

A systematic review on COVID-19 related research in HVAC system and indoor environment

Yaolin Lin^{a,*}, Jiajun Wang^a, Wei Yang^b, Lin Tian^c, Christhina Candido^b

^a School of Environment and Architecture, University of Shanghai for Science and Technology, Shanghai, China, 200093

^b Faculty of Architecture, Building and Planning, The University of Melbourne, Melbourne, Australia, 3010

^c School of Engineering, RMIT University, Melbourne, Australia, 3000

ARTICLE INFO

Keywords:

COVID-19
HVAC systems
Facilities management
Building operation guidelines
Healthy indoor environments

ABSTRACT

The on-going COVID-19 pandemic has wrecked havoc in our society, with short and long-term consequences to people's lives and livelihoods - over 651 million COVID-19 cases have been confirmed with the number of deaths exceeding 6.66 million. As people stay indoors most of the time, how to operate the Heating, Ventilation and Air-Conditioning (HVAC) systems as well as building facilities to reduce airborne infections have become hot research topics. This paper presents a systematic review on COVID-19 related research in HVAC systems and the indoor environment. Firstly, it reviews the research on the improvement of ventilation, filtration, heating and air-conditioning systems since the onset of COVID-19. Secondly, various indoor environment improvement measures to minimize airborne spread, such as building envelope design, physical barriers and vent position arrangement, and the possible impact of COVID-19 on building energy consumption are examined. Thirdly, it provides comparisons on the building operation guidelines for preventing the spread of COVID-19 virus from different countries. Finally, recommendations for future studies are provided.

1. Introduction

COVID-19 is airborne and as such, its transmission is closely related to the design and performance of indoor environments, specially in regards to Heating, Ventilation and Air-Conditioning (HVAC) systems [1,2]. Pre-pandemic, HVAC systems in buildings are designed to provide comfort indoors, acceptable Indoor Air Quality (IAQ), energy efficiency and other building and indoor environment-related performance.

Post-pandemic, HVAC systems have been enlisted to fight COVID-19 and scholars have carried out studies on how to curb the virus spread and reduce the risk of infection, especially through proper operation of the HVAC system, including recommendations for increased ventilation, adoption of mixed-mode and natural ventilation strategies, deployment of ultraviolet germicidal radiation (UVGI) technology to reduce the virus concentration in the built environment and thus the risk of infection [3,4]. Other than enhancing ventilation and providing more fresh air to increase viral inactivation rates, it is also possible to directly control the indoor conditions to create an unfavorable environment for viruses, thereby increasing the natural virus inactivation rate. For example, controlling the temperature and relative humidity of the space to maintain a harsh environment for virus [5], placing physical barriers to prevent virus spread, thus reducing the probability of infection transmission [6]. In addition, air filtration, e.g., the use of high-efficiency particulate air

(HEPA) filters is also effective to reduce the virus concentration through air filtration [7].

Post-pandemic, professional associations in various countries in the world, such as the United States, China, Europe, Japan, India, and Canada, have issued a number of guidance documents on the operation and management of HVAC systems during the pandemic to control the airborne transmission. The guidelines suggest a number of measures, such as increasing the outdoor air flow intake, using auxiliary equipment, and adjusting operating strategies. While these measures have the potential to reduce the risk of infection, they may also result in additional energy consumption and operation costs [8].

Numerous investigations have been conducted to mitigate the risk of COVID-19 infection through various approaches [9–12]. However, very few papers focus on the review of associated research in HVAC systems and the indoor environment. Berry et al. [13] conducted a review on the methods to reduce COVID-19 transmission in ventilation systems and enclosed spaces, including ventilation, air filtration, air ionization, environmental conditioning, ultraviolet light, and heat, nanoparticles, chemical, and plasma methods. Other than above mentioned aspects, the operation strategies of the HVAC systems also need to be improved, and the risk of infection can be reduced through proper redesign of the envelope and air distribution system. Furthermore, the impact of the pandemic on building energy consumption needs to be considered. Guo et al. [14] reviewed and compared several HVAC related guidelines from the United States, Europe, Japan, and China. It was found that the terminology and advice in these guidelines are mostly consistent, but are

* Corresponding author.

E-mail address: yaolinlin@gmail.com (Y. Lin).

Nomenclature

R0 final reproduction number considering the total exposure period, dimensionless

Acronyms

ACH	Air changes per hour (h^{-1})
AHU	Air handling unit
ASC	Architectural Society of China
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BTGA	Bundesindustrieverband technische gebäudeausrüstung
CAR	Chinese Association of Refrigeration
CCIAQ	Canadian Committee on Indoor Air Quality
CFD	Computational fluid dynamics
CIBSE	Chartered Institution of Building Services Engineers
COVID-19	COrona Virus Disease 2019
ECDPC	European Centre for Disease Prevention and Control
ESD	Electrostatic disinfectant
ESP	Electrostatic precipitator
FGK	Fachverband Gebäude-Klima
GJ	Giga Joule
HEAHUs	High-efficiency air handling units
HEFS	Hybrid electrostatic filtration system
HEPA	High-efficiency particulate air
HVAC	Heating, ventilation and air-conditioning
IAQ	Indoor air quality
ISHRAE	Indian Society of Heating, Refrigerating and Air Conditioning Engineers
PAC	Portable air cleaners
PVA	PolyVinyl alcohol
PVDF	Polyvinylidene fluoride
qRT-PCR	Quantitative reverse transcription polymerase chain reaction
REHVA	Federation of European Heating, Ventilation and Air Conditioning Associations
RM3	Rheem's third generation products
RTL	Raumlufttechnischen
SARS	Severe acute respiratory syndrome
SHASE	Air-conditioning and sanitary engineers
UV-C	Ultraviolet-C
UVGI	Ultraviolet germicidal radiation

contradictory in details, reflecting the underlying uncertainties on the mechanisms and characteristics of COVID-19 transmission in buildings. In addition, all the guidelines emphasize the importance of ventilation, but no specific ventilation rates have been identified that would eliminate the risk of airborne particulate matter transmission. Therefore, this paper further collects relevant guidelines with updated versions, and conducts comparisons on the detailed operations strategies.

The structure of the paper is shown in Fig. 1. Firstly, the research on ventilation system, including the usage of natural ventilation and auxiliary measures, increasing fresh air and ventilation rate are reviewed. Secondly, the air filtration technologies, including electrostatic disinfectant (ESD), charged PVDF multilayer nanofiber filter, nickel foam filter, HEPA air purification device, ultraviolet-C(UV-C) air purification device are presented. Thirdly, the evidence of virus spread through the HVAC system and corresponding improvement measures are examined, and then the impact of the pandemic on building energy consumption is analyzed. Fourthly, built environment physical design measures, such as envelope and vent locations, physical barriers, and air-flow deflectors are evaluated. Finally, comparisons of guidelines issued by various countries are made and suggestions on future research are provided.

2. Method

This article provides a systematic review of COVID-19 related research in HVAC systems and the built environment, in particular the measures to reduce the risk of infection. The advantage of this type of review is to reduce bias by using a systematic approach to selecting studies for evaluation. However, it is relatively more time-consuming than other types of reviews.

Firstly, all available literature data published in 2019–2022 from relevant databases such as Scopus, ScienceDirect, and Google, etc. were collected. The search keywords are “COVID-19”, “ventilation”, “air filter”, “air conditioning system”, “building energy consumption”, “building envelope”, “built environment”, and “guideline”. The papers were categorized into “ventilation system”, “air filtration”, “HVAC system”, “building energy”, and “physical design”. A total of 654 papers were found in the first round. The literature that are not relevant to the review topic were screened out. The remaining literature was thoroughly checked, and the literature of poor quality were eliminated. In addition, electronic documents on the building operation guidelines were found from the official website of various countries. Finally, a total of 100 references best suited to study the impact of COVID-19 on HVAC systems and the built environment and measures to reduce the risk of infection, including 32 electronic documents from the Internet and 68 published papers, were selected, as shown in Fig. 2.

3. Research on ventilation system improvement

3.1. Natural ventilation and auxiliary measures

During the pandemic, poor ventilation will increase the risk of infection, while effective ventilation and air filtration play an important role in reducing virus transmission. Proper use of natural ventilation can help reduce the risk of infection and improve indoor air quality. Adopting reasonable auxiliary equipment such as mechanical exhaust fans can help increase the ventilation rate and thus create a healthy and comfortable environment. In hospitals and isolation rooms, the high ventilation rate provided by natural ventilation can help reduce the cross-infection of airborne diseases by providing fresh air and lowering the concentration of virus [15]. Qian et al. conducted a field measurement to study the natural ventilation in a hospital ward in Hong Kong and found that the air change rate was in the range of 18.5~ 69.0 ACH with windows/door fully open to the outside and door fully open to the corridor using the decay method. The existence of a strong wind might be the cause of the maximum ventilation rate observed [15]. It is recommended to consider converting existing wards using natural ventilation into temporary isolation rooms by installing exhaust fans. In high-density public buildings, the air exchange rate of cross ventilation is much higher than that of unilateral ventilation, leading to a lower risk of infection [16]. If cross ventilation is not possible, auxiliary fans are recommended. Cheng et al. [17] studied the potential role of cross airflow in promoting cross-corridor virus transmission in Luk Chuen House with a typical hotel layout. The results show that apartments downstream of pollution sources had the highest risk of infection with eastern prevailing winds, and if northern winds prevailed, the outbreaks would not occur. They concluded that door openings and ventilation rates and indoor air pressure play important roles in virus transmission, and maintaining positive pressure and sufficient ventilation help to minimize the infection risk. Blocken et al. [18] performed field measurements on the aerosol particle concentrations in a gym with 35 people exercising. Their tested results show that ventilation alone with ACH = 2.2 has a similar effect as air cleaning with ACH = 1.39 in the room with an area of 886 m^3 , leading to a reduction of the aerosol particle concentration by 80% to 90%, respectively. Therefore, air cleaning with natural ventilation is energy efficient. Monge-Barrio et al. [3] conducted a survey on nine Spanish schools and recommended using natural ventilation to improve indoor environmental conditions during the pandemic. They also pro-

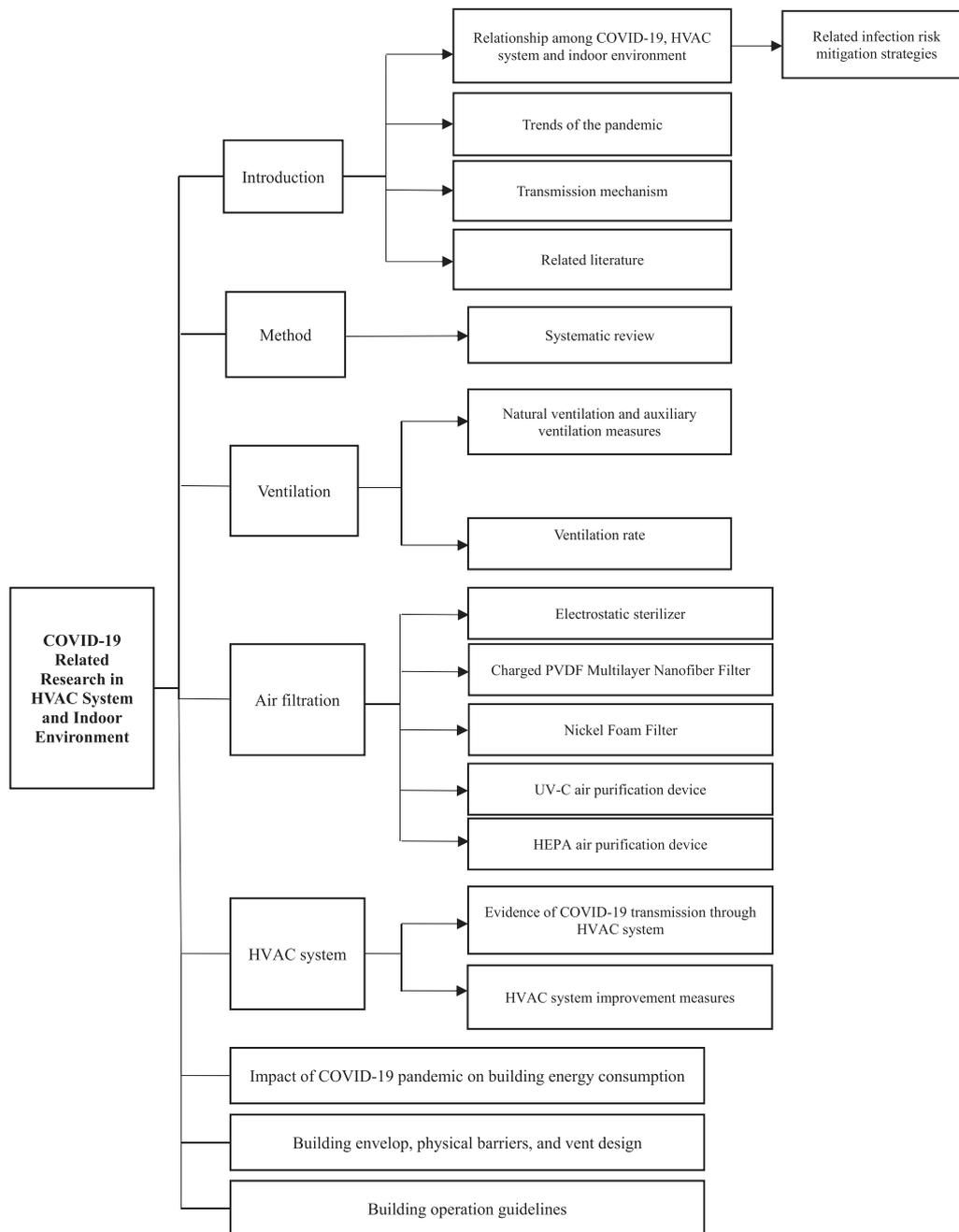


Fig. 1. Structure of the paper

posed utilizing natural ventilation to compensate for mechanical ventilation with heat recovery during the cold days. Gil-Baez et al. [19] evaluated the indoor air quality (IAQ) in a representative sample of schools in a Mediterranean climate under different occupancy patterns and ventilation actions. They concluded that natural ventilation can ensure IAQ and thermal comfort in the mild climate. Ahmadzadeh et al. [20] investigated the effects of airflow in indoor environments on the distribution and transmission of COVID-19 virus particles. The results show that air conditioning and opening windows close to an infected person had a significant effect on reducing environmental pathogens. However, virus particle concentrations near the outputs of the air flow increase greatly.

Based on the above literature survey, it can be found that natural ventilation with auxiliary equipment can help improve indoor air quality and maintain a healthy environment. In public buildings, cross ventilation or ventilation with air cleaning devices should be recommended.

For schools, natural ventilation can also help to maintain the IAQ under different occupancy patterns. For future research, attention should be paid to the combination of reasonable natural ventilation and efficient air purification devices, and measures to reduce cross-infection in hotels and dormitories, such as maintaining positive pressure in corridors and sufficient ventilation, prohibiting or reducing people’s activities outside the room, and limiting the opening time of the door of the opposite or adjacent room.

3.2. Increase fresh air/air change rate

During the pandemic, people tend to stay indoors for a much longer time than usual. As SARS-CoV-2 transmission often occurs indoors, it is very important to provide enough fresh air and increase the ventilation rate to dilute the virus concentration, thus reducing the risk of infection.



Fig. 2. Contributions of literature

By supplying 100% fresh air [11,21,22], the infection risk of SARS-CoV-2 exposure to workers can be reduced, and it is effective in addressing potential infections in indoor environments. Increasing ventilation rates can effectively reduce the risk of airborne infection [23–29]. Schibuola and Tambani [23] performed an investigation on increasing ventilation rate to contain indoor COVID-19 virus using a high efficiency ventilation unit combining thermal recovery by heat exchanger and thermodynamic recovery by heat pump. It was found that high mechanical ventilation rates permit limited facemask use (with average filtration efficiency over 50%) to achieve a basic reproduction number (R0) value under one. Even with no filtration, the final risk of infection varies from 23% (8 l/s/pers) to 7.2% (32 l/s/pers). Cheng et al. [25] compared the secondary attack rates of customers of restaurant-related COVID-19 outbreak before and after the enhancement of indoor air dilution. It was found that before and after enhanced indoor air dilution, the customer reinfection rates were 28.9% and 3.4%, respectively. Ou et al. [26] investigated the long-range airborne transmission of SARS-CoV-2 on two buses. They found that the one with an average ventilation rate of 1.72 l/s/pers had a higher infection rate (eight person infected) than the other one (two person infected) with an average ventilation rate of 3.22 l/s/pers. Dai and Zhao [28] estimated the association between infection probability and ventilation rate using the Wells-Riley equation. They found that when the exposure times are 0.25 hr. and 3 hr.s and the quantum generation rate is 14-48h⁻¹, the ventilation rate required to ensure the infection probability of less than 1% is 100-350 m³/h per infector and 1200-4000 m³/h per infector, respectively. If the infector and susceptible person wear masks, the ventilation rate can be reduced to a quarter, respectively.

Based on the above literature survey, it can be found that increasing the amount of fresh air and ventilation rate can dilute the virus concentration to reduce the risk of infection. Providing 100% fresh air, increas-

ing the ventilation rate, and reducing the amount of recirculation air, will lead to a paradigm shift in ventilation design. In the future, attention should be paid to the determination of optimal fresh air and mechanical ventilation rates to achieve a low infection risk while maintaining low energy consumption.

4. Research on air filter improvement

Air cleaning devices play an important role in reducing the indoor transmission of COVID-19 virus. According to different filtration mechanisms, they can be divided into electrostatic disinfectors, charged PVDF multilayer nanofiber filters, nickel foam filters, UV-C, HEPA, and ion filters, etc.

4.1. Non-conventional filters

4.1.1. Electrostatic disinfectant (ESD)

The ESDs use corona discharge-generated air ions to remove particulate matter and sanitize bioaerosols. For the traditional air purification method, electrostatic precipitator (ESP) has two functions of physical removal and biological disinfection [30]. The corona discharge generated by the ions can inactivate bacteria and microorganisms [31]. When an ESP is used to inactivate biological contaminants, it is called an ESD. However, there are very few studies on ESDs. Feng et al. [32] proposed a numerical model to simulate the disinfection efficiency of biological ions in the air during electrostatic discharge. They found that with an applied voltage of 6.5 kV, inlet velocity of 1 m/s, channel length of 0.5 m, channel width of 0.067 m, and 5 wires in the channel, the disinfection efficiency was close to 100%. Compared with HEPA, ESD can achieve 99% of energy reduction without sacrificing removal/disinfection efficiency.

4.1.2. Charged PVDF multilayer nanofiber filter

Filters made of polyvinyl alcohol (PVA) nanofibers have been used for aerosols filtration, which relies on mechanical diffusion [33]. At a face velocity of 5.5 cm/s, its efficiency can reach 70.6% for 100nm nano-aerosols. Charged polyvinylidene fluoride (PVDF) nanofibers can be used to improve its filtration efficiency. Stably charged PVDF nanofiber filters have been developed based on tests with NaCl aerosols [34]. For uncharged nanofiber filters, the filtration relies on diffusion and interception. Dielectrophoresis further helps trap aerosols when the nanofibers are charged. But there is no evidence that charged nanofiber filters will work against ambient aerosols, therefore, Leung and sun [35] carried out research to test the filtration effectiveness of using PVDF nanofibers to capture COVID-19 + airborne carrier simulated as ambient aerosols 100 nm. By testing the filter with 2,4,6 multiple-modules stacking-up to minimize the electrical interference among the nanofibers and reduce the flow resistance, it was found that the 6-layer filter can achieve 88%, 88%, and 96% at ambient aerosol sizes of 50, 100, and 300 nm, respectively, with a pressure drop of only 26 Pa and can be consistently maintained, which is much lower than conventional filters.

4.1.3. Nickel Foam Filter

Traditional glass fiber or aluminum metal mesh filters cannot effectively capture and inactivate viruses contained in aerosols [36]. An ideal filter should be self-heating, which requires the filter itself to be conductive. Nickel foam is highly porous and conductive. In addition, the filter device composed of multi-layer nickel foam folded sheets is electrically connected in series to increase the resistance to a manageable level and can possibly be used for virus inactivation. Yu et al. [37] fabricated a self-heating filter device based on nickel foam, and tested its ability for catching and killing aerosolized SARS-CoV-2 and anthrax spores in air-conditioning systems. They found that when the filter was heated to 200°C, the viral load of the aerosolized SARS-CoV-2 was reduced by 99.8% with a single pass. In another test, 99.9% of Bacillus anthracis was caught and killed by the same filter. The advantage of the filter is that the nickel foam is highly porous and can form a very large surface area that effectively traps airborne particles. In addition, heating is concentrated on the nickel foam, which has minimal heat transfer with the air due to the short contact time between the air and the nickel foam.

4.1.4. UV-C air clean device

The UV+ filter system can effectively capture the virus-carrying aerosol in the air through the filter and inactivate the deposited virus aerosol by ultraviolet light applied to the filter medium. Corrêa et al. [38] proposed a portable, low-cost UV-C air purification device to remove the droplets or aerosols in the air. This device generates negative pressure to allow particles to be inhaled faster and exposed to strong UV-C radiation. After being purified, the air is released to the environment via the upper part of the device. A Gram-negative bacteria strain, *Escherichia coli*, was used as a model micro-organism for testing. Results show that the UV-C device was effective in removing microorganisms in the laboratory environment with 99.9% efficiency, and in the hospital environment study, the reduction rate was 84-97% [38]. Irradiation shade spots, exposition of people to UV-C light, and insufficient light delivery can hinder the expected removal effect. Srivastava et al. [11] proposed to use an ultraviolet-C (UV-C) air disinfection device (Rheem's third generation products, RM3) Rheem's third generation products, RM3) in the HVAC ducts to clean the air carrying COVID-19 virus (severe acute respiratory syndrome coronavirus 2, SARS-CoV-2). According to the numerical results, using a combination of 100% fresh air with RM3 UV-C units could reduce the risk of infection in the office to less than 2%. Feng et al. [39] proposed a UV+ filter system to control SARS-CoV-2 through three processes: (1) physical capture by fiber filters; (2) UV disinfection before reaching the fiber filters; (3) sterilization of the aerosol deposited in the filter medium by applying UV dose. Numerical simulation shows that with proper design, UV+ filters have

100% filtration efficiency but with high energy consumption compared with Fibrous-filter, electrostatic precipitator (ESP) and hybrid electrostatic filtration system (HEFS).

4.2. HEPA filter

The air filter is used to remove fine particles in the air. When the diameter of the particles is larger than the gap between the fibers, it can effectively intercept the particles without producing ozone or other harmful by-products. A HEPA filter can theoretically remove at least 99.97% of dust, pollen, mold, bacteria, and any airborne particles with a size of 0.3 μm [40]. Air filter is considered to be a supplementary measure to remove airborne SARS-CoV-2 [41]. If outdoor air is infected, the use of high-efficiency filters or HEPA filters is an effective measure to reduce the risk of infection [42]. A number of studies have been carried out to evaluate the effectiveness of HEPA filters in COVID-19 virus removal and were confirmed with high efficiency [7,43-45]. For example, Rodríguez et al. [7] assessed the ability of Portable Air Cleaners (PAC) with HEPA filter to remove coronavirus and 80% of effectiveness was found through testing. They recommended to use Portable HEPA cleaners when ventilation is inadequate. Zacharias et al. [43] used (ϕ X174 phage) to simulate SARS-CoV-2 and other human pathogenic respiratory viruses, and the efficiency of an air purifier with a HEPA filter under a flow rate of 1000 m^3/h was tested and found to be 99.9974-99.9999%. Waring et al. [45] found through an experiment that the efficiencies of HEPA filters and ESPs are higher than those of the ionizers. In addition, portable HEPA filter can effectively remove particulate matter without producing ozone or other harmful by-products. To achieve the best virus removal efficiency, it is advised to place two portable air purifiers on either side of the walls [44]. When the infection probability is less than 10%, the portable air purifier needs to be positioned in the center of the room while supplying sufficient air flow [9]. The HEPA filters can be installed on ventilation grills to clean the circulation air and reduce the risk of hospital transmission of SARS-CoV-2 through operating room ventilation systems [46].

Table 1 presents the comparison on the efficiencies, working principles, advantages and disadvantages of different air cleaning devices.

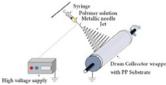
The above literature survey shows that the portable filters have high purification efficiencies by using electrostatic, charged PVDF multi-layer nanofibers, nickel foam, ultraviolet rays and other improved methods, but they can generate certain by-products. Although electrostatic filters are energy efficient, they also generate small amounts of ozone and bring the risk of electrical breakdown. The performance of HEPA is reduced as the filter gets loaded over time due to small air flow and high pressure drop. Meanwhile, although filter efficacy assessments were performed, bacteria or viruses other than SARS-CoV-2 were used. Therefore, in the future, it is advised to avoid using dangerous filtering measures such as ozone generation, rationally use HEPA air purification devices, and re-examine the filtering effect of SARS-CoV-2.

5. Research on HVAC system improvement

5.1. Evidence of COVID-19 virus spread through the HVAC system

Surface transmission, droplet or aerosol transmission, airborne transmission, and fecal-oral are suggested to be the ways that coronavirus can spread through. The research on the impact of HVAC system operation on the transmission of coronavirus and maintaining a healthy indoor environment have attracted some researchers [42,47-51]. Yin [47] believed that central air distribution flow is an important cause of cluster infection, and with effective preventive measures in the central air conditioning system the indoor virus concentration can be minimized. Mouchtouri et al. [48] collected environmental samples from a ferry-boat, a nursing home, three COVID-19 isolation hospital wards, and a long-term care facility isolating asymptomatic COVID-19 cases during the outbreak. SARS-CoV-2 was detected in swab samples collected from

Table 1
Comparison on the efficiencies and working principles of different air cleaning devices

Type	Photo description	Working principle	Effect	Pros/Cons	Ref.
Electrostatic disinfectors		Use corona discharge-generated air ions to remove particulate matter and sanitizes bioaerosols.	Airborne bacteria/virus disinfection efficiency as high as 100% with multiple wires.	Pros: Energy efficient Cons: Release a small amount of ozone	[32]
Charged PVDF Multilayer Nanofiber Filter		Use electrostatic polyvinylidene fluoride (PVDF) nanofibers to capture ambient aerosols.	Disinfection efficiency of the 6-layer (6L) electrostatically charged multilayer/multimodule nanofiber filters can reach 88%, 88%, and 96% at ambient aerosol sizes of 50, 100, and 300 nm, respectively.	Pros: minimizes electrical interference between adjacent charged nanofibers and reduces flow resistance in the filter; 100% to 180% more equivalence of existing mechanical efficiency without additional pressure drop.	[35]
Nickel Foam Filter		Capture and kill SARS-CoV-2 or anthrax spores in air conditioning systems by heating nickel foam.	When heated to 200°C, the viral load in the device in a single pass was reduced by 99.8%; Can capture and kill 99.9% of anthrax spores.	Pros: Nickel foam is highly porous and can form a very large surface area to effectively trap air particles; the heating is concentrated on the nickel foam, and the heat transfer through the air is minimal due to the short contact time between the air and the nickel foam.	[37]
UV purification device		Helps eliminate droplets or aerosols in the environment by circulating air in the UV-C reactor.	Under the laboratory environment, the removal efficiency of microorganisms was 99.9%, and in the hospital environment study, the efficiency was 84-97%; Using 100% outdoor air and UV-C, the risk of infection can be reduced to less than 2%.	Pros: Portable and low cost Cons: Radiant shadow spots, exposure of people to UV-C light, and insufficient light transmission may reduce the decontamination effect.	[11,38]
UV-C+ fiber pleated filter		Physical capture by fiber filter due to filtration mechanism; UV disinfection before fiber filter; UV dose applied to aerosols deposited in filter media.	With proper design, the filter efficiency of UV+ filter can reach 100%.	Pros: Reliable and safe Cons: High energy consumption	[39]
HEPA		Bacteriophages nebulized directly into air purifiers	Disinfection efficiency of 99.9974-99.9999% with phiX174 phage, 80% of effectiveness with coronavirus samples.	Pros: No production of ozone or other harmful by-products; low cost and easy installation.	[43]9,[44]

the surface of ferries, nursing homes, hospital isolation wards, exhaust duct screens, air conditioning filters, sewage treatment units, and air samples. Sousan et al. [49] carried out a study on the detection of SARS-CoV-2 in air samples from student dormitories. Air samples were collected from filter boxes, push button samplers, biosamplers and aerosol sensor samplers combined with direct qRT-PCR SARS-CoV-2 analysis. When a PCR-positive COVID-19 student lived on the same floor as the sampling site, SARS-CoV-2 was detected in air samples with a detection rate of 75%. For the isolation dormitory, the detection rate of SARS-CoV-2 using the AerosolSense sampler was 100%. Pease et al. [42] used a well-mixed model to study the potential impact of central ventilation systems on aerosol transmission and infectivity of SARS-CoV-2, and found that in connected spaces, increasing filtration helps reduce infection rate, while higher air exchange rates lead to higher infectivity, and only when outside air is virus free, more fresh air leads to lower virus concentration. Lu et al. [51] inspected the potential transmission routes in a restaurant in Guangzhou during COVID-19 outbreaks and found the most likely cause was droplet transmission, which is consistent with the flow direction. To prevent the spread of coronavirus in restaurants, they recommended increasing the distance between tables, and improving ventilation.

The above literature survey shows that current studies focus on collecting samples to find evidence of air-conditioning system on the spread of COVID-19 virus. The COVID-19 virus can move with air flow and deposit on surfaces through respiratory droplets/nuclei of an infected person. When HVAC systems are operating during the pandemic, high

efficiency air cleaning devices need to be installed to minimize virus spread.

5.2. HVAC system improvement measures

It has been acknowledged that inappropriate operation of HVAC system operation could contribute to the spread of COVID-19 virus, and how to improve HVAC system design and operation has received wide attention [5,23,53-59]. Pang et al. [52] discussed the appropriate HVAC operation mode in civil buildings based on engineering experience, and proposed specific operation strategies to increase the fresh air flow rate for fan coil + fresh air system and all air system for virus dilution. They suggested that each room should have an openable external window, and the HVAC system should have a backup fan. A larger fresh air fan configured with variable speed should also be provided to deal with emergency situations. Rezaei et al. [5] proposed a clean room HVAC system using longitudinal air-to-air heat exchangers for waste heat recovery from chiller condensers. The temperature and relative humidity of the exiting exhaust air is in the range of 50°C-80°C and 40%-50%, respectively. It was found that SAR-CoV-2 disappears rapidly under such a condition. Aviv et al. [53] proposed an approach that coupled membrane-assisted radiant cooling panels with natural ventilation to provide fresh air to address COVID-19 concerns. For conventional systems, increased fresh air may double the energy cost while the new approach could reduce the HVAC energy demand by 10%-45% and would still maintain thermal comfort in all major climate zones. Lee et al. [54] proposed

Table 2
Improvement measure of HVAC system under the pandemic

Improvement Measures	Effect	Ref.
Waste heat recovery from the chiller condenser using a longitudinal air-to-air heat exchanger to heat the exiting exhaust air	The system the exiting temperature and relative humidity of the exhaust air are in the ranges of 50°C-80°C and 40%-50%, under such conditions, SAR-CoV-2 disappears quickly.	[5]
Combining membrane-assisted radiant cooling panels with natural ventilation	The system is able to meet thermal comfort needs in all major climatic zones, and reduce the HVAC energy demand by 10-45% while mitigating COVID-19 spread.	[53]
Heat Pump Driven Liquid Desiccant (HPLD) Air Conditioning Systems	Under ventilation mode, cooling and dehumidification mode, and heating and humidification mode, the bacterial inactivation efficiencies were found to be 0.6, 0.74 and 0.94, respectively.	[54]
Combining dilution ventilation with ventilation cooling	If occupants follow proper protections, it can help reduce energy consumption by around 40%.	[55]
An air-to-water heat pump is installed downstream of the recovery unit of the Air Handling Unit (AHU)	The high energy consumption due to a significant increase in ventilation rates relative to standard HVAC systems can be reduced by adopting this high-efficiency air handling units (HEAHUs). In naturally ventilated classrooms, the reductions could achieve 60% to 72% based on simulation.	[23]
Install non-metallic electrostatic purification filter device and independent plenum non-metallic electrostatic purification filter device for FCU system	Sterilization and removal of volatile organic pollutants	[56]

a heat-pump-driven liquid-desiccant air-conditioning system to inactivate airborne microbial contaminants. Under ventilation, cooling and dehumidification, and heating and humidification modes, the bacterial inactivation efficiencies were found to be 0.6, 0.74, and 0.94, respectively. This study demonstrates the ability of desiccant solutions to the inactivation of airborne microbial contaminants during various air conditioning processes. Sha et al. [55] proposed a demand ventilation control ventilation strategy for dilution and ventilative cooling, where a safe dilution ventilation rate that reduces the risk of new coronavirus-19 infection to an acceptable range is determined through a modified Wells-Riley model, and cooling ventilation rate is calculated through energy model. Schibuola and Tambani [23] proposed installing an air-to-water heat pump downstream of the recovery unit of the existing air handling unit (AHU) to increase the exhaust air recovery rate and enable flexible use of the heat from the recooling condenser to produce hot water. In terms of energy performance, simulations of automated high-efficiency air handling units (HEAHUs) installed in naturally ventilated classrooms have shown a 60% to 72% reduction in energy consumption. Xu and Wang [56] proposed installing non-metallic electrostatic purification filter inside the fan coil unit and independent plenum non-metallic electrostatic purification filter. Shen and Liu [57] suggested installing air filter at the return side of the AHU. Sacconi et al. [58] performed experiments on the ability of different types of air filters to stop the spread of the SARS-CoV-2 virus. Installation of a coarse filter followed by a fine filter is confirmed to be a good practice to minimize the spread of SARS CoV-2. Meanwhile, the presence of mist eliminators can provide protection for high performance air filters. Katramiz et al. [59] proposed a ductless personalized ventilation/ exhaust system embedded in a chair integrated with displacement ventilation and assess contaminants' dispersion through Computational Fluid Dynamics (CFD) modeling. They concluded that the system could protect occupants at close proximity against cross-contamination.

Table 2 list the improvement measures on system design proposed by the researchers.

Based on the literature survey, it can be concluded that the research on the HVAC system improvement measures focuses on the following

two aspects: (1) the increase of fresh air and air cleaning device to stop/mitigate virus spread, (2) the installation of heat recovery and using other energy efficiency measures to reduce the energy consumption caused by increased ventilation rate. Future studies could focus on how to design HVAC systems that can both work under normal conditions and pandemic conditions with low energy consumption while maintaining a healthy indoor environment.

6. The impact of Covid-19 on building energy consumption

The pandemic also affects occupants' indoor activity patterns. For example, Yan et al. [60] evaluated the behavior of Wuhan residents on air conditioner operation before and after the COVID-19 lockdown from January 23, 2020 to April 8th, 2020. They found that during the lockdown period, air-conditioner continued to operate part-time intermittently, despite residents staying at home longer. During the lockdown, the trigger indoor air temperature for occupants to turn on or adjust the air conditioner was generally 1-2°C higher than before the lockdown. In addition, people spent more time at home. Therefore, the pandemic has a certain impact on building energy consumption.

Many studies have been conducted on the impact of COVID-19 pandemic on the total and building energy consumption in different countries and climate zones [8,58,59,61-69]. For example, Kang et al. [61] investigated the relationship between COVID-19 and building energy consumption using the empirical big data from 2019 to 2020 in South Korea. The average electricity and gas energy consumption were found to decrease by -4.46% and -10.35% respectively compared with the previous year. The energy consumption tends to decrease in most types of buildings but increase in residential buildings. Rouleau and Goselin [62] compared the space heating, domestic hot water and electricity energy consumption of a 40-dwelling social housing building in Quebec City, Canada, during 4 months of lockdown with one full year prior to lockdown. It was found that during the first month of lockdown, electricity and hot water consumption increased significantly, by 46% and 103%, respectively. However, no obvious changes were found for space heating. Zhou et al. [63] conducted research on the impact of lockdown

Table 3
Impact of energy consumption due to COVID-19 pandemic in different countries

Country	Building type	Impact	Ref.
South Korea	All buildings	Average electricity and gas energy consumption decreased by -4.46% and -10.35% respectively compared with the previous year.	[61]
Canada	Social housing building	In the first month of lockdown, electricity and hot water consumption increased significantly in the middle of the day, by 46% and 103% respectively. No major changes were observed for space heating usage.	[62]
United States	Standard high-rise office building	The relative energy use intensity increased by 21.72% in the "mixed humid" to "subarctic" climate zones, and decreased by 11.92% in the "warm and dry" climate to "very mild" climate.	[8]
	Households	There are no morning and evening peaks in electricity consumption on weekdays, 48.3% of the respondents reported higher or much higher consumption while 41.3% remain about the same.	[65]
	Smart community	Weekend energy usage patterns were similar before and after the pandemic. During weekdays they changed significantly, especially the electricity usage from HVAC and water heaters, which are the largest consumers of electricity in a home, experienced further increases.	[66]
	Residential buildings	HVAC system energy use increased during the pandemic. Energy use increased most in the highest and lowest income families.	[67]
China	A dormitory building	Electricity consumption was increased by 41.05%; Hourly consumption decreased from 0:00AM to 8:00AM and increased from 9:00AM to 23:00AM; Morning peak demand time was postponed from 8:00AM ~ 9:00 AM to 10:00AM to 12:00AM and evening peak demand time shifted from 22:00AM to 21:00 AM.	[63]
	Public buildings	Energy use of the HVAC system would increase by 128% under the operation guidelines issued during the pandemic.	[68]
Indonesia	Households	The average annual energy consumption of all samples during the pandemic is about 23.5 GJ, which is 3.0 GJ higher than before the pandemic.	[70]

from 25 December 2021 to 24 January 2022 on the electricity consumption of a 28-floor dormitory building at a University in Xi'an using the survey and building energy simulation method. It was found that electricity consumption increased by 41.05% during the period. The hourly consumption decreased from 0:00AM to 8:00AM and increased from 9:00AM to 23:00AM. The morning peak demand time was postponed from 8:00AM ~ 9:00 AM to 10:00AM ~ 12:00AM and evening peak demand time shifted from 22:00AM to 21:00 AM. Cortiços and Duarte [8] performed an analysis on the impact of applying new HVAC settings to mitigate the virus's spread on the building energy consumption of a standard high-rise office building in the nine climate zones in the United States. The energy consumption, CO₂ emissions and operating costs in nine climate zones were compared, and the relative energy use intensity was found to increase by 21.72% in the "mixed humid" to "subarctic" climate zones (colder zones) and decreased by 11.92% from "warm and dry" climate to "very mild" climate zones (hotter zones) [64]. Chen et al. [65] conducted a survey on the energy use pattern, social-psychological factors, climate change issues and residents' willingness to pay for home energy management system of 632 households in the New York area. Results show that there were no morning and evening peaks in electricity consumption on weekdays; most households had above-average electricity consumption; most residents' perceptions of climate change issues during COVID-19 stayed unchanged; and residents perceived moderate risk of getting COVID-19 virus were more willing to pay for home energy management system than others. Chinthavali et al. [66] studied energy usage patterns before and after the COVID-19 pandemic in smart communities in Alabama. The results show that during weekends the energy usage patterns look alike, however, there were significant changes during the weekdays. HVAC and water heaters were found to be the largest consumers of electricity in homes, with higher electricity consumption during the COVID-19 pandemic. Kawka and Cetin [67] investigated the energy use of 225 residential buildings in the United States, and found that HVAC systems consumed more energy during the pandemic. Mean-

while, energy consumption increased most in the highest and lowest income families. Zheng et al. [68] performed an analysis on the HVAC system energy consumption in China under the operation guidelines issued during the pandemic and found a 128% increase compared with that under normal operation. Surahman et al. [70] conducted an investigation on 311 urban residential building energy usage in three major cities (Jakarta, Bandung and Semarang) of Indonesia during the pandemic. The results show that the average annual energy consumption of all the samples during the pandemic is about 23.5 GJ, which is 3.0 GJ higher than before the pandemic. This change is mainly attributed to the use of air conditioning and cooking facilities.

Table 3 list the studies on the impact of energy consumption COVID-19 pandemic from different countries.

Based on the literature survey, it can be seen that most of the studies focus on the energy consumption change and usage patterns before and after the pandemic. More in-depth studies on the occupants' behavior are needed to help develop more effective strategies to combat COVID-19 in the future.

7. Vent location, building envelope and physical barriers design to mitigate virus transmission

Other than natural ventilation and the operation of the HVAC system, proper arrangement on the vent locations, adding physical barriers, new sanitizing Trombe walls, modular breathing wall system, and airflow deflectors are the ways to mitigate virus transmission.

Dao and Kim investigated the impact of positions of the exhaust air outlets on the virus removal efficiency through CFD simulation, and found that the efficiency is the highest when the grill is placed above the patient's head [71]. Mirzaie et al. [72] found through CFD simulation that the installation of a transparent barrier in front of the seats could help to reduce the average cough droplet concentration to a certain extent. Ren et al. [12] suggested placing a physical barrier with a

Table 4
Comparisons on the building operation guidelines

Item	Specification	ASHRAE (United States)	ASC, CAR (China)	SHASE (Japan)	REHVA, ECDC (Europe)	BTGA, FGK, RIT (Germany)	ISHRAE (India)	CIBSE (United Kingdom)	CCIAQ (Canada)
HVAC system operation	Increase outdoor air intake.	√					√		
	Increase ventilation rate through ventilation systems and operable windows.								
	The fresh air to return air ratio should be higher than 40% when operating under maximum fresh air mode.		√						
	The total central exhaust air flow rate for each floor should not be less than 70% of the design fresh air flow rate.		√						
	The air change rate per hour (ACH) should be maintained at ≥2.0 with the window fully open for several minutes at least once every 30 minutes.				√				
	Use 100% outdoor air.				√				
	Avoid the use of economizer, such as demand control ventilation through timer or CO ₂ sensor.				√				
	Increase outdoor air intake and reduce air recirculation rate.					√			
	Evaporative coolers must draw air from the outside.						√		
	Increase outdoor air intake and exhaust air flow rate.							√	
	Use natural ventilation.							√	
	Increase outdoor air intake, preferred 100% outside air and 100% exhaust air.								√
	Humidify or dehumidify the air seasonally.								√
	Disable demand-control systems.	√							√
	Prolong system operation (24/7 if possible).	√							√
Temperature and humidity settings	Turn on the system two hours before occupied mode starts.	√							
	24 hour proper operation of the ventilation system.	√							
	Use summer ventilation technology.			√	√				
	No change on heating, cooling and humidity setpoints of the HVAC system.				√				
	Recirculation air should be used with proper air filtration.					√			
	It is recommended to limit the return air circulation;						√		
	If no fresh air is provided, it is recommended to introduce a fresh air duct on the central in-line fan filter unit, and distribute the fresh air to the space or near the indoor unit through the grille.						√		
	Avoid air recirculation.		√						√
	If a room or area has little or no outside air ventilation, it is recommended to turn off the fan coil unit and chilled water beam.							√	√
	Install new passive (blinds/air bricks) or mechanical (extraction fans, new HVAC) systems.							√	
Upgrading ventilation system or installation of new systems.								√	
Reset the setpoints according to the actual situation.	√								
Supply air temperature setpoints in winter and summer should be raised and lowered, respectively.		√							
The minimum indoor temperature should not be lower than 16°C-18°C.			√						
The indoor air temperature and relative humidity should be in the ranges of 17°C-28°C and 40%-70%, respectively.				√					
Humidification is not effective in infection risk reduction.					√				
The indoor relative humidity should be in the range of 40%-60%.						√			
The indoor air temperature and relative humidity should be in the ranges of 24°C-30°C and 40%-70%, respectively.							√		
Proper temperature and relative humidity at above 40%.								√	

(continued on next page)

Table 4 (continued)

Item	Specification	ASHRAE (United States)	ASC, CAR (China)	SHASE (Japan)	REHVA, ECDC (Europe)	BTGA, FGK, RIT (Germany)	ISHRAE (India)	CIBSE (United Kingdom)	CCIAQ (Canada)
Special building	<p>Maintain negative pressure in isolation wards.</p> <p>The design pressure difference between the isolation ward (with lowest pressure) and its adjacent buffer room, buffer room and corridor (with highest pressure) should not be less than 5 Pa.</p> <p>Based on the Building Management Act, the building must be maintained and managed in accordance with the relevant environmental regulation standards.</p> <p>The bathroom exhaust system should be operating 24/7 to maintain negative indoor pressure. Actively use operable windows for buildings without mechanical ventilation system.</p> <p>Minimize or avoid spillage in different zones (if possible, maintain air balance in each zone)</p> <p>A minimum of 10-15 ACHs is recommended for industrial facilities; The mechanical exhaust air flow rate is 70% ~ 80% that of the outside air flow rate. In the air-conditioned wards where the normal exhaust system cannot be installed, or using unit air conditioners, an isolation hood can be installed in the ward, and the exhausted air is filtered by HEPA filters and provide negative pressure indoor.</p> <p>The exhaust fans (if installed) in the toilets should be operating continuously, and the windows in the toilet should be closed.</p> <p>Install special exhaust system in the high infection risk areas; Install high air volume exchange ventilation systems in buildings with limited mechanical ventilation or air conditioning system; 100% outdoor air for medical facilities.</p>	√	√	√	√	√	√	√	√
Air Filtering	<p>Increase the grade of the central air filter to MERV-13 or the highest level compatible with the filter frame and seal the edges of the filter to limit bypass air; Consider Ultraviolet Germicidal Radiation (UVGI) or a portable HEPA filter.</p> <p>The air-conditioning and heating system serving the clean room configured with sub-high efficiency or higher level filter, the system can be used normally in the original way; Open windows frequently for ventilation; Use portable HEPA filter.</p> <p>Use HEPA filters; Use high-performance air purifiers.</p> <p>No recommendation on replacing the existing outdoor air filter; Consider adding UVGI to the HVAC system; Consider using HEPA filter; Place the air purifier close to the breathing zone.</p> <p>Use filters with ePM1≥60% to replace F7 filters; Use double filters; Application of air humidification; Use dilution ventilation.</p> <p>Use MERV 13 or higher grade filters; Slightly open the window to allow outdoor air infiltration/exfiltration when air-conditioner is operating; Use a suitable air purifier, ideally, it can achieve 3-4 ACHs.</p> <p>Design according to the actual situation; Use HEPA or UVC purifiers; Ozone-generating filters are not recommended.</p> <p>Upgrade the fan filter unit to include a MERV 13 or higher grade filter, or a HEPA filter; Increase the ACH; Check and adjust the position of the diffuser and clear any blockage; Consider changing or removing partitions that interfere with air circulation and create airflow stagnation area; Consider upstream and downstream airflow distribution when placing local fans or air purifiers.</p>	√	√	√	√	√	√	√	√

(continued on next page)

Table 4 (continued)

Item	Specification	ASHRAE (United States)	ASC, CAR (China)	SHASE (Japan)	REHVA, ECDC (Europe)	BTGA, FGK, RIT (Germany)	ISHRAE (India)	CIBSE (United Kingdom)	CCIAQ (Canada)
Heat recovery	The heat recovery unit can be used if air leakage rate is acceptable Rotary heat recovery units and the ones that involve mass transfer are not recommended to be used. Heat recovery units can be used when air leakage rate is below 5%. Check heat recovery unit, including differential pressure and temperature, to ensure air leakage is under control. Supply and exhaust systems should be separately designed. Keep rotation wheel in OFF mode, when restarting, the wheel must first be sanitized Avoid any leakage from the supply side to the exhaust side. Prevent leakage and use when safe enough.	√	√	√	√	√	√	√	√
Other	Disinfect high-touch areas of HVAC and other building service systems (e.g., on/off switches, thermostats); Disinfect the interior of refrigeration equipment (such as refrigerators); The bathroom exhaust fans should operate continuously; The toilet lid should remain closed. Clean or replace the filter in the air-conditioning room where it is located; Packaged in a sealed plastic bag before taking it out, if it needs to be taken out of the air-conditioning room for cleaning (or replacement, destruction, etc.); Laundering is strictly prohibited in the occupied area (including public restrooms). Seal the equipment during reinstallation after cleaning and replacement; Inspect and clean the condensate pan in accordance with the requirements of the operation management specification; Clean the HVAC system before and during operation. Reduce occupant density; Reasonable management and thorough disinfection of public goods; Flush the toilet with the lid closed; Keep the exhaust fan running continuously, and check the water seal regularly. Duct cleaning has no real effect in disinfection; Replace and maintain the filters regularly; Introduce indoor air quality sensor network. Wear personal protective equipment (PPE) and safety glasses when performing maintenance and replacement of the filters. Do not provide fresh air provided by fans; Actively use operable windows; Flush the toilet with the lid closed. Reduce occupant density when possible; When pressure drop or service time exceed the limits, the filter must be replaced. Thorough cleaning prior to re-occupancy with an area-specific cleaning plan in place; Ensure that the barrier to intercept potentially infectious droplets has at least 30 cm of open space on the floor and sufficient clearance between the top of the barrier and the ceiling; Check exhaust/return regulators and clear blockages.	√	√	√	√	√	√	√	√
Ref.		[75–83]	[84–87]	[88–92]	[93–98]	[98,99]	[100]	[101–104]	[105,106]

height of at least 60 cm over the desk (80 cm in height) to reduce the risk of infection in open office space. Xie et al. [6] proposed a disinfected Trombe wall that has a glass cover, small air gap and back plate with high absorptivity to heat the circulation air to high temperature for virus inactivation and space heating. The Trombe wall was tested with an average thermal efficiency of 0.45. The maximum single pass inactivation ratios of SARS-CoV-1, SARS-CoV-2 and MERS-CoV were 0.893, 0.591 and 0.893, while the total clean air productions were 112.3, 63.8 and 114.7 m³, respectively. Che et al. [73] proposed installing an air flow deflector to external windows to diffuse the natural ventilation air flow and reduce the infection risk. When the pollution source is located at the center of the classroom and the side wall, the risk of infection can be reduced by 19.29 and 17.47%, respectively. Kumar et al. [74] carried out parametric studies on the vertical void configurations of a double-loaded apartment building for ventilation improvement in tropical developing countries. Through CFD simulation, they concluded that the optimal combination of fin size and aspect ratio could maximize ventilation under prevailing wind direction.

Based on the literature survey, it can be concluded that vent location, physical barrier, building envelope design, and flow deflector can all play a role in preventing virus spread. Future research can also look into the building layout as well as the combination of those improvement measures together with HVAC operations to minimize the risk of infection.

8. Building operation guidelines during Covid-19

In order to ensure that the building operation can help to maintain a healthy indoor environment to prevent the spread of COVID-19 virus, various guidelines have been issued by relevant associations and governments in different countries, including ASHRAE, the Chinese Association of Refrigeration (CAR), the Architectural Society of China (ASC), the Society of Heating, Air-Conditioning and Sanitary Engineers (SHASE) of Japan, the Federation of European Heating, Ventilation and Air Conditioning Associations (REHVA), European Centre for Disease Prevention and Control (ECDC), the Bundesindustrieverband Technische Gebäudeausrüstung (BTGA), Fachverband Gebäude-Klima (FGK) and Raumluftechnischen (RTL), the Indian Society of Heating, Refrigerating and Air Conditioning Engineers (ISHRAE), the Chartered Institution of Building Services Engineers (CIBSE), the Canadian Committee on Indoor Air Quality (CCIAQ), etc.

Table 4 makes a detailed comparison on the building operation guidelines issued from various countries and organizations. There are some subtle differences among the guidelines. For example, regarding the ventilation, ASHRAE recommended local exhaust for source control and opening the outside air damper to 100% when occupied and to a minimum outside air position when unoccupied [75]; ASC and CAR recommended the all-air system to operate with 100% fresh air and the total exhaust air flow exceeding 70% of the total designed fresh air flow for each floor [87]; SHASE recommended the ACH to be ≥ 2.0 . However, all the guidelines agree that increasing fresh air supply is helpful for reducing the risk of infection. Regarding the range of indoor air relative humidity, ASHRAE does not make explicit recommendations for indoor temperature and humidity set points; REHVA casts doubt on the effectiveness of moderate relative humidity (40~60%) on reducing the survival rate of SARS-CoV-2 and does not recommend air humidification; CIBSE recommended relative humidity to be $\geq 40\%$; SHASE, BTGA, FGK, RIT, and CCIAQ recommended to control the indoor air relative humidity to be in the range of 40%~60%; ISHRAE recommended the relative humidity to be 40%~70%. Regarding fecal-oral transmission, ASHRAE, SHASE, REHVA and ISHRAE all recommended to close the lip of the toilet when flushing.

All the guidelines emphasize that HVAC systems should be inspected and adjusted as necessary, and maintained in accordance with respective national technical recommendations. Compared with the pre-pandemic stage, current guidelines have an agreement on the transmission mech-

anism of the COVID-19 virus. Although they differ in the operation of HVAC systems and filter applications, they tend to agree that air conditioning and ventilation systems and air purifiers can help reduce the spread of airborne viruses. It is recommended to increase air exchange rate, avoid air recirculation, run the HVAC systems for 24 hours, naturally ventilate enclosed spaces for frequent air exchange through window opening, and run the heat recovery units when the air leakage rate is below 5%.

9. Conclusions

This paper presents a review on the relevant research of the impact of COVID-19 on HVAC system and indoor environment, including ventilation system, air filtration device, HVAC system, building envelope design, and vent location arrangement, etc. The impact of COVID-19 on building energy consumption and building operation guidelines issued from various countries are also presented. The following conclusions can be made:

- 1) Natural ventilation with auxiliary equipment can help improve indoor air quality and maintain a healthy environment. However, 100% fresh air supply leads to increased building energy consumption. Future research should focus on how to provide enough fresh air through the combination of reasonable natural ventilation and efficient air purification to achieve a low infection risk while maintaining low energy consumption during the pandemic.
- 2) Considerations must be given to the by-products that may arise when using certain high-performance filters. Additionally, bacteria or viruses other than SARS-CoV-2 were often used in the efficiency assessment. Therefore, future research should prioritize reevaluating the filtering efficiency using SARS-CoV-2 samples.
- 3) Current research focuses on the increase of fresh air and air cleaning device to stop/mitigate virus spread, as well as heat recovery and new air-conditioning system to reduce the energy consumption caused by increased ventilation rate. Future studies could focus on how to design HVAC system that can both work in normal conditions and during a pandemic with low energy consumption while maintaining a healthy indoor environment.
- 4) Most of the studies focus on the energy consumption change and usage patterns before and after the pandemic. However, more in-depth studies are needed on the occupants' behavior to help develop more effective strategies to combat COVID-19.
- 5) Vent location, physical barrier, building envelope design, and flow deflector can all play a role in preventing virus spread. Future research can explore the impact of building layout and the synergistic effects of combining these improvement measures with HVAC operations to effectively minimize the risk of infection.
- 6) It is recommended to increase air exchange rate, avoid air recirculation, run the HVAC systems for 24 hours, naturally ventilate enclosed spaces for frequent air exchange through window opening, and run the heat recovery units when air leakage rate is below 5%.

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.

CRediT authorship contribution statement

Yaolin Lin: Conceptualization, Methodology, Supervision. **Jiajun Wang:** Investigation, Writing – original draft. **Wei Yang:** Writing – review & editing, Investigation. **Lin Tian:** Writing – review & editing. **Christina Candido:** Writing – review & editing.

References

- [1] G. Buonanno, A. Robotto, E. Brizio, L. Morawska, A. Civra, F. Corino, D. Lembo, G. Fico, L. Stabile, Link between SARS-CoV-2 emissions and airborne concentrations: Closing the gap in understanding, *J. Hazard. Mater.* 428 (2023) 128279.
- [2] L. Morawska, J. Allen, W. Bahnfleth, P.M. Bluyssen, A. Boerstra, G. Buonanno, J. Cao, S.J. Dancer, A. Floto, F. Franchimon, et al., A paradigm shift to combat indoor respiratory infection, *Science* 372 (6543) (2021) 689–691.
- [3] A. Mikszewski, L. Stabile, G. Buonanno, L. Morawska, The airborne contagiousness of respiratory viruses: a comparative analysis and implications for mitigation, *Geosci. Front.* 13 (6) (2022) 101285.
- [4] J.L. Jimenez, L.C. Marr, K. Randall, E.T. Ewing, Z. Tufekci, T. Greenhalgh, R. Tellier, J.W. Tang, Y. Li, L. Morawska, et al., What were the historical reasons for the resistance to recognizing airborne transmission during the COVID-19 pandemic? *Indoor Air* 32 (8) (2022) e13070.
- [5] N. Rezaei, M. Jafari, A. Nazari, S. Salehi, F. Talati, R. Torab, R. Nejad-Rahim, A novel methodology and new concept of SARS-CoV-2 elimination in heating and ventilating air conditioning systems using waste heat recovery, *AIP Adv.* 10 (8) (2020) 085308.
- [6] H. Xie, B. Yu, J. Wang, J. Ji, A novel disinfected Trombe wall for space heating and virus inactivation: Concept and performance investigation, *Appl. Energy* (2021) 291.
- [7] M. Rodríguez, M.L. Palop, S. Seseña, A. Rodríguez, Are the Portable Air Cleaners (PAC) really effective to terminate airborne SARS-CoV-2? *Sci. Total Environ.* 785 (2021) 147300.
- [8] N.D. Corticos, C.C. Duarte, COVID-19: The impact in US high-rise office buildings energy efficiency, *Energy Build.* 249 (2021) 111180.
- [9] H. Dai, B. Zhao, Reducing airborne infection risk of COVID-19 by locating air cleaners at proper positions indoors: analysis with a simple model, *Build. Environ.* 213 (2022) 108864.
- [10] R.M. Lynch, R. Goring, Practical steps to improve air flow in long-term care resident rooms to reduce COVID-19 infection risk, *J. Am. Med. Dir. Assoc.* 21 (7) (2020) 893–894.
- [11] S. Srivastava, X. Zhao, A. Manay, Q. Chen, Effective ventilation and air disinfection system for reducing coronavirus disease 2019 (COVID-19) infection risk in office buildings, *Sustain. Citi. Soc.* 75 (2021) 103408.
- [12] C. Ren, C. Xi, J. Wang, Z. Feng, F. Nasiri, S.J. Cao, F. Haghighat, Mitigating COVID-19 infection disease transmission in indoor environment using physical barriers, *Sustain. Citi. Soc.* 74 (2021) 103175.
- [13] G. Berry, A. Parsons, M. Morgan, J. Rickert, H. Cho, A review of methods to reduce the probability of the airborne spread of COVID-19 in ventilation systems and enclosed spaces, *Environ. Res.* 203 (2022) 111765.
- [14] 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.
- [15] H. Qian, Y. Li, W.H. Seto, P. Ching, W.H. Ching, H.Q. Sun, Natural ventilation for reducing airborne infection in hospitals, *Build. Environ.* 45 (3) (2010) 559–565.
- [16] S. Park, Y. Choi, D. Song, E.K. Kim, Natural ventilation strategy and related issues to prevent coronavirus disease 2019 (COVID-19) airborne transmission in a school building, *Sci. Total Environ.* 789 (2021) 147764.
- [17] P. Cheng, W. Chen, S. Xiao, F. Xue, Q. Wang, P.W. Chan, R. You, Z. Lin, J. Niu, Y. Li, Probable cross-corridor transmission of SARS-CoV-2 due to cross airflows and its control, *Build. Environ.* 218 (2022) 109137.
- [18] B. Blocken, T. van Druenen, A. Ricci, L. Kang, T. van Hooff, P. Qin, L. Xia, C.A. Ruiz, J.H. Arts, J.F.L. Diepens, G.A. Maas, S.G. Gillmeier, S.B. Vos, A.C. Brombacher, Ventilation and air cleaning to limit aerosol particle concentrations in a gym during the COVID-19 pandemic, *Build. Environ.* 193 (2021) 107659.
- [19] M. Gil-Baez, J. Lizana, J.A.B. Villanueva, M. Molina-Huelva, A. Serrano-Jimenez, R. Chacartegui, Natural ventilation in classrooms for healthy schools in the COVID era in Mediterranean climate, *Build. Environ.* 206 (2021) 108345.
- [20] M. Ahmadzadeh, E. Farokhi, M. Shams, Investigating the effect of air conditioning on the distribution and transmission of COVID-19 virus particles, *J. Clean. Prod.* 316 (2021) 128147.
- [21] H. Alkalamouni, E. Hitti, H. Zaraket, Adopting fresh air ventilation may reduce the risk of airborne transmission of SARS-CoV-2 in COVID-19 unit, *J. Infect.* 83 (5) (2021) e4–e5.
- [22] M.A. William, M.J. Suárez-López, S. Soutullo, A.A. Hanafy, Evaluating heating, ventilation, and air-conditioning systems toward minimizing the airborne transmission risk of *Mucormycosis* and COVID-19 infections in built environment, *Case Stud. Therm. Eng.* 28 (2021).
- [23] L. Schibuola, C. Tambani, High energy efficiency ventilation to limit COVID-19 contagion in school environments, *Energy Build.* 240 (2021) 110882.
- [24] C. Li, H. Tang, Study on ventilation rates and assessment of infection risks of COVID-19 in an outpatient building, *J. Build. Eng.* 42 (2021) 103090.
- [25] V.C.C. Cheng, D.C. Lung, S.C. Wong, A.K.W. Au, Q. Wang, H. Chen, L. Xin, A.W.H. Chu, J.D. Ip, W.M. Chan, H.W. Tsoi, H. Tse, K.H.L. Ng, M.Y.W. Kwan, S.K. Chuang, K.K.W. To, Y. Li, K.Y. Yuen, Outbreak investigation of airborne transmission of Omicron (B.1.1.529) - SARS-CoV-2 variant of concern in a restaurant: Implication for enhancement of indoor air dilution, *J. Hazard. Mater.* 430 (2022) 128504.
- [26] C. Ou, S. Hu, K. Luo, H. Yang, J. Hang, P. Cheng, Z. Hai, S. Xiao, H. Qian, S. Xiao, X. Jing, Z. Xie, H. Ling, L. Liu, L. Gao, Q. Deng, B.J. Cowling, Y. Li, Insufficient ventilation led to a probable long-range airborne transmission of SARS-CoV-2 on two buses, *Build. Environ.* 207 (2022) 108414.
- [27] 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, *Build. Simul.* 2 (4) (2009) 281–289.
- [28] H. Dai, B. Zhao, Association of the infection probability of COVID-19 with ventilation rates in confined spaces, *Build. Simul.* 13 (6) (2020) 1321–1327.
- [29] A.K. Melikov, COVID-19: Reduction of airborne transmission needs paradigm shift in ventilation, *Build. Environ.* 186 (2020) 107336.
- [30] H. Kim, B. Han, Y. Kim, T. Oda, H. Won, Submicrometer particle removal indoors by a novel electrostatic precipitator with high clean air delivery rate, low ozone emissions, and carbon fiber ionizer, *Indoor Air* 23 (2013) 369–378.
- [31] P. Zhou, Y. Yang, A.C.K. Lai, G. Huang, Inactivation of airborne bacteria by cold plasma in air duct flow, *Build. Environ.* 106 (2016) 120–130.
- [32] Z. Feng, S.J. Cao, J. Wang, P. Kumar, F. Haghighat, Indoor airborne disinfection with electrostatic disinfectant (ESD): Numerical simulations of ESD performance and reduction of computing time, *Build. Environ.* 200 (2021) 107956.
- [33] W.W.F. Leung, Y.T. Chau, Experiments on filtering nano-aerosols from vehicular and atmospheric pollutants under dominant diffusion using nanofiber filter, *Separat. Purificat. Technol.* 213 (2019) 186–198.
- [34] Q. Sun, W.W.F. Leung, Charged PVDF multi-layer filters with enhanced filtration performance for filtering nano-aerosols, *Separat. Purificat. Technol.* 212 (2019) 854–876.
- [35] W.W. Leung, Q. Sun, Charged PVDF multilayer nanofiber filter in filtering simulated airborne novel coronavirus (COVID-19) using ambient nano-aerosols, *Sep. Purif. Technol.* 245 (2020) 116887.
- [36] R. Tellier, Review of aerosol transmission of influenza a virus, *Emerg. Infect. Dis.* 12 (2006) 1657.
- [37] L. Yu, G.K. Peel, F.H. Cheema, W.S. Lawrence, N. Bukreyeva, C.W. Jinks, J.E. Peel, J.W. Peterson, S. Paessler, M. Hourani, Z. Ren, Catching and killing of airborne SARS-CoV-2 to control spread of COVID-19 by a heated air disinfection system, *Mater. Today Phys.* 15 (2020) 100249.
- [38] T.Q. Correa, K.C. Blanco, J.D. Vollet-Filho, V.S. Morais, W.R. Trevelin, S. Pratavieira, V.S. Bagnato, Efficiency of an air circulation decontamination device for micro-organisms using ultraviolet radiation, *J. Hosp. Infect.* 115 (2021) 32–43.
- [39] Z. Feng, S.J. Cao, F. Haghighat, Removal of SARS-CoV-2 using UV+Filter in built environment, *Sustain. Citi. Soc.* 74 (2021) 103226.
- [40] EPA. What is a HEPA filter? [https://www.epa.gov/indoor-air-quality-iaq/what-hepa-filter#:~:text=It%20is%20an%20acronym%20for,of%200.3%20microns%20\(C%26B5m\)](https://www.epa.gov/indoor-air-quality-iaq/what-hepa-filter#:~:text=It%20is%20an%20acronym%20for,of%200.3%20microns%20(C%26B5m).). (Last accessed time: July 4, 2023).
- [41] B. Zhao, Y. Liu, C. Chen, Air purifiers: A supplementary measure to remove airborne SARS-CoV-2, *Build. Environ.* 177 (2020) 106918.
- [42] L.F. Pease, N. Wang, T.I. Salsbury, R.M. Underhill, J.E. Flaherty, A. Vlachokostas, G. Kulkarni, D.P. James, Investigation of potential aerosol transmission and infectivity of SARS-CoV-2 through central ventilation systems, *Build. Environ.* 197 (2021) 107633.
- [43] N. Zacharias, A. Haag, R. Brang-Lamprecht, J. Gebel, S.M. Essert, T. Kistemann, M. Exner, N.T. Muters, S. Engelhart, Air filtration as a tool for the reduction of viral aerosols, *Sci. Total Environ.* 772 (2021) 144956.
- [44] E.S. Mousavi, K.J. Godri Pollitt, J. Sherman, R.A. Martinello, Performance analysis of portable HEPA filters and temporary plastic anterooms on the spread of surrogate coronavirus, *Build. Environ.* 183 (2020) 107186.
- [45] M.S. Waring, J.A. Siegel, R.L. Corsi, Ultrafine particle removal and generation by portable air cleaners, *Atmos. Environ.* 42 (20) (2008) 5003–5014.
- [46] S. Yeo, I. Hosein, L. McGregor-Davies, Use of HEPA filters to reduce the risk of nosocomial spread of SARS-CoV-2 via operating theatre ventilation systems, *Br. J. Anaesth.* 125 (4) (2020) e361–e363.
- [47] P. Yin, COVID-19 epidemic and central air conditioning system, *J. HV&AC* 50 (10) (2020) 24–30 + 86.
- [48] V.A. Mouchtouri, M. Koureas, M. Kyritsi, A. Vontas, L. Kourentis, S. Sapounas, G. Rigakos, E. Petinaki, S. Tsiodras, C. Hadjichristodoulou, Environmental contamination of SARS-CoV-2 on surfaces, air-conditioner and ventilation systems, *Int. J. Hyg. Environ. Health* 230 (2020) 113599.
- [49] S. Sousan, M. Fan, K. Outlaw, S. Williams, R.L. Roper, SARS-CoV-2 detection in air samples from inside heating, ventilation, and air conditioning (HVAC) systems-COVID surveillance in student dorms, *Am. J. Infect. Control* 50 (3) (2022) 330–335.
- [50] C.A. Faulkner, J.E. Castellini Jr., W. Zuo, D.M. Lorenzetti, M.D. Sohn, Investigation of HVAC operation strategies for office buildings during COVID-19 pandemic, *Build. Environ.* 207 (2022) 108519.
- [51] J. Lu, J. Gu, K. Li, C. Xu, W. Su, Z. Lai, D. Zhou, C. Yu, B. Xu, Z. Yang, COVID-19 Outbreak Associated with Air Conditioning in Restaurant, Guangzhou, China, 2020, *Emerg. Infect. Dis.* 26 (7) (2020) 1628–163147.
- [52] Y. Pan, C. Du, Z. Fu, M. Fu, Re-thinking of engineering operation solutions to HVAC systems under the emerging COVID-19 pandemic, *J. Build. Eng.* 43 (2021) 102889.
- [53] D. Aviv, K.W. Chen, E. Teitelbaum, D. Sheppard, J. Pantelic, A. Rysanek, F. Meggers, A fresh (air) look at ventilation for COVID-19: estimating the global energy savings potential of coupling natural ventilation with novel radiant cooling strategies, *Appl. Energy* 292 (2021) 116848.
- [54] J.H. Lee, J.I. Bang, M. Sung, J.W. Jeong, Inactivation of airborne microbial contaminants by a heat-pump-driven liquid-desiccant air-conditioning system, *J. Build. Eng.* 50 (2022) 104157.
- [55] H. Sha, X. Zhang, D. Qi, Optimal control of high-rise building mechanical ventilation system for achieving low risk of COVID-19 transmission and ventilative cooling, *Sustain. Citi. Soc.* 74 (2021) 103256.
- [56] Z. Xu, Y. Wang, Improvements and operation methods of HVAC system in Shanghai Library (East Zone) under the background of COVID-19's normalization prevention and control, *J. Build Energy Effic.* 49 (06) (2021) 87–91.

- [57] J. Shen, Y. Liu, Countermeasures to prevent and control COVID-19 should be re-seanable, appropriate and compliant, *J. HV&AC* 50 (06) (2020) 6–11 +59.
- [58] C. Sacconi, A. Guzzini, C. Vocale, D. Gori, M. Pellegrini, M.P. Fantini, A. Primavera, Experimental testing of air filter efficiency against the SARS-CoV-2 virus: The role of droplet and airborne transmission, *Build. Environ.* 210 (2022) 108728.
- [59] E. Katramiz, N. Ghaddar, K. Ghali, Novel personalized chair-ventilation design integrated with displacement ventilation for cross-contamination mitigation in classrooms, *Build. Environ.* 213 (2022) 108885.
- [60] L. Yan, J. Li, M. Liu, M. Hu, Z. Xu, K. Xue, Heating behavior using household air-conditioners during the COVID-19 lockdown in Wuhan: An exploratory and comparative study, *Build. Environ.* 195 (2021) 107731.
- [61] H. Kang, J. An, H. Kim, C. Ji, T. Hong, S. Lee, Changes in energy consumption according to building use type under COVID-19 pandemic in South Korea, *Renew. Sustain. Energy Rev.* 148 (2021) 111294.
- [62] J. Rouleau, L. Gosse, Impacts of the COVID-19 lockdown on energy consumption in a Canadian social housing building, *Appl. Energy* 287 (2021) 116565.
- [63] T. Zhou, X. Luo, X. Liu, G. Liu, N. Li, Y. Sun, M. Xing, J. Liu, Analysis of the influence of the stay-at-home order on the electricity consumption in Chinese university dormitory buildings during the COVID-19 pandemic, *Energy Build.* 277 (2022) 112582.
- [64] N.D. Corticos, C.C. Duarte, Energy efficiency in large office buildings post-COVID-19 in Europe's top five economies, *Energy Sustain. Dev.* 68 (2022) 410–424.
- [65] C.F. Chen, G.Z. de Rubens, X. Xu, J. Li, Coronavirus comes home? Energy use, home energy management, and the social-psychological factors of COVID-19, *Energy Res. Soc. Sci.* 68 (2020) 101688.
- [66] S. Chinthavali, V. Tansakul, S. Lee, M. Whitehead, A. Tabassum, M. Bhandari, J. Munk, H. Zandi, H. Buckberry, T. Kuruganti, J. Hill, C. Cortner, COVID-19 pandemic ramifications on residential Smart homes energy use load profiles, *Energy Build.* 259 (2022) 111847.
- [67] E. Kawka, K. Cetin, Impacts of COVID-19 on residential building energy use and performance, *Build. Environ.* 205 (2021) 108200.
- [68] W. Zheng, J. Hu, Z. Wang, J. Li, Z. Fu, H. Li, J. Jurasz, S.K. Chou, J. Yan, COVID-19 impact on operation and energy consumption of heating, ventilation and air-conditioning (HVAC) systems, *Adv. Appl. Energy* 3 (2021) 100040.
- [69] Y. Bai, Z. Wang, F. Xie, L. Cen, Z. Xie, X. Zhou, J. He, C. Lu, Changes in stoichiometric characteristics of ambient air pollutants pre-to post-COVID-19 in China, *Environ. Res.* 209 (2022) 112806.
- [70] U. Surahman, D. Hartono, E. Setyowati, A. Jurizat, Investigation on household energy consumption of urban residential buildings in major cities of Indonesia during COVID-19 pandemic, *Energy Build.* 261 (2022) 111956.
- [71] H.T. Dao, K.S. Kim, Behavior of cough droplets emitted from Covid-19 patient in hospital isolation room with different ventilation configurations, *Build. Environ.* 209 (2022) 108649.
- [72] M. Mirzaie, E. Lakzian, A. Khan, M.E. Warkiani, O. Mahian, G. Ahmadi, COVID-19 spread in a classroom equipped with partition - A CFD approach, *J. Hazard. Mater.* 420 (2021) 126587.
- [73] W. Che, J. Ding, L. Li, Airflow deflectors of external windowsto induce ventilation: towards COVID-19 prevention and control, *Sustain. Citi. Soc.* 77 (2022) 103548.
- [74] N. Kumar, R. Bardhan, T. Kubota, Y. Tominaga, M. Shirzadi, Parametric study on vertical void configurations for improving ventilation performance in the mid-rise apartment building, *Build. Environ.* 215 (2022) 108969.
- [75] ASHRAE. ASHRAE Positions on Infectious Aerosols. https://www.ashrae.org/file%20library/about/position%20documents/pd_infectious-aerosols-2022_edited-january-2023.pdf (Last accessed time: January 18, 2023).
- [76] ASHRAE. Guidance for Building Operations During the COVID-19 Pandemic. <https://www.ashrae.org/news/ashraejournal/guidance-for-building-operations-during-the-covid-19-pandemic>. (Last accessed time: January 18, 2023).
- [77] ASHRAE, ASHRAE Offers COVID-19 Building Readiness/Reopening Guidance, 2020. <https://www.ashrae.org/about/news/2020/ashrae-offers-covid-19-building-readiness-reopening-guidance>. (Last accessed time: June, 28 2021).
- [78] 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>. (Last accessed time: May, 9 2021).
- [79] ASHRAE. ASHRAE Epidemic Task Force Releases Updated Building Readiness Guide,2021. <https://www.ashrae.org/file%20library/technical%20resources/covid-19/ashrae-building-readiness.pdf>.(Last accessed time: January 15, 2023).
- [80] ASHRAE. Core Recommendations for Reducing Airborne Infectious Aerosol Exposure,2021. <https://www.ashrae.org/file%20library/technical%20resources/covid-19/core-recommendations-for-reducing-airborne-infectious-aerosol-exposure.pdf>. (Last accessed time: January 15, 2023).
- [81] ASHRAE. Does ASHRAE's guidance agree with guidance from WHO and CDC? <https://www.ashrae.org/file%20library/technical%20resources/covid-19/does-ashraes-guidance-agree-with-guidance-from-who-and-cdc.23aug21.pdf>. (Last accessed time: January 15, 2023).
- [82] ASHRAE. One Page Guidance for Residential Buildings. <https://www.ashrae.org/file%20library/technical%20resources/covid-19/guidance-for-residential-buildings.pdf>. (Last accessed time: January 15, 2023).
- [83] ASHRAE. ASHRAE EPIDEMIC TASK FORCE SCHOOLS & UNIVERSITIES. 2021. <https://www.ashrae.org/file%20library/technical%20resources/covid-19/ashrae-reopening-schools-and-universities-c19-guidance.pdf>. (Last accessed time: January 15, 2023).
- [84] Notice on printing and distributing guidelines for the operation and management of air-conditioning and ventilation systems in offices and public places during the COVID-19 epidemic, *Bull. Nat. Health Commis. People. Republ. China* 02 (2020) 56–57.
- [85] ASCThe Design Standard of Infectious Disease Emergency Medical Facilities for Novel Coronavirus (2019-nCov) Infected Pneumonia, China Building Industry Press, Beijing, 2020.
- [86] ASC. Guidelines for office buildings to deal with “new coronavirus” operational management emergency measures. https://www.mohurd.gov.cn/xinwen/gzdt/202002/20200207_243794.html. (Last accessed time: January 18, 2023).
- [87] The Chinese Association Of Refrigeration, Recommendations for the Safe Use of Air-Conditioning (Heating) Systems in Response to the COVID-19 Epidemic, 2020. http://www.car.org.cn/index.php?s=/articles_1348.html. (Last accessed time: May, 9 2021).
- [88] DAIKIN. <https://www.daikin.co.jp/air/life/ventilation/office>. (Last accessed time: January 15, 2023).
- [89] SHASE. http://www.shasej.org/recommendation/covid-19/2020.09.07covid19_kaitei.pdf. (Last accessed time: January 15, 2023).
- [90] Ministry of Health Labour, and Welfare. For managers of commercial and other facilities: ventilation methods to improve closed space with poor ventilation. April 3, 2020 (in Japanese). <https://www.mhlw.go.jp/content/10900000/000618969.pdf>. (Last accessed time: January 15, 2023).
- [91] Expert meeting on novel coronavirus infectious disease. A view on novel coronavirus infectious disease control. March 9, 2020 (in Japanese). <http://www.mhlw.go.jp/content/10900000/000606000.pdf>. (Last accessed time: January 15, 2023).
- [92] Ministry of Health, Labour and Welfare. Ventilation to improve closed space with poor ventilation in commercial and other facilities. March 30, 2020 (inJapanese). <https://www.mhlw.go.jp/content/10900000/000616069.pdf>. (Last accessed time: January 15, 2023).
- [93] REHVA, REHVA COVID-19 Guidance Document, 2020. https://www.rehva.eu/fileadmin/user_upload/REHVA_COVID-19_guidance_document_ver2_20200403_1.pdf. (Last accessed time: May, 9 2021).
- [94] REHVA. REHVA COVID-19 guidance document, 2020. https://www.rehva.eu/fileadmin/user_upload/REHVA_COVID19_guidance_document_V3_03082020.pdf. (Last accessed time: January 15, 2023).
- [95] REHVA. REHVA COVID-19 Leitfaden – Version 4.1.2021. https://www.rehva.eu/fileadmin/content/REHVA_COVID19_Leitfaden_V4.1.pdf. (Last accessed time: January 15, 2023).
- [96] ECDC, Heating, ventilation and air-conditioning systems in the context of COVID- 19 2020. <https://www.ecdc.europa.eu/sites/default/files/documents/Ventilation-in-the-context-ofCOVID-19.pdf>. (Last accessed time: January 15, 2023).
- [97] ECDC, Heating, ventilation and air-conditioning systems in the context of COVID-19: first update 2020. <https://www.ecdc.europa.eu/sites/default/files/documents/Heating-ventilation-air-conditioning-systems-in-the-context-of-COVID-19-first-update.pdf>. (Last accessed time: January 15, 2023).
- [98] RLT. Operation of ventilation and air-conditioning systems under the boundary conditions of the current Covid-19-pandemic[EB/OL].(2020-04-22) <https://sante.public.lu/dam-assets/fr/espace-professionnel/recommandations/direction-sante/000-covid-19/000-covid-191-annexes/operation-ventilation-air-conditioning.pdf>. (Last accessed time: January 15, 2023).
- [99] RLT. Operation of ventilation and air-conditioning systems under the boundary conditions of the current Covid-19 pandemic.2020. https://downloads.fgk.de/RLT_Covid19_V3_200904_EN.pdf. (Last accessed time: January 15, 2023).
- [100] ISHRAE. ISHRAE COVID-19 Guidance Document for Air Conditioning and Ventilation. 2020. https://ishrae.in/mailer/ISHRAE_COVID-19_Guidelines.pdf. (Last accessed time: January 15, 2023).
- [101] CIBSE. CIBSE COVID-19 Ventilation Guidance. 2020. https://schools.oxfordshire.gov.uk/cms/sites/schools/files/folders/folders/documents/healthandsafety/proceduresaz/CIBSE_Covid_19_Ventilation_guidance.pdf. (Last accessed time: January 15, 2023).
- [102] SAGE-EMG. Role of Ventilation in Controlling SARS-CoV-2 Transmission. www.gov.uk/government/publications/EMG-role-of-ventilation-in-controlling-SARS-cov-2transmission-30-June-2020. (Last accessed time: January 15, 2023).
- [103] CIBSE. CIBSE COVID-19:Ventilation. 2021. https://go.cibse.org/l/698403/2021-07-16/58mijt/698403/1626442809vU1W2onf/COVID_19_Ventilation_v5.pdf. (Last accessed time: January 15, 2023).
- [104] CIBSE. CIBSE COVID-19: Air cleaning technologies.2021. https://go.cibse.org/l/698403/2021-07-16/58mijt/698403/1626877012AHovOcJ8/COVID_19_Air_cleaning_technologies_v1.1.pdf. (Last accessed time: January 15, 2023).
- [105] CCIAQ. Addressing COVID-19 in Buildings. 2020. https://www.researchgate.net/publication/346829067_Addressing_COVID-19_in_Buildings_In_collaboration_with_and_approved_by_the_Canadian_Committee_for_Indoor_Air_Quality. (Last accessed time: January 15, 2023).
- [106] CCIAQ. Addressing COVID-19 in Buildings. 2021. <https://iaqresource.ca/wp-content/uploads/2021/07/Module15V2.pdf>. (Last accessed time: January 15, 2023).