



Research article

Review of component designs for post-COVID-19 HVAC systems: possibilities and challenges

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ARTICLE INFO

Keywords:

UVGI
•OH radical
MOFs
Personalized ventilation
HVAC
Airborne transmission
SARS-CoV-2

ABSTRACT

The globally occurring recurrent waves of the COVID-19 pandemic, primarily caused by the transmission of aerosolized droplets from an infected person to a healthy person in the indoor environment, has led to the urgency of designing new modes of indoor ventilation. To prevent cross-contaminations due to airborne viruses, bacteria, and other pollutants in indoor environments, heating ventilation and air-conditioning (HVAC) systems need to be redesigned with anti-pandemic components. The three vital anti-pandemic components for the post-COVID-19 HVAC systems, as identified by the authors, are: a biological contaminant inactivation unit, a volatile organic compound decomposition unit, and an advanced air filtration unit. The purpose of the current article is to provide an overview of the latest research outcomes toward designing these anti-pandemic components and pointing out the future promises and challenges. In addition, the role of personalized ventilation in minimizing the risk of indoor cross-contamination by employing various air terminal devices is discussed. The authors believe that this article will encourage HVAC designers to develop effective anti-pandemic components to minimize the indoor airborne transmission.

1. Introduction

Since the first case traced back in China in November 2019, as of January 13, 2022, worldwide the total numbers of confirmed cases and deaths due to COVID-19 have surpassed 315 and 5 million, respectively [1]. The globally occurring recurring waves of the infection have raised a major question: how long will the infection take to get eradicated completely? Such an enormous spread of COVID-19 has been possible owing to its airborne behavior within closed indoor environments. Although the relative contributions of different transmission routes for spreading COVID-19 remain controversial, current evidence is sufficiently strong to consider indoor airborne transmission as the dominant route [2, 3, 4]. Wang et al. [5] elaborated the mechanism of generation and transmission of respiratory viruses through aerosols and the factors affecting the transmission process in an indoor environment.

In another study, Somsen et al. [6] observed that the visible large droplets with a diameter of 500 μm produced through coughing tend to settle down on the ground from an average speaking height of 160 cm within 1 s owing to the effect of gravity. However, for smaller droplets with a typical radius of 5 μm , the time to reach the ground from the same speaking height was estimated to be 9 min following Stokes' law. Wang

et al. [5] also showed that aerosol having sizes of 100, 5, and 1 μm took approximately 5 s, 33 min, and 12.2 h to reach the ground from a height of 1.5 m. Thus, although the short-range transmission (<1 m) through inhalation of the "droplet nuclei" has been recognized as the most dominant route, the long-range transmission (>2 m) through inhalation of the "aerosols" cannot be ignored [7]. Significant precautions, including social distancing, wearing masks, frequent washing of hands, disinfecting surfaces, improving the indoor air exchange rate, and employing portable air cleaners, have already been adopted within the built environment. These measures are effective for reducing the number of new infections, but inadequate for total eradication of the infection [8]. Therefore, implementing engineering control within an indoor environment is essential to prevent both short-range and long-range transmissions.

The world has experienced the devastating nature of the COVID-19 pandemic through millions of deaths. Break-down of the health management system, shortage of personal protective equipment and oxygen cylinders, unavailability of hospital and ICU beds were common scenarios in many countries. As social distancing is an essential safety measure against the spread of infection, people living in the underprivileged part of the world, subject to poverty and poor healthcare facilities, are more

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vulnerable to infection and spreading the disease [9]. Hence, no country or continent can end the pandemic on its own until the majority of the world's population is vaccinated [10]. Recently, vaccines have been globally implemented as a key measure to fight the COVID-19 pandemic. Nevertheless, vaccine manufacturing is in the hands of a few rich countries. According to the WHO dashboard [1], approximately 0.86 billion vaccine doses have been administered as of December 22, 2021. These doses include both the 1st and 2nd doses and represent only 10 % of the world's total population. Therefore, it may take at least 3–5 additional years to administer at least two doses of vaccine to 70 % of the world's population, including people from middle- and low-income countries.

The long-term efficacy of the vaccines is also a controversial issue. Questions, such as how long the vaccine can protect a fully immunized person, whether a booster will be necessary, how frequently the booster should be administered, and what are the potential risks of taking frequent boosters, are yet to be answered [11]. Furthermore, people's reluctance to take a vaccine may also substantially prolong the pandemic. Kaplan and Milstein [12] reported that the overall public acceptance of receiving the COVID-19 vaccine remains questionable based on three major arguments: (i) how effective is the vaccine against the infection, (ii) what are the minor side effects, and (iii) what are the long-term adverse reactions. A survey conducted by Thompson et al. [13] on 3,950 participants reported that a full immunization and single dose of mRNA-based vaccines made by Moderna and Pfizer-BioNTech were respectively, 90% and 80% effective against infection (it was conducted between December 14, 2020, and March 13, 2021 prior to the emergence of Delta (B.1.617.2) variant).

Another recent survey on 4272 people by Bernal et al. [14] reported that the BNT162b2 vaccine by Pfizer–BioNTech was only 30.7% and 93.7% effective against delta variant after the first and second dose (full immunization) respectively. At the same time, the ChAdOx1 nCoV-19 vaccine by AstraZeneca exhibited even worse effectiveness (67% effective after full immunization). Nevertheless, the efficacy of most vaccines against the symptomatic disease was found to be lower for the Delta variant than that for the Alpha variant [11]. Thus, the emergence of new and more deadly variants of the SARS-CoV-2 virus in different countries (e.g., delta [15], lambda [16] and omicron [17]) has become a major concern, and uncertainty prevails regarding the ability of the existing vaccines to prevent infection caused by the emerging new variants [18]. According to U.S. SIG (SARS-CoV-2 Interagency Group) variant classification scheme, variants of the SARS-CoV-2 virus are classified into four sub-categories: variants being monitored (VBM), variants of interest (VOI), variants of concern (VOC), and variants of high consequence (VOHC). As of December 1, 2021, ten variants have been identified as VBM and two variants (Delta (B.1.617.2) and Omicron (B.1.1.529)) as VOC [19].

Furthermore, the occurrence of pandemics caused by viral respiratory diseases has increased in the last two decades (e.g., SARS-CoV-1 in 2003, MERS-CoV in 2012, and SARS-CoV-2 in 2019). Therefore, it is likely that other novel severe acute respiratory syndrome viruses will emerge in the coming decades. Thus, developing an advanced heating ventilation and air-conditioning (HVAC) system with the airborne virus and bacterium inactivation ability is equally vital to vaccination. The role of the HVAC system in minimizing the indoor airborne transmission has already been discussed in this context [20, 21, 22].

Somsen et al. [23] reported that the characteristic time for a 50 % decrease in aerosol concentration in a well-ventilated space is 4–5 times less than that in a poorly ventilated room. Thus, constant refreshing of the indoor air with the outdoor air at a high air change rate per hour (ACH) is considered the most effective measure to prevent airborne transmission of COVID-19. However, such natural ventilation cannot ensure the thermal comfort of indoor occupants as the humidity and temperature of the supply air cannot be controlled. “Sick building syndrome” may also appear due to various fungus and mold growths if the outdoor air humidity is very high [24]. Natural ventilation in urban areas can also be challenging due to air pollution, low wind velocity, noise, and urban heat island effect [25].

Therefore, redesigning a mechanical HVAC system with anti-pandemic components to inactivate airborne microbial contaminants, decompose volatile organic compounds (VOCs), and remove air particulate matters (PMs) from indoor air is of utmost importance to ensure both thermal comfort and health safety of the occupants. The key question that needs to be answered in this regard is whether the latest research outcomes are sufficient to develop effective anti-pandemic components that can minimize the indoor airborne transmission of highly infective viruses and bacteria. The purpose of this article is to provide an answer to this question by reviewing the cutting-edge research outcomes reported in the literature. The possibilities and challenges for scientifically designing different anti-pandemic components for the post-COVID-19 HVAC systems are addressed. In addition, personalized ventilation (PV) may be employed in combination with room ventilation to further reduce the risk of indoor transmission of aerosolized viruses and bacteria [26]. A comprehensive discussion on the role of PV in indoor infection control is also presented. To the best of the authors' knowledge, these issues have not been addressed in any other relevant review in the literature. The authors believe that this article will be helpful in envisioning the new anti-pandemic design standards for building HVAC systems in the post-COVID-19 era.

2. COVID-19 and role of HVAC systems

The role of the HVAC system in the spread and prevention of aerosolized SARS-CoV-2 viruses in indoor environments is controversial. Although an appropriate ventilation rate, airflow direction, and differential pressure can effectively mitigate the transmission risk, an incorrect design may substantially augment it. Fresh intake of outdoor air at a high ACH can significantly dilute the concentration of aerosolized droplet nuclei generated through coughing and sneezing from an infected person in the indoor environment and reduce the risk of airborne transmission. The probability of infection and ventilation rate are mathematically correlated according to Eq. (1) [5]:

$$P = \frac{N}{S} = 1 - e^{-\frac{Iqt}{Q}} \quad (1)$$

where P is the probability of infection, N is the number of confirmed infection cases, S is the number of susceptible cases, I is the number of infectors, q is the quanta per hour (infectious dose), p is the pulmonary ventilation rate of a susceptible individual, t is the exposure time, and Q is the indoor ventilation rate.

Thus, poor ventilation in a crowded room may lead to a high infection rate. Therefore, the professional HVAC societies in different countries, [including but not limited to ASHRAE (The American Society of Heating, Refrigerating and Air-Conditioning Engineers), REHVA (The Federation of European Heating, Ventilation and Air Conditioning Associations), SHASE (The Society of Heating, Air-Conditioning and Sanitary Engineers of Japan), JSRAE (The Japan Society of Refrigeration and Air-Conditioning Engineers), PAHO (Pan American Health Organization), HSE (Health and Safety Executive), Chinese Association of Refrigeration, and The Architectural Society of China] have issued, or are considering issuing, guidance for the proper use of HVAC systems in buildings to minimize the infection. Guo et al. [27] reviewed the COVID-19 guidance published by different HVAC societies and compared the main strategies/countermeasures proposed to abate the risk of transmission through HVAC operations (Appendix A in [27]).

Pan et al. [28] emphasized re-thinking the design practice for building HVAC systems by increasing the ventilation rate and cleaning capacity as HVAC equipment in existing buildings are sized and selected based on design standards under normal conditions. They also suggested several operation strategies to enhance the ventilation rate without significantly affecting the normal operation of building HVAC systems. Sodiq et al. [20] discussed the transmission of airborne infectious diseases in closed environments from a historical perspective and made

several recommendations for their prevention and containment, including the use of ultraviolet germicidal irradiation (UVGI) and nanoporous air filters.

Faulkner et al. [29] stressed on improving indoor air quality either by diluting the concentration of indoor air contaminants (i.e., supplying 100 % outdoor air) or by source elimination (i.e., use of filters). However, their simulation showed that implementing the above measures have other effects on the HVAC operation. For example, the use of 100 % outdoor air significantly increases the heating energy consumption, and the use of a high-efficiency minimum efficiency reporting value (MERV) 13 filter increases the site energy consumption by approximately 3 %. The University of Tokyo, Daikin Industries, and Nippon Paint collaboratively published a “reference guide” [30] focused on infection minimization in educational sites. Based on experimental evidence, the reference guide states that use of portable air cleaners in combination with natural/mechanical ventilation systems noticeably reduces the particle concentration in indoor environments.

The WHO published a roadmap [31] to ensure proper ventilation in the indoor environment and suggested a minimum ventilation rate in the context of COVID-19. According to the roadmap, the minimum ventilation rates for different facilities are as follows: 160 L/s/patient (when aerosol-generating processes are performed) or 60 L/s/patient in health care facilities and 10 L/s/person in non-residential and residential buildings. In addition to increasing the ventilation rate, avoiding the recirculation of air, installing CO₂ sensors to monitor the accumulation of exhaled air (CO₂ level should be lower than 700–800 ppm), and utilizing aerosol sensors to evaluate the efficiencies of HVAC filters are also crucial for minimizing the indoor airborne transmission [5].

3. Essential anti-pandemic components for post-COVID-19 HVAC systems

Several anti-pandemic components may be necessary in redesigning the building HVAC systems to completely safeguard occupants from the health hazards imposed by various indoor air contaminants. However, a biological contaminant inactivation unit, a VOC decomposition unit, and an advanced air PM filtration unit are the most vital components for providing indoor occupants with clean air free of contaminants such as viruses, bacteria, other particulates, and gaseous contaminants. Therefore, a critical discussion on the design of these three important anti-pandemic components is presented in the current article. A simple schematic diagram depicting the integration of these units within a typical HVAC system is shown in Figure 1.

3.1. Biological contaminant inactivation unit

Inactivation of biological contaminants in indoor air through the utilization of various methods in building HVAC systems is not new. Particular examples include the applications of UVGI [32] and plasma cluster ions [33], photocatalytic oxidation [34], microwave heating [35], ozone sterilization [36], disinfection using chlorine dioxide gas [37], and dispersion of atomized nanoparticles in air [38]. However, recent studies [39,40] have demonstrated the superiority of UV-C against the SARS-CoV-2 virus among the other commonly employed methods. Consequently, designing an in-duct air disinfection system using UVGI to prevent pandemics is now receiving more attention [41,42]. Therefore, the discussion in this article is limited to the application of UVGI for the

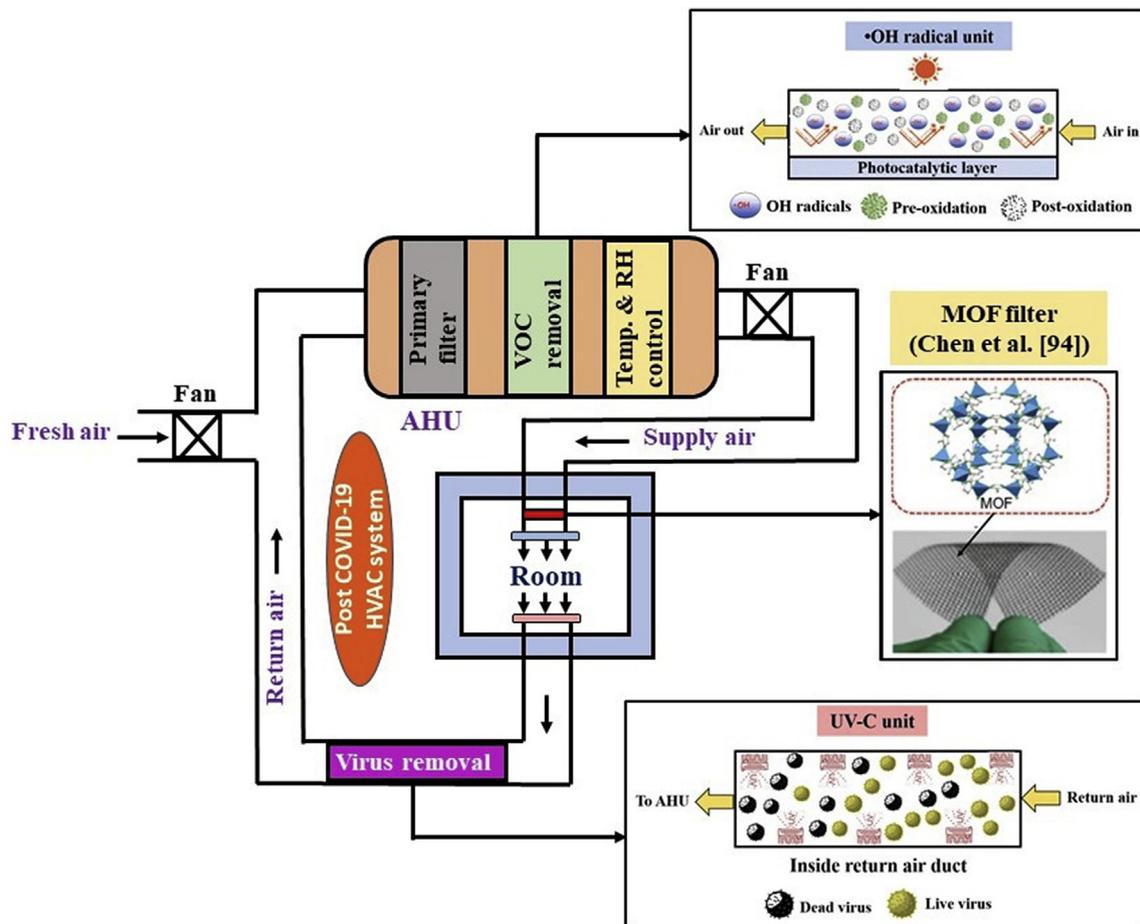


Figure 1. Concept of integrating anti-pandemic components within a typical HVAC system (Image of MOF filter reprinted with copyright permission from [94]).

inactivation of biological contaminants. Before discussing the application of UVGI in HVAC systems, a summary of recent studies demonstrating the efficacy of UVGI against the SARS-CoV-2 virus is presented below.

3.1.1. Efficacy of UVGI against the SARS-CoV-2 virus

The concept of applying UVGI to inactivate airborne viruses and bacteria dates back several decades [43, 44, 45]. UVGI can be classified into three subcategories according to the wavelength of irradiation: UV-A (320–400 nm), UV-B (280–320 nm), and UV-C (200–280 nm). When a pathogen absorbs photons produced by the UV irradiation, its genetic composition (i.e., the deoxyribonucleic acid (DNA) in the cases of bacteria and fungi, and ribonucleic acid (RNA) in the cases of viruses) is altered (Figure 2 (a)), leading to inactivation and inability to reproduce. A detailed discussion on the molecular mechanism of DNA damage or repair induced by UV radiation is beyond the scope of the current article. Avid readers interested in such details are suggested to read the review article by Rastogi et al. [46].

UV-C is considered the most effective germicidal irradiation because its peak wavelength (260–265 nm) coincides with the peak UV absorption of DNA [47]. The relative sensitivities of various microorganisms to UVGI absorption were summarized by Memarzadeh et al. [44], as shown in Figure 2(b), where a higher Z value indicates a stronger sensitivity to UVGI. Thus, the possibility of employing UVGI to inactivate the SARS-CoV-2 virus has also been investigated, and promising outcomes have been achieved.

A pioneering study on the inactivation of the SARS-CoV-2 virus using UVGI was conducted by Inagaki et al. [39], who demonstrated a rapid inactivation of a SARS-CoV-2 sample within 60 s by employing irradiation at a wavelength of 280 ± 5 nm (dose of 225 mJ/cm^2). Virus samples were collected from a patient infected with COVID-19 from the cruise ship Diamond Princess in Japan. The samples were placed at a working distance of 20 mm and irradiated with an intensity of 3.75 mW/cm^2 . The impact of different exposure times (0, 1, 10, 20, 30, and 60 s) was evaluated. They observed that the virus-infected cells had a morphology similar to that of the mock cells after irradiating for approximately 60 s (Figure 2 (c)). They also achieved a 99.9 % reduction in the infectious titer after irradiating the virus cells for only 10 s.

In another study, Buonanno et al. [40] reported that the utilization of far UV-C with a wavelength of 222 nm can inactivate 99.9 % of aerosolized human coronavirus alpha HCoV-229E and beta HCoV-OC43 within 25 min utilizing low doses between 1.7–1.2 mJ/cm^2 . Owing to the similar genomic size, they anticipated that UV-C would also be effective against the SARS-CoV-2 virus. They also mentioned that the inactivation time is strongly dependent on the magnitude of the UV dose. Sabino et al. [48], in a controlled *in vitro* experiment, investigated the effect of various doses and exposure times by employing a 254 nm wavelength UV-C irradiation and assessed the lethal dose for inactivation. Their results showed that 99.999 % of the SARS-CoV-2 viral particles could be inactivated within 49.42 s at a dose of 108.714 mJ/cm^2 .

Storm et al. [49] investigated the inactivation process for both wet and dry SARS-CoV-2 viruses using UV-C irradiation with a 254 nm wavelength. Their results showed that the inactivation time for the dry virus was nearly twice that of the wet virus. Thus, the inactivation

efficiency of a typical HVAC system may vary substantially depending on the relative humidity of the air. Schuit et al. [50] investigated the inactivation of SARS-CoV-2 in two different media under simulated sunlight and observed that the decay rate was slower when the virus was suspended in a culture medium compared to that in saliva. Thus, the matrix in which the virus is suspended may also affect the inactivation process.

Biasin et al. [51] investigated the viral growth kinetics for three different virus concentrations to determine whether UV-C irradiation could prevent viral replication over time. They also employed 254 nm wavelength UV-C irradiation with an intensity of 1.082 mW/cm^2 . Their results showed that at the highest viral concentration, a high dose of 16.9 mJ/cm^2 was necessary to completely prevent the viral replication over time. For the medium and lowest viral concentrations, a low dose of only 3.7 mJ/cm^2 was adequate to prevent reproduction. A summary of the wavelength (λ), dose (D), exposure time (t), and intensity (I) of UV-C irradiation employed in the above studies to achieve inactivation beyond 99.99 % are presented in Table 1.

Recently, the application of UV-C has also been suggested for sterilization of N95 respirators and personal protective equipment (PPE). Weaver et al. [52] demonstrated the inactivation of the human coronavirus NL63 on the N95 mask material after 15 min of UV-C exposure at 61 cm ($232 \mu\text{W}\cdot\text{cm}^{-2}$). Dexter et al. [53] proposed the use of UV-C for preoperative infection control in healthcare facilities. Thus, UV-C is an effective tool for the inactivation of the SARS-CoV-2 virus. If employed in an HVAC system, it has a significant potential to provide virus- and bacteria-free clean air to the indoor occupants. A brief discussion on the application of UV-C in HVAC systems is presented in the following section.

3.1.2. Application of UV-C to the HVAC system

Owing to the high feasibility of inactivating the SARS-CoV-2 virus using UV-C irradiation for less than a minute, its application in HVAC systems for air purification is now considered seriously. Both Centre for Disease Control and Prevention (CDC) [54] and ASHRAE [55] have recommended redesigning the building ventilation system using UVGI, particularly in high-risk buildings where a large number of people gather every day for economic activities.

Luo and Zhong [41] reviewed and analyzed critical design factors, such as UV lamp output, energy consumption, microbial response to UV doses, and the effect of airflow parameters (e.g., velocity, temperature, and humidity), for in-duct airborne bioaerosol disinfection using UVGI. Nardell [42] emphasized the utilization of UVGI as an essential component of the HVAC system to reduce the spread of the COVID-19 infection. Sodiq et al. [20] suggested that combining UVGI with a nanoporous air filter in an HVAC system may help to prevent the spread of COVID-19 in indoor environments.

According to the ASHRAE guidelines [56], it is feasible to employ UV-C in an HVAC system by irradiating the upper room air or by irradiating the air as it passes through the ducts. However, irradiating the upper room requires additional wall and ceiling mountings. Thus, the irradiation of air within the return air duct is relatively easier to implement. Another advantage of using UV-C within the return air duct is that a rapid inactivation is feasible by employing a higher UV dose without

Table 1. Wavelength (λ), dose (D), exposure time (t), and intensity (I) of UV-C irradiation employed in different studies to achieve inactivation over 99.99 %.

Reference article	Sample type	Wavelength (λ) nm	Exposure time (t) s	Dose (D) mJ/cm^2	Intensity (I) mW/cm^2 ($I = D/t$)
Inagaki et al. [39]	SARS-CoV-2	280 ± 5	60	225	3.75
Buonanno et al. [40]	α -HCoV-229E β -HCoV-OC43	222	1500	1.7–1.2	0.001133–0.0008
Sabino et al. [48]	SARS-CoV-2	254	49.42	108.714	2.2 ± 0.2
Storm et al. [49]	SARS-CoV-2 (wet)	254	4	3.396	0.849
	SARS-CoV-2 (dry)		9	7.641	
Biasin et al. [51]	SARS-CoV-2	254	15.61	16.9	1.082

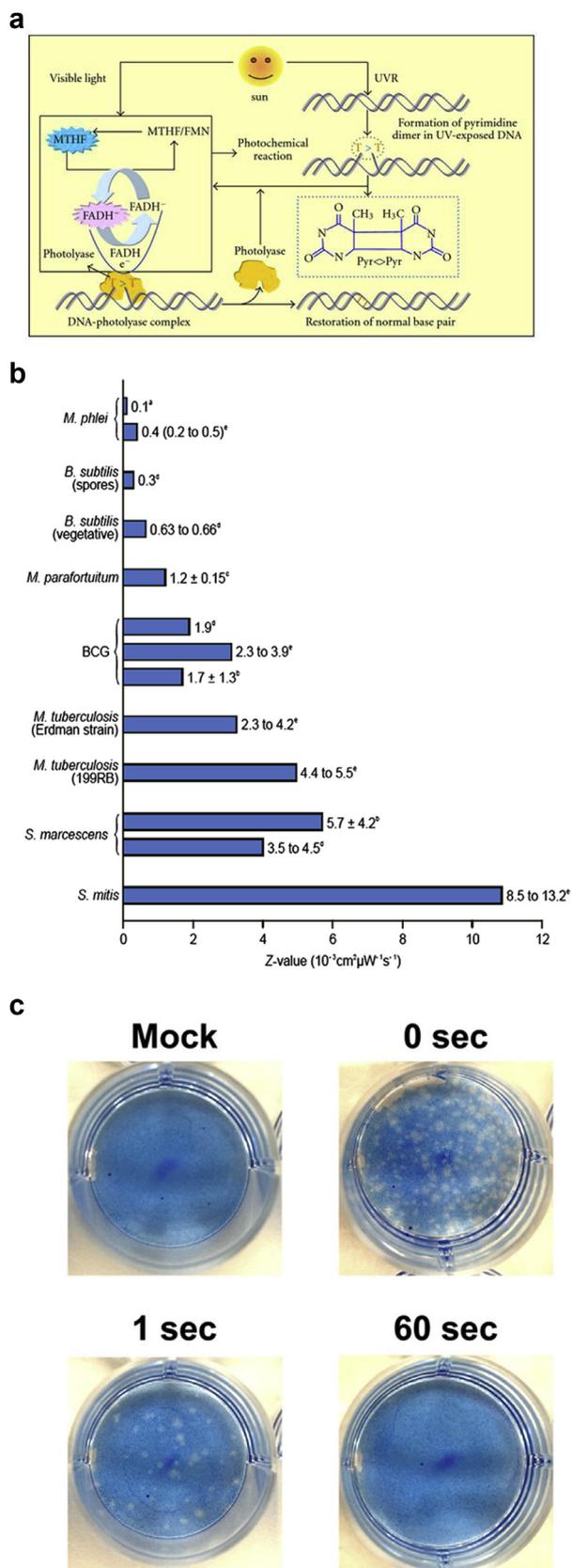


Figure 2. Schematic representation of (a) DNA alteration process induced by ultraviolet radiation as illustrated by Rastogi et al. [46]; (b) sensitivity of various microorganisms to UVGI irradiation as summarized by Memarzadeh et al. (reprinted with copyright permission from [44]); (c) inactivation of the SARS-CoV-2 virus under deep UV irradiation with a wavelength of 280 ± 5 nm as demonstrated by Inagaki et al. [39].

any concern regarding the exposure limit of UV-C for human eyes and skin. It is to be noted that UV irradiation may cause severe clinical effects on human eyes and skin [57].

According to the data presented in Table-1, it is evident that for rapid inactivation in less than a minute, the necessary UV-C dose may vary between 108.714 and 225 mJ/cm² subject to the wavelength of the irradiation. Furthermore, according to the American Conference of Governmental Industrial Hygienists (ACGIH), the threshold limit values (TLVs) for UV-C doses with wavelengths of 254 and 280 nm in public places are 6.00 and 3.40 mJ/cm², respectively, considering their detrimental effects on human eyes and skin [58]. Therefore, implementing a high UV-C dose within the return air duct of the HVAC system (as shown in Figure 1) should be more appropriate for the rapid inactivation of highly infectious viruses.

Recently, Zhang et al. [59] investigated different environmental conditions for turbulent airflow inside an HVAC duct equipped with UV lamps and using three different test bacteria, namely *Staphylococcus epidermidis*, *Pseudomonas alcaligenes*, and *Escherichia coli*. Their results showed that the disinfection efficacy decreased as the airflow velocity and air relative humidity increased. In addition, the resistance to the UV irradiance varied with the types of bacteria, and the disinfection efficacy was slightly lower for a black inner surface of the duct. The typical experimental setup used in this study is shown in Figure 3.

Studies conducted by other researchers assessing the efficacy of UVGI for the inactivation of various microorganisms in the in-duct airflow are also prevalent in the literature. Bang et al. [60] investigated the sterilization effectiveness of in-duct UVGI (ID-UVGI) in a liquid desiccant and indirect/direct evaporative cooling-based 100 % outdoor air system. Capetillo et al. [61], Atci et al. [62], and Yang et al. [63] numerically investigated the in-duct inactivation of microbial contaminants under the effect of UVGI using the Lagrangian particle tracking approach. Nunayon et al. [64] compared the performances of stationary and rotating UV-C light-emitting diodes (LEDs) in the upper room air against aerosolized *E. coli*, *S. marcescens*, and *S. epidermidis*. They observed that the rotating system could enhance the inactivation performance by 22.36–49.86 %.

Another key question in designing ID-UVGI, which is not discussed in the literature mentioned earlier, is whether the UV lamps should be placed to directly irradiate the air stream or irradiate the filter at which the microbial contaminants are trapped. Orazio and Alessandro [65] attempted to answer this question by experimenting with a hospital HVAC system. Their results showed that at least under the considered experimental conditions, irradiation of the filter surface achieved a higher inactivation percentage and reduced the pressure drop compared to those achieved by irradiating the air stream without the filter.

3.1.3. Challenges toward implementing UVGI

The key challenge toward implementing this method is that most experimental studies related to the inactivation of the SARS-CoV-2 virus by direct irradiation under UV-C were carried out in a controlled *in vitro* environment. Studies related to employing UV-C in HVAC systems have been conducted using other less infectious viruses and bacteria. Thus, the inactivation efficiency for the SARS-CoV-2 virus using UV-C irradiation under HVAC airflow conditions needs to be determined.

Furthermore, controversial information exists in the literature regarding the influence of relative humidity and temperature on the inactivation rate for the SARS-CoV-2 virus under UV irradiation. Schuit et al. [50] evaluated the effect of relative humidity (RH) (20, 45, and 70 % at a temperature of 20.1 °C) on the inactivation rate for the SARS-CoV-2 virus under simulated sunlight and observed no significant influence. In contrast, Ijaz et al. [66] reported that the RH and temperature of air significantly affect the half-life of airborne human coronavirus 229E (HCV/229E). Their results showed that at an air temperature of 20 ± 1 °C, the half-life of the viruses was the lowest at an RH of 80 % (3.34 ± 0.16 h). When the air temperature was lowered to 6 ± 1 °C, the half-life at an RH of 80 % increased remarkably (86.01 ± 5.28 h). The longest survivability was observed for an RH of 50 % at both

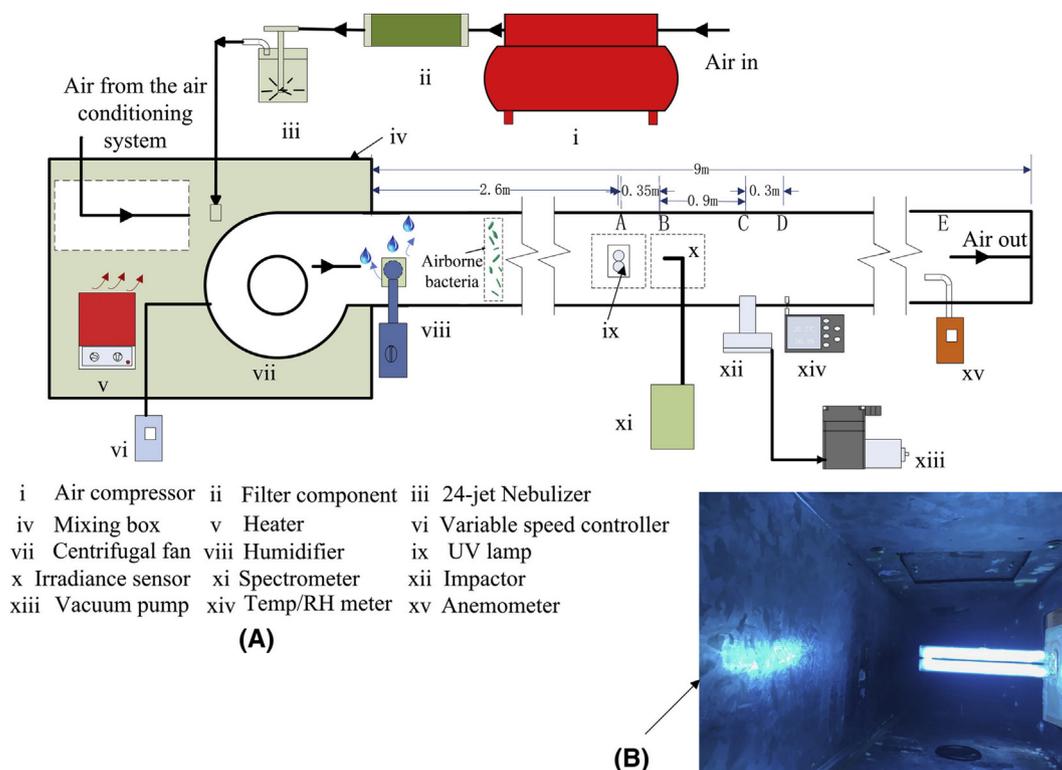


Figure 3. Schematic of the experimental setup used in the study by Zhang et al. for the in-duct disinfection of various bacteria using ultraviolet lamps under different environments (reprinted with copyright permission from [59]).

temperatures. Thus, additional experiments are necessary to precisely determine the required UV dose, intensity, and exposure time to inactivate the SARS-CoV-2 virus under typical HVAC airflow conditions, considering the effects of different airflow velocities, temperatures, and humidities.

3.2. Volatile organic compound decomposition unit

VOCs present in the air (e.g., benzene, formaldehyde, toluene, acetaldehyde, and acetone) also pose a risk of adverse health effects to the building occupants and thus, need to be treated appropriately. Detailed information on the concentration of important VOCs in the indoor environment and their exposure limits according to indoor air quality (IAQ) guidelines of different organizations are available in the review by

Shrubsole et al. [67]. Nearly all organic compounds present in indoor air can undergo photocatalytic oxidation in the presence of highly reactive species [68]. The hydroxyl ($\bullet\text{OH}$) radical, also known as “mother nature’s vacuum cleaner” [69], is a highly reactive compound that can be employed in an HVAC system to readily decompose VOCs to provide clean air for the occupants. However, implementing the $\bullet\text{OH}$ radical in air cleaning may be considered an optional choice depending on the quantity and types of VOCs present in the indoor air in a specific area.

3.2.1. Decomposition of VOCs using $\bullet\text{OH}$ radicals

A graphical representation of the decomposition mechanism of VOCs in the presence of the $\bullet\text{OH}$ radical is shown in Figure 4. When a photocatalytic material is exposed to UV irradiation of wavelength <400 nm, it undergoes a series of photocatalytic reactions in the presence of

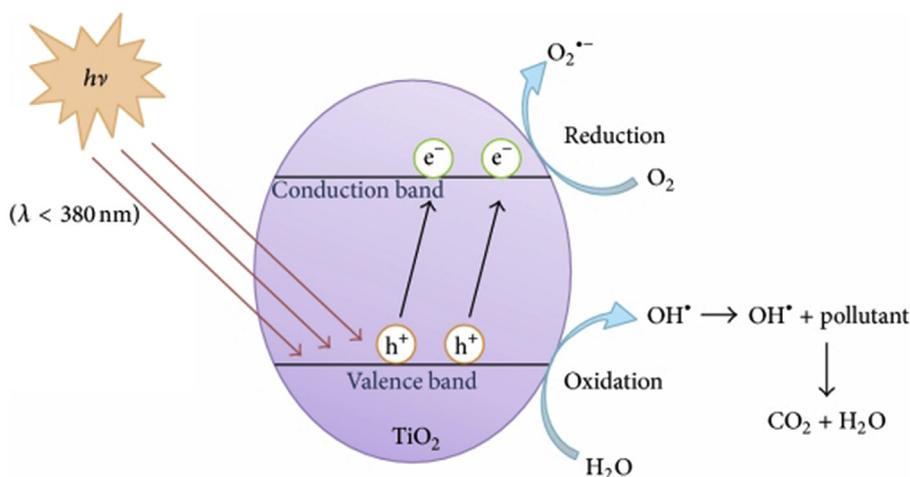
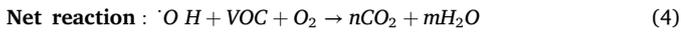


Figure 4. Illustration of the decomposition mechanism of VOCs by the $\bullet\text{OH}$ radical [72].

atmospheric water vapor. As a result, the highly reactive •OH radicals and other compounds, such as reactive oxygen species, superoxide anion radicals, and hydrogen peroxide [70], are formed. The oxidation, reduction, and net reaction with VOCs in the simplest form can be expressed as follows (Eq. (2)–(4)) [71]:



Detailed information on the types of photocatalysts, their preparation, coating techniques, reaction kinetics, and their implications in the photocatalytic reactor and HVAC air purification are available in the review article by Mo et al. [71].

3.2.2. Generation of •OH radicals using sunlight/visible light

Although various photocatalytic materials are available, titanium dioxide (TiO₂) is the most popular because of its low cost, high stability, efficiency, and environment-friendliness [73]. However, one major challenge toward designing a photocatalytic air cleaning device is the utilization of natural sunlight or visible light to generate •OH radicals because the utilization of UV lamps consumes additional primary energy. Recently, it was reported that the reduced form of TiO₂ surfaces co-doped with non-metals, such as nitrogen (N), fluorine (F), or phosphorus (P), can generate •OH radicals under the sunlight/visible light spectrum (i.e., at a wavelength >400 nm). The low bandgap energy of the modified TiO₂ surface-bulk structure (Figure 5) makes it suitable for visible light absorption [70,74]. Therefore, the production of •OH radicals under sunlight/visible light should be considered in HVAC systems as an inexpensive and efficient means to remove VOCs from indoor air. Nevertheless, in the absence of sunlight, it is necessary to employ electrical UV lamps.

3.2.3. •OH radicals in air cleaning

Several studies have demonstrated the potential of employing •OH radicals for indoor air quality management [68,75,76]. Sarwar et al. [77] proposed an indoor air quality model to estimate the concentration of •OH radicals in indoor air by simulating indoor homogeneous reactions. Hodgson et al. [78] experimentally evaluated the conversion efficiency of different VOCs using an ultraviolet photocatalytic oxidation device for indoor air cleaning purposes. Won and Rim [79] numerically modeled the conversion of various VOCs by •OH radicals generated from the photolysis of nitrous acid (HONO) in an indoor room under various lighting and HVAC operating conditions. Chen et al. [80] designed a photocatalytic HVAC filter for the oxidation of formaldehyde by coating TiO₂ onto a stainless steel filter using an electrophoretic deposition method. Auvinen and Wirtanen [81] evaluated the conversion efficiency

of VOCs using different photocatalytic interior paints aimed at producing •OH radicals to improve the indoor air quality. Thus, it is evident that •OH radicals can suitably be utilized to decompose VOCs in indoor air.

3.2.4. Challenges toward implementing •OH radicals

One major concern toward the decomposition of VOCs by •OH radicals in the HVAC system is the incomplete oxidation and formation of intermediate species in the absence of an adequate concentration of •OH radicals. Several studies [78,81] reported the formation of formaldehyde and other VOCs, which can be even more stable and harmful than the parent VOCs, due to incomplete oxidation. Therefore, developing a more efficient photocatalytic material capable of producing a sufficient concentration of •OH radicals under sunlight/visible light is crucial to prevent incomplete oxidation and improve energy efficiency. Furthermore, a detailed investigation on the conversion efficiency of VOCs by •OH radicals under the influence of air temperature, relative humidity, and flow velocity in a typical HVAC system needs to be performed. The presence of other gaseous compounds in indoor air may also affect the conversion process, which also needs to be clarified. To date, no HVAC systems have been reported in the literature that use •OH radicals produced by visible light or sunlight for the decomposition of VOCs.

3.3. Air particulate matter filtration unit

Suspended air PMs with various size distributions, particularly PM₁₀, PM_{2.5}, and ultrafine particles (UFPs) (particle diameter <100 nm), have severe adverse health effects on indoor occupants [82,83]. Therefore, the removal of PMs from indoor air through appropriate filtering is another essential criterion for post-COVID-19 HVAC systems. In an air filtration device, PMs can be captured either passively (e.g., through inertial impaction, Brownian motion, interception, and gravity) or proactively (e.g., using coulombic and dielectrophoretic forces) [84]. A graphical representation of the PM capture mechanisms is illustrated in Figure 6. A

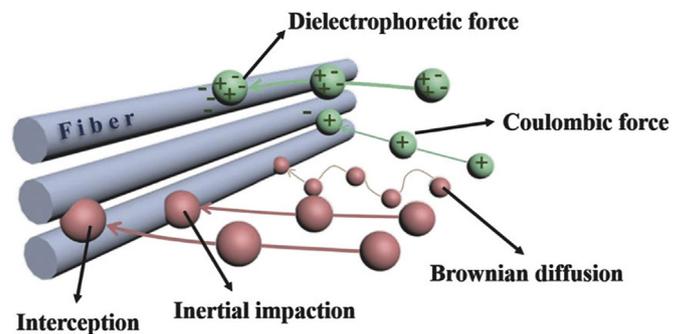


Figure 6. Illustration of passive (red) and proactive (green) PM capture mechanisms (reprinted with copyright permission from [84]).

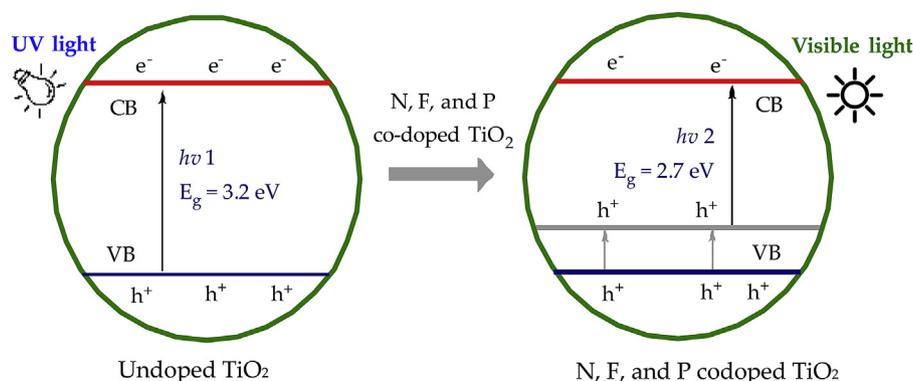


Figure 5. Low bandgap energy and visible light absorption by modified TiO₂ surface [70].

theoretical explanation of these mechanisms and the detailed effects of thermal rebound, humidity, fiber diameter, fiber Reynolds number, particle shape, morphology, and loading on the PM capture is available in the review article by Wang and Otani [85].

Several promising materials, such as carbon-based materials (e.g., activated carbon, carbon nanotubes (CNTs)), polymeric nanofibers, metal-organic frameworks (MOFs), silk, oxides, and metals, are available for designing air filters. The comparative advantages and disadvantages of employing these materials for PM removal have been reviewed by Xiao et al. [84]. However, most air filtration materials can be broadly categorized as either porous membranes or fibrous media [84]. Porous membranes are effective for filtering only larger particles (usually $> PM_{10}$) owing to their large pore size. In addition, porous membranes suffer from a high pressure drop due to their low porosity, usually below 30% [84]. Filters made of fibrous media (either polar or non-polar) are more effective for filtering smaller particles with size distributions of PM_{10} , $PM_{2.5}$, and UFPs. Therefore, fibrous media are widely employed in commercially available high-efficiency particulate air (HEPA) filters [86].

3.3.1. Passive vs. proactive capturing of PM

The performance of a typical air filter is usually determined by the quality factor, defined as the ratio of the filtration efficiency to pressure drop [84]. Filters made of non-polar fibrous media (e.g., coarse glass fibers, coated animal hair, vegetable fibers, synthetic fibers, synthetic foams, metallic wools, and expanded metals and foils [87]) rely on passive capture mechanisms in which the fibrous medium acts as an obstacle. Therefore, such filters usually have low MERV [88] ratings between 1 and 4. Fibrous filters with a high MERV rating between 14 and 16 exhibit a large pressure drop due to their extended depth and extensive pleating [87]. Cleaning and reusability of densely packed and randomly oriented fibrous media are also major drawbacks in the wide-scale implementation of these filters in commercial and residential buildings.

In contrast, filters based on a proactive capture mechanism achieve a high MERV rating without increasing the pressure drop [87] because of the high filtration efficiency originating from the strong electrostatic interactions between the polarized PM and filter medium. It should be noted that PMs exhibit high polarity in air owing to the presence of ions and water vapor. Moreover, considering the transmission of aerosolized droplets produced through coughing and sneezing, air filters need to be capable of filtering various wetting and non-wetting droplets [89]. A proactive capture mechanism is also important for capturing the wetting and non-wetting droplets. Several material options, such as polarized polymer fibers, CNT fibers, and MOFs, are available for the fabrication of electrostatic filters.

In addition to removing the PMs, MOF-based filters also demonstrate multifunctionality by removing UFPs [90], selectively capturing toxic gaseous compounds (e.g., SO_2) [91] and VOCs (e.g., toluene) [92], and exhibiting photocatalytic bactericidal capability [93]. Such multi-functionalities originate from their tunable pore size, pore structure, and functional groups, which make the MOF-based filters the most promising candidate for air filtration in the post-COVID-19 HVAC systems. Thus, this review focuses on the potential of employing MOF-based filters in next-generation air filtration.

3.3.2. State-of-the-art literature on MOF-based filters

Removal of $PM_{2.5}$ and PM_{10} : MOF-based air filters offer excellent PM filtration efficiency due to the following interactions (Figure 7): (i) bonding between PM and open metal sites of MOFs; (ii) electrostatic attraction of PM toward polar functional groups and nanocrystals of MOFs.

Zhang et al. [91] fabricated different MOF-based filters by electro-spinning four different MOFs (zeolite imidazolate framework (ZIF-8), UiO-66-NH₂, MOF-199, and Mg-MOF-74) in three different polymers (polyacrylonitrile (PAN), polystyrene (PS), and polyvinylpyrrolidone (PVP)). The fabricated filters achieved a high filtration efficiency ($88.33 \pm 1.52\%$ for $PM_{2.5}$ and $89.67 \pm 1.33\%$ for PM_{10}) for a continuous operation for 48 h and exhibited a low flow resistance (pressure drop < 20 Pa at a flow rate of 50 mL/min).

To facilitate mass production and lower manufacturing costs, Chen et al. [94] developed a large-scale roll-to-roll production of MOF-based filters using the hot press method. They used five different substrates (plastic mesh, melamine foam, nonwoven fabric, glass cloth, and steel mesh) and three different MOFs (ZIF-8, ZIF-67, and Ni-ZIF-8). The designed filter also exhibited a low pressure drop (30 Pa at 500 mL/min) and high removal efficiency ($99.5\% \pm 1.7\%$ for $PM_{2.5}$ and $99.3\% \pm 1.2\%$ for PM_{10} using ZIF-8@melamine foam 3rd).

Removal of UFPs: UFPs can be more easily deposited into the lung; they impact the other organs through blood circulation and even reach the brain through the olfactory nerve [90]. Therefore, special care should be taken to remove UFPs from indoor air. Furthermore, the size of the SARS-CoV-2 virus is reported to be between 80 and 140 nm (with a median of 100 nm) [95]. Thus, the removal of UFPs by the post-COVID-19 HVAC systems is also vital to reduce the possibility of the SARS-CoV-2 virus passing through the filters.

Bian et al. [90] demonstrated a scalable MOF-based nanofiber filter (ZIF-67@PAN) that could remove UFPs up to 15 nm. The filtration efficiencies for particles of various size distributions obtained by the filter were as follows: 96.6 ± 0.8 , 98.1 ± 0.7 , and 99.9% for $PM_{2.5}$, PM_{1} , and PM_{10} , respectively, under a face velocity 0.26 m/s. The high filtration efficiency for PM_{1} was achieved owing to the combined effect of

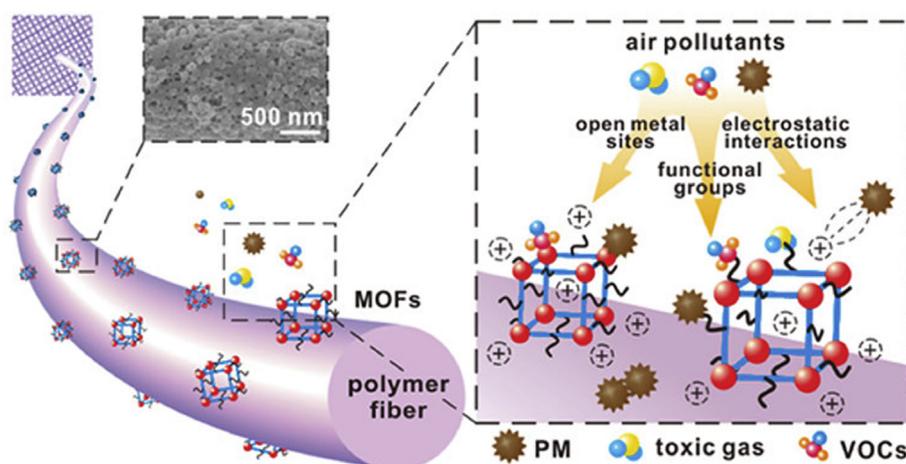


Figure 7. Mechanism of PM capture by MOF-based filters proposed by Zhang et al. (reprinted with copyright permission from [91]).

Brownian diffusion and electrostatic interaction. They also evaluated the pressure drop performance of the filter, which was nearly six times smaller than that of a commercial HEPA filter. The reported pressure drops for the ZIF-67@PAN and HEPA filters under the same face velocity of 0.054 m/s were 59 and 300 Pa, respectively. Thus, the ZIF-67@PAN filter developed by Bian et al. exhibits a significant potential to be employed in HVAC systems for UFP removal.

Removal of toxic gaseous compounds and VOCs: MOF-based filters also demonstrated the adsorption of SO₂ and VOCs from polluted air streams. The ZIF-8/PAN filter fabricated by Zhang et al. [91] was exposed to 100 ppm SO₂/N₂ flow at a rate of 50 ml min⁻¹. The results showed that while the SO₂ concentration at downstream of the polymer filter remained the same, the MOF-based filter showed a good SO₂ adsorption capacity. Zhang et al. [92] fabricated E-MOFilters by coating MIL-125-NH₂ particles onto MERV 13 electret filter media, demonstrating a toluene removal efficiency >80 %.

Antibacterial ability: Antibacterial ability is another desired characteristic for air filters to be employed in the post-COVID-19 HVAC systems for effective inactivation of airborne microbial contaminants. Li et al. [93] reported a ZIF-8/nonwoven fabric filter exhibiting excellent photocatalytic bactericidal capability against *E. coli*. They also fabricated a MOFilter mask using ZIF-8 and evaluated its antibacterial performance against *E. coli* under visible sunlight, and the MOFilter mask outperformed the commercially available N95 mask. Zhu et al. [96] fabricated a self-decontaminating antibacterial face mask filter (Figure 8) UiO-PQDMAEMA@PAN by electrospinning a layer of antibacterial polymeric quaternary ammonium compound (QAC) poly [2-(dimethyl decyl ammonium) ethyl methacrylate] (PQDMAEMA) onto the surface of a metal-organic framework (UiO-66-NH₂). The fabricated filter exhibited excellent inactivation efficiencies of 97.4 and 95.1 % for Gram-positive (*S. epidermidis*) and Gram-negative (*E. coli*) airborne bacteria, respectively, after 2 h of contact. The positively charged nitrogen (N⁺) of UiO-PQDMAEMA caused damage to the cells of the bacteria through electrostatic interactions, which led to the antibacterial ability of this filter.

3.3.3. MOF-based filter in a real environment

Several research groups have assessed the feasibility of employing MOF-based filters in real living environments. Chen et al. [94] demonstrated the robustness of their filters by exposing them to various harsh conditions. For example, ZIF-8@ plastic mesh 7th could tolerate rubbing by grit 320 sandpaper, ZIF-8@ melamine foam could resist bending, twisting (100 cycles), and mechanical stirring (200 rpm, 30 min), ZIF-8@ glass cloth and ZIF-8@ metal mesh could withstand high temperatures up to 200 °C. In addition, the filters could be easily cleaned using simple brushing,

tap water, and ethanol washing and finally dried for 3 h at 60 °C. The filters exhibited nearly the same filtration efficiency after three washing cycles.

Chen et al. [94] also evaluated the long-term and high-temperature filtration efficiencies of their filters. The ZIF-8@melamine foam 3rd exhibited an efficiency >95.4 % after 12 h of operation in a simulated pipe with incense smoke. The filtration efficiency of the ZIF-8@glass cloth and metal mesh at 200 °C was nearly identical to that at room temperature inside a pipe furnace. To demonstrate the feasibility of employing these filters in a real living environment, two pieces of ZIF-8@plastic mesh were mounted onto a wooden frame (having a width of 20 cm and length of 40 cm) and were placed on an open window for more than a month. The filtration efficiencies achieved after a month for PM_{2.5} and PM₁₀ were >90 %.

Bian et al. [90] evaluated the durability and long-term efficiency of the developed filter for over a month in a living environment under mild wind at a corresponding face velocity of 0.01 m/s. The long-term filtration efficiency for PM_{2.5}, obtained after a month, was 99.6 %; however, the pressure drop slightly increased from 9 to 12 Pa. They also demonstrated an easy cleaning process for the filters. The ZIF-67/PAN filter could be cleaned ultrasonically using ethanol for approximately 5 s after capturing PM_{2.5} with high concentrations (>2000 µg/m³) for 5 min.

3.3.4. Challenges toward employing MOF-based filters

Although MOF-based filters offer a promising ability, it is necessary to overcome several design challenges for the practical implementation of these filters in a building HVAC system. One major criterion for deciding an HVAC system's air filters is the face velocity at which the filtration efficiency is evaluated. At a high face velocity, the filtration efficiency can drop significantly. According to ASHRAE Handbook – HVAC Applications 2015/Section 48 Noise and vibration control/Table-9, the maximum recommended air velocity at the opening of the supply air duct is 1.8–2.2 m/s for corresponding room criteria (RC) of 25–30 (RC is the arithmetic average of the sound pressure level in the 500, 1,000, and 2,000 Hz octave bands, which is the speech interference level affecting speech communication privacy and impairment). However, the typical air velocity around the opening of the supply air duct can be maintained at approximately 1 m/s.

The filtration efficiencies and pressure drop performances of MOF-based filters reported by different researchers are summarized in Table 2. The table shows that the ZIF-8/nonwoven fabrics developed by Li et al. were tested at a high face velocity of 0.7 m/s. Thus, employing MOF-based filters around the opening of the supply air duct, where the air velocity is usually low, is feasible. A schematic of the potential location for employing MOF-based filters in a building HVAC system is shown in Figure 1.

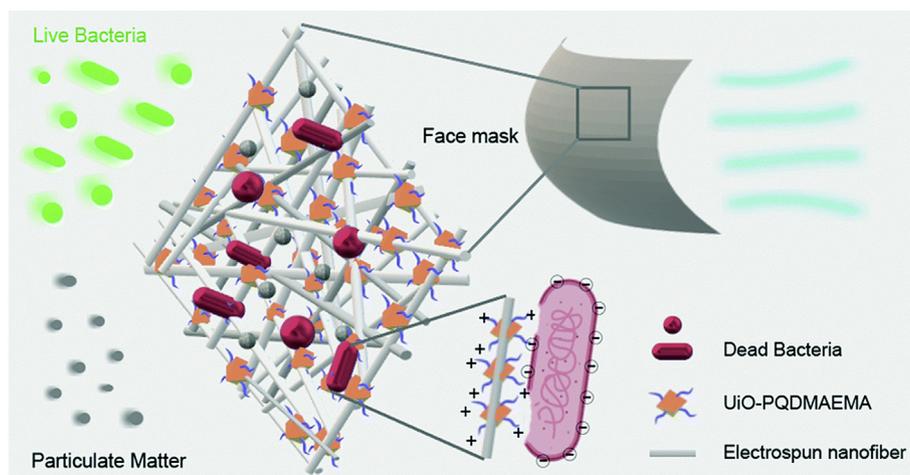


Figure 8. Antibacterial ability of MOF-based face mask filter UiO-PQDMAEMA@PAN [96].

Table 2. Summary of filtration efficiencies and pressure drops in MOF-based filters reported in the state-of-the-art literature.

Ref. article	Filter type	Removal efficiency (%)			Face velocity (m/sec.)	Pressure drop (Pa)
		PM ₁₀	PM _{2.5}	PM ₁		
Zhang et al. [91]	ZIF-8/PAN	89.67 ± 1.33	88.33 ± 1.52	-	-	20 @ 50 mL/min
Chen et al. [94]	ZIF-8/Melamine foam	99.3 ± 1.20	99.5 ± 1.70	-	-	30 @ 500 mL/min
Bian et al. [90]	ZIF-67/PAN	99.9	99.00 ± 0.60	98.50 ± 0.90	0.08	59@ 0.054 m/s.
			98.60 ± 0.80	98.10 ± 0.70	0.26	
Li et al. [93]	ZIF-8/Nonwoven fabrics	97.7	96.8	-	0.7	64 @ 0.7 m/s.

However, the filtration efficiencies of other MOF-based air filters were evaluated at low face velocities. In addition, their feasibility to be used in a real environment was demonstrated by placing them at a house window under a mild wind condition. The flow conditions within the air duct of an HVAC system are substantially different from above. Therefore, a detailed evaluation of the filtration efficiencies of these MOF-based filters under typical HVAC airflow conditions needs to be performed. Further improvement of the filter design may be necessary to maintain the long-term durability of these filters under a high face velocity larger than 1 m/s.

Furthermore, maintaining the long-term efficiency of the air filter under high RH (%) conditions is challenging. A study conducted by Mörizt et al. [97] reported that at a high RH (>80 %), bacterial proliferation occurred on the filter, and the bacteria were eventually released into the filtered air stream. Thus, the antibacterial ability of the MOF-based filters needs to be tested under different humidity conditions. Preserving the long-term chemical stability of MOF crystals under high-humidity conditions is another challenge that has been rarely discussed in the literature. High dust loading can significantly reduce the filtration efficiency and longevity of sophisticated MOF-based filters. Therefore, a primary filter can be employed at the entrance of the air handling unit (AHU) to remove larger particles, as shown in Figure 1.

4. Personalized ventilation

4.1. Significance of personalized ventilation

To date, the two most common modes of ventilation used in majority of the buildings are mixing ventilation (MV) and displacement ventilation (DV). MV creates a homogeneous mixture of air, and thus, the probability of inhaling aerosolized droplets by a healthy person is independent of the location in the room [98]. In contrast, DV generates an upward airflow from the floor or wall-mounted diffusers, which reduces the risk of cross-infection. However, in a dynamic office environment, even with a DV, the airflow pattern is disturbed by the movement of people, and settled particles on the surface tend to be resuspended in the air and promote cross-infection [98]. Thus, the flow trajectories of aerosolized droplets depend on the airflow patterns generated by the room ventilation. Depending on the airflow pattern, ventilation may increase or decrease the risk of indoor airborne transmission, particularly on large office floors or in restaurants where people sit close to each other. Shao et al. [99] reported that optimizing ventilation settings is critical for reducing the concentration of airborne particles. Otherwise, local hot spots may appear under an inappropriately designed ventilation, which further increases the risk of infection. Therefore, advanced air distribution methods that employ various air terminal devices (ATDs) (known as PV) in combination with room ventilation have been suggested in the literature. PV can reduce the risk of indoor airborne infection by providing fresh air directly in the breathing zone of an occupant [26,100,101]. A more detailed discussion on PV from the perspective of minimizing indoor airborne transmission is presented below.

4.2. State-of-the-art literature on personalized ventilation

Melikov [102] performed a detailed review on the various aspects of PV, such as the designs of ATDs, types of airflow, quality of inhaled air, thermal comfort of the occupants, application of PV in practice, future direction of research to improve the performance of PV, and public response to PV. Melikov et al. [103] also evaluated the performances of various ATDs as a means for PV, including a movable panel (MP), computer monitor panel (CMP), vertical desk grill (VDG), horizontal desk grill (HDG), and personal environment module (PEM), as shown in Figure 9.

The role of PV in reducing the risk of aerosolized transmission of airborne viruses and bacteria in the indoor atmosphere has been investigated by several researchers since long before the COVID-19 pandemic. Habchi et al. [104] numerically investigated the optimization between the risk of cross-contamination and occupancy density for an office floor using a ceiling PV with desk fans. The results showed that the use of PV could provide better air quality with reduced energy consumption.

Several numerical studies conducted by Shen et al. [105], Katramiz et al. [106], and Xu et al. [107] also focused on the effects of employing PV to minimize the risk of indoor airborne transmission between occupants. Gao and Niu [108] investigated the effects of PV in a commercial aircraft cabin. They reported that PV could shield up to 60 % of the

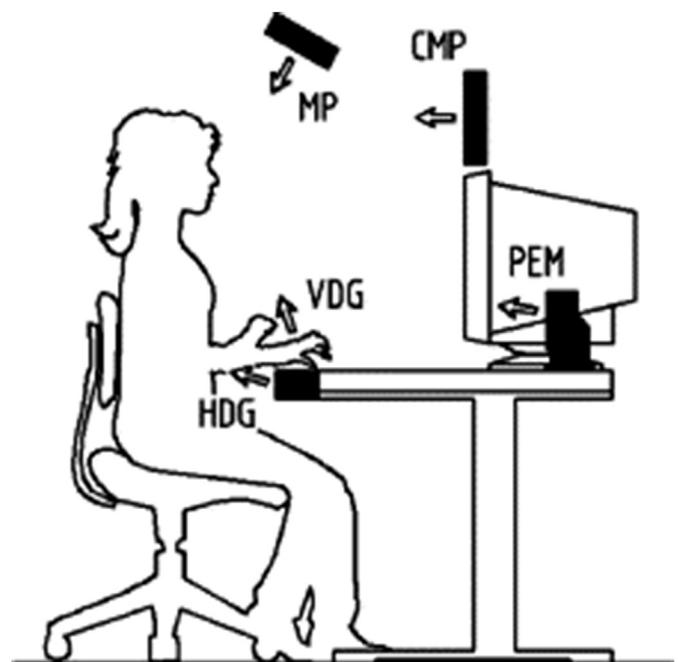


Figure 9. Different ATDs feasible to be used for personalized ventilation: movable panel (MP), computer monitor panel (CMP), vertical desk grill (VDG), horizontal desk grill (HDG), and personal environment module (PEM) (reprinted with copyright permission from [103]).



Figure 10. Interaction between airflows generated by various sources around the human body in an office environment: (1) free convective flow, (2) personalized flow, (3) respiratory flow, (4) ventilation flow, and (5) thermal flow (reprinted with copyright permission from [102]).

polluted air from being inhaled by the passengers. In contrast, without PV, the exhaled particles could be transported up to three rows from the sneezing person, and only 20 % of the particles could be exhausted.

Yang et al. [109] investigated the performance of a combined PV–personalized exhaust (PE) system. They reported that PE for an infected person exhibited a better performance than that of PV for a healthy person. Recently, Xu et al. [110] conducted experiments to evaluate the effect of PV on short-range bioaerosol deposition and their inhalation by a healthy person and reported that the deposition of bioaerosols on the face and body and their inhalation could be reduced by 98, 85, and 100 %, respectively, through the use of PV.

4.3. Challenges toward implementing personalized ventilation

Positive outcomes have been reported in the abovementioned studies regarding the use of PV. However, controversial opinions are also prevalent, corroborating that PV can enhance the risk of exposure to aerosolized droplets under certain circumstances. As shown in Figure 10, PV creates a complex airflow pattern around the human body when applied in combination with room ventilation (MV or DV). Designing an advanced ATD that can prevent exposure to aerosolized droplets by 100 % under complex flow interactions is extremely difficult.

Xu et al. [107] reported that the interaction between PV flow and exhalation flow from an infected person increases the airborne transmission in two ways: first, applying PV to the infected person causes 90 % of the indirect exposure, and second, entrainment of the PV jet directly from the infected person's exhalation causes 50 % of the direct exposure. Shen et al. [105] reported that a high airflow rate caused by PV may disrupt the airflow due to room ventilation. Consequently, it may increase the risk of exposure to airborne microbial contaminants. Katramiz et al. [106] reported that depending on the sitting position (i.e., face to face or tandem sitting), the inhaled intake fraction can be different, and an adjustment in the PV air flowrate is also required.

Thus, although PV with an advanced ATD can improve the inhaled air quality, it may also increase the risk of exposure to exhaled droplets from an infected person. Such an exposure risk depends on the PV airflow velocity and direction, ventilation flow condition in the room, sitting position, and distance between infected and healthy individuals. The WHO website [111] also mentions that high-velocity air blown by a fan from an infected person to a healthy person in a closed space may increase the risk of infection. An outbreak of COVID-19 was reported in a high-rise building with vertically aligned apartment units connected by a single air duct, indicating the risk of airborne transmission through shared air [5]. Therefore, the authors suggest that the ventilation in the post-COVID-19 HVAC systems should be designed such that the airflow is unidirectional (the importance of unidirectional airflow is also emphasized in the WHO roadmap [31]) and remains completely separated between individuals. Physical boundaries (e.g., inexpensive PVC sheets) can be implemented between individuals to design such ventilation systems. A typical concept of an individualized ventilation system is shown in Figure 11. To prevent air stratification in areas outside the physical boundary, wall-mounted fans can be employed. Such a ventilation system prevents the flow of air from one individual to another,

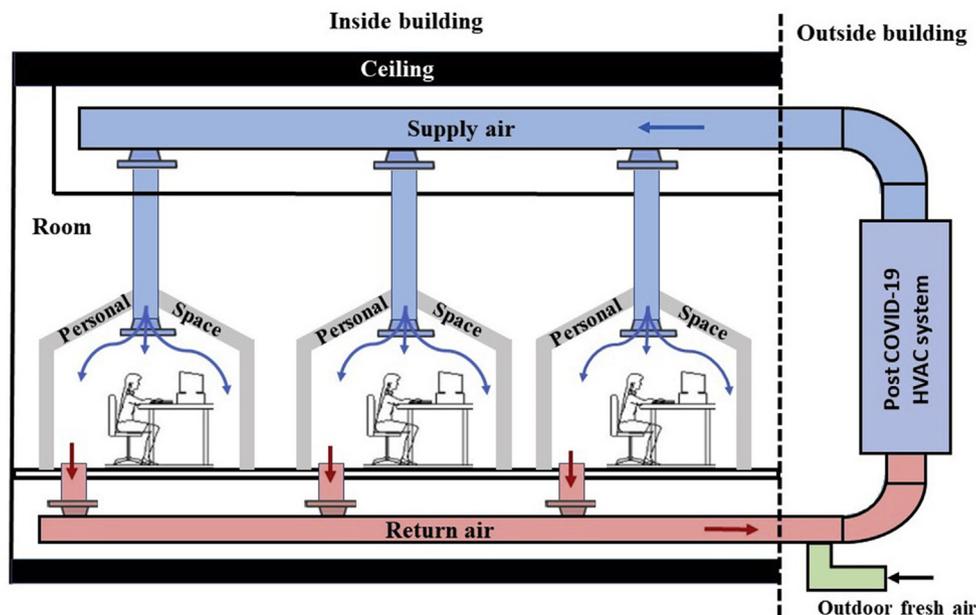


Figure 11. Concept of the individualized ventilation system to achieve zero indoor airborne transmission.

resulting in zero indoor airborne transmission. A typical large office space where hundreds of people sit and work together on the same floor, the patients' wards in hospitals, and large restaurants are suitable for employing such a ventilation.

5. Conclusion

In addition to providing thermal comfort, the role of the HVAC system needs to be extended in the upcoming decades to ensure safe breathing of indoor occupants. Re-designing conventional HVAC systems with anti-pandemic components is crucial to achieve the new goal of the HVAC system in the post-COVID-19 era. The three vital anti-pandemic components suggested in this article to ensure proper health safety of the occupants in the built environment are: a UVGI unit for inactivation of highly infectious viruses and bacteria, an $\bullet\text{OH}$ radical unit for decomposition of VOCs, and an advanced filtration unit for removal of PMs. A comprehensive discussion on the possibilities and challenges toward designing these anti-pandemic components is presented. The role of PV in minimizing the chances of indoor cross-infection is also discussed. The following conclusions can be drawn based on the discussion presented in this article:

UV-C: The current literature discussed highly promising outcomes in the inactivation of the SARS-CoV-2 virus by employing UV-C. However, for rapid inactivation within less than a minute, a high UV-C dose is required that exceeds the exposure limit for the human eye and skin. Therefore, employing this method within the return air duct of an HVAC system is suggested as a more suitable design option. Several researchers have investigated the real-time efficacy of UV-C against various microbial contaminants inside the return air ducts of HVAC systems. However, none of these studies used the SARS-CoV-2 virus. To date, the inactivation of the SARS-CoV-2 virus using UV-C has been studied only in *in vitro* experiments. This leaves room for further investigation on the inactivation of the SARS-CoV-2 virus using UV-C under typical airflow conditions in an HVAC system.

$\bullet\text{OH}$ radical: The current literature documents the efficacy of $\bullet\text{OH}$ radicals in indoor air cleaning to remove VOCs. However, one major challenge in implementing this method is the generation of $\bullet\text{OH}$ radicals under natural sunlight or visible light to reduce energy consumption. Recently, modified TiO_2 surfaces doped with non-metals (nitrogen (N), fluorine (F), or phosphorus (P)) have shown promise for solving this issue. However, the incomplete oxidation and low conversion efficiency of VOCs due to insufficient generation of $\bullet\text{OH}$ radicals by modified TiO_2 photocatalysts under the visible light/sunlight may become another major issue. Therefore, developing a more efficient photocatalytic material is essential to employ $\bullet\text{OH}$ radicals in a real HVAC system under sunlight/visible light. In addition, evaluation of the conversion efficiency of different VOCs by $\bullet\text{OH}$ radicals under different velocities, temperatures, and humidities of airflow needs to be performed.

MOF-based filters: The current literature shows that MOF-based filters have demonstrated their superiority over other air filters owing to their multifunctionality originating from the tunable pore size, pore structure, and functional groups. In addition to removing $\text{PM}_{2.5}$, and PM_{10} , MOF-based filters can effectively remove UFPs (up to 15 nm), selectively capture toxic gas (SO_2) and VOCs, and exhibit an antibacterial ability. These features cannot be achieved using other air filters. The feasibility of employing MOF-based filters in a real living environment has also been assessed. However, a key problem is that the filtration efficiencies of MOF-based filters are evaluated at low airflow velocities <1 m/s. Further investigation is necessary to design MOF-based filters capable of handling high airflow velocities over 1 m/s. Another alternative solution is to employ MOF-based filters in the low-velocity area of the HVAC system (e.g., around the opening of supply air diffusers) and use conventional low-pressure drop air filters at the entrance of the AHU to remove large particles and reduce dust loading.

Personalized ventilation: Finally, the role of PV in preventing indoor cross-infection is discussed. The current literature provides a

controversial conclusion in this regard. Some studies suggest that employing ATDs as a means of PV can significantly reduce indoor cross-infection. Others suggest that the interaction of PV airflow with room ventilation flow can generate a complex flow pattern, and under certain circumstances, this can promote indoor cross-infection. This article proposes the concept of an individualized ventilation system that prevents the mixing of airflow between individuals by employing a physical boundary to overcome this dilemma.

Declarations

Author contribution statement

All authors listed have significantly contributed to the development and the writing of this article.

Funding statement

This work was supported by JST-CREST Grant No. JPMJCR17I3, Japan.

Data availability statement

No data was used for the research described in the article.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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