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Editorial

Indoor and Built Environment

Indoor and Built Environment
2023, Vol. 32(10) 1893–1899
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DOI: 10.1177/1420326X231201440
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Healthy and resilient HVAC design for public buildings in post COVID-19 pandemic era

Na Li[1], Chunwen Xu[1] and Chuck Wah Francis Yu[1,2]

Accepted: 31 August 2023

People spend around 90% of their lifetime in buildings that serve important physiological, psychological and social functions, especially when considering public and occupants' health.[1,2] Public buildings, such as offices, hospitals, schools, shopping malls, hotels and transportation spaces, are places where people carry out various public activities with relatively large amounts of space and high flows of people, which can easily lead to airborne disease transmission. The outbreak of COVID-19 since 2019 has raised intense focus on the indoor air quality in these public buildings. Even if the COVID-19 pandemic is at an end as announced by the World Health Organization (WHO),[3] conventional heating, ventilation and air conditioning (HVAC) systems in public buildings are still not capable of coping with potential future severe epidemic situations, and a resilient HVAC would be needed to provide a meaningful retrofit measure to cope with the future epidemics.[4–7]

Back in 2012, the UN responded to natural disaster risk management by referring to the concept of 'resilience',[8,9] which referred to the ability of a system to predict, absorb, adapt and recover from changes in events in a timely and effective manner while retaining its basic structure and function.[10] With reference to this definition, the concept of 'resilient HVAC' was proposed during the pandemic of COVID-19 to develop healthy and energy-efficient HVAC systems for buildings, which aimed to increase the adaptability of buildings in response to this disease.[11] In the post-pandemic period of COVID-19, when public buildings encounter similar public health emergencies, HVAC systems should be able to timely, quickly and reasonably transform into an emergency state to cope with challenges. Flexible design and construction of these HVAC systems by considering both peacetime and epidemic periods will be an important new development direction.

This special issue is a continuation of the Special Issue that was published in June 2022.[4] The special issue addresses the issues of ventilations, HVAC, distribution of airborne and droplet transmissions, restriction control to prevent the spread of COVID-19, community settlement in response to COVID-19 and effects on learning.

This editorial paper focuses on the problems of HVAC systems and the resilience of HVAC systems in response to epidemic/pandemic episodes.

Major problems with conventional HVAC systems exposed during the pandemic of COVID-19

Insufficient fresh air volume

Ventilation is considered an important measure in reducing the airborne disease transmission risk in indoor environments by diluting the pathogen concentrations.[12] The exposure concentration and proximity of the virus of SARS-CoV-2 was found to be a key factor in the accumulation of the virus in the nasal cavity and throat.[13] Amongst the reported transmission modes of SARS-CoV-2 by WHO,[14] including droplet, aerosol, contact and contamination, aerosol transmission is one of the most critical routes for infection prevention and control, and it is usually associated with clusters of infection in public spaces, especially when poorly ventilated. In public buildings where people are in high density, it is often difficult to ensure the delivery of the desired amount of fresh air to individuals. Although the amount of fresh air needed to prevent the transmission of various airborne diseases including COVID-19 is still controversial, for example, the normally used standard, GB/T 18883-2022, Standards for Indoor Air Quality,[15] for the supply of fresh air of 30 m^3/h per person in indoor settings is

[1]College of Pipeline and Civil Engineering, China University of Petroleum, Qingdao, China
[2]The International Society of the Built Environment (ISBE), Milton Keynes, UK

Corresponding author:
Chunwen Xu, College of Pipeline and Civil Engineering, China University of Petroleum, No. 66 West Changjiang Road, Huangdao District, Qingdao 266580, China.
Email: cxu@upc.edu.cn

far from enough in response to the prevention of airborne disease transmission. A total fresh air system or recirculated air system with high efficiency particulate air filter (HEPA) is often recommended during the pandemic of COVID-19, and the corresponding problems with the system, including high energy cost, the adaption of fan pressure and frequent changes of filters, should be fully considered in the HVAC system design.

The surface of the equipment inside the air conditioner may provide a breeding ground for viruses.

The viruses of SARS-CoV-2 were once detected on the surface of exhaust steel pipes in a ship hospital as well as on the air conditioning screen filters in a sanatorium in China.[16,17] This implies the possibility of the HVAC equipment being a breeding ground for these viruses. Experiments conducted on surfaces of several materials indicated that the SARS-CoV-2 could survive on plastic and stainless steel surfaces for up to 72 h.[18] The survival time of SARS-CoV-2 on permeable materials such as textiles and paper towels was reported to be much shorter than that on impermeable materials.[19] An HVAC system is normally composed of complex functional units (e.g. filters, air deflectors, copper evaporators and ducts), and the interior of the HVAC system is often difficult to clean or disinfect, which may easily provide a survival environment for microorganism, including the viruses. Moreover, if the HVAC system is not cleaned and disinfected regularly, it may become a pathway for airborne disease transmission. This implies the necessity to increase the frequency and intensity of virus disinfection for HVAC systems during the outbreaks of airborne diseases.

Low filtration efficiency in present HVAC systems

Droplet nuclei or aerosols generated from various human respiratory activities are normally defined with a diameter of <5 μm.[12] The aerodynamic diameter of the virus SARS-CoV-2 was reported to be around 0.06–0.14 μm.[20] The filtration effect of an HVAC system is important to eliminate the transmission of infectious respiratory particles, especially when the filtration efficiency of particles <5 μm is high. However, most filters used in the present HVAC system for normal operation are coarse and/or medium filters, and their abilities to eliminate airborne respiratory particles are still low. The filtration efficiency of particles >2 μm for a coarse filter is merely about 50% and the filtration efficiency of particles >0.5 μm is about 70%, which is low for the capture of SARS-CoV-2 viral particles, whereas the filtration efficiency of a HEPA for particles >0.5 μm can reach over 99.5%.[21] ASHRAE[22] also recommends the use of MERV-13 high efficiency filters in its documents. However, due to the increase in the filtration efficiency of filters, the operating resistance of the system as well as the resulting fan energy consumption and management costs associated with prolonged use of these high efficiency filters can dramatically increase.

Operating conditions of HVAC system may affect virus activity

Some previous studies indicated the relevance between the viral activity of SARS-CoV-2 and the thermal environment. Santos et al.[23] found that viruses were more likely to be inactivated in environments with relative humidity higher than 80% or temperatures higher than 30°C. Temperatures and humidity were often not independently related to the survival of the virus, and the coronavirus showed strong stability at 21~23°C and relative humidity around 65%. Derby et al.[24] suggested that controlling temperature and humidity could reduce the spread of the virus. When the temperature was increased from 25°C to 55°C, the structure of the viral protein would change significantly. When the relative humidity (RH) was above 80%, the lipid envelope would restrict the flow of the virus. Meanwhile, the protective mechanism of the human nasal mucosa could be impaired at low relative humidity, and some researchers believe the control of humidity in the design of HVAC systems is useful to minimize the airborne transmission of viruses.[24,25] Ahlawat et al.[25] suggested a minimum standard of 40% relative humidity in public buildings to prevent the spread of COVID-19. Santos et al.[23] suggested that humidification should be carried out in cold regions, and the humidity should also be controlled in tropical regions.

However, some studies indicated that the diagnosis of infected cases has an incubation period with a lagging effect and the control of temperature and humidity should have no obvious correlation with the spread of the virus.[26] Federation of European Heating, Ventilation and Air Conditioning Associations (REHVA)[27] also do not consider it necessary to change the setting point of the air conditioner. There is considerable debate about changing the temperature and humidity settings to prevent the spread of viruses. Although there may be relevance between the viral activities and the thermal environment, however, it is still infeasible to control the operation parameters to a range that is not conducive to viral activity without considering human thermal comfort. The settings of HVAC parameters alone cannot be a solid solution to inactivate the viruses, and other intervention measures would still be required.

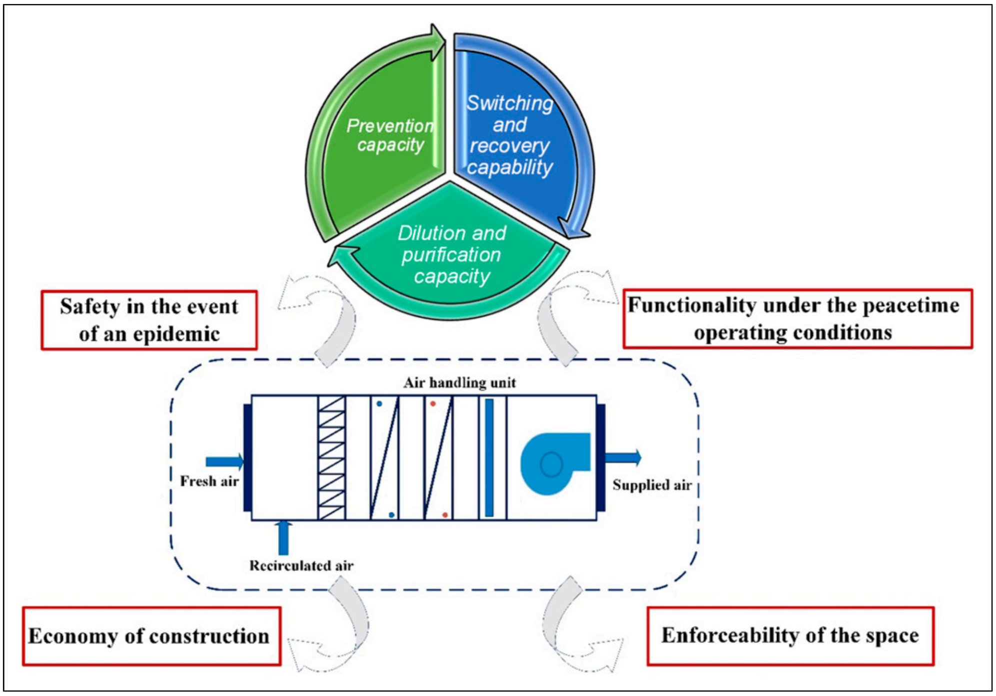

Figure 1. Schematic of the concept of a resilient HVAC system.

Resilient HVAC systems to adapt to both normal and epidemic periods

In view of the uncertain hazard factors in the future, buildings should have the ability to transform rapidly from peacetime to epidemic period in order to reduce the impact of hazards of infectious diseases. The elastic systems are often described by phases of initial conditions, fragility, bearing, recovery and new equilibrium.[28] In this study, three important indicators are proposed to evaluate the capacities of a resilient HVAC system, which should include 1) the prevention capacity, 2) dilution and purification capacity and 3) switching and recovery capacity. Figure 1 shows the basic concept of a resilient HVAC system.

Prevention capacity

Prevention capacity refers to preparedness in response to public health emergencies. Here below are some examples of the prevention measures that can be applied:

- CO_2 sensors can be installed to monitor the indoor air quality.[27] As CO_2 can be used as an indicator of the exhaled pollutants from occupants, the monitoring of CO_2 concentration can aid the control of the operation of the HVAC system to ensure relatively good air quality with sufficient fresh air, especially during epidemics.[29]
- To improve the ability to prevent airborne transmission, the key sanitary components of the HVAC system, such as filters, air supply outlets, surface coolers and ducts, should be cleaned and maintained regularly.[30] For systems with recirculated air, the main components of the HVAC system should be disinfected regularly, especially during epidemics.
- To prevent the spread of aerosols in toilets by maintaining a negative pressure inside is necessary, and regular monitoring of the water seals in the toilets would also be needed.[27] Toilet lids should be closed when toilets are flushed. Toilet exhaust systems should be switched on when the space is occupied, and disinfection facilities such as ultraviolet lamps should be installed to disinfect toilets during the period without occupancy.
- For hospitals, the areas with infected patients need correct pressure differences between the isolation ward and the neighbouring space.[30] When there is a need to shift general wards to isolation wards, an adaptive pressure control and monitoring system would be required.

Dilution and purification capacity

Dilution and purification capacity refers to the ability to reduce the concentration of airborne viral contaminants within a confined space and to reduce the exposure risk of susceptible individuals during an epidemic period.

Dilution ventilation is considered an effective way to reduce the potential airborne infection risk. The dilution effect of contaminants is often determined by the fresh air volume at a certain ventilation principle. A minimum fresh air volume of 30 m^3/h per person is normally used for commercial buildings, like office buildings, schools and transport buildings. During the epidemic period, to enhance the dilution effect of ventilation, the fresh air volume should be maximized in the air system. Natural ventilation would be a good practice as it can achieve a high ventilation rate with low energy consumption and robust energy-saving potential has been shown in warm climate regions.[12] However, most public buildings are equipped with mechanical ventilation, which is incorporated into an air conditioning system. Especially in extremely cold or hot weather conditions, the application of natural ventilation alone cannot meet the thermal comfort requirement for occupants. There should be optimized operation strategies to shift between natural ventilation, mechanical ventilation with recirculated air or mechanical ventilation with full fresh air between the peacetime and the epidemic period.

The HVAC systems in public buildings are normally in the form of all-air systems and/or fan coil systems. Some improvements to these HVAC systems would be helpful in preventing the spread of airborne diseases. For example, for a fan coil system, the return air from ceilings should be prohibited when the ceiling area is shared by different rooms. All-air systems should be run with all fresh air or a fresh air ratio >40% during the epidemic period and the supplied air should be protected from contamination by infected sources.[30]

Despite increasing the fresh airflow volume, the adoption of novel ventilation strategies with higher efficiency than traditional ventilation strategies (e.g. mixing ventilation) would also be helpful to mitigate the airborne transmission risk indoors.[12] The protected zone ventilation and downward ventilation are considered suitable for clinical facilities. Personalized ventilation that is flexible in forms to work with surfaces around the human body (such as desktops, ceilings and seats) can deliver clean air directly to occupants' breathing zone efficiently. Local exhaust ventilation, targeting the human microenvironment, is aimed at eliminating the respiratory particles produced by infectious sources. However, the efficiencies of these localized ventilation strategies are susceptible to several factors, such as the installation locations of the air outlet, the relative distance from the person, the airflow volume and so on.[31] They are still in development and further investigations are needed.

Several air purification measures can be integrated into the ventilation systems to eliminate the spread of viruses, as shown in Table 1. The air purification devices can be roughly divided into two types: fan-driven passive type (e.g. air filters) and active type by releasing purifying substances (e.g. plasma and UV). A combination of different levels or types of filters is a solution to cope with both peacetime and epidemic periods and meanwhile to reduce the whole energy consumption. For example, the coarse and medium efficiency filters can be used during peacetime and switch to high efficiency filters during the epidemic period. In addition, some physical sterilization technologies, such as bionic composite filters, high nano-fibre filters and UV-LED integrated light sterilization devices have emerged, which would provide more options for eliminating viruses from the air during an epidemic.[32]

The chlorine-containing disinfectants, peracetic acid, 75% ethanol and compound quaternary ammonium salts are all effective in inactivating SARS-CoV-2.[14] Amongst them, chlorine-containing disinfectants and peracetic acid are corrosive and are usually used on the surface of objects, indoor environments and space. For the disinfection of metal objects or easily corrosive surfaces, compound quaternary ammonium salt and 75% ethanol would be more appropriate. These disinfectants can be used for cleaning the surfaces of components in an HVAC system, but they cannot be directly added to the room air.

Switching and recovery capability

Switching and recovery capability refers to the ability of an HVAC system that can rapidly convert into the epidemic prevention and control state after an outbreak has taken place and return to the normal state when the epidemic is over. The flexibility design of the switching capability from 'normal' to 'epidemic' and the recovery capability from 'epidemic' to 'normal' mainly depend on three aspects: spatial planning flexibility, functional layout flexibility and energy-saving flexibility.[33]

At the initial stage of an architectural design, the main consideration should be the reasonable system layout. During the pandemic of COVID-19, hospitals or nursing homes encountered major difficulties in renovation; and the strategy of modular zoning was recommended. They should be divided into 'three zones and two passages', which are clean zone, semi-contaminated zone, contaminated zone, staff passages and isolation personnel passages. The general wards during peacetime can be quickly converted to isolation wards during an outbreak. Saeed et al.[34] proposed that sustainable schools and office buildings should be divided into multi-regions, and measures such as using green plants or isolation screens between regions can achieve rapid transformation for epidemic prevention.

In addition, the flexible design of functional layouts such as indoor HVAC pipes and valves would help to reduce the spread of epidemics. For example, the air supply and exhaust ducts in an all-air system should be equipped with regulating valves to control the airflow volume between the peacetime and the epidemic period. When the condensate is

Table 1. Some commonly used air purification strategies that can be integrated with HVAC systems.

Strategies	Working principle	Advantages	Shortcomings
HEPA	The filter screen collides and intercepts the particles passing through	The filtration efficiency can reach 99.97% for 0.15 micron particles	Increased resistance and cost with higher efficiency
Electrostatic filter	After the particles are charged by a high-voltage electrostatic field, the particles are collected by a dust collecting plate	It has low resistance and high purification efficiency for particles of various diameters	Sparks, noise, ozone and nitrogen oxides may be generated; and dust removal on the dust collection plate is a problem; reduced efficiency after dust collection
Low temperature plasma filtration	Non-thermal plasma purification uses high-voltage discharge technology to ionize the gas and accelerate electrons to produce a large number of active ions and free radicals	Fast purification and efficient killing of microorganisms	It may produce by-product nitrogen oxide and ozone
Ultraviolet radiation	To kill the virus by destroying its helical structure	It has an excellent sterilization effect	It has no purification effect on particles; needs a certain exposure time to kill the virus; short life of ultraviolet lamp; inconvenient installation and maintenance; harmful to human body; and may lead to secondary pollution such as ozone or nitrogen oxides

generated by the air conditioner and is processed together with ordinary drainage, an air check valve should be installed in the drainage pipe to prevent air backflow.[30]

HVAC systems are not only about maximizing efficiency but also about minimizing operating costs. Energy storage technology is important in the HVAC sector as there are always mismatches between the end-of-pipe demand and the energy supply. The energy storage system can cope with the HVAC systems during an epidemic period to provide a resilient energy supply. In addition, variable frequency technology, variable fresh air systems and occupant-centric control technology can also be integrated into the HVAC systems to improve the energy efficiency of both peacetime and epidemic periods.

Conclusion and future research

In the post-pandemic era of COVID-19, public buildings still need measures to cope with potential future epidemics. A resilient HVAC design is important to adapt to both the peacetime and the epidemic periods. Conventional HVAC systems have encountered several problems with the purpose of preventing airborne disease transmission in the indoor environment during the pandemic of COVID-19, and there is an urgent need to develop evaluation criteria or guidelines for resilient HVAC system design to solve these problems. This paper provides an elementary framework to evaluate the capacity of a resilient HVAC system to quickly shift between normal and epidemic times. A resilient HVAC system should own the capabilities to prevent the spread of pathogens, dilute their concentration or purify the air with devices, and switch quickly between normal and epidemic states. While this concept is still developing, future research is needed to promote the development of resilient designs for HVAC systems that can be applied to healthy buildings. Here below are some recommendations for future research:

- More feasible technical measures are required to support the prevention capacity, dilution and purification capacity as well as the switching and recovery capability of a resilient HVAC system.
- Resilient HVAC system is highly dependent on intelligent monitoring and control algorithms, which are needed and should be properly integrated into the system to optimize the operation modes with multiple objectives.
- The combined effect of a resilient HVAC system in terms of feasibility, effectiveness of epidemic control and energy cost should be comprehensively evaluated and new evaluation metrics would need to be developed.

- To create healthy public buildings in the post-pandemic era of COVID-19, standardized guidance is needed for promoting healthy and resilient HVAC designs.

Authors' contribution

All authors contributed equally in the preparation of this paper.

Declaration of conflicting interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: The authors would like to acknowledge the coordinated support from the Natural Science Foundation of China (Grant Nos. 52278131 and 51808555) and the Danish Agency for Higher Education and Science International Network Programme (case no. 0192-00036B).

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