

# Re-thinking of engineering operation solutions to HVAC systems under the emerging COVID-19 pandemic

Yungang Pan<sup>a,\*</sup>, Chenqiu Du<sup>b</sup>, Zhuzhou Fu<sup>a</sup>, Mushu Fu<sup>a</sup>

<sup>a</sup> China Architecture Design & Research Group, Beijing, 100044, China

<sup>b</sup> Joint International Research Laboratory of Green Buildings and Built Environments, Ministry of Education, Chongqing University, Chongqing, 400045, China

## ARTICLE INFO

### Keywords:

Engineering thinking  
Virus transmission prevention  
HVAC system  
Ventilation  
Operation strategy

## ABSTRACT

The purpose of the study is to discuss the appropriate HVAC operations in civil buildings from a perspective of engineering experience, to provide a safe and healthy indoor environment for working and living, responding to the prevention of COVID-19 transmission in buildings. The study reviewed the previous theoretical studies of relations between increased ventilation and the transmission of the virus, and based on a premise of value orientation, addressed that increasing the ventilation was still one of the most effective ways to promote the anti-epidemic property in the buildings. The study thus summarized the current characteristics of different HVAC systems in buildings, and put forward the target operation strategies respectively, which effectively increased the fresh air flow rate and meantime ensure the normal operation of the buildings. Suggestions as to the anti-epidemic designs for the newly constructed buildings were further presented. The outcomes of HVAC operation strategies are beneficial for instructing the normal operation of the building HVAC systems in the epidemic.

## 1. Introduction

The COVID-19 suddenly outbreak in the earlier 2020 and spread rapidly worldwide. However, there are currently no consistent conclusions with regards to the virus transmission mechanism and approaches. Possible ways include contact transmission, droplet transmission and aerosol transmission, among which the former two are relatively acknowledged by the public [1]. As for the aerosol transmission, controversial viewpoints existed, for example, the virus outbreak and transmission in the Diamond Princess cruise ship [2]. Some current researches indicate that different sizes of droplets would form when patients cough or sneeze, and the droplets with bigger sizes quickly deposit in the range of 1~2 m. While droplets with relatively smaller diameters enable to transmit for a long distance, depositing more than 2 m from the patient source. In this case, for individuals, keeping individual distance and wearing personal protective equipment are effective ways to decrease the risks for droplet transmissions [3].

The issues of virus transmission have been paid more attention for public buildings such as offices, hotels, commercial buildings and public transportation, to maintain the development of the economy. Especially for HVAC systems in buildings, at the initial periods of COVID-19 outbreak, it is questioned by the common public: whether the virus may spread through the air-conditioning system in buildings when the sys-

tem is on; how to deal with such situations and how to conduct the precautions of HVAC systems in a building. Due to a lack of sufficient knowledge for this kind of virus, people once were panicked at the use of air conditioning systems in buildings while no corresponding guidelines or suggestions were available for the existing operation and management specification for HVAC systems in buildings [4].

In response to such questions, the authors re-thought the engineering solutions regarding HVAC operation in buildings and proposed appropriate operation strategies for various systems during the COVID-19 pandemic periods at the beginning of the earliest pandemic outbreak. Such control and strategies were adopted by a guideline entitled "Guidelines for an emergency operation and management of office buildings for dealing with novel coronavirus (T/ASC08-2020)", issued by the Architectural Society of China issued [5]. This was the earliest file regarding HVAC operation in China, which provided effective strategies and guidelines for HVAC operations during the COVID-19 pandemic and referred by later published files. In this study, we aim to combine with the previous engineering experiences by the authors and elaborate the main principles and approaches of operating the building HVAC systems, to ensure a safe and comfortable indoor environment. Meantime, it ensures the potential and ability of HVAC systems and minimizes the transmission risks during the COVID-19 pandemic. Certainly, through rethinking the adaptive HVAC designs in buildings, the

\* Corresponding author.

E-mail address: [panyg@cadg.cn](mailto:panyg@cadg.cn) (Y. Pan).

<https://doi.org/10.1016/j.job.2021.102889>

Received 25 January 2021; Received in revised form 24 May 2021; Accepted 13 June 2021

Available online 22 June 2021

2352-7102/© 2021 Elsevier Ltd. All rights reserved.

proposed operations and management are not only suitable for the COVID-19 virus, but also for other pandemic scenarios, which contribute to the concept of combining normal time with the emergency in buildings in future.

## 2. Concept of engineering thinking

Human thinking is a significant feature that distinguishes human from animals. The way of thinking is also regarded as the people's passive and active responses to the world, serving as a basis to guide all human activities. Generally speaking, there are two ways for human thinking: scientific and engineering [6]. For any engineering activities, they are to achieve a designed goal under certain constraint conditions. However, during this process, a creative but convergent thinking mode is needed, which is named "engineering thinking". Considering the operation of building HVAC systems, as a typical engineering activity, is highly dependent on the methodology of engineering thinking, the following sections firstly discussed the basis of engineering thinking and its practical applications in HVAC management [7].

### 2.1. Core and objective of engineering thinking

The core of scientific thinking is truth-oriented, as it focuses on understanding the world, namely, answer "what" and "why" of the objective world is. A typical example is a basic research on COVID-19 (pathogenesis, mode of transmission, etc.). In contrast, engineering thinking pays much attention to transforming the world. It works to answer "what people should do". Engineering activity is indeed an activity with constrained conditions. For example, under current situations of the COVID-19 epidemic, to get the maximum protection and reduce the risk of infection, the best way is to stop any social or production activities, but this is impossible and unrealistic. To maintain economic and society development during the pandemic period, normal activities/productions in buildings should be ensured. In this context, the core of engineering thinking is value-oriented and it acts to solve the practical problems with prerequisites. Therefore, the value orientation should be considered when taking measures for the HVAC system under the emerging COVID-19 pandemic situation. That is, to optimize the HVAC operations to maintain the normal operation of buildings and coordinate the development of society and economy, based on controlling COVID pandemic situations rather than pursuing zero infection.

### 2.2. Fundamental principles of engineering thinking

#### ① Baseline principle

The engineering activity should be following the basic laws of science. The basic laws obtained by scientific research should not only provide basic guidance for technological invention but also provide a baseline for engineering practice. All engineering practices should exist with a prerequisite of basic scientific principles. In the process of pan-

demical prevention and control, all works must be conducted based on basic medical research and achievements.

#### ② Value principle

Value maximization serves as the optimal objective in engineering thinking. In particular, the goal for each project is to achieve the expected value with minimum cost. Therefore, the output/input ratio is often the primary concern for every engineer and administrator. For example, the different measures taken by different countries around the world to deal with the outbreak of the COVID-19 pandemic are essentially an optimization of the output/input ratio, according to the actual situations among different countries.

#### ③ Spatial and temporal principle

There is no engineering technology that is "one-fit-all". All engineering activities and value creation are referred to the already mastered resources and experiences (e.g., basic scientific principles, technological achievements, natural and social resources, etc.).

### 2.3. Engineering thinking application for the HVAC

According to the aforementioned three fundamental principles, several perspectives should be considered when balancing and optimizing the HVAC operation strategies.

#### 2.3.1. Combination of goal and process

The goal of HVAC designs is to create a comfortable indoor environment. During this process, there are demands for objective requirements and subjective initiation by people, while the latter often plays a crucial role. The whole process is achieved by a cascade adjustment system with strong subjective interference, as shown in Fig. 1, which enables to correct the goal and measure continuously and timely.

Taking the indoor temperature control in hospital wards and hotels with adjustable air supply terminals as an example, each occupant would have specific requirements when entering the room. Although the temperature has already been set up, patients and guests must be enabled to adjust the terminal airflow rate flexibly to achieve the setting conditions in a short or long time. When a higher airspeed at the terminal is chosen, the temperature can be achieved within a short period, while it may cause a higher noise caused by high fan speed. In contrast, when a lower airspeed at the terminal is chosen, though it takes relatively a long time to achieve the setting conditions, the room would be quiet during this process.

#### 2.3.2. Theory and experience

The basic theory takes advantage of revealing the objective essence, while the engineering experience reflects practical achievements. The majority of the basic theoretical research on HVAC systems are obtained under certain conditions, but there are also some engineering activities conducted beyond the conditions. Therefore, the importance of

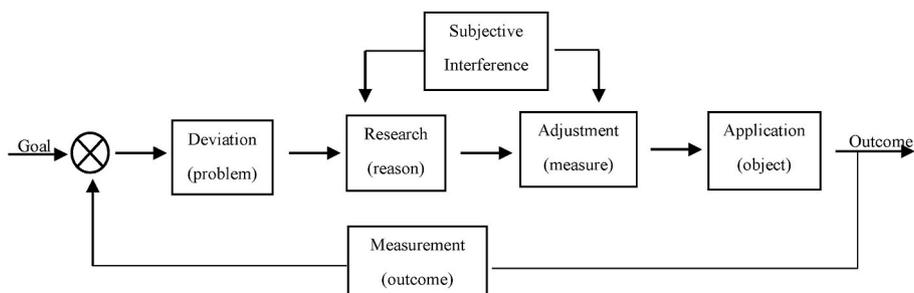


Fig. 1. Goals and process.

engineering experience in specific projects should be highlighted. As no clear conclusions for the air transmission characteristics of the COVID-19 virus presently, the corresponding operation strategies can only refer to theoretical analysis and previous experience, combining with the specific features of building HVAC systems.

### 2.3.3. Demand and restriction

Pursuing comfortable environments is the fundamental demand for people. However, there are various restrictions when making the HVAC operation strategies for a certain project, including the resources, geography, climate, investment and management. When no pandemic occurs, energy saving of the HVAC system is one of the most important requirements. The maximum comfort is pursued with the whole goal of energy consumption limitations. During the pandemic, the demands are transferred to transmission prevention, to ensure people safety and health. In such cases, engineering thinking is to maximize the benefits by optimizing and integrating suitable technologies and measures.

### 2.3.4. Rules and breaks

Rules are the laws in engineering and presented by regulations, by-laws, guides, specifications and other legal documents, which serve as baselines for all kinds of engineering projects. However, most of the engineering rules are the summary of previous experience. When an unprecedented problem occurs, the existing rules may be unsuitable. In this case, breaking the existing rules is necessary from the perspective of engineering thinking. However, this needs an innovative system, and its rationality should be verified critically. The issue of the "Guidelines for an emergency operation and management of office buildings for dealing with "novel coronavirus" in China is indeed the outcome under such situations.

### 2.3.5. Partial and holistic view

The partial and holistic view is a way of thinking about how to achieve the optimization of the goal and the holistic value. Under the circumstance of pandemic prevention and economic recovery, basic principles of engineering thinking are needed in the application. In the premise of virus transmission, a good indoor air environment is needed and the major goal should be changed dynamically responding to different cases.

## 3. Re-thinking of building ventilation

### 3.1. Delusion effects of fresh air and airflow rate

During the SARS outbreak in 2003, through in-depth onsite investigation in hospital wards, it was found that if the dilution ratio of the total ventilation airflow rate reached more than 10,000 times to the patients' exhaled airflow rate, the air in the wards with patients would be safe [8]. That is, theoretically healthy people who enter the wards with enough ventilation will not be infected with coronavirus, even no protective measures are taken. If the amount of air exhaled by each patient is about  $0.3 \text{ m}^3/\text{h}$  and thus the dilution ventilation required for each patient ought to approximately  $3000 \text{ m}^3/\text{h}$  according to the dilution ratio of 10,000 times.

In contrast, the designed fresh airflow rate for infection wards is about 12 ACH [9] based on the current design standards. For each ward, the fresh airflow rate ranges from 500 to  $600 \text{ m}^3/\text{h}$ . The ventilation flow volume cannot meet the requirements and is much less than the demands of  $3000 \text{ m}^3/\text{h}$  for safety delusion ratio. Therefore, it is necessary to take strict personal protective measures for healthy people like medical personnel, etc., when entering the ward. In addition, the special designs for ventilation airflow patterns in the infection wards should be carefully made.

As for the design criteria for ordinary civil buildings, the minimal fresh air design is based on the basic hygienic needs and the  $\text{CO}_2$  con-

centration is considered. For most civil buildings in China, the fresh airflow rate is about  $30 \text{ m}^3/(\text{h}\cdot\text{p})$  [10]; it cannot ensure the safety demands without protective measures. In fact, for common civil building, the actual indoor fresh airflow rate varies during the operation of the HVAC system and is closely related to the types of the HVAC systems. For the HVAC system with fan coil unit (FCU) + fresh air system, the fresh air volume is usually equal to the design value, which cannot be increased significantly over the whole year. While for an HVAC system equipped with the dual-fan AHU system, the system enables to adjust the fresh airflow rate with time, in order to make full use of fresh air during the transition season and pursue energy savings.

### 3.2. Safety for outdoor air

When the COVID-19 broke out early in China, it was first compared to the SARS in 2003, which was also transmitted by the corona virus. Though the basic reproduction number (RO) of COVID-19 and SARS are not exactly the same, they have a similar transmission carrier. Therefore, it is reasonable to refer to some known knowledge of SARS and put forward corresponding countermeasures for the COVID-19. At the early stage of the pandemic, in cooperation with the research team of Tsinghua University, we adopted the Gaussian plume diffusion model and explored the diffusion and dilution of aerosols in the atmosphere, under scenarios of the outdoor average wind speeds being  $0.2 \text{ m/s}$  (nearly windless),  $1.0 \text{ m/s}$  and  $3 \text{ m/s}$  respectively. Coupled with previous findings during the SARS period, the conclusions show that when it is windless (the average wind speed  $\leq 0.2 \text{ m/s}$ ), it is safe to maintain a distance of more than 5 m with the patient; while when the outdoor wind speed increases, it is equal to increase the air exchange rate, and thus the safety distance is shortened [11]. To note, the clean air mentioned in the paper especially refers to air without virus, or air is diffused to a safe concentration, including both fresh air from the outdoor and filtered air without virus. Despite this, the results confirm that it is safe to keep the aforesaid distance for a long time stay when engaging in outdoor activities. Therefore, the outdoor air is quite safe for the prevention of the COVID-19 pandemic.

## 4. Re-thinking of engineering operation for building HVAC systems during the COVID-19 pandemic

Unlike the wards for patients, the common buildings differ in many ways such as design, construction, operation and management. Thus, the main goal is to ensure the indoor environment and prevent virus transmission, where a trade-off of pros and cons is needed.

According to the previous analysis, due to the safety of outdoor air, increasing the fresh airflow rate is beneficial for the dilution of indoor air pollutants and is an effective approach to prevent virus transmission in an indoor environment. With such perspectives, operations for several typical HVAC systems are discussed in the following sections. To note, buildings with radiant heating/cooling systems and radiators for heating have no indoor-outdoor air exchange, the indoor air diffusion and pollution of coronavirus is exclusively considered in this study. In addition, as there is no mechanical air supply in most of the residential buildings in China, increasing the ventilation by opening windows is the best precaution during the pandemic for such residences. Therefore, this paper mainly focuses on the buildings with air convection systems and terminals such as office, hotel, shopping mall and transplantation, and discusses the appropriate operation strategies for HVAC systems.

### 4.1. Operation for fan coil unit (FCU) plus fresh air system

Given the fan coil unit (FCU) plus fresh air system is the most commonly used HVAC system in buildings, several typical types are discussed here.

#### 4.1.1. Application of indoor convective terminals

The terminal devices of the FCU and the direct expansion air conditioning systems are both convective heat transfer terminals. Thus there is a concern whether such terminals would expand the indoor virus spreading under the assumption that a “suspected” patient is in the space. However, considering at present the commonly used air distribution modes are “upper-supply and upper-return”, “upper-supply and lower-return”, “side-supply and side-return”, the answers are dependent:

- 1) If the concern is about the settled “droplets” being stirred by the air supply and spreading in the air again, it can be possibly explained by the fact: most of the settled droplets have adhered to the ground or the lower surfaces of the furniture. According to the simulations of the air distribution in the room, if the return air velocity in the occupied zone is well controlled with not more than 0.3 m/s [22] in the HVAC system, there is no obvious diffusion effect for the settled particles, except for the air distribution of “the lower supply and lower return”. It is unlikely the settled droplets on the floor will be transmitted to air by the HVAC system.
- 2) If this concern comes from the spread of “virus aerosol” in the indoor air, the judgement based on the distance of each seat in the office room is less than 5 m, and the actual activity radius of the occupants inside the office building has far exceeded the safety radius (1~2 m) for droplet transmissions, even more than 5 m. If the virus aerosol exists, the speed and intensity of transmission through the fan coil or indoor air unit are much weaker than that caused by occupants' movement in the space. In this case, the transmission caused by the HVAC system is slight. This is in agreement with ASHRAE guidance for building operations, where the HVAC systems play a minor role in infectious disease transmission [12].

#### 4.1.2. Increase of fresh air volume

##### ① Room with exterior windows

If the exterior windows are available in the room, the most direct and effective measure is to properly open the exterior window, as shown in Fig. 2.

If the fan of the PAU has a constant speed, the designed maximum airflow rate is indeed the minimum fresh airflow rate required by the hygienic standard. When the exterior window is opened, the air supply resistance of the whole fresh air system decreases, due to the enhanced exhaust air effectively. The decreased value is equal to the value that maintains the positive pressure (5–10Pa) indoors under the common design conditions. According to the coupling performance curve of the fan and the air supply duct, under the condition of opening windows, the airflow rate of the fresh air system can be increased by about 5%–10%.

If a variable speed fan has been used in the PAU and operated at low speed during normal operation situations, i.e., meets the minimum fresh airflow rate, the fan speed could be increased during the pandemic. In this way, the fresh airflow rate would be much more than the minimum value, which is beneficial for diluting the indoor air pollutants.

##### ② Room without exterior windows

There are two commonly used ventilation design patterns for rooms without exterior windows.

##### 1) Cross-flow air heat exchanger

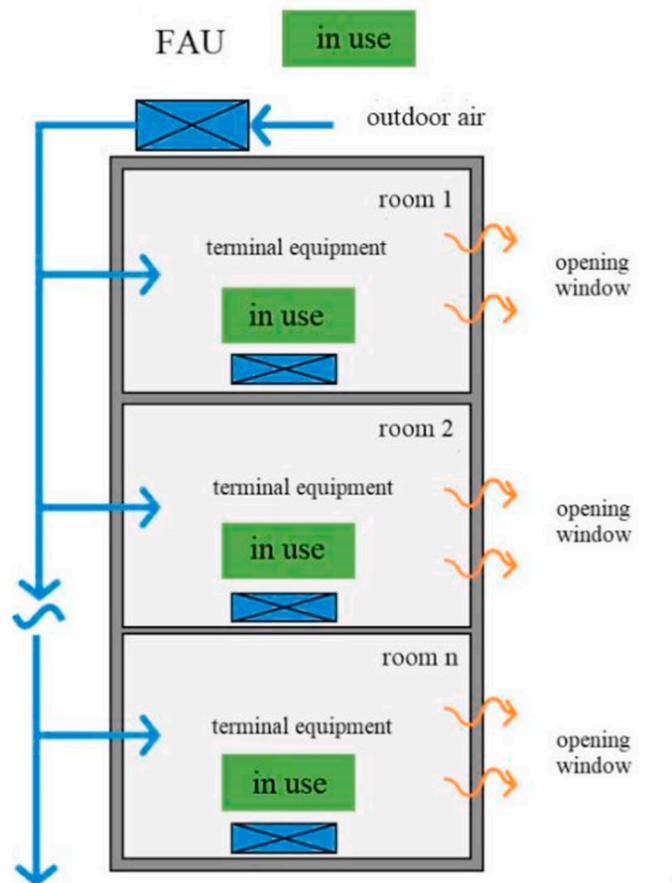


Fig. 2. Room with exterior windows – open the windows.

Fig. 3 shows the application of one air heat exchanger installed in one single room. In actual projects, one air heat exchanger can serve multiple rooms (connecting with air duct) and the setting and working principles are the same as those serve for one single room. The two kinds of settings have the same controlling and operating methods, namely, supply fresh air to the indoor space. As a result, they are different from the HVAC systems that are designed to maintain proper room temperatures.

There are three widely used types of heat exchanger: plate-fin type made by polymer membrane (Figs. 3–1), rotary heat recovery wheel (Figs. 3–2) and plate-fin type made by metal (Fig. 3–3). According to Ref. [13], the pollution rate of exhaust air to fresh air is about 6%–9% for polymer membrane plate-fin type heat exchanger and about 10%–30% for rotary heat recovery wheel. Due to no mass transfer for metal plate-fin type heat exchanger (Fig. 3–3), there is no consideration of cross-contamination for the third type. In contrast, the first and second types of heat exchanger must be modified before the operation, to prevent cross-contamination. A simple way is to bypass the fresh air to completely separate the fresh air from the return air. In such conditions, the principle of value-orientated should play the dominant role: no heat recovery is available and pandemic prevention should be given priority over energy-saving in normal situations.

##### 2) Centralized fresh air supply and exhaust system for each floor in the buildings

Ensuring the effective ventilation for each room should be given priority for such HAVC system in buildings. In this case, measures such as opening the door, setting a grille louvre on the room door, or installing the ventilation duct (or fan) between the room and the corridor, etc. can be adopted. This ensures that the air in the room can be exhausted

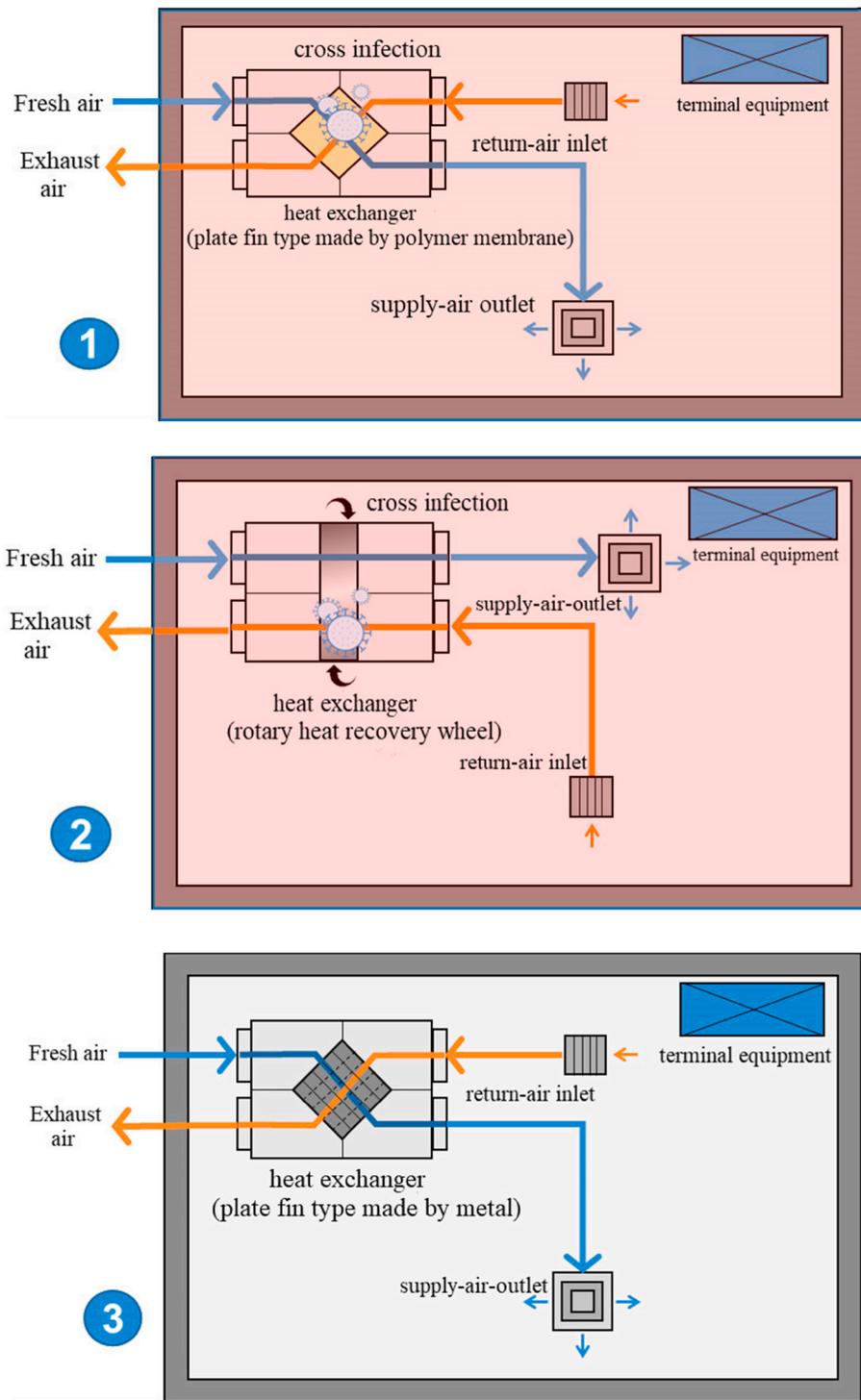


Fig. 3. HVAC systems with different plate-fin type heat exchanger: 1. polymer membrane, 2. rotary heat recovery, 3. metal.

to the corridor more effectively and then quickly be exhausted to the outdoor by the centralized exhaust system set in the hallway.

#### 4.2. Operation for all-air system

Being different from the “FCU + PAU” air conditioning system, the all-air system is equipped with centralized return air duct, which causes more worries and concerns for the virus transmission in such systems.

##### 4.2.1. Single room based all-air system

There are two commonly used all-air systems for single space. One is a single fan system (only the supply fan is equipped, see Fig. 4(a)), and the other is a double fan system (supply fan and return fan or exhaust fan are equipped, see Fig. 4(b)).

When the all-air system only serves for a single room, the return air delivered by the centralized return air duct is from the served space. According to the previous analysis for the fan coil unit in the room, the return air in such a system would not expand the virus diffusion in the room. Therefore, it is safe for an all-air system servicing a single room, when it is operated properly as usual.

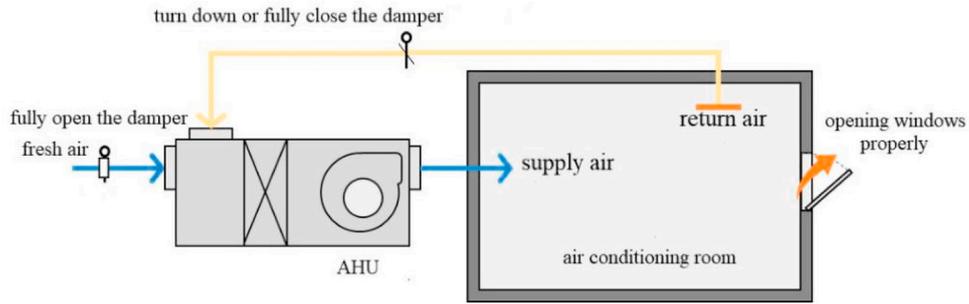


Fig. 4a. Single-fan AHU system serving one room.

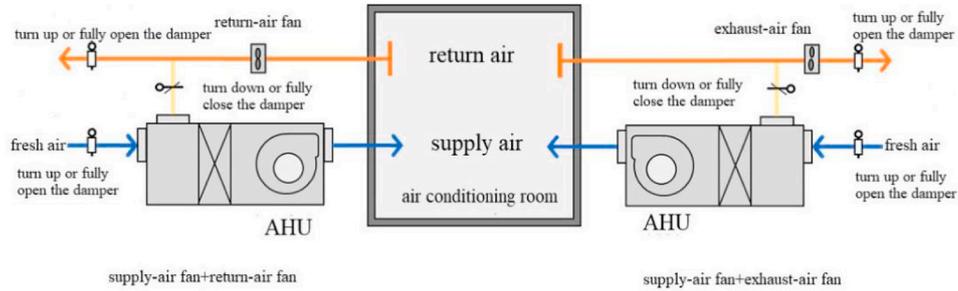


Fig. 4b. Dual-fan AHU system serving one room.

To increase the fresh airflow rate as much as possible during the pandemic period and maintain the necessary room temperature at the same time, appropriate measures can be taken by properly turning up the fresh air damper, turning down the return air damper and opening the exterior windows. For systems in Fig. 4, the size of the fresh air duct is smaller than that of the supply air duct in most actual buildings. Despite this, the fresh airflow rate can be increased by about 12%–15% compared to the designed condition, when the return air damper is closed. This is approximately equal to 35%–50% of the designed flow rate for supply air.

4.2.2. Several rooms based all-air system

The variable airflow rate system with terminal box (VAV Box) widely used in office buildings is a typical application for multiple rooms (see Fig. 5). The return air from various rooms are recollected and ducted back to the air handling unit, and then sent to each room again through the supply air fans and ducts. In this case, if the air in one room is contaminated, there would be risks for cross infection among rooms through air redistribution via the air duct systems. Considering the lack of fully understanding of the COVID-19 virus and its mecha-

nism through aerosol transmission, such situations should be avoided as possible. Therefore, it is reasonable to close the return air damper to prevent cross-infection via the VAV system in an office building. The air handling units are recommended to switch to 100% outdoor air. Also, it is an alternative to set high efficient air filter inside AHU, which ensures clean air delivered into the room. However, the efficiency and performance demands of such air filter are underexplored.

4.3. Measures to guarantee indoor temperatures

When the fresh airflow rate is increased compared to the designed conditions, the capacity of cooling/heating coils for the air conditioning unit (AHU or PAU) maybe not enough. Therefore, necessary control measures for the HVAC systems should be considered, to operate according to the actual situation and ensure acceptable comfort for occupants.

For the centralized cooling/heating system, the setting points for the supply temperature of chilled water should be appropriately reduced as far as possible for central cooling, while the hot water supply temperatures for heating should be also increased, to meet optimal ability. In

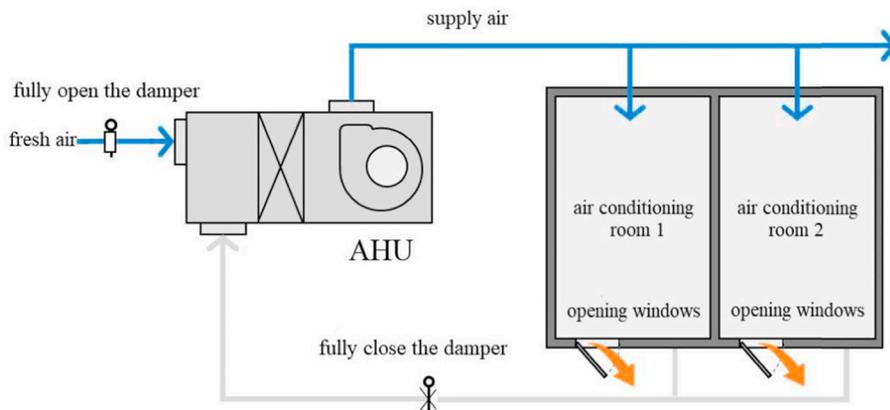


Fig. 5. VAV system serving several rooms.

terms of terminal control, it is suggested to reduce the temperature setting points for cooling and increase setting points for heating. For the direct-expansion unit, the evaporation temperature should be properly reduced during cooling and the condensation temperature should be increased appropriately during heating.

In addition, during transition seasons, there is no need for heating or cooling. Introducing fresh air by natural ventilation and mechanical ventilation would benefit the building energy-saving, meantime improve the indoor air quality and comfort. In particular, it is significantly encouraged to respond to the pandemic precautions.

## 5. Discussions

### 5.1. Building HVAC operations under pandemic situations

In engineering and social practice, value is always a key element. Under normal conditions, the HVAC systems ensure to create a good environment for buildings, meantime achieve energy savings and carbon emission reduction as much as possible. However, in the pandemic period, pandemic prevention has become the core for the whole society. Despite this, the normal work/life should be still guaranteed, to maintain the economy and social development. Therefore, this study innovatively adopts the “engineering thinking”, that is, to maximize the building operation and develop the society/economy and meantime prevent and control the new pandemic transmission. It addresses the goal of controllable risk instead of an absolute “zero infection”. In other words, taking excessive pandemic prevention and control measures will inhibit the normal use of buildings, but do not consider pandemic prevention and pursuing a high comfort environment are against the baselines from the point of view of engineering thinking. As a result, this study addresses the balance and coordination in Section 2.3, from five aspects of goal and process, theory and experience, demand and restriction, rules and breaks as well as partial and holistic view, regarding the actual practice of HVAC design and operation. It is inconsistent with the principle of engineer thinking if just one aspect is highlighted. From this point of view, this study proposes the concept of creating an “acceptable indoor environment” during the pandemic period and provides the strategies of increasing fresh air or clean air via building HVAC systems. This addresses the value optimization, considering the overall requirements of pandemic prevention and control.

During the SARS epidemic periods in 2003, increasing the fresh air ventilation was encouraged and promoted. However, few relevant research was available on how to properly operate the building air conditioning system during the COVID-19 epidemic, particularly in the earlier stage of the COVID-19 outbreak. This thus raises a worry and misleading for the public that the HVAC system may increase the risks for virus transmissions and should not be used in buildings. Under such contexts, the innovations of this study are objectively analyzing the different types of building HVAC systems and proposing appropriate measures for operations. The authors had engaged in setting operation strategies and edited the guidelines in earlier February 2020 [5]. It was beneficial for advancing understandings of people on HVAC operations during the epidemic period and managers to control the system safely. Later with the unexpected outbreak and transmission of the COVID-19 around the world, the U.S. ASHRAE issued two statements on April 2020 [12]; the REHVA in Europe updated the COVID-19 guidance document on April 2020 with seven revisions and additions [14]; the CIBSE in the UK issued the coronavirus COVID-19 and HVAC system in May 2020 [15]; the Japan SHASE also issued the operation of air conditioning equipment in May 2020 [16]. Overall, all these guidelines were issued after May 2020 and the contents varied slightly among different standards. Sufficient ventilation with effective airflow patterns has been also highlighted as the most efficient control strategy for infectious diseases in buildings [17], by diluting the indoor air around the source and removing the infectious agents. In late 2020, the WHO [18] had also ad-

vocated the viewpoint of increasing ventilation in public, which gradually alleviates the fear of using HVAC systems in buildings. However, on the other hand, this is expected to have a higher ventilation thermal load in buildings and thus higher energy and economic costs; a trade-off between both should be explored further. In addition, the WHO only considered aerosol transmission when procedures or support treatments that produce aerosol are performed. Due to the underlying uncertainty of the transmission mechanism and characteristics of COVID-19 in the air, the specific ventilation rate eliminating the risks of transmission of the airborne virus has not been established [19].

### 5.2. HVAC operations in future buildings based on value orientation

For future buildings, the general thoughts of the new strategies include two goals, one is to ensure the safety and healthiness of people, the other is to provide the best indoor environment. According to engineering thinking, the first goal is mandatory and the second one is optional which needs to be optimized.

#### 5.2.1. Operation strategies of HVAC systems in the existing building in the post-pandemic

During the pandemic, safety and healthiness should be put in the first place. Combined with the actual situations in the existing buildings, it is important to provide an acceptable indoor environment as much as possible.

When the buildings are in operation, increasing the indoor ventilation rate to dilute the virus concentration is one of the effective ways. However, decreasing the resistance of the ventilation system during this process should be considered. The possible strategies include opening doors and windows, decreasing the resistance of fresh air ventilation system and decreasing return airflow rate, etc. On the other hand, increasing ventilation may lead to the invasion of scorching air in the summer and freezing air in the winter, which disturbs the HVAC system to maintain a proper indoor environment. Therefore, it is essential to focus on regulating the indoor temperatures during the process. Reasonable automatic control measures and changing heating and cooling parameters at terminals should be taken to maintain an acceptable indoor environment.

#### 5.2.2. Suggestions for the construction and design of new buildings based on a concept of combining normal time with emergency

Responding to this COVID-19 pandemic, a concept of combining normal time with the emergency in building designs is carefully considered and accepted by populations, which reflects the engineering thinking well. As for HVAC systems in buildings, we should not only consider the requirements under normal situations, such as the comfort of the indoor environment, energy saving during system operations, etc. but also consider the adaptive ability for sufficient clean air exchange volume when an unexpected pandemic occurs. Based on the aforementioned analysis of the various HVAC systems, some suggestions can be summarized here:

- 1) Each room in use is suggested to have openable external windows. When it is not guaranteed due to specific reasons, the designed air supply volume of the fresh air system in rooms should reach more than 200% of the normal fresh air volume according to the health standard. The ventilation system can be operated daily to meet the standard of hygienic fresh air volume; in case of a pandemic, the system has adaptations to operate in maximum designed fresh air volume.
- 2) For the all-air system, the “double fan system” shown in Fig. 4 is encouraged. When the pandemic occurrences, it can turn off return air and increase the fresh air exchange rate in the room. When the all-air system serves for multiple rooms, in addition to the air filters

that meet the normal use, the system should be able to replace or add filters with high and medium efficiency in case of a pandemic.

- 3) The adjustable fans with variable speeds are recommended in AHU and PAU systems, which can operate at low speed at daily times and at high speed in case of a pandemic situation.
- 4) When the exhaust air heat recovery is equipped in the fresh air system, the bypass shall be set at the fresh air side or exhaust air side.

In addition to designs, proper operation of the HVAC system, such as running system 2 h before and after occupancies, or keeping low ventilation rates even without occupancy are suggested. Moreover, the HVAC filters have been acknowledged for reducing virus transmission; the ASHRAE also recommends the measure of increasing the filter level in the air-conditioning system. However, at present, the return air filters in the HVAC system usually use filters with pore diameter often  $> 1 \mu\text{m}$ , which do not meet HEPA standards and are usually unable to filter virus particles effectively. As using high-efficiency filters would inevitably increase system resistance, there should be a trade-off of choosing an appropriate air filter. This reminds us to rethink the design and operation of buildings during extreme events such as a global pandemic. Awada et al. [20] discussed some questions concerning occupant health in buildings during normal operations and extreme events including the COVID-19 pandemic. The current buildings are not well equipped to combat airborne transmissions of infectious diseases efficiently. The HVAC equipment is sized and selected under normal design conditions and it has not adequate ventilation flexibility or cleaning capacity to cope with these events.

Therefore, for the post-epidemic era, how to design buildings and HVAC system appropriately should be carefully considered [21]. Designers, facility managers, and occupants need pragmatic guidance to reduce health risks and a combination of normal time with the emergency in buildings is highly expected in future. To note, since there is no thoroughly and widely recognized research upon the transmission mechanism, the intensity of pathogenesis and other basic knowledge on COVID-19 virus, it is relatively difficult to quantify some measures, for example, the accurate volumes of clean air for ventilation. Therefore, deeper research cooperation in future should be encouraged in interdisciplinary, including architecture, engineering and medical field, to advance our understandings both in basic science and technology applications.

## 6. Conclusions

Being different from exploring the mechanism of COVID-19 transmission in the scientific field, this study innovatively proposes applications of engineering thinking and principles in building ventilation and HVAC operations. From a review of the existing findings, increasing the fresh air for ventilation is identified as one of the most efficient ways during the pandemic period to ensure building operation. The design of the HVAC system should be adaptive by foreseeing the needs of emergent situations such as the pandemic. The larger volume of fresh air supply should be considered in the design. The design flexibility of an HVAC system should be considered such as a backup fan system, extra filtration system and disable the heat recovery system at emergencies. Such measures are value-orientated and based on engineering practice experiences, which provides alternative considerations of increasing fresh airflow rate during a pandemic and achieving thermal comfort and energy savings during normal situations in future buildings.

## Author statement

Yungang Pan: Conceptualization, Writing-Original Draft, Supervision, Project administration.

Chenqiu Du: Fundamental Research, Writing-Review & Editing.

Zhuzhou Fu: Methodology, Writing-Review & Editing.

Mushu Fu: Resources, Writing-Review & Editing.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgement

The work was supported by the National Key R&D Program of China (Grant No: 2018YFC0705000). The authors also thank for the theoretical supports offered by professor Bin Zhao from Tsinghua University in his article "the key to prevent the spreading of COVID-19".

## References

- [1] WHO, Transmission of SARS-CoV-2: implications for infection prevention precautions, 2020. <https://www.who.int/news-room/commentaries/detail/transmission-of-sars-cov-2-implications-for-infection-prevention-precautions>.
- [2] S. Zhang, et al., Estimation of the reproductive number of novel coronavirus (COVID-19) and the probable outbreak size on the Diamond Princess cruise ship: a data-driven analysis, *Int. J. Infect. Dis.* 93 (2020) 201–204.
- [3] ASHRAE, ASHRAE position document on infectious aerosols, 2020. [https://www.ashrae.org/file%20library/about/position%20documents/pd\\_infectiousaerosols\\_2020](https://www.ashrae.org/file%20library/about/position%20documents/pd_infectiousaerosols_2020).
- [4] GB50365-2005. Code for Operation and Management of Central Air Conditioning System, Issued by Ministry of Construction of China, General Administration of Quality Supervision, Inspection and Quarantine of China, 2006-03-01 (In Chinese).
- [5] T.. Asc08-2020, Guidelines for Emergency Operation and Management of Office Buildings for Dealing with "Novel Coronavirus", The Architecture Society of China, 2020-02-05 (In Chinese).
- [6] B. Li, Engineering and engineering thinking, *Science* 66 (6) (2014) 13–16 (In Chinese).
- [7] Y. Pan, X. Fu, M. Chen, Reflection on cultivation of engineering thinking in undergraduate education of building environment and energy application engineering, *HV&AC* (2018) 48 (In Chinese).
- [8] Y. Jiang, B. Zhao, X. Li, X. Yang, Z. Zhang, Y. Zhang, Investigating a safe ventilation rate for the prevention of indoor SARS transmission: an attempt based on a simulation approach, *China-Build Simul 2* (2009) 281–289.
- [9] GB50849-2014, Code for Design of Infectious Diseases Hospital, Ministry of Housing and Urban-Rural development of China, 2015-05-01 (In Chinese).
- [10] GB50736-2012. Design Code for Heating Ventilation and Air Conditioning of Civil Buildings, Ministry of Construction of China, General Administration of Quality Supervision, Inspection and Quarantine of China, 2012-10-01 (In Chinese).
- [11] B. Zhao, Safe Distance between People during Outdoor Activities-Control and Prevention for Coronavirus COVID-19, Building Energy Efficiency Center for Tsinghua University, 2020-02-14 (In Chinese).
- [12] ASHRAE, ASHRAE issues statements on relationship between COVID-19 and HVAC in buildings, 2020. <https://www.ashrae.org/about/news/2020/ashrae-issues-statements-on-relationship-between-covid-19-and-hvac-in-buildings>.
- [13] J. Nie, Z. Li, Q. Zhang, G. Wang, L. Fang, Experimental Measurement and Analysis of Contaminants Transfer in Total Heat Recovery Unit, *Building Science*, 2017-08.
- [14] REHVA, REHVA COVID-19 guidance document, 2020. [https://www.rehvaeu/fileadmin/user\\_upload/REHVA\\_COVID19\\_guidance\\_document\\_ver2\\_20200403\\_1.pdf](https://www.rehvaeu/fileadmin/user_upload/REHVA_COVID19_guidance_document_ver2_20200403_1.pdf).
- [15] CIBSE, Coronavirus COVID-19 and HVAC systems, 2020. [http://www.cibse.org/coronavirus-\(covid-19\)/coronavirus-covid-19-and-hvac-systems](http://www.cibse.org/coronavirus-(covid-19)/coronavirus-covid-19-and-hvac-systems).
- [16] SHASE, Operation of air-conditioning equipment and other facilities as SARS-CoV-2 infectious disease control 2020, [http://www.shasej.org/recommendation/Operation\\_of\\_air-conditioning\\_equipment\\_and\\_other\\_facilities20200407.pdf](http://www.shasej.org/recommendation/Operation_of_air-conditioning_equipment_and_other_facilities20200407.pdf).
- [17] L. Morawska, et al., How can airborne transmission of COVID-19 indoors be minimised?, *Environ. Int.* 142 (2020) 7.
- [18] W.H.O. Coronavirus, Disease (COVID-19) advice for the public: mythbusters, 2020. <https://www.who.int/emergencies/diseases/novel-coronavirus-2019/advice-for-public/myth-busters>.
- [19] M. Guo, P. Xu, T. Xiao, R. He, M. Dai, S.L. Miller, Review and comparison of HVAC operation guidelines in different countries during the COVID-19 pandemic, *Build. Environ.* 187 (2021) 107368.
- [20] M. Awada, B. Becerik-Gerber, S. Hoque, Z. O'Neill, G. Pedrielli, J. Wen, T. Wu, Ten questions concerning occupant health in buildings during normal operations and extreme events including the COVID-19 pandemic, *Build. Environ.* (2020) Available online, <https://doi.org/10.1016/j.buildenv.2020.107480>.
- [21] J. Wang, Vision of China's future urban construction reform: in the perspective of comprehensive prevention and control for multi disasters, *Sustain Cities Soc* 64 (2021) 102511.
- [22] Z. Xu, *Principles of Air Cleaning Technology*, third ed., Science Press, 2003.