux. Equation 11.9 can then be related to the volume flow rate of a buoyant plume in a heated uniform room developed by Morton *et al.*²⁰

$$\dot{V} = C (BH)^{1/3} z^{5/3} \quad (11.10)$$

where C is a function of domain conditions and z is the variable for vertical distance above the heat source. Li²¹ provides a comparative analysis of analytical models and discusses the applicability of the equations.

11.3 Computational Models

Computer models also provide details for the performance of ventilation strategies and air flow patterns. There are three basic models known as the multi-zone model, the zonal model, and computational fluid dynamics. Each model will be presented in some detail, with the last model being the focus of Chapter 12.

Multi-zone models provide an effective way to predict air exchange rates in buildings with and without mechanical systems for ventilation. Their purpose extends to prediction of ventilation efficiency and energy requirements, and there are models that incorporate the transport of species that represent pollution or smoke. The multi-zone models are based on the conservation equations for mass and energy but presume that the air is quiescent and therefore momentum effects are neglected. The models also assume uniform air temperature, which limits the predictive capabilities of thermal stratification. Thus, a room can be modeled as a homogenous environment and ventilation through a building can be predicted by connecting multiple zones, that is, rooms.

A few software tools have been developed by government offices such as the U.S.

Department of Energy (DOE) and the National Institute of Standards and Technology (NIST). The DOE tool EnergyPlus²² evaluates energy requirements, and heating and cooling loads necessary to achieve thermal comfort in whole buildings. It includes weather-based input, radiation and convection effects, and mass transfer models to predict moisture. EnergyPlus is a standalone simulation program that strictly reads input and writes output as text files and does not offer a graphical-user interface (GUI). The NIST tool CONTAM²³ is a multi-zone air flow and contaminant transport analysis program designed to determine indoor air quality and ventilation. It provides details for air flow and pressure through multiple rooms, infiltration, exfiltration, buoyancy effects due to temperature differences internal and external to the building, and the transport of contaminants. CONTAM can be coupled to CFD codes to provide input for detailed simulations of an internal zone. NIST has also developed LoopDA,²⁴ a design tool for natural ventilation that can determine the size of natural ventilation openings to provide air flow rates that satisfy ventilation and cooling load requirements. Another example of a multi-zone air flow model is the program Conjunction of Multizone Infiltration Specialists (COMIS).²⁵

A comprehensive overview of multi-zone modeling is offered in Ref.²⁶ although many multi-zone models were developed to predict the transport of contaminants.^{27,28} A recent study presents a multi-zone model program for natural ventilation (MMPN) that can predict wind and buoyancy effects.²⁹ Wang and Chen³⁰ evaluated the assumptions used in multi-zone models and reported guidelines to maintain accuracy.

For rooms or buildings where thermal stratification is prevalent, zonal models are used. Zonal models divide the room into zones so that temperature differences can be predicted. Although zonal models tend to provide more detailed information, they require more computational time to solve than multizone models. A limiting factor with zonal models is their ability to accurately predict wind-driven flows. A review of zonal models for indoor environments presents the latest developments.³¹ These models have incorporated more physics, such as moisture and pollutant transport. With increased computer speeds, zonal models can be solved for many zones and provide a solution that is similar to a lower accuracy CFD calculation that uses a very coarse grid resolution.

While all of these aforementioned methods are used to calculate ventilation conditions, CFD offers more complete details related to air flow, pressure, and temperature variations, as well as a means to visualize the conditions. In [Chapter 2](#), the physics of air flow is described for a general audience to explain terms that are commonly used by architects. The mathematical principles form a set of partial differential equations that describe the transport of a fluid. CFD is the numerical approach that solves for the dependent field variables of velocity, pressure, and temperature. The governing equations and models are presented next for those readers interested in the details.

The conservation equations are derived by considering a small volume of fluid and applying basic laws for mass, momentum, and energy.³² The equation for conservation of mass is

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{V}) = 0 \quad (11.11)$$

where t is time, V is the velocity vector, and ρ is the density. The physical interpretation of density is the mass per unit volume. The gradient Δ is a mathematical symbol to represent the spatial partial derivatives

$$\nabla = \frac{\partial}{\partial x} \hat{i} + \frac{\partial}{\partial y} \hat{j} + \frac{\partial}{\partial z} \hat{k}$$

where the gradient has been written in a Cartesian coordinate system. Equation 11.11 represents the change of fluid density over time and space as it moves.

Conservation of momentum is

$$\frac{\partial}{\partial t}(\rho \vec{V}) + \nabla \cdot (\rho \vec{V} \vec{V}) = -\nabla p + \nabla \cdot \vec{\tau} + \rho \vec{g} \quad (11.12)$$

where p is static pressure, $\vec{\tau}$ is the fluid stress tensor, and $\vec{g}$ is the gravitational force. The fluid stress tensor for a Newtonian fluid is

$$\vec{\tau} = \mu \left[(\nabla \vec{V} + \nabla \vec{V}^T) \right]$$

where μ is the fluid dynamic viscosity. The last term on the right hand side of Equation 11.12 represents the buoyancy force. The Boussinesq model is employed to solve for buoyancy effects and assumes that density can be treated as a constant except in the buoyancy force term. The approximation is only valid when temperature differences are small so that density variations are very small.³³ Relating changes of density and temperature, the thermal expansion coefficient, is defined as

$$\beta = -\frac{1}{\rho} \left(\frac{\partial \rho}{\partial T} \right)_p \approx -\frac{1}{\rho_0} \frac{\rho_0 - \rho}{T_0 - T} \quad (11.13)$$

and the subscript 0 represents the reference value. Rearranging Equation 11.13, the Boussinesq approximation can be represented as

$$(\rho_0 - \rho) \approx \rho_0 \beta (T - T_0) \quad (11.14)$$

Equation 11.14 is used to solve for ρ and substituted into the $\rho \vec{g}$ term of Equation 11.12. The other density terms in Equations 11.11 and 11.12 are constant equal to ρ_0 . Conservation of energy is written as

$$\frac{\partial}{\partial t}(\rho E) + \nabla \cdot [\vec{V}(\rho E + p)] = \nabla \cdot k_{\text{eff}} \nabla T + \nabla \cdot \left(\vec{\tau}_{\text{eff}} \cdot \vec{V} \right) + S_h \quad (11.15)$$

where E is total energy and k_{eff} represents the effective conductivity, which considers the turbulent thermal conductivity in addition to fluid thermal conductivity. Viscous heating is also included, which is the second term on the right-hand side of Equation 11.17. The last term models volumetric heat sources, if such conditions exist (e.g., heat loads).

The following chapter will outline steps to model and predict natural ventilation using

CFD. The flows are assumed incompressible and include buoyancy but neglect viscous heating. The form of the time-dependent, incompressible conservation equations are

$$\begin{aligned}\nabla \cdot \vec{V} &= 0 \\ \frac{\partial \vec{V}}{\partial t} + \vec{V} \cdot \nabla \vec{V} &= -\frac{1}{\rho_0} \nabla p + \frac{\mu}{\rho_0} \nabla^2 \vec{V} + \vec{g} - \beta(T - T_0) \vec{g} \\ \frac{\partial T}{\partial t} + \vec{V} \cdot \nabla T &= \frac{k_{\text{eff}}}{\rho_0 c_p} \nabla^2 T + \frac{1}{\rho_0 c_p} S_h\end{aligned}\quad (11.16)$$

Further details related to turbulence modeling will be explained in [Chapter 12](#) to complete the set of equations.

Computational fluid dynamics has been used to determine air flow patterns in and around buildings, as well as to assist in the design of ventilation systems.³⁴ Excellent reviews have been written by Liddament³⁵ and Jones and Whittle³⁶ related to earlier work as CFD began to advance as a tool. Today the literature is filled with numerous studies related to the use of CFD, appropriate modeling techniques, validation, and applications for ventilation. The greatest advancement was related to turbulence modeling, and Chen³⁷ provides an overview to complete the picture a decade later. There has been significant research conducted using numerical techniques to model air flow in and around a single-room building,^{38, 39} but few detailed studies of whole buildings.^{40, 41, 42, 43} The following chapter will present examples to demonstrate successful modeling techniques for modeling ventilation through large buildings and rooms.

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Chapter 12

Computational Fluid Dynamics

Computational fluid dynamics is the numerical solution of partial differential equations that describe conservation of mass, momentum, and energy. The physics are further complicated due to the turbulent nature of the flows; therefore, additional equations are required to model turbulence. [Chapter 2](#) describes the physics and models, and the set of equations that are solved in CFD are discussed in [Section 11.3](#). A CFD simulation provides time-dependent flow fields for pressure, velocity, and temperature. Herein lies the advantage of using CFD to analyze ventilation: a rich history of data is provided for the entire room or building of interest. Visualization tools can plot the three-dimensional data and provide a ‘window’ into the movement of air and corresponding heat transfer patterns.

Computational fluid dynamics has been used during the last quarter century to provide insight into the complex physics of air flow and heat transfer inside buildings. The first CFD studies were performed decades ago at a time when computational resources were in their infancy. Today, it is possible to simulate full-scale three-dimensional buildings on a personal computer without the need for high-performance computing.

The goal of this chapter is to distill the basics of a well-posed CFD model for informative predictions of natural ventilation. Included are tips to determine what methods are best and demonstrate how to visualize the results.

12.1 Numerical Modeling

There are a number of commercially available software packages that are capable of modeling a large variety of flows. The more common codes include Fluent¹ and CFX² (both are products by ANSYS) and OpenFOAM.³ Some commercial codes are GUI-based and guide a user through the various models that can be selected. There are numerous methods that can be employed to solve the coupled set of partial differential equations, and some methods are more robust than others. The following will outline model choices that are offered in commercial software.

The first step is to create a model of a building; if the building is complicated, computer-aided design (CAD) software will provide the most capabilities to model and draw detailed rooms, windows, doors, staircases, and so on. An example of an intricate building is shown in [Figure 12.1](#) of the Affleck House to demonstrate that each wall partition, staircase, skylight, window, and door can be represented. The CAD drawing can then be imported into a CFD package that has the capabilities to generate a mesh within the building. An intermediate step is to use grid-generating software, which may be more user-friendly, to create the complex mesh before importing into a CFD package. The skeleton of the house is shown in [Figure 12.1\(a\)](#), and [Figure 12.1\(b\)](#) is a meshed region in the main portion of the house where ventilation is studied. Because the image is small, the

grid cells appear as a black region. Red cells have been used to identify the windows and blue cells identify the doors. The skylight is also shown in red. What is unique about this house, as described in [Section 1.3.1](#), is that there is an opening in the floor where ambient air enters the building; this region of air entrainment below the house is shown with purple cells. Issues related to grid resolution will be described in [Section 12.2](#) and boundary conditions will be discussed in [Section 12.3](#).

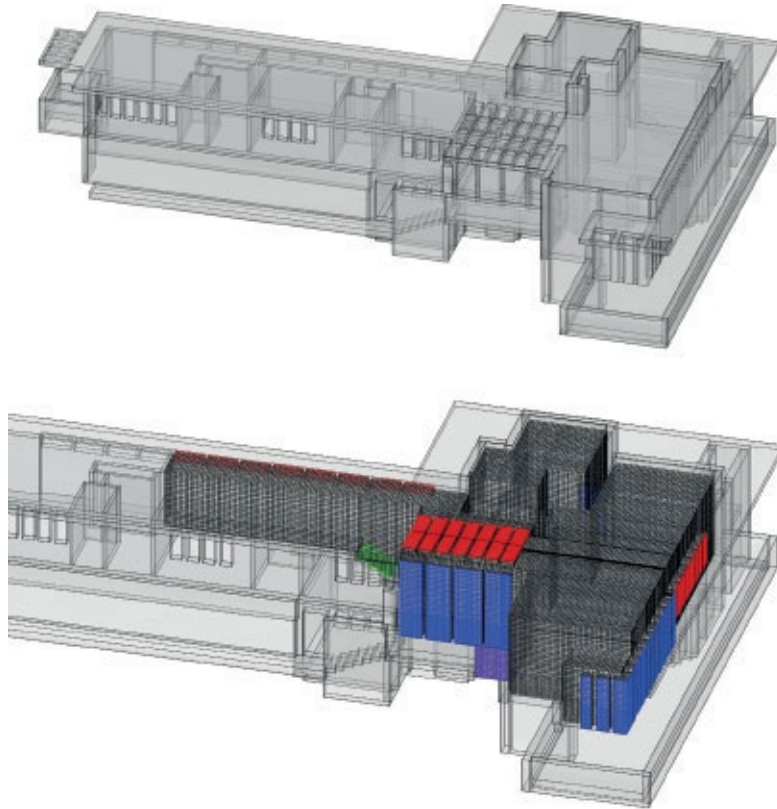


Figure 12.1

(top) CAD model of the Affleck House and (bottom) the mesh used to model the main interior.

Most ventilation problems are dependent on time, but assuming steady state can be a reasonable approach depending on the complexity of the problem or building. If a time-dependent solution is desired, a first-order implicit method is reasonable to use. A solution can be initiated by first assuming the flow is steady for a few iterations before turning on the time-dependent formulation.

To solve for flows that may be driven by wind, pressure, and/or buoyancy, care must be taken to select appropriate solvers that couple the partial differential equations. Ventilation flows are considered to be incompressible, and special methods are used. The pressure-based method is the most common method to numerically solve incompressible fluid-flow problems.⁴ The method couples the dependent variables for pressure and velocity so that efficient computational techniques can be used. An algorithm known as the semi-implicit method for pressure-linked equations (SIMPLE) solves the pressure-velocity coupling.⁵ In the SIMPLE algorithm, the momentum equations are initially solved with a guessed pressure field, which is then used to solve the velocity field. Further corrections to velocity and pressure continue until the final velocity field satisfies conservation of mass. To accommodate the buoyancy that may develop in ventilation problems, the Boussinesq model should be used so that density changes can be calculated in the buoyancy force term

in the momentum equation. CFD packages may have the option to turn gravity on or off, and to properly model buoyancy, gravity must be specified.

Equations that describe the turbulent nature of the flow are also solved. The three-dimensional conservation equations are solved by using either an averaging or a filtering approach and are coupled with a turbulence model. The former approach is the Reynolds-averaged Navier-Stokes (RANS) equations, which solves for averaged flow variables to capture the bulk (large-scale) motion and models the turbulence.⁶ The latter approach, which has gained recent attention, is large eddy simulation (LES).⁷ The Navier-Stokes equations are filtered to resolve the large-scale eddy motion and more of the turbulent behavior. The filtering removes the small-scale eddies and the filter size is grid-dependent. Both computational approaches require closure models that will predict the turbulent flow.

The most common turbulence closure model is the k - ϵ model, in which the turbulent kinetic energy, k , and turbulent dissipation rate, ϵ , are modeled and solved using two transport equations.⁸ There are three types of k - ϵ turbulence models: standard k - ϵ , renormalization group theory (RNG), and realizable k - ϵ .⁹ The standard k - ϵ model is considered as the simplest two-equation turbulence model. The RNG model includes an additional term to improve the accuracy in the ϵ transport equation for rapidly strained flows and for swirling flows. The transport equation for ϵ is also modified for the realizable k - ϵ model to satisfy certain mathematical constraints on the Reynolds stresses. Recent computational studies have shown that the traditional standard k - ϵ model predicts air flow in buildings with good accuracy.^{10, 11, 12, 13} Unfortunately there is no consensus on closure models,¹⁴ so the user may need to test a few to determine if the simulation is sensitive to the turbulence model. The LES approach has received some attention in the area of building ventilation,^{15, 16} but will not be presented here.

The standard k - ϵ turbulence model assumes that the flow is turbulent and the effects of molecular viscosity are negligible. The turbulent kinetic energy, k , and its rate of dissipation, ϵ , in the flow field are calculated from two additional transport equations.¹⁷ The k - ϵ transport equations are:

$$\frac{\partial}{\partial t}(\rho k) + \nabla \cdot (\rho k \vec{V}) = \nabla \cdot \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \nabla k \right] + G_k + G_b - \rho \epsilon \quad (12.1)$$

$$\frac{\partial}{\partial t}(\rho \epsilon) + \nabla \cdot (\rho \epsilon \vec{V}) = \nabla \cdot \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \nabla \epsilon \right] + C_{1\epsilon} \frac{\epsilon}{k} (G_k + C_{3\epsilon} G_b) - C_{2\epsilon} \rho \frac{\epsilon^2}{k} \quad (12.2)$$

In these equations, G_k and G_b are the production of turbulent kinetic energy due to mean velocity gradients and buoyancy, respectively; μ_t is the turbulent viscosity; $C_{1\epsilon}$, $C_{2\epsilon}$, and $C_{3\epsilon}$ are constants; and σ_k and σ_ϵ are turbulent Prandtl (Pr) numbers for k and ϵ respectively. The constant $C_{3\epsilon}$ determines the degree to which is affected by the buoyancy and is calculated using a relationship between the velocity vector parallel and perpendicular to the gravitational vector. Most commercial codes use defaults for the

constants that the user can change.

The equations for momentum, energy, and turbulence can be solved using discretization schemes that are second-order accurate, such as the upwind scheme. Examples of second-order methods to resolve the gradient terms include the least squares cell based (LSCB) and Green-Gauss based methods. The PREssure STaggering Option (PRESTO!) is the recommended numerical scheme to interpolate for pressure in natural convection flows. The discretization formulas can affect the performance of a simulation, and there are options for under-relaxation factors to help improve convergence. Care should be taken when changing the defaults, and the user can refer to the literature for recommendations.

12.2 Grid Resolution and Validation

The discretization of the partial differential equations facilitates a computational solution using a grid or mesh. Discretization simply means taking a large volume and representing it with smaller volumes, known as grid cells. A grid is composed of hundreds of thousands of cells that are the internal volumes (or elements) of the domain being modeled. The partial differential equations ([Section 11.3](#)) are solved for each grid cell to give the pressure, velocity, and temperature fields in a very small volume. Each cell will have a different solution that provides details of the overall fluid motion and heat transfer.

Two-dimensional problems can use a relatively simple mesh, where the domain is divided into equally spaced cells in the shape of squares or rectangles. Three-dimensional problems pose greater challenges, especially if intricate details are being modeled in a building. Returning to the three-dimensional model of the Affleck House ([Figure 12.1](#)), a close-up view of the mesh on the opposite side of the house is shown in [Figure 12.2](#). Grid cells fill the interior volume (rooms), windows, doors, and open space under the house where wind enters through a horizontal vent in the floor (purple cells). The windows (red) and doors (blue) identify regions where boundary conditions can be applied if they are to be modeled open for ventilation. In addition, as the air flows within the house, the influence of the stairs (green) will be captured. The entire building is modeled using 390,000 grid cells, where the approximate size of a cell is 10 cm × 10 cm × 10 cm. The size of each rectangular cell may vary in order to accommodate the geometry (such as the stairs), so the edge of a cell may range from 7 cm to 14 cm.

The number of grid cells is important for modeling to ensure that the predicted flow fields can be considered accurate. There are guidelines for meshing a domain, although detailed computational studies may be required to ensure that the solution is not adversely affected by the grid resolution. Commercial codes may have the capability to use standard wall functions for the flow field near surfaces to properly model the turbulent nature of the flow.⁸ Recommendations would be given to ensure that enough grid cells are present near a surface to capture the fluid-wall interaction.

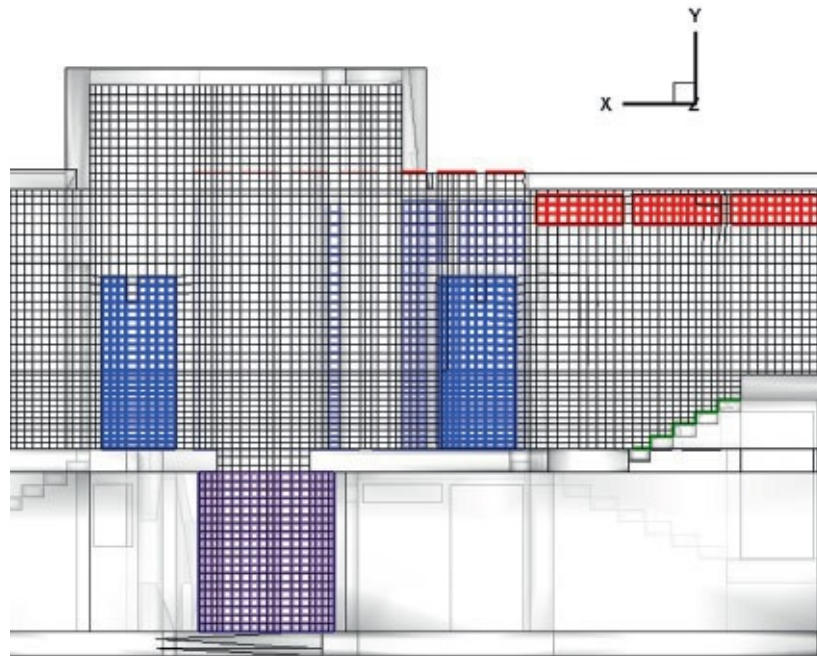


Figure 12.2

Enlargement of grid resolution for the Affleck House using a view rotated 180°, as shown in [Figure 12.1](#).

For complicated building geometries, it is not always feasible to investigate if appropriate computational models have been selected for the CFD simulation. However, a smaller problem can be examined first to help determine that the models and grid resolution are satisfactory. Validating a more well-known problem can provide confidence with using selected models and grid resolution. The published literature is a good place to seek if there is an experiment for which data can be used for validating the CFD. One example is the stack ventilation experiment performed by Mahajan.¹⁸ [Figure 12.3](#) (left) is a representation of the room with a heater and the doorway through which ambient air entered. The study provided temperature and velocity data at a doorway, which can be used to test CFD modeling. Grid resolution can also be examined to determine that a sufficient number of cells are being used to discretize the domain. Validation of a simpler study can be used to justify the modeling techniques and mesh for a full-scale simulation of a building. [Figure 12.3](#) (right) compares the experiments of Mahajan with the CFD predictions from Park¹⁹ for three different cell sizes. Park showed that a grid cell with edge lengths of 6 cm was acceptable for very good accuracy with a reasonable size grid of 326,000 cells for the three-dimensional domain.

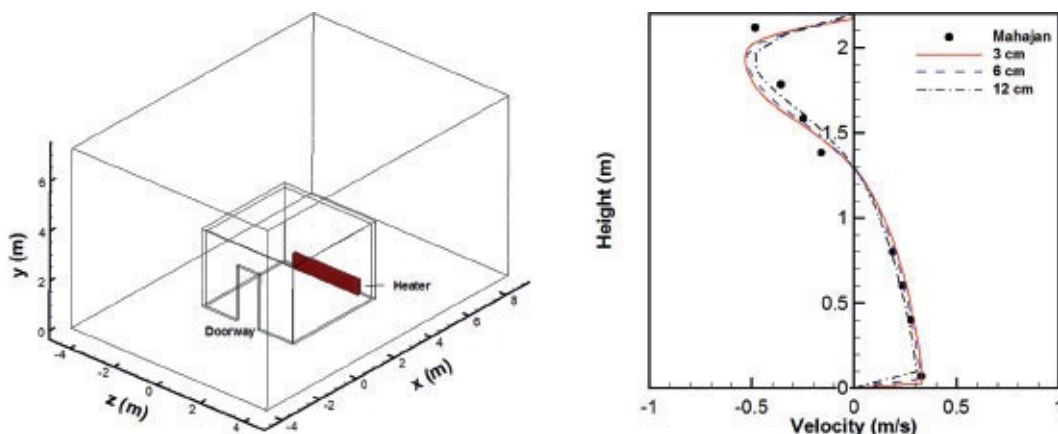


Figure 12.3

(left) Computational domain used to model the Mahajan experiments and (right) grid resolution validation study comparing velocity profile in the doorway.

12.3 Initial and Boundary Conditions

Initial conditions in a CFD simulation provide a starting guess of the flow field. The modeling techniques described in [Section 12.1](#) use the guess to determine if the partial differential equations are satisfied and, if not, refine the answer until a solution is reached. The answer for each refinement is compared to the previous answer and the difference is then compared to a prescribed error tolerance, known as the convergence criterion. The criterion prescribes that the differences between two solutions are small, for example, smaller than 0.00001. Thus, for the simulation to advance in time, there is an iterative process until the answer meets the criterion.

Defining the time step for a transient simulation can be estimated using the Courant–Friedrichs–Lewy (CFL) number. The CFL relates a characteristic velocity and length to determine an appropriate time step. The CFL is

$$\text{CFL} = \frac{V \Delta t}{\Delta_c} \quad (12.3)$$

where V is the mean (or characteristic) velocity (see [Equation 11.1](#)) and Δ_c is the typical grid cell size (usually the smallest length). For most incompressible flows, the $\text{CFL} = 1$, and the time step Δt can be estimated.

Boundary conditions are required for any wall and opening. It is standard to use the no-slip boundary condition for walls to ensure the fluid velocity is zero at a surface. If heat transfer is also modeled, using an adiabatic wall condition eliminates solving for conduction through the wall and greatly simplifies the simulation. The adiabatic wall condition ensures that there are no temperature gradients within a wall. There are different boundary conditions that can be used for an opening, depending on the type of ventilation. Wind can be prescribed through an opening using a velocity boundary condition and a temperature can be prescribed if heat transfer is modeled. An opening through which the air velocity is not known is modeled by prescribing the outdoor ambient pressure and temperature. [Sections 12.3.1](#) to [12.3.3](#) will elaborate on the most common types of ventilation scenarios.

In order to incorporate the external environment of a building, it is important to ensure that the boundaries of the computational domain provide a realistic representation of wind and other ambient conditions. Furthermore, modeling the environment surrounding a building increases the overall domain used in a simulation. For example, Schaelin *et al.*²⁰ simulated the conditions in a room with a door (single-sided ventilation) and heater, where the room dimensions were 4.2 m long $\times$ 3 m high $\times$ 4 m wide. The simulations were based on the experiments of Mahajan.¹⁸ However, Schaelin *et al.* modeled the environment of size 34 m $\times$ 25 m $\times$ 18.7 m, which is more than 300 m³ larger than the volume of the room. Based on the computational resources in the late 1980s, the entire domain was discretized using a grid resolution where each grid cell was approximately 1 m³ (16,000

grid cells). Such a coarse grid resolution really only provides a qualitative understanding of the air flow. Reducing the size of the domain that represents the surrounding environment allows for higher grid resolution (i.e., more grid cells) to resolve the computational domain, as shown in [Figure 12.3](#) (right) by Park.¹⁹ The outermost domain boundaries used ambient pressure to model the environmental conditions.

Using a smaller computational domain requires careful consideration of the boundary conditions. Care must be taken when specifying the wind velocity in the immediate vicinity of an opening to ensure that the velocity is realistic. As will be shown next, three types of flows have been modeled and simulated using boundary conditions specific to the type of flow. Recommendations will be mentioned to help guide the modeling techniques with best practices.

The final consideration when defining a problem to be solved using CFD is related to the boundary conditions and the infinite number of combinations for conditions. For example, the Affleck House has more than two dozen doors and windows that can be open, partially open, or closed. Then, there is the consideration of weather. What is the wind speed and temperature? Clearly it is not possible to simulate all scenarios, so the designer must try to define a few key scenarios that may include the slowest and fastest wind speeds and minimum and maximum temperatures. A few windows and doors can be modeled open. Thus, a select number of simulations may provide sufficient information to help the designer determine where there are problems with ventilation. The following examples have followed this philosophy.

[12.3.1 Wind-Driven Flows](#)

One of the benefits of ambient wind is that it is a natural source of energy that can be used to ventilate a building. Wind serves as a vehicle for forced convection when temperature gradients are present. As described in [Section 7.2](#), cross-ventilation and single-sided ventilation are the two most common strategies to induce air flow into a building or room. Modeling wind-driven flows requires knowledge of the wind conditions such as wind velocity and temperature, which constantly change in time and on any given day. Thus, one modeling approach is to presume specific values for the environment near a building to estimate the effects of ventilation.

Two wind velocity conditions were investigated for cross-ventilation in Room 1–2 ([Figure 7.11](#)) and Room 1–3 ([Figure 7.12](#)) by Detaranto.²¹ The room was modeled by specifying a velocity inlet boundary condition into the left window and ambient pressure at the right window on the opposite side of the room. These scenarios represent passive cooling, where the initial room temperature was 4 °C higher than the ambient temperature. The Grashof number for these flows is $Gr = 3.17 \times 10^9$ ([Figure 7.11](#)) and $Gr = 0.39 \times 10^9$ ([Figure 7.12](#)), using the window height as the characteristic length (refer to [Equation 11.2](#)).

As can be seen in [Figure 7.11](#), the velocity vectors show air movement with the same patterns and only differ in velocity magnitude. The streamlines elucidate the recirculation regions and show how the flow continuously ‘circles’ to form a spiral pattern. The scale

for the velocity field is shown above each image. The high-velocity flow is ten times greater than the low-speed flow. Therefore, the Reynolds numbers for the low and high velocities are 57,700 and 577,000, respectively (refer to [Equation 11.1](#)). The only obvious difference for these wind-driven simulations is the recirculation zone in the upper-left corner. The size of the recirculation zone is due to the effects of buoyancy as a result of the difference in wind temperature and initial temperature of the room. For the high wind velocity, the wind-driven flow dominates the buoyancy effects and creates upper and lower recirculation regions of equal size. In contrast, the low wind velocity competes with buoyancy, resulting in a smaller recirculation zone above the window opening. To emphasize the use of non-dimensional parameters in [Section 11.1](#), the Reynolds and Grashof numbers indicate the importance of forced convection versus buoyancy. Using Gr/Re^2 , the values are 0.95 and 0.0095 for the low- and high-velocity cases. A value close to one indicates both effects are important and a very small value indicates that the flow is dominated by forced convection, as shown in [Figure 7.11](#). Similar conclusions can be made for the smaller opening window of Room 1–3 ([Figure 7.12](#)), where $Gr/Re^2 = 0.5$ and 0.005. It should be noted that the cross-ventilation simulations do not include additional heat loads due to people, electronic devices, or heaters, which would change the air flow patterns. These simulations help to visualize where in the room the air may become stale or where pockets of hot (or cold) air may accumulate.

Prescribing the boundaries for wind-driven flow is more challenging when a whole building (or large section) is modeled in CFD. The distinct feature of the Affleck House is the vent in the first floor ([Figures 1.8](#) and [1.13](#)), through which ambient wind is entrained. The model shown in [Figures 12.1](#) and [12.2](#) identifies a boundary using the color purple where a low velocity is specified as the boundary condition to replicate the wind speed as it moves under the house. In effect, the vertical boundary is merely a computational boundary to represent the outdoor conditions, thus reducing the need to model the entire ambient environment surrounding the house. [Figure 7.6](#) shows results for temperature contours and the streamlines of the air flow into the vent (refer to the lower pop-out image). The same idea was used to model Casa Giuliani, shown in [Figure 8.10](#). A low-speed flow was prescribed at the vertical domain edge above the balcony ledge to facilitate the wind that moves between the congested urban buildings. The advantage is that the overall computational domain is contained to the immediate region around the building and therefore allows more grid cells to be used within the building to improve computational accuracy.

[12.3.2 Buoyancy-Driven Flows](#)

The variation in temperature within a building or between the external and internal environment can initiate buoyancy-driven flows. The changes in temperature are coupled to changes in density of the air, which initiate air movement. Warm, lighter air rises and cold, heavier air sinks. Thus, buoyancy can contribute to ventilation without requiring forced convection. Of course, buoyancy-driven flow can be combined with wind, thus coupling the effects of air mixing and thermal changes.

Referring to the study of cross-ventilation by Detaranto²¹ for Room 1–2 and 1–3,

buoyancy-driven flow was simulated to demonstrate the effect between a warm ambient environment and the room. These scenarios represent passive heating, where the initial room temperature was 4 °C less than the ambient temperature. The window height for Room 1–2 is twice the window height for Room 1–3 and can be used as the characteristic length to calculate the Reynolds and Grashof numbers. The non-dimensional parameters for Room 1–2 are $Re = 56,190$ and $Gr = 2.96 \times 10^9$. The parameters for Room 1–3 are $Re = 28,090$ (one-half the value for Room 1–2) and $Gr = 3.7 \times 10^8$.

Images shown in [Figure 12.4](#) present the temperature changes over time (every 60 s), and streamlines are used to show the direction of the air flow. The color bands represent cooler temperatures using blue and warmer temperatures using red. What is most striking is that the large window opening modeled in Room 1–2 shows significantly warmer air flow throughout the entire room. Comparing the Grashof and Reynolds numbers using Gr/Re^2 , the ratio is 0.94 for Room 1–2 and is 0.47 for Room 1–3. Therefore, both rooms have mixed conditions where buoyancy and the air entrained into the rooms are important effects. However, the effects due to buoyancy in Room 1–2 are more pronounced.

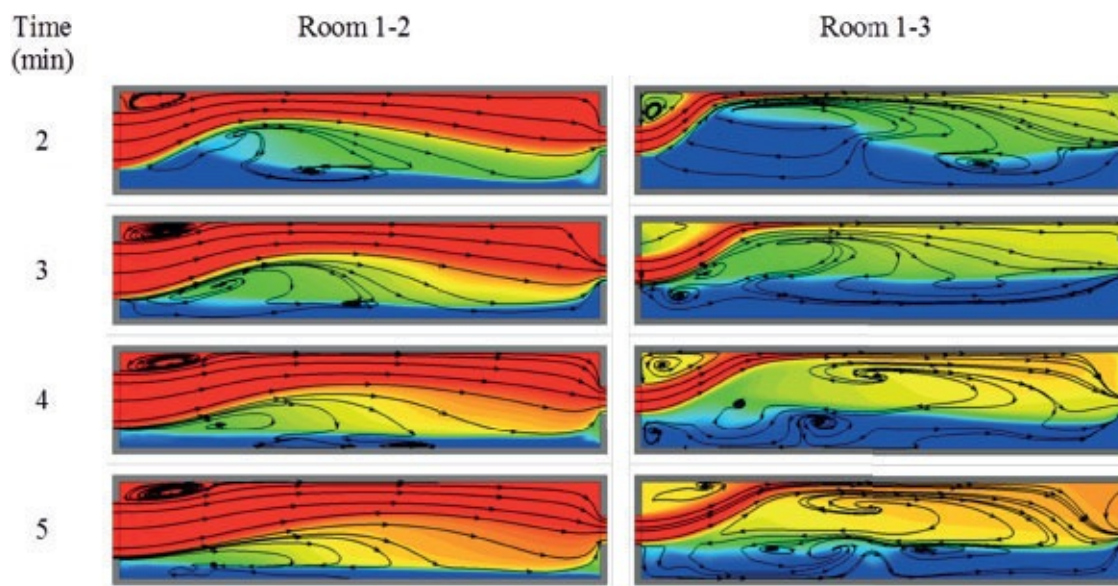


Figure 12.4

Buoyancy-driven flow for warm ambient conditions comparing temperature and streamlines for cross-ventilation: Room 1–2 and Room 1–3.

12.3.3 Pressure-Driven Flows

Pressure-driven flows are the simplest flows that demonstrate natural convection. The thermal conditions contribute to the motion of the air, and thus a pressure difference develops between the room and ambient conditions. In a flow that is driven by both buoyancy and pressure, the choice of boundary condition becomes important. Heiselberg²² showed that the solution of combined-effect flows is dependent on the relative magnitude of the forces due to buoyancy and pressure.

The cross-ventilation in Room 1–2 was modeled by specifying ambient pressure at both window openings.²¹ The ambient air temperature was 4 °C less than the room temperature to model a scenario for passive cooling. [Figure 12.5](#) shows the time-dependent

temperature changes every 15 minutes, with streamlines to identify the air flow patterns. Unlike the wind- and buoyancy-driven flows, the pressure-driven flows take a very long time to reach a steady state. The air velocities are much slower and the hot air near the ceiling still persists even after 45 minutes of passive cooling. It is also interesting to note that the cooler air enters near the upper portion of the window and forms a jet-like flow that impinges the floor, creating a large recirculation region in the middle of the room.

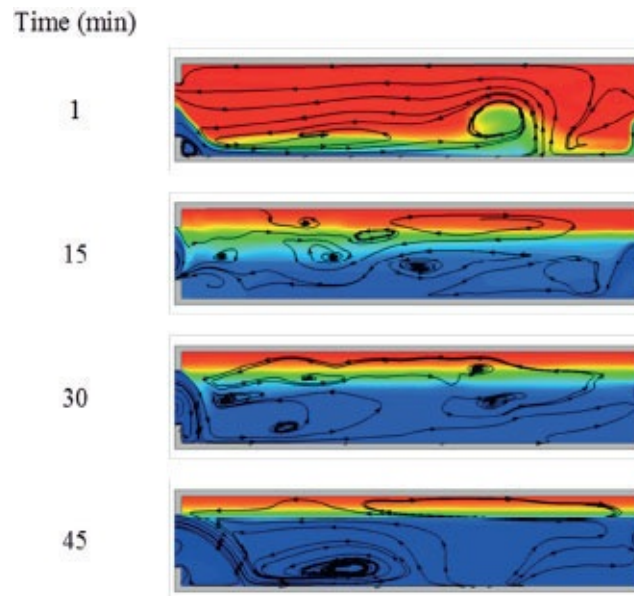


Figure 12.5

Pressure-driven flow time sequence of temperature and streamlines for cross-ventilation: Room 1–2.

Using the CFD results to calculate the velocity through the left opening (Figure 12.5), the corresponding Reynolds number is 23,090. The Grashof number is $Gr = 3.17 \times 10^9$. The flow presented in Figure 12.5 corresponds to a buoyancy-dominated flow, where $Gr/Re^2 = 6$, and confirms that the flow velocity is very low into the room. To quantify the ventilation, the air changes per hour (ACH) is used. ACH is defined as the volume flow rate (m^3/hr) per volume of the room (m^3) and gives a value of how often the air changes per hour. The ACH for this flow is estimated to be 1. While this is acceptable and exceeds the minimum ASHRAE²³ recommendation of 0.35, it is below the Royal Institute of British Architects (RIBA)²⁴ recommendation of 2 to 15 to remove heat for cross-ventilation. The ACH values for cross-ventilation were shown in Table 7.2 for the wind-driven flows (Figure 7.11). These values ranged from 12 to 240. In contrast, the buoyancy-driven flows (Figure 12.4) contributed to an ACH of 1.

Although the pressure-driven flow does not presume a velocity at the openings, the simulation can predict the velocity. In another example, single-sided ventilation is used to demonstrate the steady state velocity field in Room 2–1 (Figure 7.13), where ambient conditions are 4 °C less than the initial room temperature.²¹ The discussion in Section 7.2 presented results for Room 2–1 where a 1 m/s velocity was specified at the lower opening. The corresponding ACH values for cross-ventilation were shown in Table 7.2 for the wind-driven flows. Here, a pressure-driven flow is modeled, where ambient pressure is specified at the openings. Figure 12.6 (left) presents the results for the pressure-driven flow, where the velocity vectors elucidate that flow enters through the upper window and

creates a large mixing region whereby the air leaves the room through the lower window. The simulations predicted that the flow entered the window at 0.4 m/s ($Re = 6,734$). A similar scenario was modeled but the air velocity was specified as 1 m/s at the upper window ($Re = 19,240$). The results for the pressure-driven and wind-driven flows look almost identical, except that the latter has a velocity field with a magnitude almost three times as large. The Grashof number for these flows is 1.47×10^7 . These simulations demonstrate that for the single-sided ventilation with windows far apart, the flow is dominated by bulk motion of air and buoyancy is not significant. The ACH for the pressure-driven flow in Room 2–1 is approximately 3, which meets recommendations.

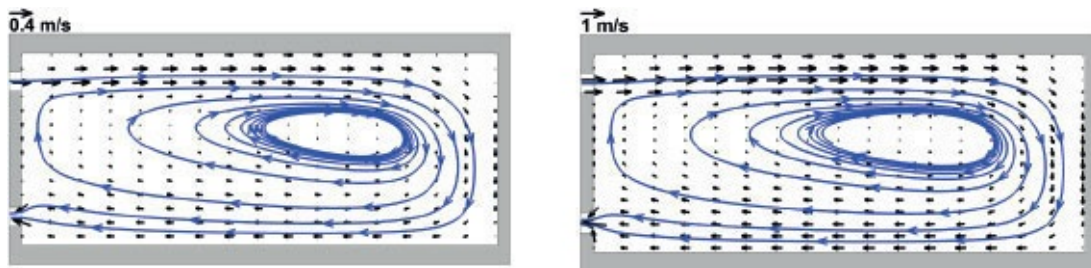


Figure 12.6

(left) Pressure-driven flow and (right) wind-driven flow comparing velocity field and streamlines for single-sided ventilation: Room 2–1.

The placement of the openings has a far greater impact for pressure-driven flow. A simulation for single-sided ventilation with openings close together (Room 2–2) is shown in [Figure 12.7](#). The natural tendency for this passive cooling strategy is for the air to enter through the upper opening, in contrast to the wind-driven flow simulations ([Figure 7.13](#)). However, there are two recirculation regions that divide the room and prevent sufficient ventilation. The ACH for this room is below 1 and is not acceptable according to ventilation recommendations by ASHRAE and RIBA. It is worth noting that for this scenario, $Re = 2886$, $Gr = 1.47 \times 10^7$ (same temperature difference and window size as Room 2–1), and the ratio $Gr/Re^2 = 1.76$. Therefore, buoyancy is responsible for reducing the temperature gradients as the room cools.

12.4 Visualizing the Driving Dynamics of Ventilation

The plethora of data generated using CFD is a rich source of information that includes the temporal and spatial relationship between pressure, velocity, and temperature. A three-dimensional simulation can be visualized by creating movies that advance in time to show the direction of the air movement and the cooling or heating of a building. While movies may be an ideal way to visualize flow, we are often left with ‘two-dimensional’ means for visualization. In other words, we use static images to convey the motion. Pressure, velocity, and temperature fields are of primary interest, and two of these variables can be shown simultaneously to provide a more complete picture. For example, superimposing velocity vectors over pressure contours demonstrates where pressure is low or high relative to large motions of the flow. Another issue is visualizing the time-dependent transition and the air flow changes. The following will present natural ventilation scenarios of complex three-dimensional buildings to demonstrate different presentation

techniques that can be used for visualization.

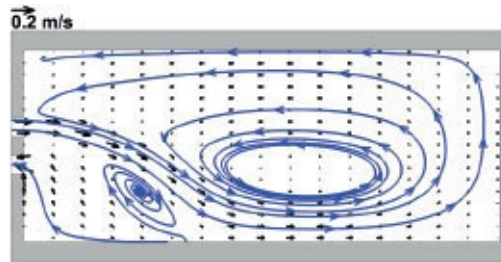


Figure 12.7

Pressure-driven velocity flow field and streamlines for single-sided ventilation: Room 2-2.

A study related to natural ventilation by Park¹⁹ presented the stack effect for a room with a doorway (single-sided ventilation), a radiator, and furniture and heat loads due to electrical equipment, shown in the schematic of Figure 12.8 (top left). The complicated air flow patterns often make it difficult to discern the three-dimensional motion. To appreciate the complexity of the flow, three-dimensional views for warm and cold ambient air conditions are shown in Figures 12.8 (top right) and 12.8 (bottom), respectively. These views are called instantaneous because they are for a particular instant in time, such as when ten minutes has elapsed. Temperature contours provide knowledge of where regions in the room are warmer or cooler. Blue identifies the coolest regions (no lower than 10 °C) and red the warmest regions (no greater than 40 °C). The color bands in between show where the air has mixed to intermediate temperatures. Streamlines, created from the velocity field, are used to identify the path of the flow. These flow patterns are random at some instant in time, and it is difficult to discern if there are pockets or regions where the air flow is not significant. While a three-dimensional view provides a ‘big picture,’ it is difficult to interpret temperature gradients. As proper ventilation is the primary concern, the designer wants to ensure the best air exchange possible for a given geometry and set of ambient conditions.

Referring to the discussions related to Figures 12.4 and 12.5, multiple images of the same view are shown, where each image is a different moment in time. The arrangement of the figures provides a chronological progression of the changes in temperature and air flow patterns. Consider the temperature in Room 1-2 (Figure 12.4). There is initially a large region just downstream of the window where the temperatures are low but gradually increase with time. However, for Room 1-3, the air remains more stratified and a cooler region persists near the floor over time. Figure 12.5 shows that initially, warm air exits close to the upper part of the window on the left, while cold air enters the window through the lower portion. Examining the right window at $t = 1$ min and 15 min, there is one streamline that shows that air enters and moves to the left, eventually exiting through the left window. Once 15 minutes have elapsed, the cooler air enters through the entire window area and exits through the right window. After 45 minutes, there is still a warm region of air near the ceiling, but the air is passing through the room with an ACH = 1.

Visualization can be improved by examining cross-sectional planes at different locations within the full domain. Two such planes are shown in Figure 12.9, where the temperature and velocity vectors are shown at a y - z plane at the doorway ($x = 0$ m) and a

y - x plane at $z = 0$ m that intersects the center of the room through the doorway. The images in Figure 12.9 (top) are for warm ambient air conditions and for Figure 12.9 (bottom) are cold ambient air. The two-dimensional views provide more quantitative details related to the magnitude and direction of the flow using velocity vectors. Superimposing the vectors with the temperature field elucidates where the air is warmer and cooler and the direction air moves to create these temperature gradients. Heat transfers from hot to cold regions and buoyancy induces motion so that hot air ascends and cold air descends. The cold ambient air enters closer to the floor and warm air exits through the upper half of the door, demonstrating the stack effect. Also noticeable is the heat that is dissipated from the computer monitor (see Figure 12.8), causing warm air to rise. Using a combination of streamlines and temperature helps to further visualize where the flow recirculates, or where mixing of air is reduced, which can sometimes lead to stratification.

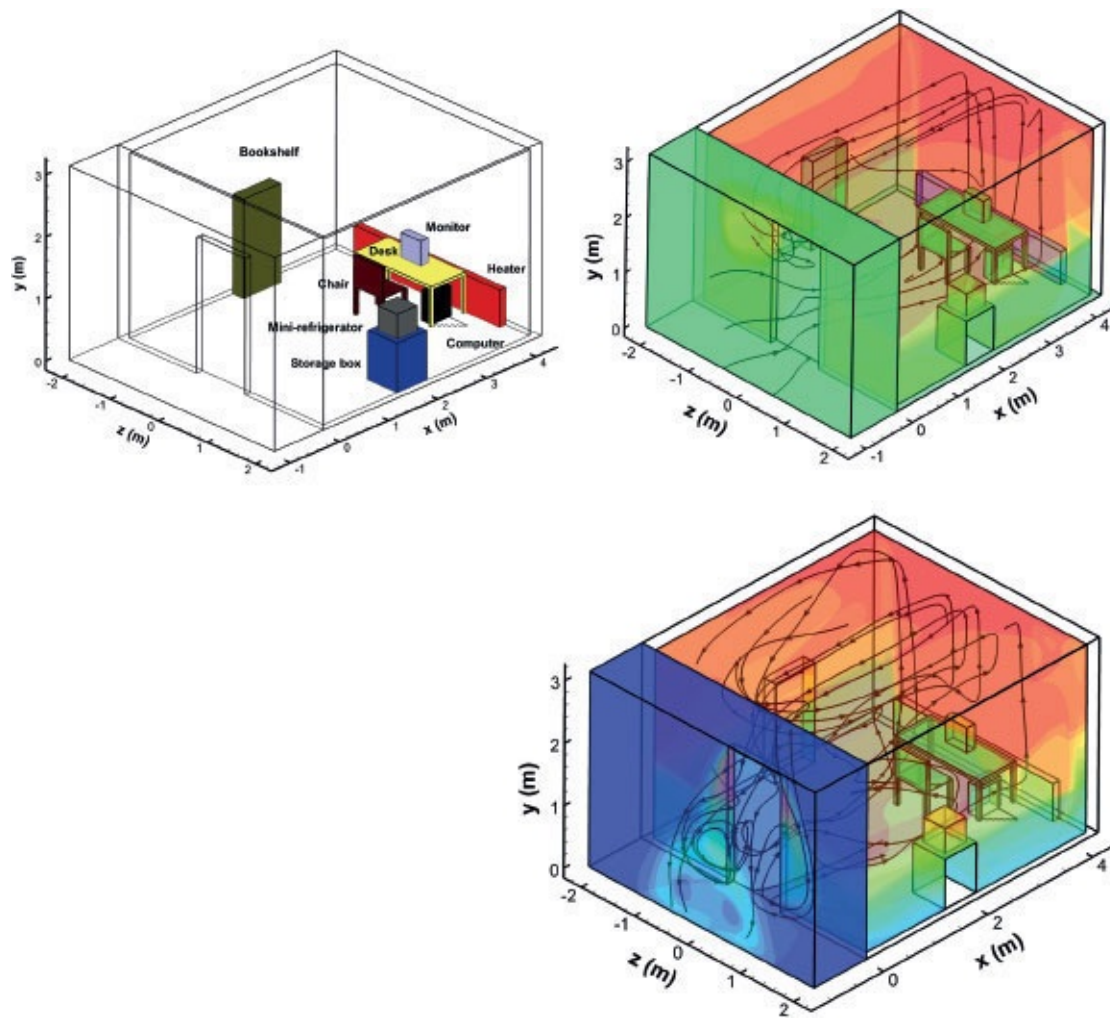


Figure 12.8

Three-dimensional view of (top left) room layout and temperature contours imposed with streamlines for (top right) warm ambient temperature and (bottom) cold ambient temperature.

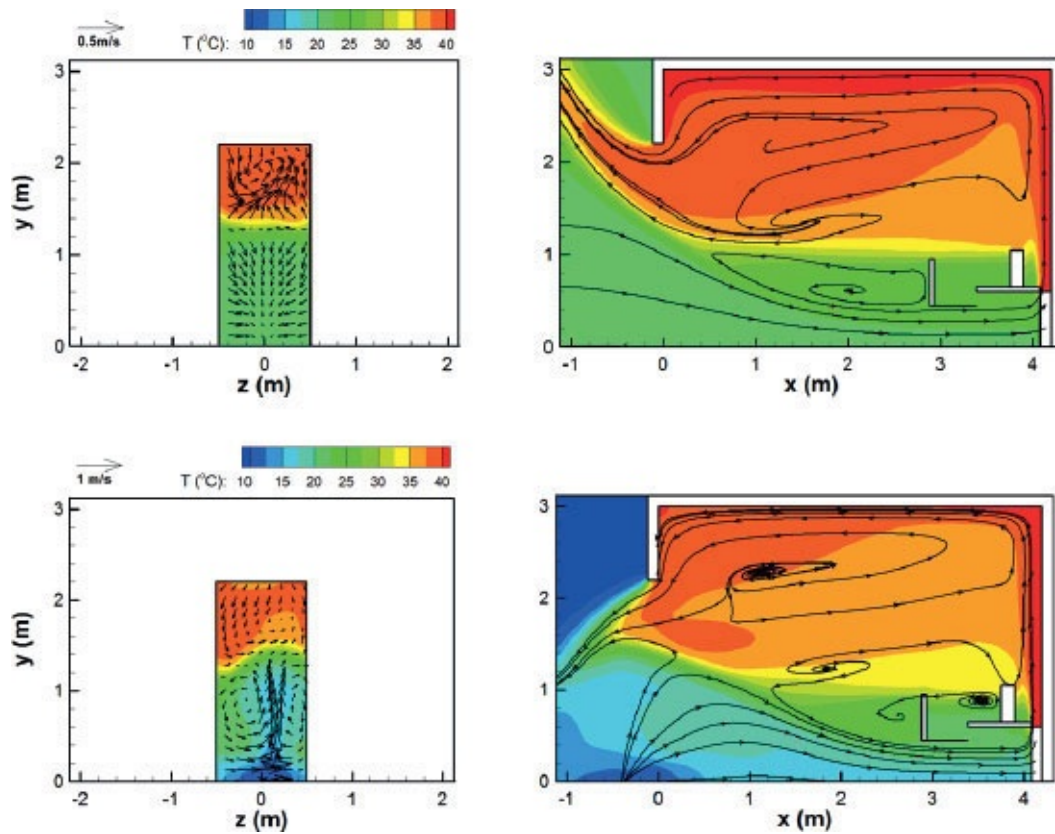


Figure 12.9

Two-dimensional views of temperature contours superimposed with vectors and streamlines for (top) warm ambient temperature and (bottom) cold ambient temperature.

Additional CFD simulations were presented in [Chapter 8](#) for the Casa Giuliani apartment showing three-dimensional views ([Figure 8.9](#)). In addition, [Figure 8.10](#) is used to show how the air exits through the vent. Two planes were identified to show both temperature and streamlines. The streamlines begin from the balcony, which is open to entrain ambient air. For the section of the apartment with the open vent (plane closest to the right side), the streamlines show movement through the doorway (located halfway through the apartment) and exit through the vent. However, the other plane indicates that the air does not leave the apartment, and the streamlines persist in a circular motion known as a recirculation zone. In fact, the air is very warm towards the upper half of the room because it is not exhausted through the vent. [Figure 8.10](#) is another way in which three-dimensional flow can be visualized using the volume of the building and identifying specific planes.

To bring the work full circle that started the collaboration between the authors on natural ventilation using passive techniques, [Figure 12.10](#) shows the CAD drawing of the Viipuri Library (view from the rear of the building). Prior to the restoration efforts of the library,²⁵ ventilation was achieved by opening the front doors as well as a side door to induce a pressure difference through the building. Passe and Battaglia wanted to explore ventilation strategies using CFD, and thus the architect and engineer began their collaboration, which culminated in this book.^{26, 27} Simulations performed by Stoakes²⁸ are shown in [Figure 12.10](#) using the full three-dimensional building volume (rotated 180 degrees from the CAD view above). As was shown throughout this book, most buildings have many windows and doors; thus, there are a large number of combinations for which

doors or windows are fully or partially open, to induce ventilation. The images shown in [Figure 12.10](#) modeled the front doors as fully open as well as the side door; however, the office windows along the front of the building were presumed closed. The simulation began with warm stagnant air in the library. Presuming that the library is open mid-morning, the simulation used a prescribed velocity at the library doors to model the wind at a lower ambient temperature. As time elapses, it is obvious that the great hall of the library begins to cool and streamlines show that the air flow is circulating to create a more comfortable internal environment. The figures elucidate that opening some of the office windows would help with the air flow and remove the warm stratified air through the offices and corridor. It is simulations like these that can help the architect, designer, and engineer make better choices for ventilation strategies. We hope that this book has stimulated your interest in using natural ventilation and encourages architects and engineers to work more closely together to design energy-efficient structures.

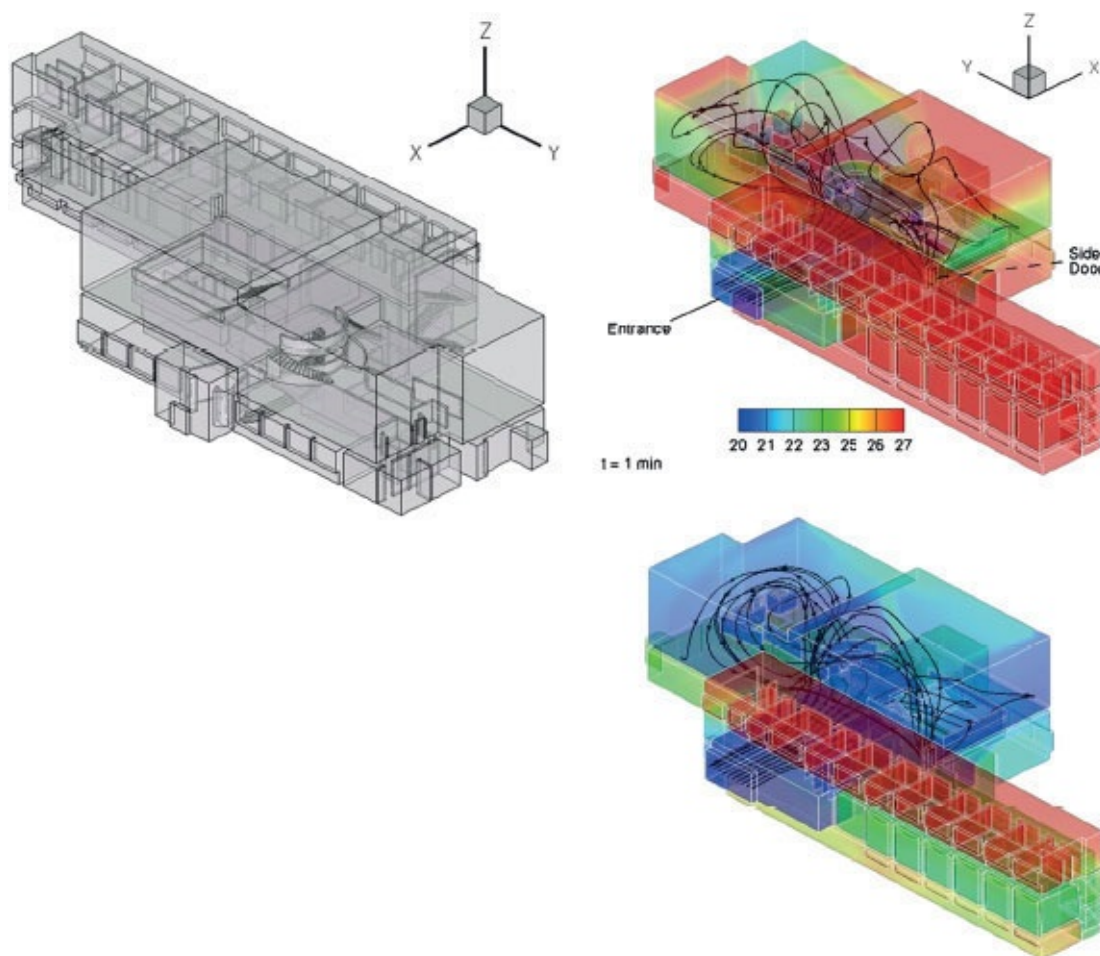


Figure 12.10

CAD model of the Viipuri Library and two images of temperature and streamlines as time elapses to demonstrate passive cooling.

Notes

- 1 See <http://www.ansys.com/Products/Simulation+Technology/Fluid+Dynamics/Fluid+Dynamics+Products/ANSYS+Flue>
- 2 See <http://www.ansys.com/Products/Simulation+Technology/Fluid+Dynamics/Fluid+Dynamics+Products/ANSYS+CFX>
- 3 See <http://www.openfoam.org/>.

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Author biographies

Ulrike Passe is Associate Professor of Architecture at Iowa State University, USA, where she teaches architectural design and environmental technologies. She joined the faculty at ISU in 2006 and is the Director of the Center for Building Energy Research. She received her Diplom-Ingenieur degree (equivalent to an M.S. in Architecture) in Architecture from the Technical University in Berlin, Germany, in 1990. She is a licensed architect in Germany, was a member of the Bund Deutscher Architekten (BDA) from 2005 to 2010 and is now an International Associate of the American Institute of Architects (AIA). Her work experience includes more than 15 years of professional practice in architecture specializing in energy-efficient buildings and six years teaching and researching in architectural design and building technology at the Technical University in Berlin. Her firm Passe Kaelber Architekten won the 1998 BDA (Bund Deutscher Architekten) Young Architect's Award in Berlin, Germany.

Ulrike Passe was the Principal Investigator and Faculty Advisor to the ISU Solar Decathlon Team to build an entirely solar-powered house on the National Mall in Washington, D.C., in fall 2009. The project involved interdisciplinary research into energy-efficient building envelopes, passive and active solar technologies, passive cooling strategies and natural ventilation, green design and technologies, thermal comfort, and bio-composite materials.

Further funded research includes "The Fluid-Dynamics of Air-Flow in Free-Flow Open Space: An Architectural Approach to Energy Efficient Building," funded by the Boston Society of Architects Research Award 2007 and conducted in collaboration with co-author Dr. Francine Battaglia, Professor of Mechanical Engineering at Virginia Tech, and an NSF EFRI EAGER grant "Multi-Scale Material and Dynamic Thermo-fluid Computational Models and Controls for Sustainable Buildings Using Efficient Energy Harvesting Materials." Passe is also an investigator in the Iowa NSF EPSCoR project "Harnessing Energy in the Biosphere to Build Sustainable Energy Systems," where she leads the state-wide building science plank. Passe's interest expands into the history of environmental technologies and its position in the architectural curriculum. Passe is the recipient of the 2010 Impact Award from the ISU Alumni Association and the 2009 College of Design award for extraordinary performance as well as two ISU Live Green Awards for her collaborative work with students. She has frequently been invited to speak at international engineering and architecture conferences.

Francine Battaglia, Professor of Mechanical Engineering at the Virginia Polytechnic Institute and State University, joined the faculty in 2007 and is the Director of the Computational Research for Energy Systems and Transport (CREST) Laboratory. She received her B.S. degree (1991) in Mechanical Engineering and M.S. degree (1992) in Aerospace Engineering from the State University of New York at Buffalo, and her Ph.D. (1997) in Mechanical Engineering from the Pennsylvania State University. From 1997 to 1999, she was a National Research Council Postdoctoral Fellow at the National Institute of Standards and Technology in the Building and Fire Research Laboratory. Prior to

joining the Virginia Tech faculty, Dr. Battaglia was on the mechanical engineering faculty at Iowa State University from 1999 to 2007. Dr. Battaglia served as director of Iowa State's Center for Building Energy Research from 2004 to 2007, and developed a multidisciplinary center that emphasized research for efficient and renewable energy technology related to buildings. Dr. Battaglia's research endeavors to include using computational fluid dynamics and developing computational models to explore issues related to the fluid and thermal sciences. Her current research interests include multiphase turbulent and reacting flows for applications in coal and biomass gasification, syngas production, and building energy utilization. Dr. Battaglia is in *Who's Who in America*, is a member of the American Institute of Aeronautics and Astronautics (AIAA), American Physical Society (APS), American Society of Engineering Education (ASEE), and Sigma Xi, and is a Fellow of the American Society of Mechanical Engineers (ASME).

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