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A review of different ventilation modes on thermal comfort, air quality and virus spread control

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ABSTRACT

In the era of Corona Virus Disease 2019 (COVID-19), inappropriate indoor ventilation may turn out to be the culprit of microbial contamination in enclosed spaces and deteriorate the environment. To collaboratively improve the thermal comfort, air quality and virus spread control effect, it was essential to have an overall understanding of different ventilation modes. Hence, this study reviewed the latest scientific literature on indoor ventilation modes and manuals of various countries, identified characteristics of different ventilation modes and evaluated effects in different application occasions, wherefore to further propose their main limitations and solutions in the epidemic era. For thermal comfort, various non-uniform ventilation modes could decrease the floor-to-ceiling temperature difference, draft rate or PPD by 60%, 80% or 33% respectively, or increase the PMV by 45%. Unsteady ventilation modes (including intermittent ventilation and pulsating ventilation) could lower PPD values by 12%–37.8%. While for air quality and virus spread control, non-uniform ventilation modes could lower the mean age of air or contaminants concentration by 28.3%–47% or 15%–47% respectively, increase the air change efficiency, contaminant removal effectiveness or protection efficiency by 6.6%–10.4%, 22.6% or 14%–50% respectively. Unsteady ventilation mode (pulsating ventilation) could reduce the peak pollutant concentration and exposure time to undesirable concentrations by 31% and 48% respectively. Non-uniform modes and unsteady modes presented better performance in thermal comfort, air quality and virus spread control, whereas relevant performance evaluation indexes were still imperfect and the application scenarios were also limited.

1. Background

Corona Virus Disease 2019 (COVID-19) appeared in December 2019 and spread rapidly all over the world within a short period. As of January 7, 2022, World Health Organization (WHO) had reported 298,915,721 COVID-19 confirmed cases in the world, of which 5,469,303 cases died [1]. Against the outbreak of COVID-19, it was reported that its transmission rout had a significant impact on the number of infections [2], and patients spread virus with aerosol during daily activities, such as breathing, speaking, coughing, sneezing and etc. [3]. Aerosol was composed of dispersed particles suspended in the air, of which diameters were less than 5 μm . In normal breathing and conversation, 80%–90% of droplet sizes were less than 1 μm [4,5]. It took about 9 min for these droplets to reach the ground from a height of 1.6 m, and the virus could still survive for about 3 h in the aerosol particles [6], which made the droplet transmission a crucial factor in the respiratory virus infection. Researchers extracted samples from 30 locations

(including bus stops, public toilets, hospitals and etc.), and found that a large number of viruses floated in the air as patients gathered in space with poor ventilation [7]. High concentrations of air pollutants would reduce the resistance of natural immune system and made human body more vulnerable to viral diseases [2]. Besides, the poor indoor environment would lead to the decline of work performance and social productivity, resulting in huge economic losses. Based on the requirement of reducing air pollutants concentrations and increasing indoor air freshness in high-density space, it was urgent to improve indoor air quality and thermal environment simultaneously. However, simply increasing the air change rate and adopting inappropriate ventilation strategies increased the infection risk of dense population [8,9], so the design of appropriate indoor environment was a crucial factor.

To keep indoor comfortable conditions and low air pollutants concentrations, heating, ventilation and air conditioning (HVAC) systems have gradually been evolved into general design specifications. However, the main space of human activities was limited, and maintaining high thermal comfort performance for a large part of unoccupied space

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Nomenclature		Abbreviations	
C	Pathogens amount in oral mucus or saliva produced by respiration	ACH	Air change per hour
C_I	Concentration of particles inhaled by exposed person with PEV	AET	Average equivalent temperature
$C_{I,0}$	Concentration of particles inhaled by exposed person without PEV	ADPI	Air diffusion performance index
C_{bz}	Concentration of particles in breathing zone	ASHRAE	American society of heating, refrigeration and air conditioning engineers
C_e	Concentration of particles in the air outlet	CAV	Column attached ventilation
C_{ex}	Concentrations of particles exhaled by infected source	COVID-19	Corona Virus Disease 2019
C_{in}	Concentrations of particles inhaled by exposed person	DCV	Demand controlled ventilation
C_s	Concentration of particles in the air inlet	DPMV	Dynamic Predicted mean vote
$f(t)$	Changes in the activity of viruses or bacteria contained in aerosols over time	DPSA	Difference potential by supply air
j	Serial number of segments	DV	Displacement ventilation
m	Total aerosol size segments	EHT	Equivalent homogeneous temperature
M_{ex}	Airflow rates exhaled by infected person	HDR	Heat deficit rate
M_{in}	Airflow rates inhaled by exposed person	HEPA	High efficiency particulate air
q	Expiratory frequency of infection source	HVAC	Heating, ventilation and air-conditioning
p	Respiratory pulmonary flux of susceptible persons	IF	Intake fraction
P_I	Infection risk	IJV	Impinging jet ventilation
r_j	The size of segment j droplets owning high infectious to respiratory tract	IV	Intermittent ventilation
$T_{abdomen}$	Abdominal equivalent temperature	LAF	Laminar airflow
t_0	Exposure time	MAA	Mean age of air
t_{ex}	Breath time of infected source	MV	Mixing ventilation
T_{feet}	Feet equivalent temperature	PEV	Personalized ventilation
T_{head}	Head equivalent temperature	PIV	Piston ventilation
t_{in}	Breath time of exposed person	PMV	Predicted mean vote
$v(t)_j$	Droplet bulk density of segment j	POV	Protected occupied zone ventilation
β_j	Droplet sedimentation ratio representing the size of segment j	PPD	Predicted percentage of dissatisfied
φ_e	Volume fraction of pollutants at outlet	PUV	Pulsating ventilation
φ_{exp}	Volume fraction of inhaled pollutants	RWI	Relative warmth index
φ_s	Volume fraction of pollutants at inlet	SSV	Steady state ventilation
φ_v	Indoor average pollutants volume fraction	SV	Stratum ventilation
		TAC-UFAD	Underfloor air distribution with task air conditioning
		TAPMV	Time-weighted average IPMV
		TAPPD	Time-weighted average IPPD
		UFAD	Under floor air distribution
		WAV	Wall attached ventilation
		WHO	World Health Organization

would lead to energy waste [10,11]. In 2014, China issued the Sino US joint statement on climate change, which planned to reach the peak of carbon emissions by 2030. In 2020, the 75th UN general assembly further proposed the goal of achieving carbon neutrality by 2060. In contrast, the average annual growth rate of global energy demand was expected to be 1% before 2040 [12], which seriously hindered the goal of controlling global temperature rise within 2 °C proposed in the Paris Agreement. Hence, how to maintain a comfortable and healthy indoor environment under a low energy consumption level became the key point. In this study, existing ventilation modes were divided into uniform and steady modes, non-uniform modes and unsteady modes. Taking the control effect of virus spread, air quality and thermal comfort as evaluation indexes, specific modes under the three categories were comprehensively compared and analyzed.

2. Review methods

The scope of literature review focused on comparing applications, limitations and optimization potentials of control strategies for different buildings. In the literature retrieval stage, Science Direct (<https://www.sciencedirect.com/>) and Web of Science (<https://www.webofscience.com/wos/alldb/basic-search>) databases were used to search keywords, as listed in Table 1. Through identifying relevant references reported from the year of 1985–2021, a total of 159 documents were retrieved. Among them, there were 142 original research articles, 10

Table 1

Keywords used in the literature retrieval.

Category	Query set	Intention
Key terms	<ul style="list-style-type: none"> - Indoor environment construction - Energy conservation - Ventilation forms - Uniform state - Non-uniform state - Steady state - Unsteady or dynamic state - Public healthy 	Studying impacts of ventilation modes on the control of virus spread, air quality and thermal comfort
Search criteria	<ul style="list-style-type: none"> - Set the search scope to building or building cluster - Concerned about indoor environment and pathological protection - Concerned about the geographical location and climate of buildings 	Determining ventilation modes application fields and characteristics

manuals and 6 other documents (including thesis, conference paper, website and statistics). The review content and flowchart were shown in Fig. 1.

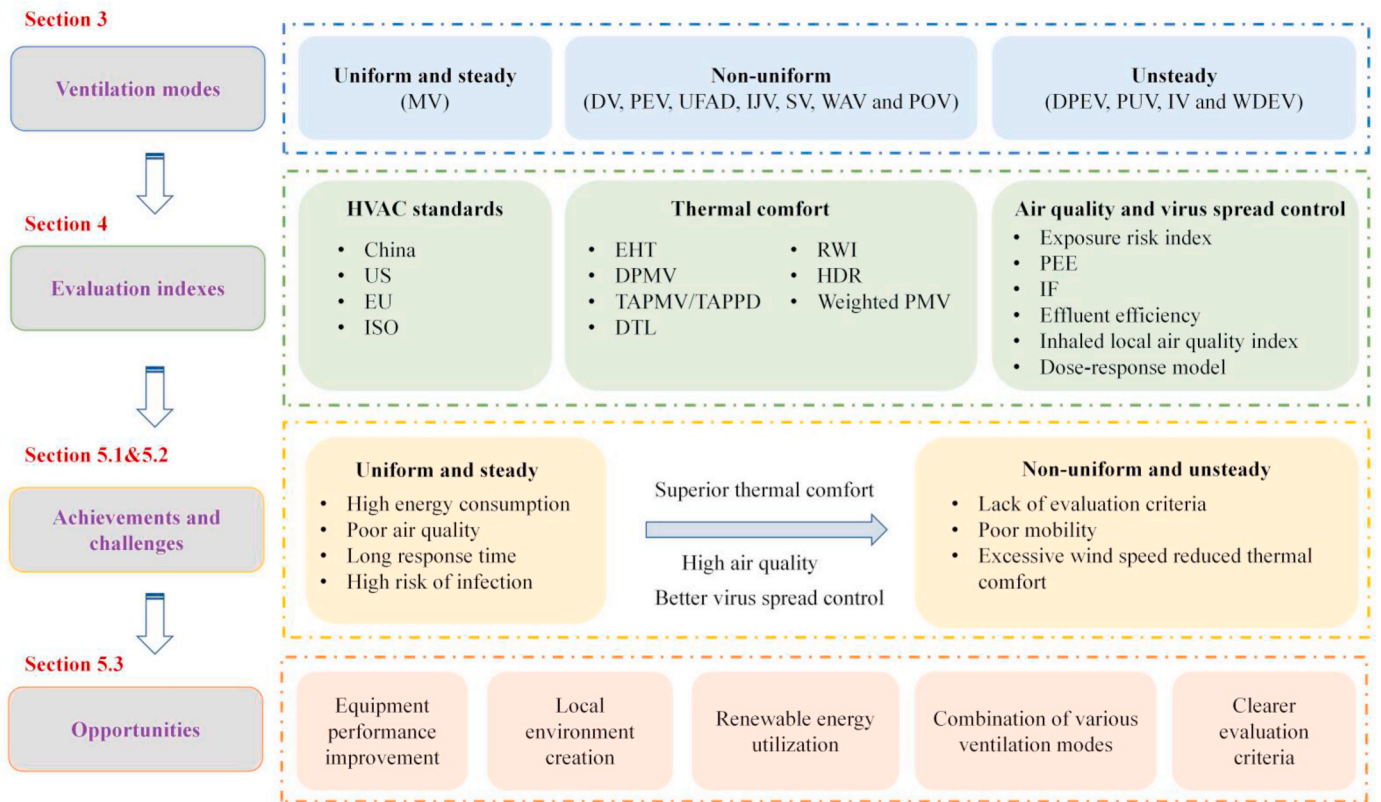


Fig. 1. Review content and flowchart of the present study.

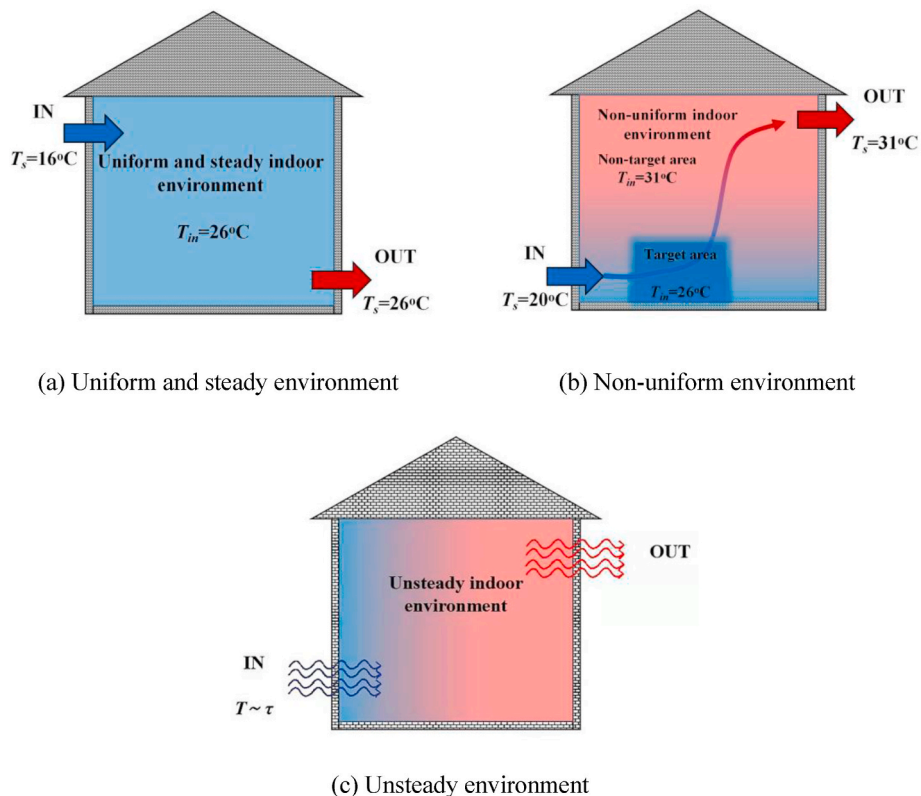


Fig. 2. Concept of different indoor environment construction methods.

3. Categories of different ventilation modes

According to different statuses of environmental parameters, ventilation modes could be divided as uniform and non-uniform, steady and unsteady (see Fig. 2). Uniform indoor environment referred to the consistent state of temperature, humidity, pollutant concentrations and other parameters at different locations of the room. Currently, there was no ventilation mode that could guarantee a completely uniform and unified indoor environment. The uniformity in indoor environment construction usually referred to a relative state, e.g., the mixing ventilation (MV) created a more uniform indoor environment compared with the stratum ventilation (SV). Steady state pointed to that the indoor environment maintained a relative stability during a certain period, and there was no violent fluctuation. Unsteady indoor environment meant that the indoor thermal environment was dynamic by changing temperature, humidity or wind speed with time to more scientifically regulate the HVAC system under the premise of human dynamic thermal comfort [13].

3.1. Traditional uniform and steady indoor environment: mixing ventilation (MV)

At present, the main method to create a uniform and steady indoor environment was MV [14–16], of which principle was air dilution as depicted in Fig. 3. After the outdoor air was processed with its temperature, humidity and pollutants concentration to be an appropriate state, it was sent into the room through air supply ports located at the upper height. Typical working conditions for MV were presented in Table 2 and temperature fields were shown in Fig. 4. After fully mixed with indoor air, part of polluted air was discharged outdoors through exhaust outlets. Since the air inlet and outlet were usually located on the ceiling [17], there would be a great probability of air short-circuit due to buoyancy. In view of this, the mode of air supply from bottom and air exhaust from top could increase the intensity of air recirculation and was more effective in airflow organization [18].

MV could provide more efficient heat and mass exchange in offices located in moderate climates [20]. For a typical office in moderate climate area under summer/winter working conditions, the air outlet temperature and velocity were set as 14.5/23 °C and 2 m/s respectively. In the case of heating, the dissatisfaction rate of air quality was only 1.7%–2.3%. While in the case of cooling, the pollutant removal rate was not well as MV often led to dead corners where clean air could not reach. The solution of increasing air flow rate would cause new problems, such as loud noise and high energy consumption [21]. In addition, MV had a higher risk of airborne infectious diseases, especially in the era of COVID-19. The mixed effects of MV could lead to a higher risk of airborne transmission, which was described as “lying in dirty bath water” by Bhagat and Linden [22].

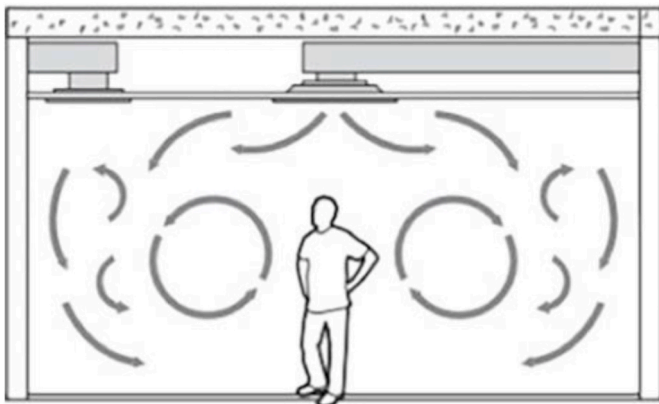


Fig. 3. The air dilution sketch of MV [19].

Table 2
Simulation conditions of MV.

Season	Supply air speed (m/s)	Supply air temperature (°C)	Wall temperature (External wall/Internal wall/Ceiling/Floor, °C)
Summer	0.8	22	29.9/27.2/26.6/27.4
Winter	0.8	24	−3.2/12.5/14.5/14.5

For an office with size of 5.16 m × 3.65 m × 2.43 m, ACH of 8 h⁻¹, supply air speed of 0.2 m/s and supply air temperature of 17.1 °C, the temperature difference between 1.1 m and 0.1 m height was 1.09 °C. When the heat load increased, the vertical temperature difference was smaller, which was conducive to improving the thermal comfort [17]. The temperature uniformity of MV was related to the high airflow speed, which also led to the strong blowing sense of personnel [23]. In addition, the energy saving effect of MV was weaker, as air in the entire room was processed, which inevitably led to energy waste in non-target area [24]. As a result, the MV in tall spaces could result in a large temperature difference between floor and ceiling and cause an additional 38% energy consumption [25]. While the energy consumption of MV was related to the location and number of diffusers, as it was more energy-saving if there were diffusers in each area for multiple areas [26].

3.2. Non-uniform indoor environment

Traditional uniform thermal environment not only consumed more energy, but also could not meet individual needs [10]. Therefore, it was important to seek energy-saving ventilation modes. The method of creating uneven thermal environment attracted more attention, which allowed fresh air to be directly sent to the target area with less mixing with indoor air [27]. This indoor environment was characterized by uneven indoor air parameters, such as air temperature, humidity, velocity and pollutants concentration. Usually, only air in the occupied space was required to be comfortable or clean, and no requirements were made for unoccupied areas, which greatly reduced the space load [14]. The ventilation system to create uneven environment was also called layered air distribution system, including displacement ventilation (DV), personal ventilation (PEV), under floor air distribution (UFAD), improving jet ventilation (IJV), stratum ventilation (SV) and etc. [4]. Fig. 5 showed sketches and Table 3 compared characteristics of different non-uniform ventilation modes.

3.2.1. Displacement ventilation (DV)

The principle of DV was to use low speed and clean air to spread on the ground, formed a thin air layer, then upward flowed to the target area, and finally exhausted with foul air [28]. Typical working conditions for DV were presented in Table 4 and temperature fields were shown in Fig. 6. Air density at different heights varied due to the difference of air temperature, resulting in buoyancy. The room was divided into two areas, i.e. the cleaning area in the lower part and the contaminated area in the upper part of the room. Thermal zoning resulted in a vertical air temperature difference of more than 3 °C between the head and ankle, which reduced the thermal comfort level [29].

DV was suitable for cooling in stadiums, shopping centers, factories and other tall spaces. It was more suitable when pollutants were lighter and the temperature was higher. Wei et al. [47] improved the ventilation mode in the factory, where fresh air was sent from the lower part of support columns to remove pollutants from the working area through thermal plumes produced by machines and workers. Compared to the circulation system that absorbed contaminated air at medium altitude and then sent filtered air down to the plant, the improved DV system reduced oil mist concentration by 70% at the 1.5 m breathing zone height. Wang et al. [48] used a DV system to remove welding smoke in the welding hall. Chen et al. [49] proposed an improved DV system for a

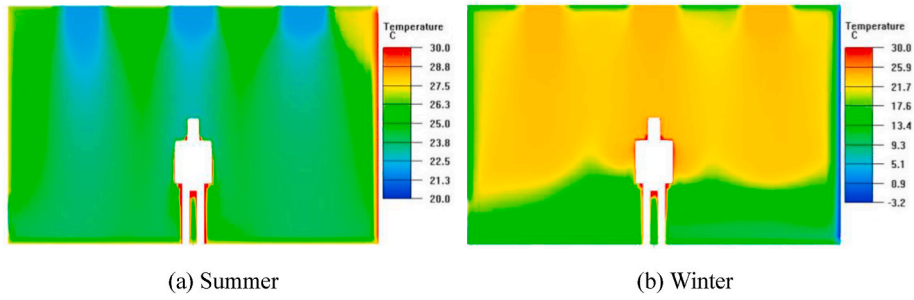


Fig. 4. Temperature field of MV.

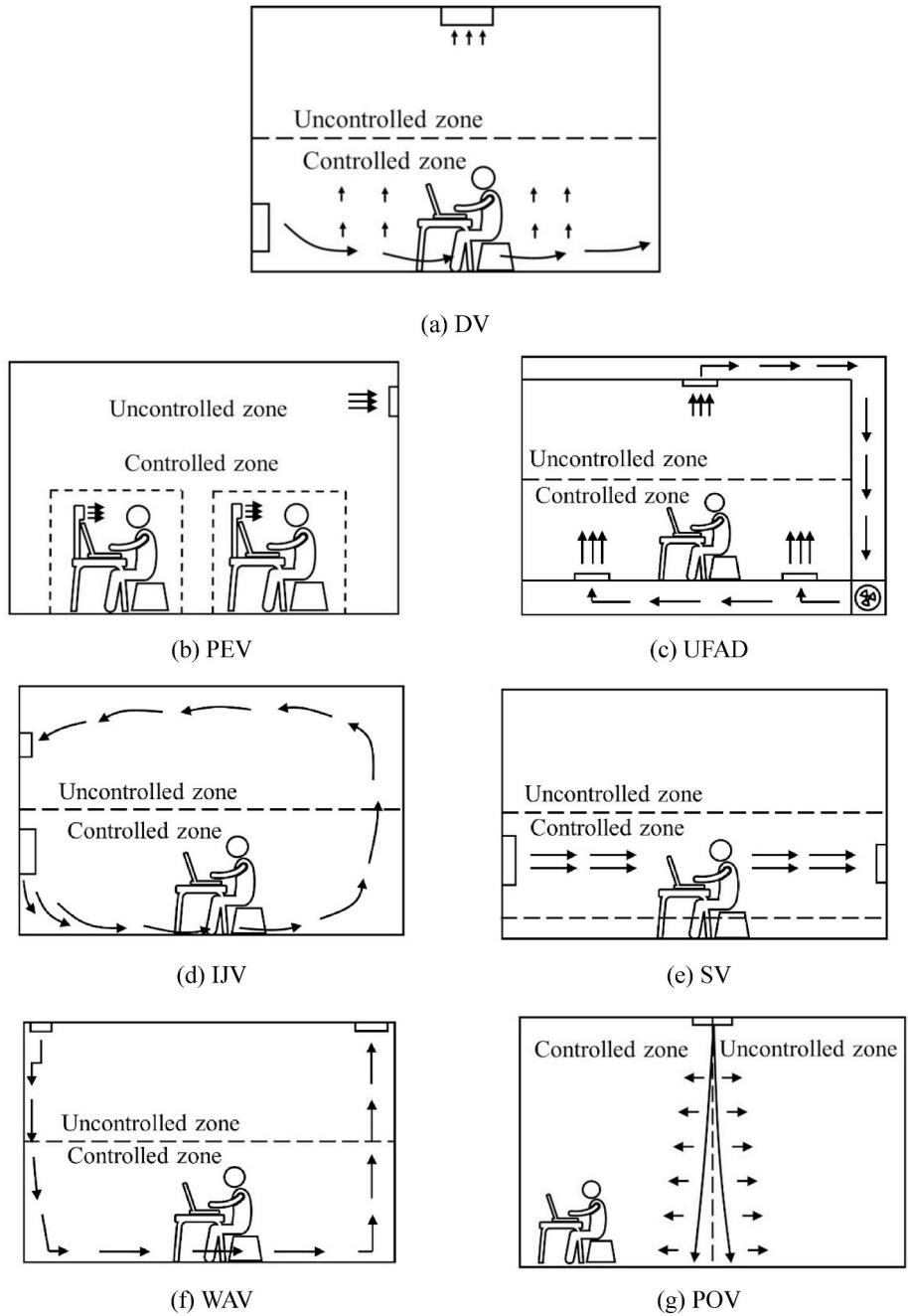


Fig. 5. Sketches of various non-uniform ventilation modes.

Table 3
Comparison of different non-uniform ventilation modes.

Modes	Layouts	Characteristics	Advantages	Disadvantages
Displacement ventilation (DV)	Air outlets were located on the side wall at a lower height [28].	Fresh air flowed upward with the thermal plume, pushing pollutants out of air vents at the top of the room [28].	Suitable for various scenarios, high air quality in the breathing zone [29].	Temperature stratification decreased the indoor thermal comfort [29].
Personalized ventilation (PEV)	Air outlets were located near the desks, chairs and other places close to occupations [30].	The environmental control of working area was strict and that of background area was not strict [31].	Directly supplied fresh air into breathing zone to avoid process of background space with contaminants [32]. Good flexibility [34].	Required high costs and inflexible locations [15].
Underfloor air distribution (UFAD)	The air outlets were located on the floor [33].	Controlled zone near the floor and uncontrolled zone near the ceiling [33].	Could be used for heating in winter [37,38].	Lower energy efficiency [15].
Impinging jet ventilation (IJV)	The air outlets were located on the side wall slightly above the ground [35].	Affected by buoyancy, rising conditioned air mixed with indoor air [36].	Low energy consumption and better air quality [42].	Directly sent cold air near the floor under cooling condition, resulting in high energy consumption [39].
Stratum ventilation (SV)	The air outlets were located on the side wall with a height of 1.2 m [40].	Controlled zone in the occupied area [41].	High ventilation efficiency and low draft sensation [44].	Strong blowing feeling in the head and large temperature difference between the head and feet [29].
Wall attached ventilation (WAV)	High momentum air supply was attached to the wall and sprayed downward [43].	The basic mechanism was extended Coanda effect, which made jet quickly spread and adhere to the floor [43].	Could be combined with other ventilation methods to improve the removal rate of pollutants [45].	Hot air floats off the floor [43].
Protected occupied zone ventilation (POV)	Divided indoor environment into protected and polluted area by jet to isolate high-concentration pollutant airflow [45].	Used a low turbulence plane jet to separate an office environment into a few subzones [46].		The application scenario was limited [45].

Table 4
Simulation conditions of DV.

Season	Supply air speed (m/s)	Supply air temperature (°C)	Wall temperature (External wall/Internal wall/Ceiling/Floor, °C)
Summer	0.8	18	29.9/27.2/26.6/27.4
Winter	0.8	26	-3.2/12.5/14.5/14.5

mechanical processing plant and compared its energy consumption with MV under the same pollutant removal and thermal comfort level. The energy consumption of DV was 17.5% lower than that of MV, as no efficient filter was needed for DV and its air volume was smaller. While in general, the energy consumption of DV was higher, as a large amount of outdoor air was used.

In addition to conventional buildings, DV was also used in some special spaces. For example, DV could effectively prevent the pollutants diffusion and keep good thermal comfort in the cabin, as presented in Fig. 7 [50]. Compared the DV mode with DV + MV combination mode (70%DV: 30%MV, 50%DV: 50%MV), and it was found that 50%DV: 50%MV mode balanced the vertical temperature difference and wind speed, making passengers obtain a more satisfactory experience [51]. Li et al. [52] designed an independent DV system for the ice and audience area, which kept the temperature of ice area at 6.8–9.6 °C and that of audience area at about 20 °C, effectively preventing fogging and maintaining thermal comfort of audience, as depicted in Fig. 8. Berlanga

et al. [53] evaluated the pollutants removal effect of DV and discussed its application possibility in infection isolation room. The indoor air distribution, heat load distribution, relative position of patients and doctors all affected the ventilation effect.

3.2.2. Personalized ventilation (PEV)

PEV could provide personalized air supply to send fresh and conditioned air into the occupied zone directly [30]. PEV divided air conditioning environment into working area and background area. To create a healthy, comfortable and efficient environment in the working area, the environmental control of background area was not strictly required. Various configurations of PEV systems have been put forward, including desk-mounted, chair-integrated, under-floor and so on [31]. Particularly, desk-mounted terminals types mainly included personalized environment mode (PEM), mobile port (MP), computer monitors port (CMP), vertical desktop grid (VDG) and horizontal desktop grid (HDG), as shown in Fig. 9 [54,55].

In PEV system, occupants could adjust the air supply parameters according to their own needs and preferences, which greatly improved the thermal comfort [56]. Furthermore, with supplying fresh air into breathing zone directly, PEV could avoid process with contaminants inside of a background space [32]. However, PEV also had some disadvantages, such as high cost and inflexible locations, and it could accelerate contaminants' spread if PEV was used by the infected occupant [56].

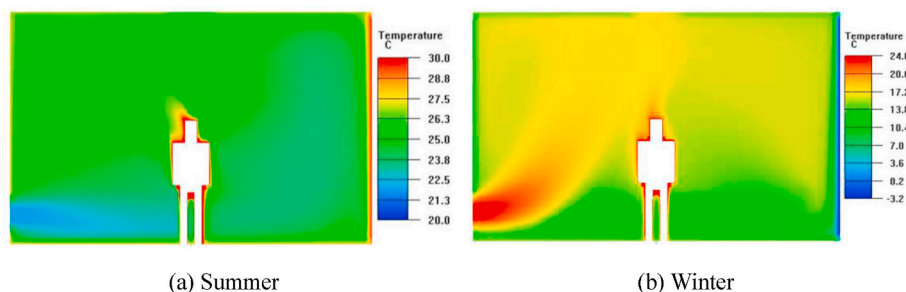


Fig. 6. Temperature field of DV.

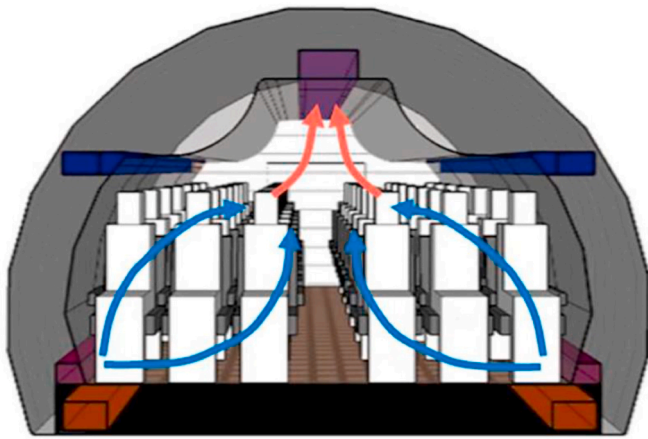


Fig. 7. Laminar airflow (LAF)/Piston ventilation (PIV) [50].

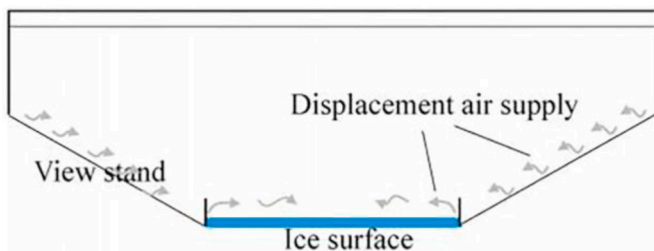


Fig. 8. Schematic diagram of DV for ice rink [52].

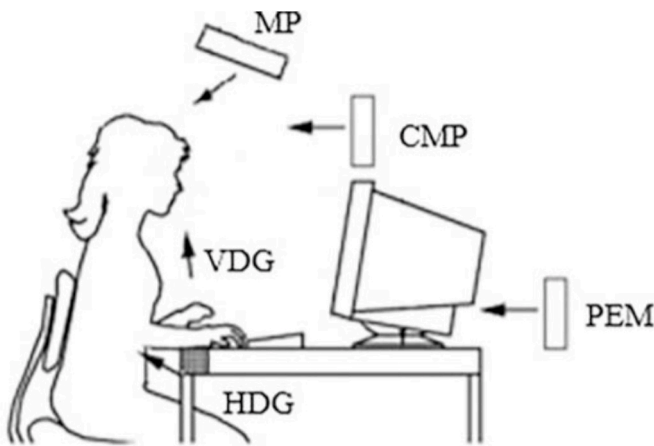


Fig. 9. Five different air personalized terminal types [54,55].

3.2.3. Underfloor air distribution (UFAD)

UFAD sent out fresh air from the air outlet of diffuser located on the floor. The conditioned air needed to flow through the plenum box located between the concrete floor and the raised floor before reaching the air outlet [33]. After being sent out through the air outlet, the fresh air occupied the personnel area, which made the pollutants automatically flow up to the air inlet [57]. The supply air and indoor air were not completely mixed, wherefore the temperature in the personnel area was lower than that in the upper part of the room, and the indoor environment was uneven. Generally speaking, as the air outlet was close to the feet area of human body, the air supply temperature in summer should not be too low (about 18–21 °C) and the air supply speed should not be too high [58].

The advantage of UFAD system lay in its good flexibility and effectiveness of air supply for personnel zone. The location of air outlet was

not fixed, and could be adjusted according to personnel needs, thus greatly improving the personnel thermal comfort. Besides, the conditioned air was directly sent to the personnel working area without considering the cooling load of other areas, which was of great help to save energy and improve the air quality [34]. However, some fresh air would be mixed with indoor air near the floor, leading to the energy efficiency of UFAD lower than that of direct air supply system.

3.2.4. Impinging jet ventilation (IJV)

The air outlet of IJV was located on the side wall slightly above the ground, and the fresh air was sent into the room at a high speed through the ultrahigh pressure pipeline. After the jet hit the ground, it spread on the ground, thus sending fresh air into the personnel area [59]. The air inlet of IJV system was often located on the higher side wall to eliminate the polluted air [35]. The flow field of impingement jet in IJV system was composed of free jet, impingement zone and wall jet [36]. Affected by buoyancy, the conditioned air rose upwards in the form of thermal plume, and mixed with indoor air to form a layered area.

IJV system not only consumed less energy consumption than MV, but also overcame the disadvantage that DV was not applicable for heating in winter [37,38]. This was because IJV had a large supply momentum, which could prevent the hot air flow from rising too fast due to buoyancy and maintain hot air stay for a long time in the personnel area [60]. IJV could provide excellent IAQ and virus spread control ability as it could offer smaller particle concentration and mean age of air (MAA) [59].

Under the cooling condition in summer, IJV system directly sent cold air near the floor, which might increase the blowing feeling of feet [39]. At the same time, too large jet velocity would cause obvious temperature stratification. In terms of energy consumption, IJV system needed 1.3 times of air supply speed and 1.1 times of fan power compared with DV system.

3.2.5. Stratum ventilation (SV)

The air outlets of SV were located on the side wall with a height of 1.2 m, which ensured the fresh air to be directly sent to the breath zone [40]. As it only ensured the thermal comfort and air quality in the occupied area, SV also showed great potential in energy saving. The air velocity and temperature of SV system were non-uniform both in vertical and horizontal directions [41]. In the vertical direction, the change trends of air flow rate and temperature presented a sandwich shape, which were different from those in upper and lower areas of other systems.

Compared with MV, SV could save more energy [42]. The thermal neutral temperature of SV was 2.5 °C higher than that of MV [61]. At the same time, its air age was greatly reduced and air quality was improved because fresh air was directly sent to the occupied zone. SV could also be used to improve the ventilation of wards and reduce the exposure risk [62] as its pollutants concentration in respiratory area was lower and dilution concentration was faster. However, it was worth noting that under the cooling condition, SV directly sent cold air to the head of occupants. It might cause strong blowing feeling in the head and large temperature difference between the head and feet [29].

3.2.6. Wall attached ventilation (WAV)

In WAV system, high momentum air supply was attached to the wall and sprayed downward. After hitting the floor, the jet quickly spread and adhered to the floor. The extended Coanda effect was the main principle for attached jets after impact [43].

Owing to the influence of jet path, the airflow velocity and temperature in room with WAV system were non-uniform. Generally, it could be divided into column attached region, primary floor attached region and confluent floor attached region. And these three areas decreased with the increase of air velocity. WAV had advantages of high ventilation efficiency and low draft sensation [44]. In addition, WAV could reduce the contaminant concentration by 15%–47% than ceiling air supply or upper sidewall air supply, indicating the potential of WAV

in virus spread control and air quality improvement [63].

3.2.7. Protected occupied zone ventilation (POV)

The purpose of POV was to divide indoor environment into protected area and polluted area by jet to isolate high-concentration pollutant airflow [45,46]. POV system could be combined with other ventilation systems to improve the removal rate of pollutants, e.g. MV, to form a hybrid protected zone ventilation.

3.3. Unsteady indoor environment

A stable thermal environment with tight temperature control could not bring occupants more comfort feelings. In contrast, such an environment would incur higher energy costs [64]. Furthermore, living in a stable thermal environment for a long time was uncondusive to human health and weakened the adaption ability of human body to natural environment [65]. Different from the tightly controlled steady thermal environment in climate chambers, real building thermal environments were usually dynamic [66]. Unsteady air supply modes were mainly composed of dynamic personalized ventilation (DPEV), pulsating ventilation (PUV), intermittent ventilation (IV) and wearable device ventilation (WDEV). Layouts, characteristics, advantages and disadvantages of the four unsteady air supply modes were compared in Table 5.

3.3.1. Dynamic personalized ventilation (DPEV)

DPEV was adopted to gently deliver a small amount of clean air to occupants breathing zone at different moments. Being operated under personnel needs and preferences, it could reduce the inhaled air pollutants of surrounding environment, effectively avoid the mix of low-temperature and high-temperature air in the room upper part [67], and hence reduce the unnecessary cooling load.

DPEV could adopt the local isothermal air supply mode with cross flow fan. As the cross flow fan and controller were integrated, its volume size was small, and could be placed horizontally or vertically. The user could control the air flow rate by adjusting the controller button according to personal needs and preferences. It could effectively improve the local thermal environment, improve the air quality in the breathing area and hence reduce energy consumption under a dynamic operating mode.

3.3.2. Pulsating ventilation (PUV)

The general principle of PUV was to change control rules of cross flow fan, and then generated simulated natural wind, as shown in Fig. 10. The device was generally composed of fan control and air flow generation unit. Through the D/A card, the control signal was converted into control voltage and input into the frequency converter. Then the fan speed was altered according to the voltage signal, to obtain the simulated wind conforming to dynamic characteristics of natural wind. Using passive or mechanical methods to produce a certain quasi-natural wind was helpful to improve human body temperature regulation function

and had the potential to decrease energy consumption if proper control strategies were adopted.

With the pulsating ventilation, fresh air was supplied to the room periodically following a predetermined dynamic trend. Air velocity supplied following the square wave and constant values were presented in Fig. 11, and results of IPMV and IPPD were compared in Fig. 12 [68]. Wu and Ahmed [69] found that a pulsating air supply could improve the indoor air quality by enhancing the mix of fresh supply air and indoor air. The ability of pulsating airflows to improve ventilation efficiency has also been theoretically validated [70].

3.3.3. Intermittent ventilation (IV)

In intermittent ventilation, a periodic on and off operation strategy was introduced. Fig. 13 showed the parameters could be used to characterize an intermittent ventilation. The ratio between the pulse duration T and period length T_p was called duty-cycle ($D = T/T_p$). With dependence on D , a desired average velocity $v = D \cdot v_{\max}$ was obtained, which was smaller than the maximum velocity v_{\max} [71].

The advantage of intermittent air supply was to supply high speed intermittent airflow to occupied zone, hence improving convective cooling performance and elevating room temperature at a higher level to maintain the same comfort level [72]. In addition, when the intermittency in supply fan was used to reduce the operation time by half, about 50% electric energy saving by the supply fan was obtained [73].

3.3.4. Wearable device ventilation (WDEV)

Fixed ventilation was unsuitable for moving occupants, wherefore wearable ventilation devices could be attached to the body to provide protection anywhere. A test ventilated suit consisted of a redesigned prototype of short-sleeve jacket with two ventilation units located at the lateral lower back sites and six ventilation holes located at the upper back (see Fig. 14). The air circulation between the ventilation jacket and manikin was managed by two fans located in the posterior-lateral side of the manikin. Two fans were powered by a smart rechargeable Li-ION battery pack, and embedded in a pocket placed inside the jacket. Fans could be adjusted at four different levels to provide different air flow rates. The air flow was channeled towards upper torso so that the air came out from the ventilation holes at the upper back, collar and sleeves [74].

Farah et al. [75] recommended to use a hybrid vest with evaporative cooling vest (ECV) and ventilation fan to enhance the limited sense of heat loss in the trunk skin area. As shown in Fig. 15 (a), ECV was comprised of three fabric layers, i.e. i) inner layer made up of waterproof fabric to prevent fluid transport to the wearer's body, ii) middle layer made up of water-absorbent fabric, and iii) outer layer made up of breathable waterproof fabric that resisted liquid water passing through, but allowed water vapor to pass. Fig. 15 (b) showed the fans were located at the lower front and back sides of the vest to blow ambient air through the microclimate airgap. During the fan operation, the ambient air flowed from the bottom to the top of the vest and left through the collar and channel at the upper part of the vest, as depicted in Fig. 15 (c).

Table 5

Comparison of different unsteady ventilation modes.

Modes	Layouts	Characteristics	Advantages	Disadvantages
Dynamic personalized ventilation (DPEV)	A small amount of clean air was gently delivered to personnel breathing zone.	Users could freely adjust and improve the quality of intake air.	Reduced the inhaled air pollutants and unnecessary cooling or heating load.	Uncondusive for moving occupants and required a background ventilation system.
Pulsating ventilation (PUV)	Changed control rules of cross flow fan to generate simulated natural wind.	Fresh air was supplied periodically following a predetermined dynamic trend.	Improved the indoor air quality and increased comfort in the personnel area.	Indoor air velocity sometimes was low, so the thermal comfort might not be guaranteed.
Intermittent ventilation (IV)	A periodic on and off operation method was introduced.	Supplied high speed and intermittent airflow to occupied zone.	Improved convective performance, elevated room temperature and reduced energy consumption.	The supply air amount was small and might not meet the requirement.
Wearable device ventilation (WDEV)	Used evaporative cooling and/or ventilation fans to control the skin heat loss.	The ambient air flowed from the bottom and left at upper ventilation holes.	Could be attached to the body to provide protection anywhere.	The sensing, driven and controlling technique were complex.

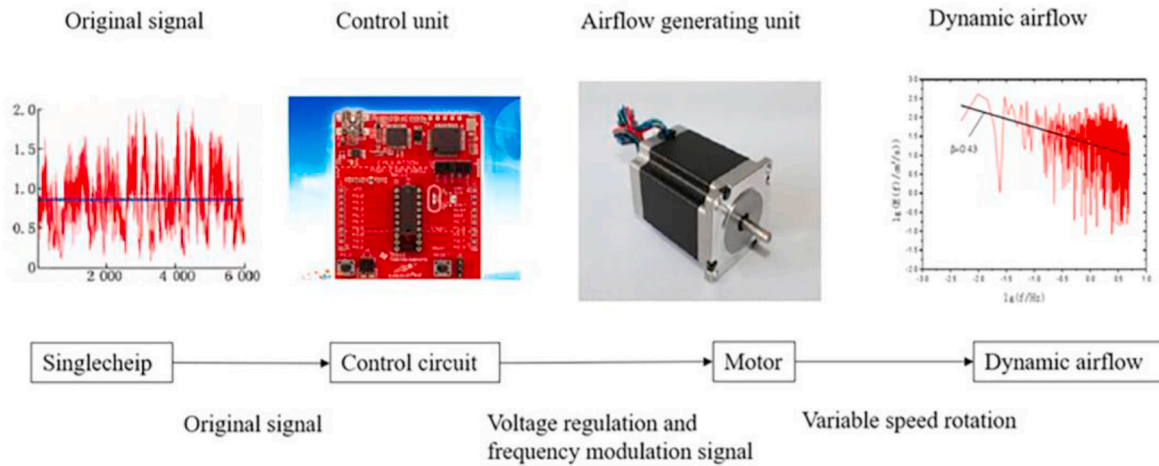


Fig. 10. Control flowchart of PUV.

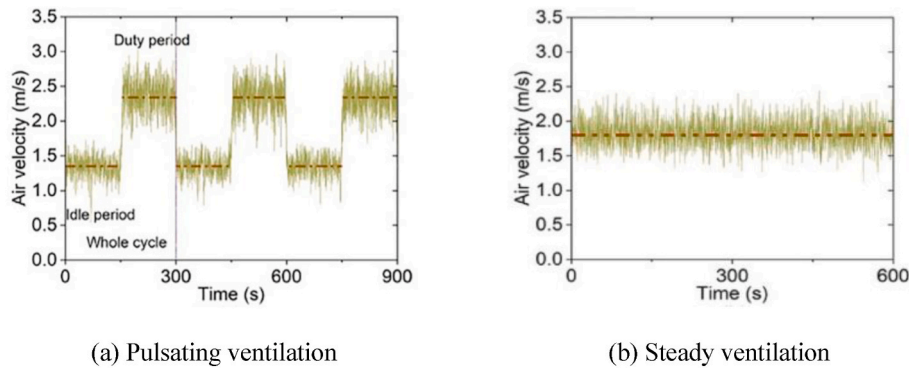


Fig. 11. Air velocity comparison for different ventilation strategies [68].

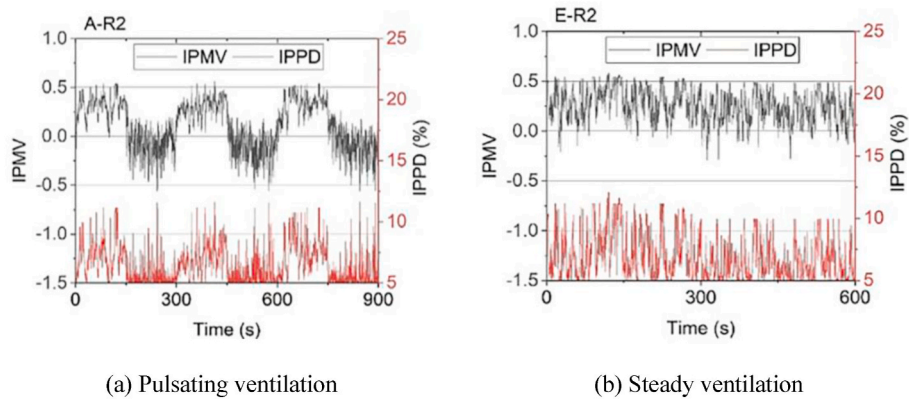


Fig. 12. IPMV and IPPD for pulsating and steady ventilations [68].

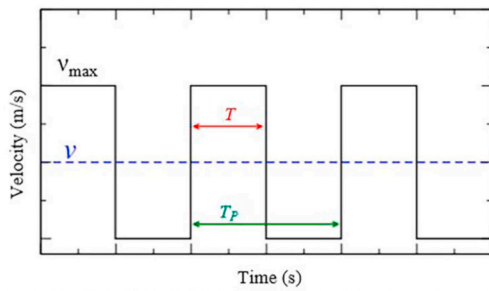
4. Impacts on thermal comfort, air quality and virus spread control

To evaluate the effect of different ventilation modes on thermal comfort, air quality and virus spread control, this section firstly compared evaluation indexes focused on office buildings in standards released by China [76,77], United States [78,79], European Union (EU) [80] and ISO [81,82], and then analyzed optimized operation strategies for different ventilation modes.

4.1. Traditional uniform and steady indoor environment control

4.1.1. Evaluation indexes

4.1.1.1. Thermal comfort. Generally, there were little difference for China, EU and ISO standards in room temperature requirements. The indoor temperature was about 24 °C in summer and 20 °C in winter. Specifically, GB/T 18883–2020 of China required indoor temperature to be maintained at 22–28 °C in summer and 16–24 °C in winter. GB 50736–2012 required indoor design temperature of air conditioning in short-term stay areas should be 1–2 °C higher than those in long-term



Note: T : pulse duration, T_p : period length, v : average velocity, v_{max} : maximum velocity.

Fig. 13. Parameters to characterize an intermittent ventilation [71].

stay areas. EU and ISO standards owned more comfort levels to provide a finer division of indoor temperatures. ASHRAE 55–2017 provided the calculation method and selection criteria for determining temperature. The comfort range was determined by the given humidity, wind speed, metabolic rate and thermal resistance of clothing, which could be obtained with the graph or simulation method. See Table 6 for detailed temperature requirements.

China did not have specific requirements for vertical temperature difference between head and ankle, an important evaluation index affecting indoor environment uniformity. While in ISO and EU standards, three grades were divided according to different satisfaction levels. The highest degree of vertical temperature difference was less than 2 °C, followed by 3 °C, and finally 4 °C. ASHRAE 55–2017 proposed that the vertical temperature difference in standing state should not exceed 4 °C, and that in sitting position should not exceed 3 °C.

In terms of humidity, GB/T 18883–2020 provided requirements for

humidity of 40%–80% in summer and 30%–60% in winter. GB 50736–2012 put forward specific requirements for humidity according to thermal comfort, and the overall requirements were not much different from GB/T 18883–2020. ISO 7730–2005, ISO 17772–2017 and EN 16798-1-2019 recommended room temperature based on 60% humidity in summer and 40% humidity in winter. ISO 7730–2005 considered that a wide range of humidity was acceptable as thermal sensation, skin moisture, dry skin and radiation all affected thermal comfort levels. ISO 17772-2017 gave the range of humidity requirements for some special buildings, such as museums. ASHRAE 62.1–2019 did not give the lower limit of room humidity, but indicated that the upper limit of humidity should be less than 65%. ASHRAE 55–2017 required that under the condition of standard atmospheric pressure and dew point temperature of 16.8 °C, the system humidity should be maintained below 0.012 kg-H₂O/kg-dry air.

As for wind speed, the maximum speed limit in GB/T18883-2020 was 0.3 m/s in summer and 0.2 m/s in winter. In GB 50736–2012, two comfort grades were divided in summer, i.e. Grade i: $v \leq 0.25$ m/s and Grade ii: $v \leq 0.3$ m/s, and winter wind speed was required to be less than 0.2 m/s. According to ISO 7730–2005, ISO 17772–2017 and EN 16798-1-2019, there were three grades of wind speed according to the comfort level: Grade i: 0.12 m/s, Grade ii: 0.19 m/s and Grade iii: 0.24 m/s. In Grade i, the comfort level was the highest and in Grade iii, the comfort level was the lowest. ASHRAE 55–2017 did not give specific limit values of wind speed, but revised the comfort range of temperature according to different wind speeds and humidity ratios. The dividing line of average air speed and humidity ratio were set as 0.2 m/s and 0.012 kg-H₂O/kg-dry air respectively, as shown in Table 7.

4.1.1.2. Air quality and virus spread control. Main indoor air pollutants

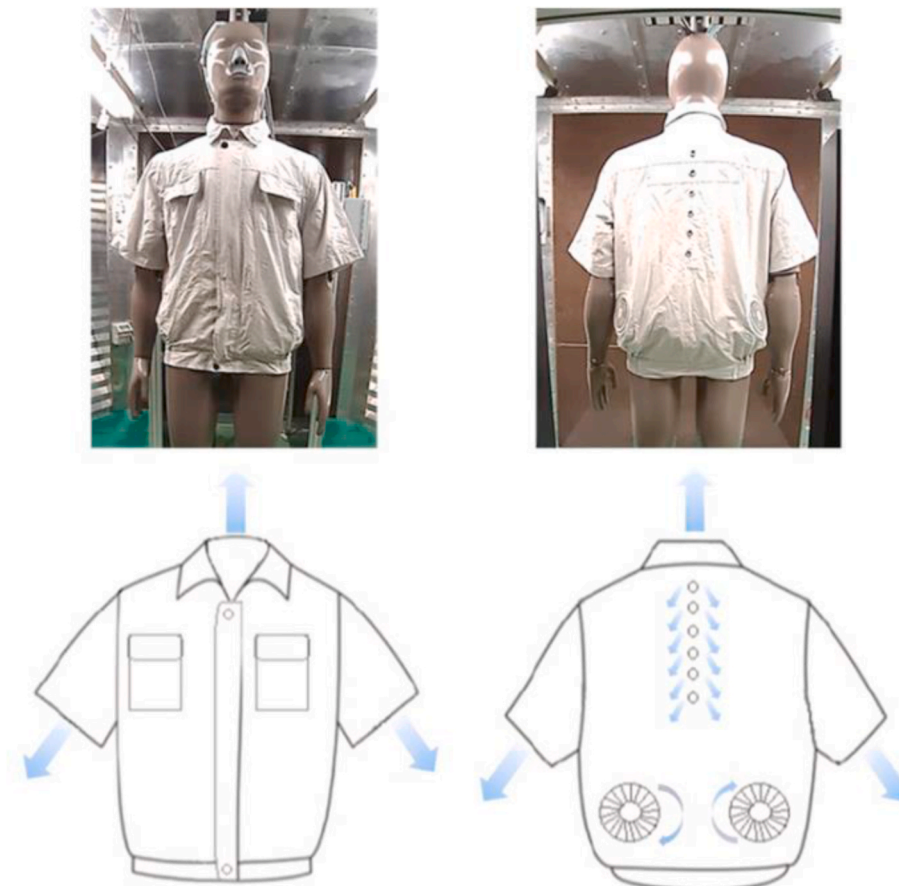
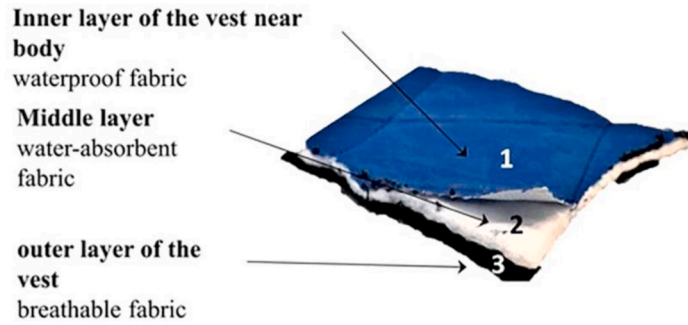
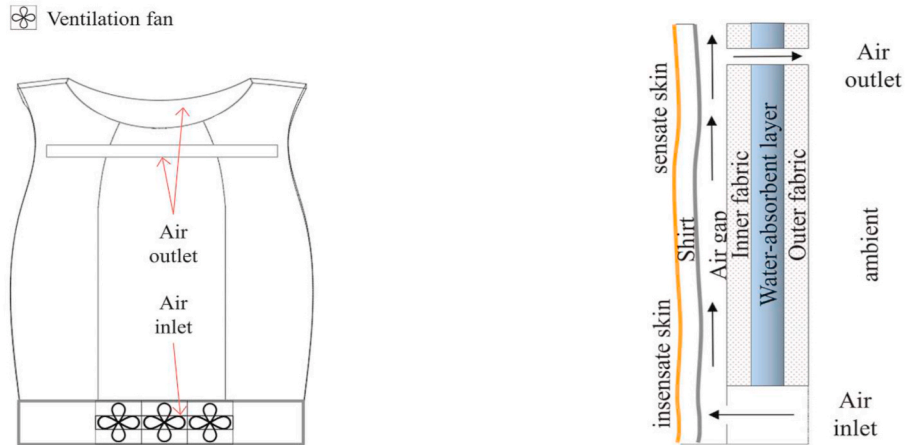


Fig. 14. The ventilation jacket with fans and openings at the back site [74].



(a) Material used in the ECV



(b) Front view of the hybrid ECV

(c) Section view of vest layers

Fig. 15. Components and structures of the hybrid vest [75].

Table 6
Specific requirements of thermal comfort in different standards.

Standard	GB/T 18883-2020	GB 50736-2012 ^a	ISO 7730-2005 ^b	ISO 17772-2017 ^c	EN 16798-1-2019 ^d	ASHRAE 62.1-2019	ASHRAE 55-2017
Temperature (Summer, °C)	22–28	I: 24-26 II: 26-28	A: 24.5 ± 1.0 B: 24.5 ± 1.5 C: 24.5 ± 2.5	I: 25.5 II: 26 III: 27 IV: 28	I: 25.5 II: 26 III: 27 IV: 28	–	–
Temperature (Winter, °C)	16–24	I: 22-24 II: 18-22	A: 22 ± 1.0 B: 22 ± 2 C: 22 ± 3	I: 21 II: 20 III: 19 IV: 18	I: 21 II: 20 III: 19 IV: 18	–	–
Vertical temperature difference (°C)	–	–	A: <2 B: <3 C: <4	I: 2 II: 3 III: 4	I: 2 II: 3 III: 4	–	Standing: 4 °C Sitting: 3 °C
Humidity (Summer, %)	40–80	I: 40-60 II: <70	60	60	60	65	0.012 kg-H ₂ O/kg-dry air
Humidity (Winter, %)	30–60	I: ≥30 II: –	40	40	40	65	0.012 kg-H ₂ O/kg-dry air
Air speed (Summer, m/s)	0.3	I: ≤0.25 II: ≤0.3	A: 0.12 B: 0.19 C: 0.24	I: 0.12 II: 0.19 III: 0.24	I: 0.12 II: 0.19 III: 0.24	–	–
Air speed (Winter, m/s)	0.2	I: ≤0.2 II: ≤0.2	A: 0.1 B: 0.16 C: 0.21	I: 0.1 II: 0.16 III: 0.21	I: 0.1 II: 0.16 III: 0.21	–	–

Notes.

^a I: 0.5<PMV≤0.5; PPD≤10%. II: 1<PMV < -0.5, 0.5<PMV≤1; PPD≤27%.

^b A: 0.2<PMV<0.2; PPD<6%. B: 0.5<PMV<0.5; PPD<10%. C: 0.7<PMV<0.7; PPD<15%.

^c I: 0.2<PMV<0.2; PPD<6%. II: 0.5<PMV<0.5; PPD<10%. III: 0.7<PMV<0.7; PPD<15%. IV: 1.0<PMV<1.0; PPD<25%.

included SO₂, NO₂, CO, O₃, PM₁₀ and so on. The values of these pollutants were required in different standards, which were obviously different, as shown in Table 8.

4.1.2. Operation strategies: mixing ventilation (MV)

According to operating guidelines of HVAC systems during COVID-19, main countermeasures included increasing fresh air volume,

Table 7
Wind speed requirement in ASHRAE 55–2017.

Average air speed, m/s (fpm)	Humidity ratio	Met	Clo
<0.20 (40)	<0.012 kg-H ₂ O/kg-dry air	1.0–1.3	0.5–1.0
<0.20 (40)	All	1.0–2.0	0–1.5
>0.20 (40)	All	1.0–2.0	0–1.5

Table 8
Specific requirements of air quality in different standards.

Pollutants	GB/T 18883–2020	ISO 17772–2017	EN 16798-1-2019	ASHRAE 62.1–2019
SO ₂ ^c	0.5 (mg/m ³)/1 h	10 min: 500 µg/m ³ 24 h: 20 µg/m ³	10 min: 500 µg/m ³ 24 h: 20 µg/m ³	1 h: 75 ppb
NO ₂ ^c	0.24 (mg/m ³)/1 h	1 h: 200 µg/m ³ 1 year: 20 µg/m ³	1 h: 200 µg/m ³ 1 year: 20 µg/m ³	1 h: 100 ppb 1 year: 53 ppb
CO ^c	10 (mg/m ³)/1 h	15 min: 100 mg/m ³ 1 h: 35 mg/m ³ 8 h: 10 mg/m ³ 24 h: 7 mg/m ³	15 min: 100 mg/m ³ 1 h: 35 mg/m ³ 8 h: 10 mg/m ³ 24 h: 7 mg/m ³	1 h: 40 mg/m ³ 8 h: 10 mg/m ³
CO ₂ ^c	0.1%/24 h	–	–	–
NH ₃ ^c	0.2 (mg/m ³)/1 h	–	–	–
O ₃ ^c	0.16 (mg/m ³)/1 h	8 h: 100 mg/m ³	8 h: 100 mg/m ³	8 h: 0.007 ppm
HCHO ^c	0.1 (mg/m ³)/1 h	100 ^a /30 ^b µg/m ³	100 ^a /30 ^b µg/m ³	–
C ₆ H ₆ ^c	0.11 (mg/m ³)/1 h	<5 mg/m ³	<5 mg/m ³	–
C ₇ H ₈ ^c	0.2 (mg/m ³)/1 h	–	–	–
C ₈ H ₁₀ ^c	0.2 (mg/m ³)/1 h	–	–	–
Benzopyrene ^c	1 (mg/m ³)/1 h	–	–	–
PM10 ^c	0.15 (mg/m ³)/24 h	24 h: 50 µg/m ³ 1 year: 20 µg/m ³	24 h: 50 µg/m ³ 1 year: 20 µg/m ³	24 h: 150 µg/m ³
TVOC ^c	0.6 (mg/m ³)/2 h	1000 ^a /300 ^b µg/m ³	1000 ^a /300 ^b µg/m ³	–
Total number of colonies	2500 cfu/m ³	–	–	–
Radon ^c	400 bq/m ³ /per year	100 bq/m ³	100 bq/m ³	–

Notes.

^a Low emitting products for low polluted buildings.

^b Very low emitting products for very low polluted buildings.

^c The average value.

increasing air change rates, extending operation time, banning indoor air circulation and increasing filters efficiency. However, the traditional air conditioning system had many shortcomings in adapting to new operation strategies, wherefore this section discussed the effect of traditional uniform and steady ventilation modes on thermal comfort, air quality and virus spread control.

In MV, there was recycling of indoor air to reduce the amount of energy used in processing outdoor air, which increased the risk of infection. Actually, the particles diameter, ventilation rate and removal efficiency were closely related. Wei et al. [83] analyzed the effect of turbulence on droplet diffusion distance of cough airflow. Small droplet (10 µm) floated farther with airflow, and the settlement effect of large

droplet (100 µm) was more obvious. Zhang et al. [84] studied the relationship between ACH and pollutant concentration in the operating room, and found that higher ACH significantly reduced pollutant concentration and wound exposure risk. A higher ventilation rate could better dilute the concentration of pathogens and reduce the risk of airborne transmission [85]. The ventilation rate of air-conditioned room was generally not less than 5 times per hour, which meant that the air-conditioned room could remove the droplet particles with the suspension time exceeding 0.2 h. When there was no ventilation, large size of particles sedimentation probability increased, resulting in lower removal rates and higher infection rates [86].

In addition to the air distribution factor, the interior partition, tuyere location shape and etc. also affected the pollutants removal capacity. Lee and Awbi [87] found that the position and height of baffle plate, clearance of diaphragm and position of pollutants sources affected the MV performance. Berlanga et al. [88] studied the exposure risk of medical staff using two different air supply structures and three different air change rates. The use of two swirl diffusers located on the ceiling could bring a lower exposure risk compared to the side wall gratings.

Besides, the use of high efficiency particulate air (HEPA) filter in mixing ventilation systems was another important way to deal with the particles and viruses. It could achieve a maximum particle removal efficiency of 99.9%, which was comparable to the virus infection prevention and control ability of air conditioning systems with 100% fresh air [89]. However, its location should be set close to the personnel activity area to improve the collection efficiency, and the filter element should be replaced frequently within a permitted period [90].

4.2. Non-uniform indoor environment control

4.2.1. Evaluation indexes

4.2.1.1. Thermal comfort.

1 Weighted PMV method

The weighted PMV method included equivalent temperature method and area weighting method. In equivalent temperature method, the weighted mean value of air temperature was firstly used to obtain a new average equivalent temperature (AET) as shown in Eq. (1) [91], and then AET was introduced into the PMV formula. The equivalent temperature weighted PMV method only considered the weight of temperature, but did not consider the influence of parameters such as humidity and air velocity. Moreover, this method could only get the overall thermal sensation.

$$AET = 0.1 \times T_{\text{head}} + 0.7 \times T_{\text{abdomen}} + 0.2 \times T_{\text{feet}} \quad (1)$$

In area weighting method, the local PMV value of each part was calculated by using non-uniform environmental parameters. Then according to the skin area percentage of each part to the total surface area of human body, the whole PMV value was obtained by weighted average [92]. However, the disadvantage of this method was that PMV calculation was based on the prediction of global thermal sensation, and it was unscientific in local thermal sensation evaluation. In addition, using the weighted value of skin surface area to get the overall thermal feeling of human body was not sufficient, as different skin parts had different feelings to the ambience.

2. Equivalent homogeneous temperature (EHT)

EHT was proposed by Wyon et al., in 1985 [93] and used in 1989 [94] to evaluate the inhomogeneous thermal environment in automobiles. Heat dissipation of human body model was used to measure the similarity between uniform environment and real environment. If the heat dissipation of dummy in two environments were the same, the

temperature in uniform environment could represent the equivalent homogeneous temperature in real environment [95]. There was a linear relationship between subjective thermal feeling voting and EHT, and the comfort range of EHT could be determined according to the linear relationship.

4.2.1.2. Air quality and virus spread control.

1 Exposure risk index

The exposure risk index was used to assess the exposure risk of pollutants [32]. The higher the system's ability to remove particles, the smaller the exposure risk index. The exposure risk index of respiratory area was calculated as follows:

$$\varepsilon_{bz} = \frac{C_{bz} - C_s}{C_e - C_s} \quad (2)$$

2. Personal exposure effectiveness (PEE)

PEE characterized the effectiveness of sending clean air into breathing zone [54]. PEE could be calculated as presented in Eq. (3). The larger the PEE, the more fresh air in the breathing area, and the better protection effect of the exposed person.

$$PEE = \frac{C_{1,0} - C_1}{C_{1,0} - C_s} \quad (3)$$

3 Intake fraction (IF)

IF indicated the concentration ratio of particles inhaled by exposed person to particles exhaled by infected person [96]. The larger the IF, the worse the virus prevention ability and the higher the infection probability. IF could be calculated as follows:

$$IF(t) = \frac{\int_0^{t_{in}} C_{in}(t) M_{in} dt}{\int_0^{t_{ex}} C_{ex}(t) M_{ex} dt} \quad (4)$$

4 Effluent efficiency

Effluent efficiency was used to denote the ability of ventilation to discharge pollutants outdoors [97]. Effluent efficiency could be calculated as follows:

$$\varepsilon = \frac{\varphi_e - \varphi_s}{\varphi_v - \varphi_s} \quad (5)$$

5. Inhaled local air quality index.

Inhaled local air quality index was used to characterize the influence of ventilation system on the concentration of pollutants inhaled by people [98]. Inhaled local air quality index could be calculated as follows:

$$\varepsilon_{exp}^c = \frac{\varphi_c}{\varphi_{exp}} \quad (6)$$

4.2.2. Operation strategies

4.2.2.1. Displacement ventilation (DV). The replacement of MV by DV could reduce the exposure of pollutants in medical staff, and the increase of ventilation rates would improve the pollutants removal efficiency. DV could bring about more significant changes under the same chemical reaction conditions on human surface. However, when ventilation rate exceeded a certain value, the number of droplets suspending and escaping throughout the room did not change much [99]. When ACH reached 12 h^{-1} , DV and MV systems achieved similar levels of pollutants exposure [88].

Many control strategies in DV aimed to avoid the change of thermal stratification height caused by disturbance of indoor air distribution. Zhang et al. [100] found that the number of suspended viruses removed by DV was twice than that by MV. Li et al. [101] discovered that DV might be superior to MV in reducing horizontal dispersion of air droplets. He et al. [102] conducted a CFD study on respiratory pollutants in human body models, and found that clean areas formed at lower positions, while polluted areas formed at higher positions. Li et al. [103] proved that DV had a stronger removal ability for droplets with small particle size ($<5 \mu\text{m}$), and UFAD was more suitable for removing large droplets ($5\text{--}10 \mu\text{m}$). However, the removal effect of DV was conditional. When the diameter of particles gradually increased, the gravity settlement effect increased and the concentration stratification decreased, thus increasing the concentration of particles of exposed person. When the flow rate was 60 L/s , this effect lasted until the particle diameter exceeded $10 \mu\text{m}$ [104]. DV thermal stratification combined with low air flow rate at the middle height of room could lead to respiratory droplets staying in the human respiratory zone for a longer time, thus possibly increasing the risk of exposure and infection [105].

The combination of DV with HEPA filter was commonly used in the operating room [106]. Because of the thermal stratification caused by DV, pollutants accumulated in the room upper part. Consequently, combining DV with upper Ultraviolet Germicidal Irradiation effectively reduced the risk of airborne viruses with minimal additional energy consumption [107,108].

4.2.2.2. Personalized ventilation (PEV). The pollutants removal by PEV was realized by controlling air flow and local exhaust to the face [32]. Through maintaining high ventilation efficiency in the breathing zone, infected airflow decreased and clean air increased [54]. However, due to the disturbance and diffusion of PEV airflow, the concentration of pollutants in the surrounding might increase, such as the passage between tables. To improve the air utilization efficiency of PEV system, Gao et al. [109] used small directional nozzles and obtained a more uniform flow field. PEV could also be combined with other ventilation systems, and the effect of PEV on pollutants removal was closely related to the background ventilation system. The interaction between PEV and DV or between PEV and UFAD was obviously stronger than that between PEV and MV [110]. Besides, improper use of ventilation strategy also reduced the ventilation effect. For example, You et al. [111] tested a PEV installed on a chair in an airplane cockpit, and found that the system had good pollutant removal potential and acceptable thermal comfort, but passengers felt cold when the air inlet was put in front of passengers' legs. In the aspect of virus spread control, PEV should maintain high ventilation efficiency around healthy people to prevent infection [32].

4.2.2.3. Underfloor air distribution (UFAD). In UFAD system, the pollutants and heat were brought to the upper zone through rising airflow so that the air quality of breathing zone was guaranteed. Compared with traditional air conditioner, pollutants could be removed more effectively. The concentrations of pollutants and CO_2 at typical locations were lower than the standard requirements [112]. The effect of UFAD system was affected by the position of air outlet. The MAA firstly decreased and then increased with the occupied zone as the boundary, and the optimal result was obtained when the air outlet was located at the upper boundary of occupied zone [56,113]. The UFAD system combined with task air conditioning (TAC-UFAD) greatly improved the indoor air quality in breathing area. TAC-UFAD system could be regarded as an effective solution to improve serious PM pollution owing to the advantages of floor-to-ceiling airflow mode and the benefits of removing smaller particles [113].

4.2.2.4. Impinging jet ventilation (IJV). IJV could fully discharge CO_2 and ensure good air quality in an acceptable time. Koufi et al. [39] found that IJV could ensure uniform concentration distribution, and the air

velocity was less than 0.25 m/s. This was in accordance with ASHRAE 55–2017. Meanwhile, IJV could reduce the concentration of pollutants and CO₂ in occupied zone [59]. As the virus was usually attached to the surface of pollutants and droplets, IJV also showed ability in virus spread control.

To improve the ventilation effect of IJV, a number of operation strategies have been studied. For example, splitting the return device from the exhaust vent could improve air quality. The air age and CO₂ concentration decreased with the height increase of air outlet, and the result reached the standard requirement at about 1.2 m [35]. In addition, the shape and number of air outlets could be optimized to provide better results in pollutant removal and air exchange efficiency [60]. By increasing ceiling exhausts, the MAA could be reduced by up to 54%, the residence time of indoor air was shortened and the inhaled air quality by occupants was better.

4.2.2.5. Stratum ventilation (SV). SV could form a temperature and velocity interlayer and isolated pollutant particles from entering the personnel area [114]. Moreover, its ventilation efficiency was higher, liquid droplets could be discharged faster and concentration was diluted [115]. Compared with radiant heating in winter, the introduction of SV in heavily polluted areas could reduce the mortality of lung cancer caused by PM_{2.5} and PM₁₀ by 28.25% and 58.75%, respectively [42]. Air supply temperature, velocity and air change rates could affect SV performance. When the air supply temperature increased from 19 to 21 °C, the MAA decreased from 475 to 443 s [116]. When the air velocity increased to 0.5 m/s, the air quality could be improved by continuously introducing fresh air into the breathing area [117].

4.2.2.6. Wall attached ventilation (WAV). In WAV system, the jet with high momentum reached the personnel area through wall attachment and impact. As it could continuously provide fresh air to personnel area, a strong pollutant removal efficiency was obtained. Compared with ceiling air supply, WAV could reduce pollutant concentration by 15%–47% [63]. Meanwhile, the negative pressure only appeared around the exhaust port, which was applicable to the isolation ward. WAV system could also be used in micro-sleeping space to ensure the comfort while maintaining low CO₂ concentration and MAA [118].

To improve the performance of WAV, Yin et al. [118] compared the performance of WAV under three different working conditions. The double-side-attached ventilation mode performed best in terms of comfort, the horizontal ceiling-attached ventilation mode performed best in terms of MAA, and the vertical wall-attached ventilation mode performed best in terms of CO₂ concentration control. As such, different air distribution modes could be selected according to specific requirements.

4.2.2.7. Protected occupied zone ventilation (POV). POV used high-speed airflow to isolate pollutants in the space and ensure air in the personnel area to be clean. The ability of POV in improving indoor air quality was obvious. Cao et al. [119] revealed that POV could separate the protected area from the polluted area by up to 2800 ppm, thus avoiding cross infection. Besides, the application of POV in hospitals to control air transmission of respiratory diseases has also been studied. On the premise of improving inhaled air quality, POV could ensure that the personnel draught risk was within the comfort standard [46]. To reduce the risk of virus transmission, the air supply velocity needed to be strictly controlled. Cao et al. [120] found that when the air supply velocity exceeded 4 m/s, the dimensionless concentration of virus was 40% lower than that of MV, which significantly reduced the infection probability.

4.3. Unsteady indoor environment

4.3.1. Evaluation indexes

4.3.1.1. Thermal comfort.

1. Dynamic PMV (DPMV)

Thermal load (TL) was used to predict human thermal sensation in uniform and steady thermal environment. Fanger obtained the regression formula of PMV and thermal load (TL) according to the test data as shown in Eq. (7). Dynamic thermal load (DTL) considered the time-varying characteristics of human thermal load, which was used to predict human thermal sensation in dynamic thermal environment. The formulas of DTL and DPMV were as shown in Eqs. (8) and (9), respectively.

$$PMV = [0.303 \exp(-0.036M) + 0.0275]TL \tag{7}$$

$$DTL = TL + K_1 \frac{dT_L}{dt} + K_2 \frac{d^2T_L}{dt^2} \tag{8}$$

$$DPMV = [0.352 \exp(-0.042M / Adu) + 0.032]DTL \tag{9}$$

2. Relative Warmth Index (RWI)

RWI was a dimensionless index similar to PMV. If there were same RWI values under different environmental conditions and activities, the human thermal sensation was similar [121]. When the partial pressure of water vapor in air was less or higher than 2269 Pa, the calculation formula of RWI was shown in Eqs. (10) and (11) respectively. See Table 9 for comparison between different RWI index values and ASHRAE comfort standard classifications.

Partial pressure of water vapor <2269 Pa:

$$RWI = \frac{M(\tau)[I_{CW}(\tau) + I_a] + 6.42(T_a - 35) + R_{I_a}}{234} \tag{10}$$

Partial pressure of water vapor >2269 Pa:

$$RWI = \frac{M(\tau)[I_{CW}(\tau) + I_a] + 6.42(T_a - 35) + R_{I_a}}{65.2 \times (5858.44 - P_a) / 1000} \tag{11}$$

3 Heat Deficit Rate (HDR)

HDR considered various factors affecting human thermal comfort, such as temperature, humidity, radiation, air flow rate, human metabolic rate and clothing thermal resistance. It reflected the heat loss per unit skin area of human body as [122]:

$$HDR = \frac{D}{\Delta\tau} = 28.93 - M(\tau) - \frac{6.42(T - 30.56) + R_{I_a}}{I_{cl}(\tau) + I_a} \tag{12}$$

4. Time-weighted average IPMV/IPPD (TAPMV/TAPPD)

The predicted mean vote-predicted percentage dissatisfied (PMV-PPD) model was applied to evaluate steady thermal environment [81]. For transient conditions, the instantaneous PMV (IPMV) and

Table 9
Thermal sensation evaluated by RWI index and ASHRAE Standard.

Thermal sensation	ASHRAE thermal sensory scale	RWI index value
Warm	2	0.25
Slightly warm	1	0.15
Comfortable	0	0.08
Slightly cool	-1	0

instantaneous PPD (IPPD) were calculated. ISO 7730-2005 stipulated that time-weighted average values of IPMV (TAPMV) and IPPD (TAPPD) could be used to predict thermal comfort under transient conditions in which only one or more parameters had minor fluctuations. The TAPPD and TAPMV results under transient conditions were also in good agreement with the actual thermal sensation votes [72,123]. The calculation equations of TAPMV and TAPPD were as follows:

$$TAPMV = \frac{\sum_0^T IPMV}{T} \tag{13}$$

$$TAPPD = \frac{\sum_0^T IPPD}{T} \tag{14}$$

5. Difference potential by supply air (DPSA)

DPSA was a dimensionless index evaluating the active regulation ability of ventilation system. It could be used for both steady and unsteady conditions. The DPSA value range was 0–2. In there was only one air outlet in the room, the DPSA value was 0. If there were several air outlets with each air outlet only affecting its control area, the DPSA value was 2 [115].

$$a_{s,p}^{n_s}(\tau) = \frac{\tilde{C}^p(\tau)}{\tilde{C}_s^{n_s}} \tag{15}$$

$$dp_{i,j}(\tau) = \sum_{n_s=1}^{N_s} |\Delta a_{s_{ij}}^{n_s}(\tau)| \tag{16}$$

4.3.1.2. Air quality and virus spread control. Inhalation ratio (IF) referred to the proportion of droplet particles inhaled by exposed person to the quantity or mass of droplet particles exhaled by infected person. Since viruses were usually attached to pollutant particles in the air, it could also be used for virus inhalation rate. The calculation formula was as follows [96]:

$$IF(t) = \frac{\int_0^{t_{in}} C_{in}(t)M_{in}dt}{\int_0^{t_{ex}} C_{ex}(t)M_{ex}dt} \tag{17}$$

The dose-response model could predict the infection risk (IR) of specific airborne diseases by considering the infectivity and activity of pathogens. Sze-To et al. [124] added aerosol size, spatial non-uniform distribution characteristics and other factors into the basic dose-response model, and predicted the change of infection risk with time when an individual was at rest or in motion:

$$P_1(t_0) = 1 - \exp\left(-\sum_{j=1}^m r_j \beta_j c p q t_0 \int_0^{t_0} v(t) f(t) dt\right) \tag{18}$$

4.3.2. Operation strategies

4.3.2.1. Dynamic personalized ventilation (DPEV). DPEV could be combined with cooling ceiling as shown in Fig. 16. Under the combination mode, energy could be saved by 8.14% compared with single cooling ceiling and the thermal comfort was improved owing to air supply. In addition, changing the stable personalized air supply to intermittent one could also improve the indoor environment. When the frequency was 0.5 Hz, it was beneficial to indoor environment improvement and 15.04% energy could be saved [125]. The supply flow rate accelerated and decelerated at a characteristic frequency, which could create a highly turbulent jet, leading to the enhancement of thermal comfort. By comparing the temperature distribution, velocity distribution and energy utilization coefficient of human body at different air supply positions, the optimal air supply mode and parameters could be obtained [126].

DPEV had advantages in virus spread control and reducing the risk of

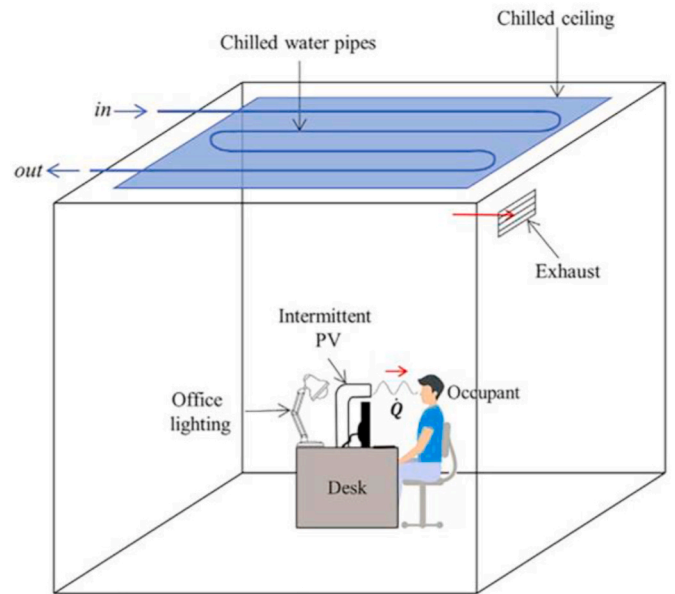


Fig. 16. The chilled ceiling system assisted by an intermittent PEV [125].

cross infection. Pantelic et al. [127] used a combination of DPEV and MV. The dose-response model was used to predict the reduction on the risk of influenza A and tuberculosis infection. It was found that both the peak concentration induced by cough and exposure time at 1–2 m were reduced. For influenza A and tuberculosis, the risk of infection was reduced by 27% and 65%, respectively.

4.3.2.2. Pulsating ventilation (PUV). Many types of unsteady (e.g. simulated natural, sinusoidal and pulsating) airflows have been shown to be more efficient for body cooling and more preferred by occupants [128–132]. Therefore, pulsating air supply devices to produce similar natural wind could be used as an optimization method. In addition, Tian et al. [68] proposed to combine SV with a pulsating air supply as depicted in Fig. 17. This mode could provide acceptable air movement and good thermal comfort at elevated room air temperatures, which could satisfy the requirements for Categories A and B of thermal environments required in ISO 7730–2005.

On the other hand, changing ventilation rates could ensure acceptable indoor air quality. With the demand-controlled ventilation (DCV) based on sensor measurement and control logic, sensors measured pollutant concentrations and air handling unit (AHU) controlled the ventilation rate [133]. At present, costs of relevant devices were relatively high and needed to be further reduced [134].

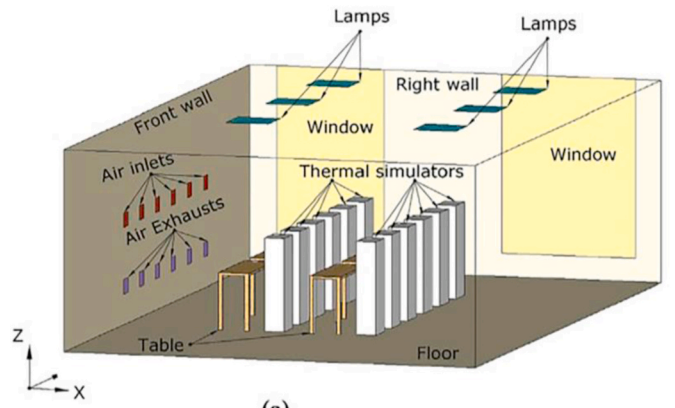


Fig. 17. Layout of the SV combined with pulsating air supply [70].

4.3.2.3. *Intermittent ventilation (IV)*. Shan et al. [135] investigated changing laws of indoor air temperature when the air conditioner was intermittently operated under dynamic boundary conditions. According to dynamic characteristics of temperature profiles, the reliable fitting model and optimized intermittent operation mode were proposed in Fig. 18. The optimal operation mode produced 18 min switching-on and 8 min switching-off of air conditioner system to maintain the air temperature in occupied zone ranging from 23.5 to 25 °C. Moreover, the energy performance of such optimal intermittent mode was superior with an extra saving of 11% cooling power consumption [135].

The air jet strategy (AJS) used air jet diffuser (AJD) as fresh air terminal device, as shown in Fig. 19 [72]. AJS attempted to simulate dynamic airflow characteristics of natural wind to improve ventilation efficiency and thermal comfort under low energy consumption. In AJS, the diffusers supply high intermittent airflow into the sitting zone. By turning on and off the forced draft fan using LabVIEW software, the wind speed changed between high pulse and low pulse, the air flow characteristics similar to natural wind was obtained and the airflow risk associated with high airflow movement was minimized [131,136–139].

For intermittent DV systems, Lichtner et al. [140] and Schultz et al. [141] conducted experiments in an office. Several internal heat sources were used and a quick removal of tracer-gas was obtained in unsteady displacement ventilation. For example, 50% of normalized tracer-gas concentration was reduced in less than 5 min in unsteady ventilation scenarios, whereas about 7 min was required in steady ventilation [142].

4.3.2.4. *Wearable device ventilation (WDEV)*. Ferraro et al. [74] conducted a “drying” test on the thermal dummy in the climate room, and studied the cooling effect of ventilation jacket. Standardized conditions with air temperature $t_a = 22.4$ °C, three different fan velocities ($v_f = 0, 2$ and 4 m/s) and three different ensembles (the single jacket, a work ensemble and a combination of both) were considered. Results showed significant increase in dry heat losses (through convection) for the trunk thermal zones, especially when fans were on. The air ventilation determined significant decrease of total thermal insulation values (up to 35%) compared to the fans-off condition, confirming the cooling effect of ventilation jacket.

For the hybrid vest proposed by Farah et al. [75], a one-dimensional transient mathematical model was combined with PA-bioheat model to predict the thermo-physiological response of human body. The effectiveness of the hybrid vest model was verified by experiments on a

heating plate. Compared with no vest, the sensory temperature of the hybrid vest decreased by 1 °C, which could improve the thermal comfort. In addition, when the activity level was 6, the heat loss of hybrid vest in cadres increased by 1.88–8.57 times.

5. Achievements, challenges and opportunities in ventilation modes

5.1. Achievements in ventilation modes

According to different statuses of environmental parameters, this study divided indoor ventilation modes into uniform and steady modes, non-uniform modes and unsteady modes. Mixing ventilation (MV) was a typical uniform ventilation mode. Non-uniform modes mainly included displacement ventilation (DV), personalized ventilation (PEV), under-floor air distribution (UFAD), impinging jet ventilation (IJV), stratum ventilation (SV), wall attached ventilation (WAV), protected occupied zone ventilation (POV), etc. Unsteady modes mainly included dynamic personalized ventilation (DPEV), pulsating ventilation (PUV), intermittent ventilation (IV) and wearable device ventilation (WDEV). The application scenarios of different ventilation modes and their effects on thermal comfort, air quality and virus spread control were summarized and compared in Tables 10 and 11.

Compared with MV, the floor-to-ceiling temperature difference in IJV was 60% less, the draft rate of POV was required to be 80% less, the PMV of UFAD was 45% better, and the PPD of DV was 33% less. Results indicated that non-uniform ventilation modes were superior than uniform modes in thermal comfort. Besides, the PPD values of IV and PUV were about 37.8% and 12%–32.3% lower than those of steady state ventilations respectively, showing that unsteady ventilation modes were also helpful in improving thermal comfort. On the hand, compared with MV, the infection risk of DV was greatly reduced, the MAA of IJV and UFAD were 37%–47% and 28.3% less respectively, the contaminants concentration of WAV was 15%–47% lower, the protection efficiency of POV was 14%–50% higher, the contaminant removal effectiveness of SV was 22.6% higher, and the air change efficiency of IV was 6.6%–10.4% higher. Results indicated great potential of non-uniform ventilation modes in air quality and virus spread control. Moreover, the peak pollutant concentration and exposure time to undesirable concentrations of PUV were reduced by 31% and 48% respectively, demonstrating that unsteady ventilation modes owned better function in air quality and virus spread control.

5.2. Challenges in ventilation modes

Various indoor ventilation modes met different challenges in coping with higher requirements of indoor environment in the epidemic era. For uniform modes, MV brought smaller vertical temperature difference and higher thermal comfort. While cleaning dead spots and pollutants diffusion could not be ignored, and hence higher energy consumption was caused as the whole space environment needed to be controlled.

As the non-uniform indoor environment was commonly created by supplying air directly into the working area, the main problem it faced was the thermal comfort caused by high wind speed. DV took advantage of air density difference between upper and lower zones, and the problem of large vertical temperature difference arose. It was unsuitable for rooms with more furniture or areas where pollutant temperature was lower than room temperature. In summer, the IJV system directly sent cold air to the vicinity of floor, which might increase the feeling of blowing on the feet. Meanwhile, excessive jet velocity might also cause excessive temperature stratification. SV had the same problem, because it directly sent cold air to personnel head, which might cause a strong sense of blowing wind on the head and a large temperature difference between head and feet. The main problems of PEV were high cost and inflexible location, which limited its use scenarios. In UFAD, energy consumption was higher because some of fresh air mixed with indoor air

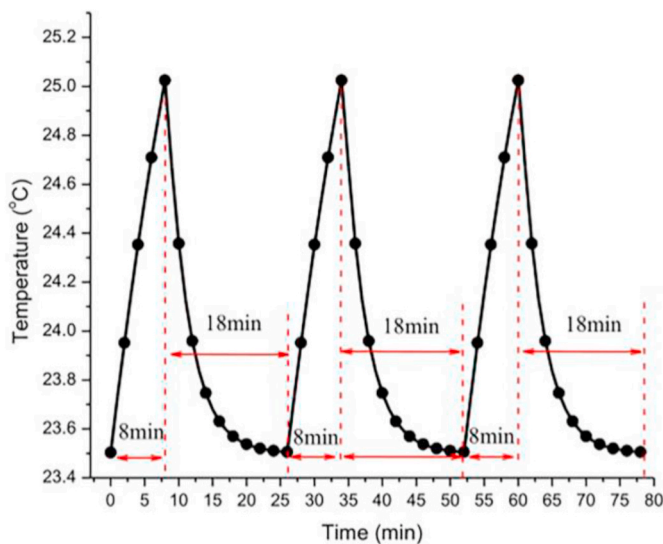


Fig. 18. Temperature change pattern under intermittent operation mode [135].

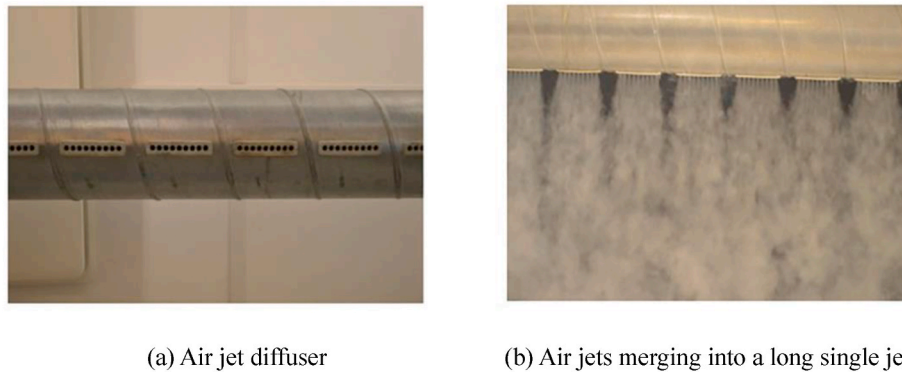


Fig. 19. Pictures of air jet diffusers and visualization operation [72].

Table 10
Comparison of thermal comfort for different ventilation modes.

Contrast type	Application scenarios	Thermal comfort					
		PD	PMV	PPD	Draft rate	Floor-to-ceiling temperature difference	Overall thermal sensation and comfort
MV vs. DV	Office	DV<10%, MV<20% [143]	-	DV<20%, MV<20% [143]	Summer: DV < MV Winter: DV > MV [19]	-	-
	Classroom	DV<10%, MV<20% [143]	-	DV<20%, MV> 20% [143]	-	-	-
	Retail shop	DV<10%, MV<20% [143]	-	DV<20%, MV> 20% [143]	-	-	-
	Industrial workshop	DV>25%, MV>25% [143]	-	DV<20%, MV> 20% [143]	-	-	-
	Aircraft cabin	MV<1%, DV: 3%–8% [144]	-	-	MV: 10%–40%, DV: 1%–5% [144]	-	-
MV vs. DV vs. SV	Office	-	-	-	MV and DV:< 20%, SV: <30% [28]	-	SV was 10% better than MV [40]
IJV vs. MV	Spaces with occupants moving frequently	-	-	-	-	IJV was 60% less than MV [38]	-
WAV vs. MV	Office	-	Similar [63]	-	-	-	-
POV vs. MV	Office	-	-	-	MV:100%, POV< 20% [46]	-	-
UFAD vs. MV	Open-plan office room	-	UFAD was 45% better than MV [145]	-	-	-	-
MV vs. DV vs. IV	Classroom	-	MV: 1.31, DV: 0.59, IV: 0.23 [72,146]	MV: 45%, DV: 12%, IV: 7.2% [72, 146]	-	-	-
SV vs. PUV + SV	Office	-	-	SV: 16%, PUV + SV: 4%	SV: 34%, PUV + SV: 8% [70]	-	-
SSV vs. PUV	Office	-	-	SSV: 36.5% [70], PUV: 4.2% [147]	-	-	-

near the floor.

For unsteady environment construction, since DPEV was mainly aimed at the working area, it was not applicable to the state of personnel movement. Pulsating and intermittent air supply were characterized by low wind speed and small air volume, so they might face problems of unsatisfactory air change rates and poor thermal comfort.

5.3. Opportunities in ventilation modes

To cope with the trend of reducing building carbon emissions, as well as requirements of better air quality and thermal comfort in the epidemic era, the main development directions of indoor ventilations were low energy consumption, high thermal comfort and high air quality.

There were currently three main prospects for energy consumption reduction. The first was to improve equipment performance, for

Table 11
Comparison of air quality and virus spread control for different ventilation modes.

Contrast type	Application scenarios	Air quality and virus spread control						
		Infection risk	Mean age of air	Concentration of contaminants	Protection efficiency	Contaminant removal effectiveness	HCHO/PM	Air change efficiency
MV vs. DV	Office	–	DV < MV [26]	–	–	–	–	–
	Aircraft cabin	MV: 0.2/0.07/0.02, DV: 0.05/0.02/0 (No mask/Mask worn by index person only/Masks worn by all passengers) [144]	Did not differ greatly [144]	–	–	–	–	–
MV vs. LJV	Large space (10 m high) or spaces with occupants moving frequently	–	LJV was 37%–47% less than MV [59]	–	–	–	–	–
MV vs. WAV	Office	–	–	WAV was 15%–47% less than MV [63]	–	–	–	–
MV vs. POV	Office	–	–	–	POV was 14%–50% higher than MV [10]	–	–	–
MV vs. SV	Office	–	–	–	–	SV was 22.6% higher than MV [62]	–	–
MV vs. UFAD	Open-plan office room	–	UFAD was 28.3% less than MV [145]	–	–	–	–	–
MV vs. IV	Office or classroom	–	–	–	–	–	–	MV: 43.7%–49.7%, IV: 54.1%–56.3% [141]
DV vs. IV	Office	–	–	–	–	–	–	DV: 56.1%, IV: 54.1% [141]
SSV vs. PUV	Residence	–	–	–	–	–	Peak pollutant concentration: PUV was 31% less. Exposure time to undesirable concentrations: PUV was 48% less [134].	–

example, selecting an efficient fan [148], improving the insulation performance of duct [149], selecting high filter efficiency with lower wind resistance [150], using heat recovery device [151], etc. The second was adopting suitable ventilation mode with specific requirements of air flow or air quality, to reduce the required air volume and heat. Non-uniform and unsteady ventilation modes were based on this idea. At present, it was a development trend to combine uniform ventilation with PEV. The maximum energy saving of DPEV + DV (40 L/s) compared with independent DV and stable PEV reached 54.61% and 31.58% respectively [152]. The third was to combine with renewable energy, such as solar energy [153] or geothermal energy [154], to reduce the utilization rate of conventional energy. Especially for uniform ventilations modes, this method would effectively reduce high energy consumption caused by controlling the environment of too large working area. In addition, it was also an important way to reduce energy consumption to improve the utilization rate of low-grade energy and realize the cascade utilization of energy oriented by the demand of indoor environment [155].

Different ventilation modes could be combined to make up for their shortcomings in maintaining thermal comfort conditions. The alternate cold and heat exposure in a moderate level could improve human comfort and was beneficial to human health. Non-uniform and unsteady air supply should be combined to achieve the effect of simulating natural wind [156]. In addition, the combination of dynamic environment

construction method and dynamic capture technology could be further developed, and indoor high-precision positioning system could be used to deal with the location change caused by personnel movement. Non-uniform and unsteady ventilation modes sent fresh air directly into the working area, which also led to the difficulty of controlling the body's blowing sensation. The current requirements of HVAC manuals for indoor environment did not consider air volume fluctuations over time. Therefore, future standards needed to consider air distribution inhomogeneity induced by non-uniform and unsteady ventilation modes, as well as thermal comfort evaluation mechanism for the working period.

As for indoor air quality, MV was more likely to lead to indoor diffusion of pollutants due to its air distribution characteristics. Therefore, the application of HEPA filter with higher efficiency or installation of additional independent air purifiers were potential options. In addition, the location relationship between tuyere, doors, windows and furniture should be fully considered to create a more reasonable air distribution and reduce the probability of air short-circuit [157]. To improve air quality and reduce the risk of infection, it was also important by combining various ventilation modes or physical measures. DV reduced the risk of infection by about 26%, while the integration of DV and zoning reduced the risk of infection by an average of 96% [89]. In addition, the combination of partial radiation systems with DV would help maintain indoor temperature gradients and reduce the risk of upper

layer pollutants entering the respiratory zone [158]. For non-uniform and unsteady ventilation modes, the thermal comfort and air quality evaluation indexes in standards were still limited, and could not reflect the relationship between different environmental parameters and occupants' feelings. It was urgent to clarify the evaluation index and algorithm of uneven and unsteady environment.

6. Conclusion

To efficiently improve the indoor overall thermal comfort, air quality and virus spread control, this study reviewed characteristics, application occasions and effects of various ventilation modes, and analyzed their main achievements, limitations and solutions in the epidemic era. According to different statuses of indoor environmental parameters, this study divided ventilation modes into three categories, i.e. uniform and steady modes, non-uniform modes and unsteady modes. The non-uniform and unsteady ventilation modes performed obviously better in improving the thermal comfort, air quality and virus spread control effect. Compared to the typical uniform ventilation mode (MV), the floor-to-ceiling temperature difference in impinging jet ventilation (IJV) was 60% less, the draft rate of protected occupied zone ventilation (POV) was required to be 80% less, the PMV of underfloor air distribution (UFAD) was 45% better, and the PPD of displacement ventilation (DV) was 33% less. While compared to the steady state ventilation (SSV), the PPD of intermittent ventilation (IV) and pulsating ventilation (PUV) were about 37.8% and 12%–32.3% lower, respectively. On the hand, compared with MV, the infection risk of DV was greatly reduced, the mean age of air (MAA) of IJV and UFAD were 37%–47% and 28.3% less respectively, the contaminants concentration of wall attached ventilation (WAV) was 15%–47% lower, the protection efficiency of POV was 14%–50% higher, the contaminant removal effectiveness of stratum ventilation (SV) was 22.6% higher, and the air change efficiency of IV was 6.6%–10.4% higher. Despite of these great achievements, there was still great resistance to the promotion of non-uniform and unsteady ventilation modes due to the immature technology, high cost and imperfect standard requirements. Hence great efforts should be made on pursuing the goal of low energy consumption, high thermal comfort and high air quality for building ventilation in the near future.

CRedit authorship contribution statement

Man Fan: Writing – review & editing, Writing – original draft. **Zheng Fu:** Investigation, Conceptualization. **Jia Wang:** Visualization, Investigation. **Zhaoying Wang:** Visualization, Investigation. **Hanxiao Suo:** Resources, Methodology. **Xiangfei Kong:** Project administration, Funding acquisition. **Han Li:** Supervision, Funding acquisition.

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.

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