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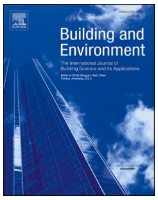

Ventilation regimes of school classrooms against airborne transmission of infectious respiratory droplets: A review

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ABSTRACT

Airborne transmission of small respiratory droplets (i.e., aerosols) is one of the dominant transmission routes of pathogens of several contagious respiratory diseases, which mainly takes place between occupants when sharing indoor spaces. The important role of ventilation in airborne infection control has been extensively discussed in previous studies, yet little attention was paid to the situation in school classrooms, where children spend long hours every day. A literature study was conducted to identify the existing ventilation strategies of school classrooms, to assess their adequacy of minimizing infectious aerosols, and to seek further improvement. It is concluded that school classrooms are usually equipped with natural ventilation or mixing mechanical ventilation, which are not fully capable to deal with both long-range and short-range airborne transmissions. In general, the required ventilation designs, including both ventilation rates and air distribution patterns, are still unclear. Current standards and guidelines of ventilation in school classrooms mainly focus on perceived air quality, while the available ventilation in many schools already fail to meet those criteria, leading to poor indoor air quality (IAQ). New ways of ventilation are needed in school classrooms, where the design should be shifted from comfort-based to health-based. Personalized ventilation systems have shown the potential in protecting occupants from aerosols generated within short-range contact and improving local IAQ, which can be used to compensate the existing ventilation regimes. However, more studies are still needed before such new ventilation methods can be applied to children in school classrooms.

1. Introduction

Since the early stage of the global pandemic of Coronavirus Disease 2019 (COVID-19), researchers have investigated the epidemiological features of paediatric patients, and it is suggested that children in general have milder symptoms than adults [1–3]. However, existing evidence is not sufficient to confirm whether children are less frequently infected or infectious of the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), which is the pathogen of COVID-19. Instead, the large proportion of asymptomatic cases among them may become a hidden threat to susceptible individuals [4,5]. The latest data show that children aged from 0 to 18 years constitute approximately 11–13% of the total number of people tested to be infected [6–8]. According to the report of COVID-19 and children by European Centre for Disease Prevention and Control [6], the proportion of infected children aged 12–18 to the total confirmed cases has slightly exceeded the population distribution of this age group among 11 EU/EEA countries. Besides, a recent systematic review of over seven thousand cases in China has revealed that all the 318 outbreaks identified with three or more cases took place between people when sharing indoor spaces [9]. Considering the long hours children spend in densely occupied classrooms every day, it is therefore important that schools can provide a safe indoor environment to protect students from cross-infections.

Among all the indoor environment quality (IEQ) control methods, ventilation has long been recognized as one of the primary measures for indoor air quality (IAQ) control [10]. Airborne transmission of infectious respiratory droplets between indoor occupants has been widely addressed as one of the major transmission routes of SARS-CoV-2 [11–13], as well as the infectious agents of several other pandemic-prone acute respiratory diseases, including SARS [14], Influenza A [15], and MERS [16]. Besides, previous research has presented a large number of pathogens that have the potential to be airborne transmissible [17]. Therefore, for cross-infection control, these pathogen-laden droplets can be treated as indoor air contaminants in occupied zones, which then can be diluted and/or removed through ventilation [18–20]. While researchers have extensively discussed the

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important role of ventilation in airborne infection control, recent studies have demonstrated that the contact distance between occupants can have significant impacts on the dispersion of respiratory droplets, and thus influence the efficiency of existing ventilation strategies [21–23]. Nevertheless, in practice, little attention was paid to such contaminants in public spaces other than hospital buildings in terms of ventilation, especially during the previous non-pandemic periods. Consequently, this may lead to an insufficiency of the conventional ventilation strategies to achieve healthy IAQ conditions in non-nosocomial indoor environments such as school classrooms.

Current standards and guidelines of ventilation in school classrooms vary among countries and regions. In most cases, a minimum ventilation rate per person and/or per unit floor area is required based on a balance between indoor air quality control and energy saving [24]. So far, such design criteria have not taken into consideration the airborne transmission of respiratory contaminants, and thus whether they are sufficient for cross-infection control remains unknown. Meanwhile, considering the diversity of schools and the uncertainty of practical operation in real life, whether such requirements can be fulfilled is hard to determine. However, what is clearly demonstrated in previous studies is that IAQ-related health, comfort, and productivity problems have been extensively reported among students across the world [25,26]. Thus, for the post-pandemic periods, new ways of proper ventilation are needed to solve the IAQ-related problems for children in school classrooms.

In recent years, several advanced air distribution methods, such as personalized ventilation system (PV), have been developed in order to improve local IAQ. Such systems are suggested to achieve better protection for occupants who are exposed to various contaminant sources [27]. Nevertheless, previous studies mainly focused on specific public spaces such as hospital wards [28], office rooms [29], and aircraft cabins [30]. Considering the differences in indoor settings and activities, as well as the specific psychological and physiological demands of children [31], whether such systems and devices can be applied into school classrooms requires further discussion.

Therefore, a literature review is conducted to address (1) the existing ventilation regimes and IAQ-conditions in school classrooms, (2) the ability of conventional ventilation methods to minimize the airborne transmission of respiratory droplets, and (3) the potential of personalized ventilation as an additional solution.

2. Methods

Databases including Google Scholar, ScienceDirect, Scopus, Wiley, SpringerLink and PubMed are used to acquire research papers from peer-reviewed journals. Initially, a combination of keywords, including airborne transmission, respiratory droplets, cross-infection, school, classroom, children, student, ventilation, and indoor air quality, was used for literature search. However, few studies can be found covering all these concepts, especially during the period prior to the pandemic of COVID-19. Therefore, based on the main focuses of this literature review, it was further divided into three topics: (1) current situation of ventilation strategies and IAQ-conditions in school classrooms; (2) features and ventilation control of airborne transmission of respiratory droplets; (3) performance and feasibility of personalized ventilation systems. Instead of presenting an exhaustive discussion on each topic respectively, this literature review is intended to extract and connect the key information among the three topics to answer the following questions: *How well do the current ventilation regimes of school classrooms work against airborne transmission of infectious respiratory droplets?* and *What are possible solutions to improve the IAQ in school classrooms for children?*

Since the three topics have relatively specific focuses, an independent literature search was performed for each topic. The keywords used for each literature search are listed in Table 1. For topic 1, the existing design criteria and requirements of ventilation and IAQ in school classrooms were discussed first, where several examples of the latest standards and guidelines were involved. These documents were obtained from the official websites of international and national agencies including International Organization for Standardization (ISO), European Committee for Standardization (CEN), American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), Federation of European of Heating, Ventilation, and Air-Conditioning Associations (REHVA) and RVO (Netherlands Enterprise Agency). In order to identify the current situation of ventilation and IAQ in real school buildings, relevant field studies conducted in primary and secondary school classrooms within the last decade were screened, and some examples from different counties were included. For topic 2, studies addressing the dispersion of human respiratory droplets were involved, with a specific focus on its relationship with droplet size and contact distance between people. Based on the discussion of topic 1, studies performed to investigate the efficiency of airborne infection control of those commonly used ventilation regimes in school classrooms were reviewed. Since fewer studies were conducted under the scenario of school classrooms, studies performed in other indoor environments (e.g., hospital wards) were also included as references. For topic 3, studies conducted to investigate different types of personalized ventilation systems among different indoor spaces with a particular target at reducing airborne transmissible contaminants were discussed.

3. Ventilation and IAQ-conditions in school classrooms

3.1. Requirements of ventilation and IAQ for school classrooms

Ventilation refers to the process of supplying fresh air to an indoor environment and exhausting polluted air [32]. The ventilation strategy inside an individual room consists of two basic elements: air distribution and ventilation rate [17,33], which can be realized either via a natural or a mechanical way or both (hybrid). Typically, ventilation rate is expressed in L/s (m^3/h) per person or L/s (m^3/h) per m^2 floor area.

To date, the most widely implemented standards and guidelines of ventilation in school classrooms issued by several authoritative international organizations and agencies include ISO 17772-1 [34], EN 16798-1 [35] and ANSI/ASHRAE Standard 62.1 [36]. Such standards, in general, put forward a minimum ventilation rate (Table 2). The type of ventilation system or regime to realize this ventilation is, however, not specified.

The minimum ventilation rate is determined by the purpose to dilute and remove the indoor air pollutants generated by the occupants (bioeffluents), their activities and the building materials and components [37]. In both ISO 17772-1 [34] and EN 16798-1 [35], the minimum ventilation rate is approximately 5 L/s per person or 2 L/s per m^2 for a classroom of 50 m^2 with 20 students. It is also stated that CO_2

Table 1
Keywords for literature search.

	Topic 1		Topic 2		Topic 3	
	AND		AND		AND	
OR	school	ventilation	airborne transmission	ventilation	advanced	ventilation
	classroom	indoor air quality	aerosol	ventilated	localized	exhaust
	educational building	indoor environmental quality	airborne infection	air quality control	personalized	air terminal device
	student		droplet			air diffuser

Table 2
Minimum ventilation rates for school classrooms.

Standard/ guideline	Minimum ventilation rate for human emissions	Minimum ventilation rate for building emissions
	L/(s per person)	L/(s m^2)
ISO 17772-1	4	0.4
EN 16798-1	4	0.4
ANSI/ASHRAE 62.1	5	0.6

concentration can be used to present the human emission, while particles (i.e., $PM_{2.5}$ and PM_{10}) are only considered as coming from outdoor emissions.

As for ANSI/ASHRAE Standard 62.1 [36], the minimum required ventilation rate (default occupant density of 25 and 35 persons/100 m^2, for children aged 5–8 years and over 9 years, respectively) in the breathing zone is approximately 7 L/s per person or 2 L/s per m^2. It should be noted that the airborne transmission of infectious agents is not addressed. In addition, ISO 17772-1 [34] and EN 16798-1 [35] are not providing relevant information on the design of natural ventilation for non-residential buildings, while it is in fact most commonly used in schools (as demonstrated in section 3.2). ANSI/ASHRAE Standard 62.1 [36], on the other hand, involves the general design procedure of natural ventilation, where the specifications of natural ventilation (e.g., ceiling height, location, and size of openings) are included.

Besides the minimum ventilation rates, many standards and guidelines have also proposed CO_2 concentration as the indicator of IAQ-condition in school classrooms, for instance EN 16798-1 [35]. Usually, different categories of CO_2 concentration are included, as listed in Table 3. According to EN 16798-1 [35], if CO_2 is used to represent human occupancy, 550, 800, and 1350 ppm above the outdoor concentration level can be taken as the default design CO_2 concentrations, which are corresponding to the ventilation rates of 10, 7, and 4 L/s per person, respectively. Such CO_2 values, as stated in the standard, can also be used for the demand-controlled ventilation systems. In response to the ongoing pandemic of COVID-19, REHVA has put forward the COVID-19 Guidance for public buildings [38], where the warning and alarm levels for CO_2 concentration monitoring in school classrooms were suggested to be set as 800 and 1000 ppm, respectively. In terms of national standards and guidelines, the Program of Requirements – Fresh Schools [39] is a specific guideline of IEQ control and energy saving for school buildings, issued by the Netherlands Enterprise Agency. In this guideline, three classes of ventilation (i.e., class A, B, C) are defined as excellent, good, and sufficient, with corresponding CO_2 concentrations of 800, 950, and 1200 ppm, respectively.

3.2. Real situation of ventilation and IAQ in school classrooms

In recent years, researchers have conducted a large number of field studies to observe ventilation and IAQ-related problems in schools of different countries and regions. Several examples published within the past decade are listed in Table 4. Among these studies, CO_2 concentration has been widely used to assess the ventilation sufficiency and IAQ-condition.

Table 3
Limit values of CO_2 concentration in school classrooms.

Standard/guideline	CO_2 concentration (ppm)		
	I/A	II/B	III/C
EN 16798-1[a]	550	800	1350
REHVA COVID-19 Guidance	–	800	1000
The Netherlands Program of Requirements – Fresh Schools	800	950	1200

[a] CO_2 concentration above outdoor level.

Table 4
Ventilation strategies in school classrooms.

Reference	Country	Schools (Classrooms)	Ventilation system[a]
[40]	United States	100 (100)	MV: 100%
[41]	United Kingdom	8 (16)	NV: 88% MV: 12%
[42]	Italy	7 (28)	NV: 100%
[43]	China	10 (32)	NV: 100%
[44]	Denmark	389 (820)	NV: 52% HV: 17% MV: 31%
[45]	France	17 (51)	NV: 73% MV: 27%
[46]	The Netherlands	21 (54)	NV: 48% HV: 19% MV: 33%
[47,48]	Finland	2 (4)	HV: 50% MV: 50%

[a] NV: natural ventilation; HV: hybrid ventilation; MV: mixing mechanical ventilation.

Haverinen-Shaughnessy et al. [40] investigated 100 fifth-grade classrooms in 100 American elementary schools (one classroom per school), which were all equipped with a balanced mechanical ventilation system. The maximum CO_2 concentrations measured in different classrooms ranged from 661 to 6000 ppm, with an average value of 1779 ppm, far exceeding the threshold values. In addition, the ventilation rates were estimated based on the CO_2 concentrations. With the fans continuously in operation, the average ventilation rate among all the classrooms was 4.2 L/s per person, where 87% of them had a ventilation rate below the ASHRAE standard 62.1. Bakó-Biró et al. [41] surveyed 16 classrooms of eight primary schools in the United Kingdom during different seasons, among which only one school had a mechanical ventilation system. The mean CO_2 concentration of each individual classroom varied from 644 to 2833 ppm, while the maximum level in several classrooms reached up to 5000 ppm. Accordingly, the ventilation rates were estimated to be around 1 L/s per person, again failing to meet the standards. De Giuli et al. [42] studied 28 naturally ventilated classrooms among seven primary schools in Italy, where children's perception of IEQ-conditions was collected together with IAQ-measurements. The results showed that the CO_2 concentrations in 22 (81%) classrooms were more than 600 ppm above the outdoor level, while 9 (33%) of them were more than 1100 ppm above. Meanwhile, children in four schools (57%) complained about poor IAQ (perceived bad smell). Zhang et al. [43] conducted a longitudinal study among 32 classrooms of 10 junior high schools in China, where the average CO_2 concentration of the two-year measurement was 1290 ppm. This study also indicated that children in these schools commonly suffered from the hazardous impacts of other air pollutants such as PM_{10}, SO_2 and NO_2, which increased the prevalence and incidence of the sick building syndrome (SBS). Toftum et al. [44] investigated 820 classrooms (natural ventilation: 52%, hybrid ventilation: 17%, balanced mechanical ventilation: 31%) in 399 Danish schools during two cross-sectional studies (732 (311) and 88 (88) classrooms (schools), respectively). In these two studies, 56% and 66% of the classrooms presented a median CO_2 concentration greater than 1000 ppm, revealing insufficient ventilation, which was found to have negative effects on children's learning outcomes. Canha et al. [45] assessed the ventilation and indoor air pollutants in 51 classrooms of 17 schools in France with natural ventilation (73%) and mechanical ventilation (27%) systems. In general, the classrooms equipped with mechanical ventilation had a better IAQ, and the air change rates and ventilation rates were significantly higher than those having natural ventilation. The concentrations of CO_2 and VOCs were also observed to be lower in the mechanically ventilated classrooms. However, it is also noticed that the average CO_2 concentration of all classrooms exceeded 1300 ppm, while the average ventilation rate was only 2.9 L/s per person, much lower than the design criteria.

Bluyssen et al. [46] conducted an IEQ-survey in 54 classrooms of 21 Dutch primary schools, of which 48% were naturally ventilated only, 19% were mechanical assisted (hybrid ventilation), and the rest (33%) were mechanically ventilated. The average CO_2 concentration in 22 of 37 classrooms measured exceeded 1000 ppm, while 63% of the children self-reported to be bothered by smell, and some also suffered from respiratory symptoms. Besides, the sunshades were found often hampering the use of windows among 29 classrooms. Vornanen-Winqvist et al. [47,48] investigated two comprehensive schools in Finland involving two classrooms equipped with fan-assisted natural ventilation (hybrid ventilation) and two with mechanical ventilation, respectively. Although the CO_2 concentrations were at a moderate level among the classrooms (average 488 ppm, maximum 1431 ppm, minimum 394 ppm), it was found that both the hybrid and mechanical ventilation regimes were initially not properly operated. After adjustments were applied, both of them showed significant improvement in reducing the concentrations of CO_2, TVOC, and $PM_{2.5}$.

4. Airborne transmission of infectious respiratory droplets: features and control

4.1. Dispersion of respiratory droplets

Normally, the cross-infection of contagious respiratory diseases (e.g., Tuberculosis, SARS, Influenza A, COVID-19) between occupants indoors consists of three stages: first, an infected person generates pathogen-containing droplets by respiratory activities such as breathing, talking, sneezing, and coughing; then the infectious droplets spread with the exhaled jet into the indoor air; and once a susceptible person is exposed to a certain dose of pathogens, infection may take place [17,49]. The movement of a droplet in the air depends largely on its size, yet is also highly subject to other factors such as the initial momentum, airflow patterns (speed and direction), and indoor environmental conditions (temperature and relative humidity) [50,51]. When a droplet is more influenced by gravity, it follows a ballistic trajectory and falls onto the ground or other surfaces (including other occupants' body) [51,52]. Meanwhile, if a droplet is more easily to be airborne and remains suspended in the air, it becomes an aerosol [17,51]. Since the sizes of expelled droplets span a continuum from 0.1 μm to over 1000 μm, the dispersion pathways of droplets also change continuously with their sizes, and thus cannot be simply classified into one of the two categories [52–54], although a size threshold of droplets and aerosols of 100 μm has been suggested [55,56]. Typically, large droplets with a diameter >100 μm can settle in proximity (1–2 m) to the source within a few seconds, while small droplets, especially for those < 5–10 μm, have a higher probability to be carried by the airflow for a long time and travelling over long distances [52,56,57]. Besides, due to the difference in temperature and relative humidity between the exhaled jet and the room air, droplets can shrink rapidly through evaporation (while keeping the same amount of infectious material), and thus increase the chance of becoming aerosols [50,53]. Compared to large droplets, aerosols are considered to be more dangerous as they can be inhaled by exposed individuals, penetrate to the deeper area of the respiratory tract, and thus cause severer symptoms [58].

Aerosols have been found to dominate the size spectrum of exhaled respiratory droplets. Yang et al. [59] investigated the size distribution of coughed droplets from human subjects, where the dominant modes were found to be 8.35 μm and 0.74–2.12 μm for the initial and dried droplets, respectively. Morawska et al. [60] examined human breathing, talking, sneezing, and coughing, and concluded that the droplet sizes of 0.8 μm and 1.8 μm presented the highest concentrations for all expiratory activities. Similarly, Somsen et al. [61,62] measured the exhaled droplets of human cough and speech, and the results showed that fine droplets of 1–10 μm were the most prevalent modes. Large droplets, though, were indicated to be mainly generated by sneezing and coughing, at a relatively low density [11,61]. Considering the real situation of a contagious disease such as COVID-19, where most infected children are found to be asymptomatic, it is very likely that the co-occupants are exposed to the infectious aerosols rather than the droplet spray [1,4]. Hence, minimizing the exposure to pathogen-laden aerosols is one of the key principles to prevent cross-infection.

Based on the dispersion features after generation, the transmission routes of respiratory droplets between indoor occupants are categorized into three types (Fig. 1): (1) direct spray of large droplets onto mucous membranes (droplet-borne transmission); (2) indirect contact via surface touching (fomite transmission); and (3) inhalation of aerosols (airborne transmission). As illustrated in Fig. 1, the airborne transmission of respiratory droplets can be further divided into two sub-routes based on the distance between the infected and exposed person, namely the short-range (at close proximity) and long-range (at room scale) airborne transmission [17,63]. Consequently, when two occupants are having close contact (<1–2 m), the recipient is exposed to both large droplets and aerosols [22,63]. A recent study by Chen et al. has revealed that during close contact (<2 m), the short-range airborne transmission of respiratory droplets is the dominant transmission route for both talking and coughing [64]. Similar results were found by Cortellessa et al., where the contribution of large droplet deposition to the infection risk is no more noticeable at a contact distance larger than 0.6 m, comparing to aerosol inhalation [23]. Meanwhile, via the long-range airborne transmission of respiratory droplets, the infectious agents can be spread throughout the indoor space, and may cause threats to a large number of susceptible people [65]. Therefore, both the short-range and long-range airborne transmission need to be taken into consideration when treating aerosol contaminants.

4.2. Ventilation control of airborne transmission

A large number of studies have shown strong evidence of the association between ventilation and the transmission of infectious diseases in the built environment [18]. According to the observed situation in school classrooms (as discussed in section 3.2), most of them are equipped with conventional natural ventilation (opening windows and doors) or mixing mechanical ventilation. Such ventilation regimes are designed to treat the indoor air in a room-based total-volume manner, and previous measurements and discussions are mainly based on the steady-state conditions [19,66].

The exhaled air from an infected person can be divided into two parts. One part flows directly to the exposed person within close contact, and thus can lead to short-range airborne transmission [67,68]. The other part flows into the occupied space and is diluted by the existing ventilation regime, which can then contribute to the long-range airborne transmission. To date, previous studies of aerosol infection mainly focused on the long-range airborne transmission of respiratory droplets, where researchers have extensively discussed whether such contaminant can be effectively tackled with conventional room-based total-volume ventilation methods. Furthermore, most of the investigations were performed under a hospital setting.

For natural ventilation, Escombe et al. [69] tested 70 clinical rooms in Lima, Peru. The results showed that when the outdoor wind speed was higher than 2 km/h (0.6 m/s), the average ventilation rate reached 697 L/s with windows and doors fully open, 458 L/s with windows and doors partly opened, and 37 L/s with windows and doors closed. Those results for outdoor wind speed lower than 2 km/h were 454, 128, and 24 L/s, respectively. The predicted infection risk of Tuberculosis was reduced by 66%–89% when windows and doors were fully open, compared to the condition when everything was closed. Gilkeson et al. [70] carried out an in-situ measurement in two large wards of a hospital in Bradford, United Kingdom, and observed an average ventilation rate in the range of 204 L/s to 390 L/s with outdoor wind speeds of 1–4 m/s. When the windows were closed, the exposure risk was calculated to be four times higher than the fully opened condition. All of these field studies used CO_2 as the tracer gas, so the results are more relevant for fine droplets

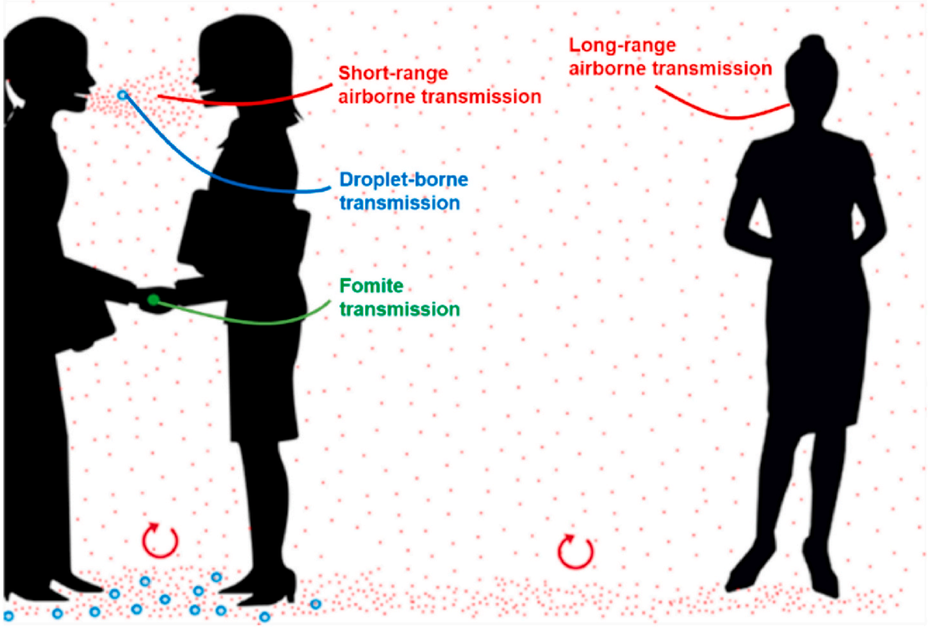

Fig. 1. Transmission routes of respiratory droplets between indoor occupants (reproduced from Ref. [51]).

<5 μm compared to the larger ones [71]. Zhou et al. [72] conducted a CFD simulation of hospital wards with a central-corridor in Nanjing, China, and the ventilation rates were obtained to be 100–700 L/s with outdoor wind speeds between 0.5 and 4.0 m/s. Such a cross-ventilation setting was proven to provide large ventilation rates, yet it can also increase the cross-infection risk between different rooms.

For mixing mechanical ventilation, Lai & Cheng [73] simulated the dispersion of two droplet sizes, 0.01 μm and 10 μm, in a chamber occupied with two standing persons. The results showed that under mixing ventilation, droplets from both two size groups were distributed homogeneously into the air within 50 s, due to a high inlet air velocity of 2 m/s (ventilation rate of 320 L/s). The large velocity of supply airflow is one of the primary features for mixing ventilation to achieve highly mixed air distribution and quick dilution of exhaled aerosols (from an infected person), as also recognized by Gao et al. [74], Li et al. [75], and Bolashikov et al. [76]. However, such ability of mixing and diluting does not necessarily lead to a lower exposure risk for the co-occupants. Instead, the exhaled aerosols can be rapidly dispersed to the breathing zone of the exposed persons under mixing ventilation (57 L/s), where the inhaled dose in the first stage (~10 s) were found to be account for almost 50% of the total inhaled dose [75]. Besides, the ventilation rate is often limited due to comfort issues [19]. For instance, under a ventilation rate of 188 L/s, the background air velocity in the occupied zone was found to exceed 0.5 m/s, which may cause draft discomfort to the occupants [76].

The short-range airborne transmission of respiratory droplets, however, cannot be treated with the classical steady-state model, as it is a highly dynamic process [66]. The simulation study conducted by Villafruela et al. [21] indicated that the human microenvironment and the interaction of breathing flows were the key determinants of airborne transmission between occupants within a short distance (<0.5 m), while the indoor ventilation flow was more important for a longer distance (>0.5 m). Similar results were observed in the experimental study of Liu et al. [22], and they suggested the threshold distance for short-range and long-range contact to be 1.5 m. Ai et al. [77] adopted a time-related method to evaluate the exposure risk via a full-scale experiment with breathing thermal manikins, and a significant difference was found between the short-term event and the steady-state condition. Based on the extensive evidence, it is concluded by a number of studies that existing ventilation methods are not appropriate for preventing short-range airborne transmission of respiratory droplets between indoor occupants, and new intervention methods, for example personalized ventilation, are recommended [22,63,77].

5. Personalized ventilation systems

Conventionally, personalized ventilation (PV) refers in particular to the systems that directly supply clean air to the breathing zone of each occupant. In this paper, PV refers to the general concept of localized (or individually controlled) air distribution system, which includes both the personalized air supply system (PS) and the personalized air exhaust system (PE). Personalized ventilation has been recognized as an efficient tool for compensating the room-based total-volume ventilation systems to improve local IAQ for each occupant, especially when sharing indoor space with others [27,66].

5.1. Personalized air supply system (PS)

Personalized air supply (PS) refers to the process of locally supply clean air to the breathing zone of each occupant. Researchers have conducted extensive studies to examine the performance of PS systems in a room with office settings. According to the location of the supply air terminal device (ATD), PS systems can be roughly classified into two types: desk-based and chair-based systems, as illustrated in Fig. 2 and Fig. 3.

It is well demonstrated that PS devices can help to efficiently reduce the exposure risk of susceptible co-occupants to airborne contaminants exhaled by a source individual [79,80]. The comparisons of contaminant removal efficiency between the conditions with and without PS in previous studies are presented in Table 5. Here, only the conditions where all occupants were provided with the same amount of supply airflow rate are included. This is considered to be more relevant to the real situation in school classrooms, where the infected children are sometimes hard to be spotted.

Cermark et al. [81] examined two types of desk-based PS devices in an experimental chamber using manikins, under a background mixing ventilation of a total ventilation rate of 80 L/s. When the personalized supply airflow rate reached 15 L/s per person, the round movable panel and vertical desk grill reduced the inhaled concentration of exhaled air (tracer gas) by 90% and 65%, respectively. He et al. [82] investigated

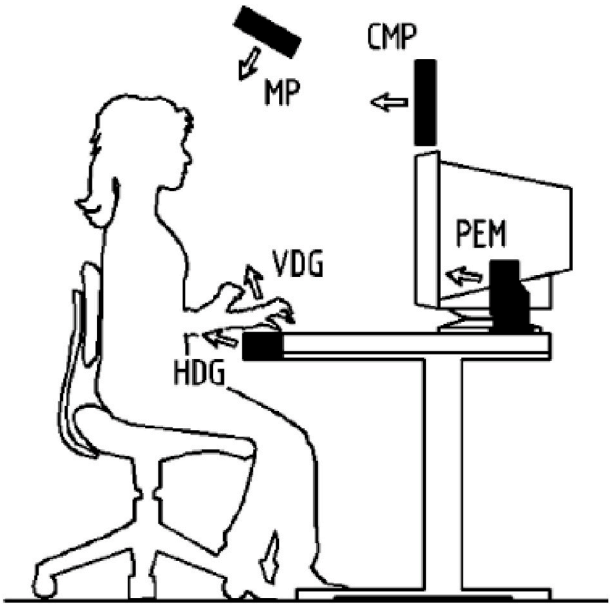

Fig. 2. Desk-based ATDs: (Round) movable panel, (R)MP; computer monitor panel, CMP; personal environment module, PEM; vertical desk grill, VDG; horizontal desk grill, HDG [78].

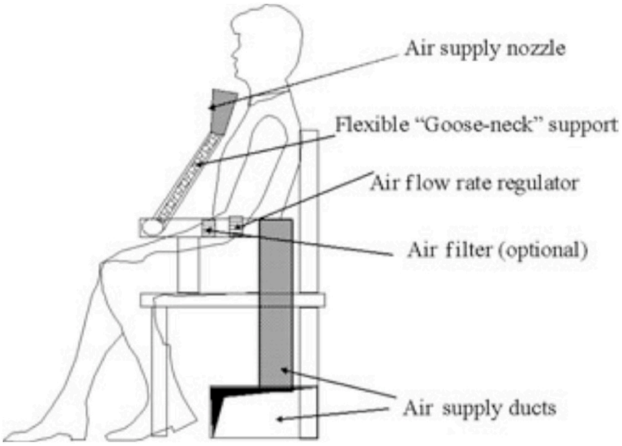

Fig. 3. Chair-based personalized air supply system [29].

the effects of a round movable panel on the dispersion and concentration of droplets (0.8 μm, 5 μm, and 16 μm) and tracer gas in an office room using CFD simulation. Under a total ventilation rate of 80 L/s, the intake fractions (IF) of the tracer gas, 0.8 μm droplets, and 5 μm droplets were reduced by 15% with a personalized supply airflow rate of 7 L/s per person, and 87% with 15 L/s per person. For the droplets of 16 μm, the IF was reduced by 46% and 90%, respectively. Similarly, Li et al. [29] simulated a chair-based PS and a horizontal desk grill in an office room with a total ventilation rate of 57 L/s. Under mixing ventilation, the chair-based PS reduced the IF of droplets (1 μm, 5 μm, and 10 μm) and tracer gas by 70% with a supply airflow rate of 0.8 L/s per person, and 90% with 1.6 L/s per person. Meanwhile, the horizontal desk grill reduced the IF by 40% and 60%, with a supply airflow rate of 3.5 L/s per person and 6.5 L/s per person, respectively. Lipczynska et al. [83] also tested the round movable panel in a manikin experiment with a background mixing ventilation. Under a total ventilation rate of 26 L/s, the personalized supply airflow rate was set as 7 L/s per person, where the IF of tracer gas was reduced by 64%. Under a total ventilation rate of 42 L/s, the personalized supply airflow rate was set at 15 L/s per person, which reduced the IF of tracer gas by 82%. It was also observed that with a moderate increase in airflow rates, PS can be performed as the only ventilation system for the mock office room.

5.2. *Personalized air exhaust system (PE)*

To date, fewer studies have been conducted on PE compared to PS, and most of them focused on aircraft cabin and hospital settings. For aircraft cabins, Dygert & Dang [84,85] designed a localized exhaust system with either built-in seat-back or overhead suction orifices (background mixing ventilation of 45 L/s). The results of CFD-simulation and experimental validation showed an average decrease in co-passengers' exposure to body-emitted contaminants up to 60% with an exhaust airflow rate of 5 L/s per person. For hospital consultation rooms, Yang et al. [86] applied both a top-PE and a shoulder-PE device to the source manikin, respectively. Under a background mixing ventilation of 110 L/s, the IF of exhaled contaminant (tracer gas) was reduced by 87% using both of the PEs with an exhaust airflow of 10 L/s per person, and further reduced by 93% with 20 L/s per person. Moreover, it is also observed that with a higher airflow rate of 20 L/s per person, the IF after a 30 min exposure was lower than that after a 10 min exposure without PE. For hospital wards, Bolashikov et al. [87] developed a wearable PE unit embedded in a headset-microphone to protect the patient from a sick doctor. Different exhaust nozzles (circular, flanged, or flared nozzles), airflow rates (0.24 or 0.5 L/s per person), and distances from mouth (0.02, 0.04, or 0.06 m) were tested with two manikins. The results showed that under a background mixing ventilation of 48 L/s, when the nozzle was placed close enough to the mouth of the source person (0.02 m), the wearable PE system reduced the exposure concentration (tracer gas) of the patients by 67% with an exhaust airflow of 0.24 L/s. Such performance was better than a pure background mixing ventilation of 192 L/s.

Table 5
Efficiency of reducing inhaled contaminants with different PS devices.

Reference	AID type	Personalized airflow rate (L/s, per person)	Total ventilation rate (L/s)	Contaminant	Efficiency (%)[a]
[81]	Round movable panel	15	80	Tracer gas	90
	Vertical desk grill	15			65
[82]	Round movable panel	7	80	Tracer gas, 0.8 μm, 5 μm/16 μm	15/46
		15			87/90
[29]	Chair-based PS	0.8		Tracer gas, 1 μm, 5 μm, 10 μm	70
		1.6	57		90
	Horizontal desk grill	3.5			40
		6.5			60
[83]	Round movable panel	7	26	Tracer gas	64
		15	42		82

[a] Percentage reduced in intake fraction (IF) of exhaled contaminants.

6. Discussion

6.1. Challenges for schools: airborne infection control with current ventilation regimes

Currently, the understanding of airborne transmission of respiratory droplets is being rapidly updated driven by the ongoing pandemic of COVID-19. Human respiratory droplets mainly comprise droplets smaller than 100 μm, which usually follow an airborne transmission route after exhalation. Airborne transmission of respiratory droplets can be divided into a long-range route (at room scale) and a short-range route (at a close proximity $< 1–2$ m), and can be controlled by IAQ control measures, such as ventilation [17,20,63]. In general, the main ventilation regimes used in primary and secondary school classrooms are natural ventilation and mixing mechanical ventilation (Table 4). Such conventional ventilation strategies, as indicated by previous studies, can effectively reduce the long-range airborne transmission. However, those analyses are mainly based on steady-state conditions, and the models used for exposure risk evaluation are sometimes restricted by the well-mixing assumption (e.g., the Wells-Riley model [88]), which are usually not the case in real indoor spaces. Meanwhile, other researchers have demonstrated that total-volume ventilation regimes are not sufficient for dealing with short-range airborne transmission, due to the dynamic features of respiratory activities and the significant impacts of microenvironment within the close contact between occupants. In addition, for natural ventilation, although it can achieve in certain situations appropriate ventilation rates and aerosol removal, the performance largely depends on several uncontrollable factors, such as local climate and occupant behavior [70,89]. According to a recent study conducted in schools in New York City, it was found that the exposure risk of airborne transmission of respiratory droplets was always higher during the heating season than during the cooling season, indicating the negative impacts of lower outdoor airflow rates when the windows and doors were closed by the occupants due to cold weather [90]. The performance of natural ventilation can also be strongly influenced by the layout of the building, such as the type of corridor [90,91]. Hybrid ventilation with exhaust fans, as observed in a number of schools as well (Table 4), is suggested to be helpful when natural forces are not strong enough (e.g., low outdoor wind speed) or opening windows and doors are not preferable (e.g., during cold wintertime) [70,89]. For mixing ventilation, although it can reduce the aerosol concentration in a more controlled manner, a proper ventilation rate remains hard to determine, as the efficiency of aerosol removal is not linearly correlated with ventilation rate [18,92]. Furthermore, since previous studies on ventilation control and airborne infection were mainly conducted in a hospital setting, future research is needed for a better understanding of the situation in school buildings. A recently performed numerical study has proposed the ventilation rates and airing procedures for reducing airborne infection risk in both naturally and mechanically ventilated classrooms [93]. The models have covered several different educational scenarios during school hours, yet they only deal with the airborne transmission at room scale. To summarize, the commonly used ventilation regimes in school classrooms are not fully capable for minimizing both the long-range and short-range airborne transmission of infectious respiratory droplets, while the required ventilation designs (including both ventilation rates and air distribution patterns) are still unclear.

Such information is also missing in relevant standards and guidelines. Current standards of ventilation and IAQ in school classrooms are more focused on the perceived air quality, which mainly target at undesirable odor levels, especially those emitted by occupants. Besides, such standards and guidelines are usually framed under the broader context of energy performance of buildings (e.g., ISO 17772-1 [34] and EN 16798-1 [35]). In many cases, CO_2 in indoor air is used as the tracer of human pollution, and the minimum ventilation rates were calculated based on such emission. However, since CO_2 is a gas, it can behave differently from aerosols of all sizes, especially at a close contact or within a short-term event [71]. Some researchers have also argued that CO_2 concentration cannot be an adequate indicator of airborne infection risk [93]. Therefore, whether the existing design criteria of ventilation in school classrooms are applicable for critical health demands, namely infection control of contagious respiratory diseases, is doubtful. Similar concern has also been addressed by other researchers, where the required ventilation rates of ordinary public spaces determined by the standards and guidelines are considered to be much lower than the suggested level for a good IAQ (8–10 L/s per person) [9]. As in response to the ongoing pandemic of COVID-19, governmental and professional agencies including WHO, CDC, REHVA and ASHRAE have all put forward additional ventilation guidance and recommendations for school managers to facilitate the prevention of cross-infection among children [38,94–96]. To some extent, such action again indicates that existing ventilation strategies in school buildings are not sufficient for tackling potential health-threatening problems. Moreover, these temporary measures cannot be relied on as permanent solutions, since many of them need to be performed at the cost of comfort and energy efficiency. Hence, new criteria of ventilation design in school classrooms are needed, which should be shifted from a comfort-based paradigm towards a health-based one. Human respiratory droplets need to be taken into consideration as one of the major indoor air pollutants in classroom environments, and be handled by proper ventilation.

Apart from the infectious diseases, IAQ-conditions in school classrooms have been proven to be related to children's health, comfort, and academic performance [24,97]. Yet, according to a number of field studies, ventilation and IAQ-conditions were found to fall short of the existing requirements in a majority of school classrooms across the world prior to the pandemic, which already implies poor ability of health-based control. Therefore, concerning both the potential threats of airborne cross-infection and the unsatisfactory reality of ventilation performance, it is of an urgent need to improve IAQ in school classrooms through rethinking the ventilation strategies.

Moreover, dealing with indoor air contaminants not only influence IAQ-related health and comfort, but can also have impacts on other perceptions such as thermal, visual, and acoustical quality through the interaction of IEQ-factors [98]. One simple example is that an increased ventilation rate may result in undesirable draught [99,100]. Other evidence includes, for instance, increasing ventilation rate may be accompanied with an increase in the background noise level caused by mechanical systems, which leads to annoyance and discomfort, while pollutants' emission rates may increase with sunlight heating indoor surfaces [37]. Previous studies have also well addressed the cross-modal effects of thermal parameters, sound, and illumination level on perceived air quality and odor perception [101,102]. Therefore, all these possible interactions need to be considered while solving IAQ-problems. Meanwhile, human body mechanisms, together with influences by confounders, modifiers, and individual differences, can produce interaction effects at occupant level [37]. According to an experiment conducted in the SenseLab, children's assessment of smell was significantly affected by the background sound type, especially "children talking", suggesting the possible pre-conditioning in their response by hearing children talk [103,104]. Nevertheless, analysis of such interactions is still short of evidence, and further studies are needed to better tackle the complex IAQ-problems in school classrooms.

6.2. Possible solutions to minimize airborne transmission: personalized ventilation

With regard to the ventilation and IAQ-related problems in school classrooms discussed in section 6.1, personalized ventilation is proposed as a promising solution, which can be adopted as a complementary system to the total-volume ventilation regimes. PV systems, including PS and PE, have been proven to efficiently decrease the exposure risk (usually indicated as IF) of exhaled contaminants of the source person within a close proximity, and improve local IAQ for the co-occupants. Therefore, while the room-based ventilation can deal with long-range airborne transmission, the PV systems can be used to minimizing short-range airborne transmission.

Among all these studies listed in Table 5, two occupants (manikins) were involved, namely the source person and exposed person, and they were seated at a close distance with each other (1–2 m). Such results, therefore, evidently demonstrated the ability of PS to reduce the short-range airborne transmission of respiratory droplets between indoor occupants. However, the efficiency of PS varies largely with the AID type and supply airflow rate, with a range of 15–90%, meaning a specific configuration and a higher supply airflow rate are often needed for PS to achieve a desirable aerosol removal efficiency. Previous studies have also indicated that PS-systems can achieve positive effects only when the supply airflow rate for the exposed person is equal to or larger than that for the infected person [29,81,82], while the performance is partly determined by the relative position of the occupants [80]. Consequently, such limitations may hinder the flexibility of individual control.

According to the literature discussed in section 5.1 and 5.2, PE in general showed a more stable performance in terms of decreasing the intake fraction (IF) or exposure risk of the respiratory contaminants for the exposed occupants compared to PS. Although less evidence can be found about the development and assessment of PE, several studies have already demonstrated that PE can achieve significantly better performance than PS under the same experiment conditions, even with a lower airflow rate [30,105]. Therefore, further investigations are needed to explore the possibilities of PE in future applications.

To date, the research on personalized ventilation with the aim of lowering infection risk is still limited to several specific indoor environmental settings. For PS, besides office rooms, researchers have mainly discussed PS devices in hospital wards [28], aircraft cabins [30], and car cabins [106]. For PE, the scenario is further restricted to aircraft cabin and hospital rooms. Little attention has been paid to school classrooms under this topic. However, when taking into consideration the differences in ventilation strategy, occupant density, and indoor activity, existing results of personalized ventilation systems are difficult to apply to children in school classrooms directly, because such factors can easily affect the efficiency of the system. Particularly, a combination of personalized ventilation systems and natural ventilation has not yet been investigated, yet a majority of schools has not been equipped with mechanical ventilation systems. Hence, further research is needed to determine how to make use of such advanced technologies for improving ventilation and providing healthy IAQ-conditions for children in school classrooms. Moreover, besides the ability of minimizing airborne infection, personalized ventilation systems have also been indicated to have the potential of improving local thermal comfort as well as reducing energy consumption [87,106,107]. Accordingly, personalized ventilation system can be considered as a versatile and sustainable tactic to improve overall IEQ in school classrooms.

7. Conclusions

This literature review discussed the current ventilation strategies and IAQ-conditions in school classrooms with a specific concern of airborne infection control, as well as the possible solutions for further improvement.

A major conclusion of this review is that there is a clear lack of knowledge of what ventilation rates and designs are required to provide classroom environments that are reasonably safe from airborne transmissible diseases.

The commonly used ventilation regimes in school classrooms include natural ventilation and mixing mechanical ventilation. Such ventilation regimes are not fully capable to reduce the airborne infection risk of contagious diseases, mainly due to the unique features of respiratory aerosols that differ from other indoor air pollutants, in particular their generation and dispersion. Pathogen-laden aerosols are usually small droplets (<100 μm) generated from human respiratory system, and thus can directly reach the breathing zone of an exposed person within close contact (<1–2 m), or remain suspended in the air and travel over long distances, which are named as short-range and long-range airborne transmission, respectively. Conventional ventilation regimes are mainly based on the assumptions of steady-state condition and well-mixing model, which are not applicable to short-range airborne transmission, since it is a highly dynamic process and the concentration of aerosols is not evenly distributed. Besides, although room-based ventilation can efficiently deal with long-range airborne transmission, the proper ventilation rates and air distribution patterns are hard to determine. In other words, the required ventilation for minimizing either the long-range or short-range airborne transmission are still unclear.

Currently, the relevant standards and guidelines of ventilation in school classrooms mainly focus on the perceived air quality, and are subject to the demand of energy saving. Besides, CO_2 concentration is often used to represent human pollution, yet it is not an adequate proxy of respiratory aerosols. Consequently, existing standards and guidelines may not be able to provide sufficient information for establishing environments in school classrooms where the risk of airborne transmission is acceptably low. Moreover, although the required minimum ventilation rates are already considered to be relatively low, in reality a large proportion of school classrooms have failed to meet the requirements, while IAQ-related health, comfort, and performance problems have been widely reported. Hence, developing new criteria of ventilation and IAQ in school classrooms is of an urgent need, where respiratory droplets should be considered as a major indoor air pollutant in classroom environments, and tackled by proper ventilation. For future research, ventilation design should shift from a comfort-based design towards a health-based design, and take into account the different contact scenarios between occupants. A more flexible and versatile ventilation strategy is needed, in order to deal with the indoor air contaminants both at the occupant level and room level.

Personalized ventilation, including personalized air supply systems and personalized air exhaust systems, can efficiently decrease the exposure risk of exhaled contaminants of the source person within a close contact, and improve local IAQ for the co-occupants. Therefore, PV systems have a promising potential to be used as a complementary solution to the conventional ventilation regimes, by reducing the short-range airborne transmission of respiratory droplets. However, the efficiency of PV systems varies significantly from one to another, and is largely dependent on the indoor environmental settings. Considering also the types of occupants and their activities, further studies are needed to determine the suitable way to apply PV systems into school classrooms.

Changes in IAQ-conditions can affect other IEQ-factors including thermal comfort, acoustical quality, and visual quality. Such interactions can have significant impacts on occupants' health and comfort, and thus also need to be taken into account when rethinking the ventilation in school classrooms.

Overall, a holistic optimization of ventilation strategies is needed in order to tackle the airborne transmission of infectious respiratory droplets and provide children with healthy IAQ-conditions in school classrooms.

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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