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Review of ventilation strategies to reduce the risk of disease transmission in high occupancy buildings

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ABSTRACT

An unforeseen pandemic is facing the world caused by a corona virus known as SARS-CoV-2. Numerous measures are being put in place to try and reduce the spread of this deadly disease, with the most effective response to the outbreak being mass quarantines, a public health technique borrowed from the Middle Ages. The widely accepted main transmission mechanism is through droplet borne pathways. However, many researchers and studies are considering that this virus can also spread via the airborne route and remain for up to three hours in the air. This is leading to questions as to whether enough is being done regarding ventilation to reduce the risk of the spread of this or other diseases that may be air borne. Ventilation and air conditioning systems are the main focus when it comes to the transmission of such deadly pathogens and should be appropriately designed and operated. This paper reviews and critically evaluates the current ventilation strategies used in buildings to assess the state of the art and elaborates if there is room for further development, especially for high occupancy buildings, to reduce or eradicate the risk of pathogen transmission and adapt ventilation measures to new threats posed by pandemics.

1. Introduction

An unprecedented viral disease has brought our globe to a halt, impacting most of mankind's activities. At the time of writing, more than 620,000 people are dead worldwide, the global economy is on the verge of an unprecedented depression, with the COVID-19 pandemic still raging and a second wave predicted as inevitable. COVID-19 belongs to the group of coronavirus, also known as Severe Acute Respiratory Syndrome Corona Virus 2 (SARS-CoV-2) [1]. This virus has already surpassed the number of infections of two other epidemics in this century [2]. Current measures introduced worldwide, and designed to control the spread of the virus include lockdowns, self-isolation, social distancing, use of face masks and the recommendation to wash hands as frequently as possible, [3]. N95 masks have been recommended by WHO and have been known to help prevent infected individuals from spreading the virus if not necessarily preventing healthy individuals from contracting it from others [1, 4].

COVID-19 is one of the most contagious viruses that mankind has experienced, spreading across most of China in only 14 days [2], then worldwide within a couple of months. The widely accepted mechanism of COVID-19 transmission is by droplet and contact methods as backed-up by the WHO, but the possible air transmission route has been broadly documented by new scientific research [5] and the WHO is not ruling out this possibility. As individuals are infected with the respiratory disease, the rate of expiratory events increases which in turn increases the generation and dispersion of droplets containing the virus. Such expiratory events include not only coughing and sneezing but also talking [6]. Considering how fast this disease has spread across the world, many researchers [7] state that an additional mode of transmission, nuclei borne by air droplets, plays an important role in the spread of this virus.

Flow dynamics of air particles can be complex and include turbulent jets, droplet evaporation, air-mucous interaction and particle sedimentation amongst others [5]. These flow dynamics and particle interaction with air is at the core of transmission of the COVID-19 virus. As mentioned previously, a variety of physical containment methods have been introduced, such as wearing the recommended personal protective equipment (PPE) and improving personal hygiene. However, since the vast majority of infections occur indoors [8], it has been noted that ventilation strategies can play a vital role in controlling or at least reducing the risk of respiratory infections [9].

Droplet nuclei are fine air particles that remain airborne for a considerable length of time. Any air particles below 5 μm are classified as being able to be airborne. SARS-CoV-2 is yet to be officially classified as an airborne disease by the WHO, however, a weight of

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Nomenclature

Dimensionless numbers

Cd	drag coefficient [dimensionless]
$\in$	effectiveness [dimensionless]
Re	Reynolds number [dimensionless]

Greek symbols

ρ	density [kg/m^3]
μ	dynamic fluid viscosity [N.s/m^2]
u	flow velocity [m/s]
v	velocity [m/s]
μm	micrometre x10^{-6} [m]

Roman symbols

C	concentration [μg/L: x10^{-6} [kg/m^3]]
D	diameter [m]
Fd	drag force [kg.m/s^{-2}]
G	pollution load of chemical [μg/s: x10^{-9} [kg/s]]
g	gravitational acceleration [m/s^{-2}]
ppm	parts per million x10^{-6}[ppm]
Q	ventilation rate [L/s: x10^{-3} [m^3/s]]
U	heat flux [W/m^2/K]

Abbreviations

AC	air conditioning
ACH	air change per hour
AHU	air handling unit
ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
CFD	computational fluid dynamics
CIBSE	Chartered Institution of Building Services Engineers
CO_2	carbon dioxide
CoV	corona virus
COVID	corona virus disease
MERS	middle east respiratory disease
MVHR	mechanical ventilation with heat recovery
PIV	positive input ventilation
PPE	personal protective equipment
SARS	severe acute respiratory disease
WHO	World Health Organization

emerging evidence is being established for aerosol driven infections [10–13]. The Chartered Institution of Building Services Engineers, CIBSE, recently provided guidance on using ventilation as a way of diluting airborne pathogens. It is stated that: “there is good evidence that demonstrates room occupants are more at risk of catching an illness in a poorly ventilated room than in a well-ventilated room.” Besides this, new evidence that has been found shows high rates of infection in poorly ventilated spaces [14].

Since SARS-CoV-2 has spread around the world at an unprecedented pace, infecting millions of people, and further aerosol driven infections are highly likely to emerge, ventilation plays a key role in efforts to limit the transmission rate of this and other diseases. This paper will discuss the factors affecting air particle properties in-terms of flow dynamics and critically analyse current ventilation strategies and mechanisms and identify areas for improvement in the search for the reduction of indoor infections. Thoughtful modifications to the built environment — to how schools, offices or health-care facilities are designed, operated and maintained — could help curb the spread of infectious disease, reducing the toll of future outbreaks as well as the current COVID-19 pandemic.

2. Literature review

This section will review the current state-of-the-art covering characteristics of respiratory particles, the ability of viruses to spread as well as the mechanisms for airborne transmission and how current ventilation strategies can affect the risk of transmission.

2.1. Respiratory particle characteristics and their role in virus transmission

Respiratory particles are formed during any respiratory activity such as coughing, sneezing, talking and breathing. Once the particles are released into the surroundings, the mechanisms in-which they flow and settle depend on the fluid dynamics of the particles and the conditions in the vicinity.

Fluid dynamics can characterise the evaporation rate of the particles which allows the determination of the prevalence of small droplets and nuclei droplet transport [5].

COVID-19 belongs to the betaCoVs pathogen group and has an approximate diameter of 60–140 nm. The shape of the virus can be spherical or ellipsoidal [15]. Particle trajectories depend primarily on their size and the balance of various forces acting on the particle in the air. Gravitational and aerodynamic forces are the two primary forces acting on such particles, where the latter force dictates the flow behaviour of the particle. Fig. 1 shows the trajectories for particles of various sizes ranging from 0.01 μm to 100 μm [8].

Stokes law explains the frictional force relation exerted on spherical objects with very small Reynolds numbers in viscous fluid. To help explain the trajectories of air particles, the aerodynamic drag coefficient (Cd), shown in Eq. (1) of a spherical particle relative to Reynolds number, shown in Eq. (2), is not constant. Reynolds number is a ratio between inertial and viscous forces that originate from interactions between a body and a fluid. The equation for Reynolds number is shown below.

$$Cd = \frac{Fd/A}{1/2\rho u^2 A} \tag{1}$$

where Fd is the aerodynamic drag force, and A is the frontal area.

$$Re = \frac{\rho v D}{\mu} \tag{2}$$

Using Reynolds equation, for natural ventilation systems with air velocity of 0.3 m/s and a particle size of 140 nm, the Reynolds number is calculated at 0.003. This shows that for such air flow environment, the flow is laminar whereby the viscous forces prevail. Therefore, drag coefficient for viscous non-separated flow around a sphere can be defined by Eq. (3). However, this equation implies that drag force is proportional to the diameter which is not entirely accurate.

$$Cd = \frac{24}{Re} \tag{3}$$

The resistance coefficient may decrease with increasing diameter, but the drag force increases linearly with the diameter. However, since the gravitational force increases with the mass, it increases with diameter cubed, thus, more rapidly than the drag force as the diameter increases. Therefore, larger particles have the tendency to settle [16]. This phenomenon helps to explain why smaller particles are more likely to be airborne.

The drag coefficient for a sphere as a function of Reynolds number can be plotted to show the influence of changing flow regime on the drag coefficient. This is shown in Fig. 2, whereby a sphere exhibits a reduction in drag coefficient until the flow regime becomes turbulent causing a sudden dip. Furthermore, when the boundary layer on the leading surface becomes turbulent, the separation occurs farther round the sphere and the drag coefficient decreases. A rough surface, such as on a golf ball, promotes an earlier transition to turbulence. The numbers

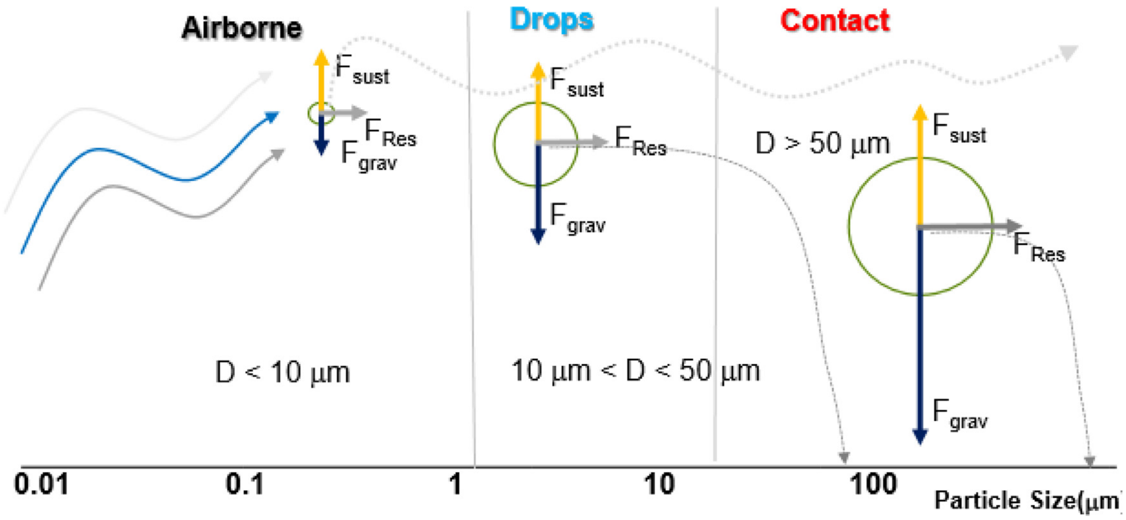

Fig. 1. Trajectories of particles with various sizes [8].

on Fig. 2 refer to various flow regimes and their corresponding changes in the drag coefficient. Flow regime 2 on the figure refers to Stokes flow and steady separated flow, whereby the Reynolds number is less than 1 which is typical for fluid velocities are very slow and the viscosities are very high. Flow regime 3 on the figure refers to separated, unsteady flow, whereby a laminar flow boundary is formed upstream of the separation and producing vortex street. Flow regime 4 refers to separated unsteady flow with a laminar boundary layer at the upstream side and chaotic turbulent wake downstream of the sphere. Regime 5 refers to a turbulent boundary layer [16].

Various parameters affect the transmission of droplet borne infections, including density, initial velocity and the size distribution of the droplets that are released during respiratory activities, as well as indoor air velocity and direction. Many research studies have been carried out to measure these characteristics [17]. Sneezing is the respiratory activity that ejects the most droplets, in the range of 10^4 or more. The droplets from sneezing have initial velocities in the range of 20 m/s. Other respiratory activities release droplets at a significantly lower density and lower initial velocities. Table 1 shows the droplet densities and velocities for the common respiratory activities.

The terminal velocity at which any spherical particle settles due to gravity in a fluid can be explained by Stokes' law for fine particle size and Newton's law for coarse particles. Both equations have been shown below.

Stokes' law Eq. (3a)

$$v_T = \frac{g(\rho_S - \rho_F)d^2}{18\mu} \tag{3a}$$

Newton's law Eq. (4a)

$$v_T = \sqrt{\frac{4g(\rho_S - \rho_F)d}{3C_D\rho_F}} \tag{4a}$$

where

g = gravitational acceleration
ρ_S,ρ_F= density of solid and fluid respectively
d = particle diameter
C_D= drag coefficient
μ = fluid viscosity.

The terminal velocity equations shown above have been used to generate graphical representations of the expected particle speeds at various conditions as shown below in Fig. 3.

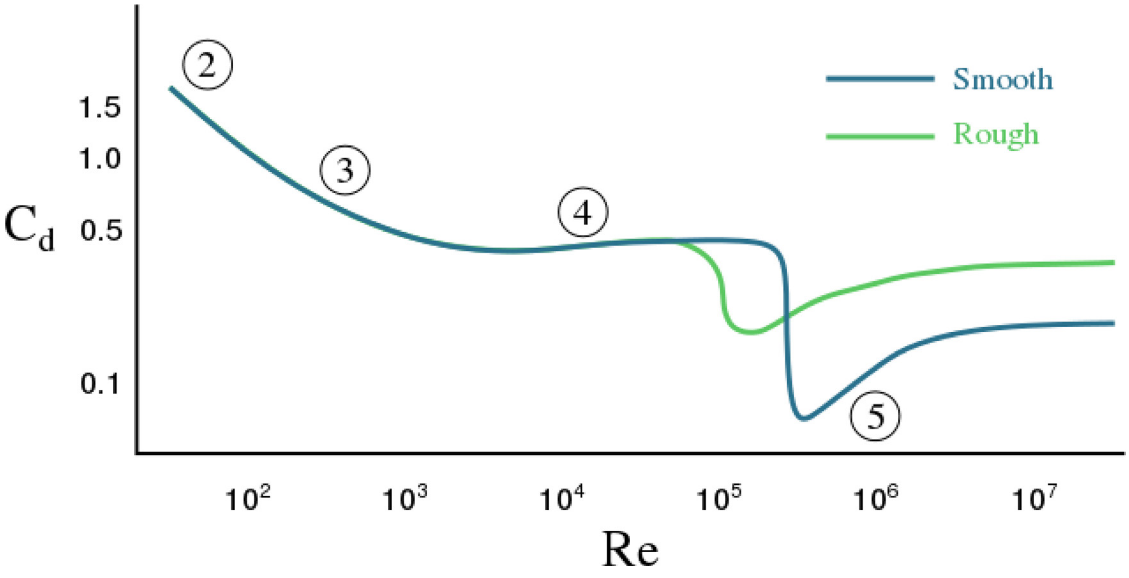

Fig. 2. A graph of aerodynamic drag coefficient against Reynolds number [16].

Since COVID-19 has an approximate diameter of 60–140 nm [15], Stokes' law applies for ventilation in buildings whereby the air flow exhibits a laminar behaviour. Fig. 3 shows that at very small diameter particles of less than 0.1 μm, the terminal velocity is almost negligible which further amplifies the fact that if COVID-19 was proven to be airborne then the virus and its potent materials could be airborne for long durations especially if enclosed environments are not ventilated adequately. A mathematical model by Cummins et al. shows that particles with a diameter smaller than 70 μm (Stoke's number $\leq 8.5 \times 10^{-5}$) are almost unaffected by the gravity and air extraction is very efficient at removing these fine particles [19]. This is explained by the major impact of the drag forces on the particle's movement for this diameter. The settling velocity calculated by Stokes' law (Eq. (3)) is proportional with the diameter squared. Particle terminal velocities remain elusive due to a vast number of factors, such as droplet diameter, droplet density, contributing to this phenomenon and primarily due to the difficulty in making measurements of such parameters [18,20,21].

Table 1
Respiratory activities with their corresponding number of droplets and associated velocities.

Respiratory activity	No. of droplets	Velocities (m/s)	Reference
Sneeze	10,000	20	[18]
Cough	100–1000	10	[7]
Talk	50	< 5	[7]

2.2. Viral transmission mechanisms

2.2.1. Mode of transmission

Pathogen transmission can occur through different routes: direct contact, indirect contact, droplet borne or airborne such as shown in Fig. 4 [22–24]. The direct contact route covers any contact between a contagious person and a susceptible person: touching, kissing, sexual contact, contact with skin lesions or oral secretion. This route is well documented and outside the scope for this paper. In the indirect contact transmission mode, the contagious person touches or expels contaminated droplets containing infectious organisms which settle on an inanimate object, such as a doorknob or an elevator button, called "fomite". The person being infected touches this fomite and then an area where the pathogen can enter the body such as the eyes, nose, or mouth [7].

Droplet transmission can occur when infective large droplets expelled from a contagious person reach an uninfected person. Airborne transmission occurs when very small particles (5–10 μm in diameter) or small droplets evaporating to a small enough size [26], are expelled by coughing, sneezing, speaking, or breathing. These droplets are small enough to remain airborne for long periods of time (up to several hours), until they are inhaled by or land on the uninfected person. Airborne transmission is not yet widely accepted for various transmissible respiratory diseases. In the case of SARS-Cov-2, the World Health Organisation only recognises the risk for airborne transmission under certain medical procedures producing large amounts of infective respiratory particles [22,23,27–29]. There is now growing pressure on the WHO from the scientific community to relax the dogmatic and outdated division between aerosols and small droplets and acknowledge the mounting evidence for the indoor spreading of the COVID-19 infection through the air [30]. In the case of SARS-Cov-1 and MERS-CoV, retrospection on the different outbreaks and multiple studies make a strong case for the route as an opportunistic transmission, meaning that the virus will transmit preferably through other routes but can potentially infect by means of respiratory particles when conditions are met.

Another factor explaining the elusive validation of airborne transmission is the dilution of small particles after they are emitted. Indeed, people standing farther away from a contagious emitter see an exponentially decreasing concentration of droplet nuclei. The potential transmission over larger distances is by nature more difficult to identify especially in the context of an outbreak or a pandemic when the sources are multiple. Furthermore, when the transmission happens close to an identified source, the transmission is indiscernible from that due to droplets or indirect transmission [27,29].

2.2.2. Airborne viruses

In order for viruses to be transmitted through the airborne route, some conditions must be satisfied: the virus must be able to remain viable outside of the host, withstand the external conditions and be transported to a susceptible area of a new host. The effect of evaporation, light, humidity and temperature on the concentration and virality (capacity to infect and reproduce) of the pathogen needs to be further researched to make conclusions on the threat level of the airborne route [31].

There are already multiple pathogens for which the airborne route is acknowledged. Such viruses including Adenovirus, Influenza, Measles, Meningococcal disease, Mumps, Pertussis, Parvovirus B19,

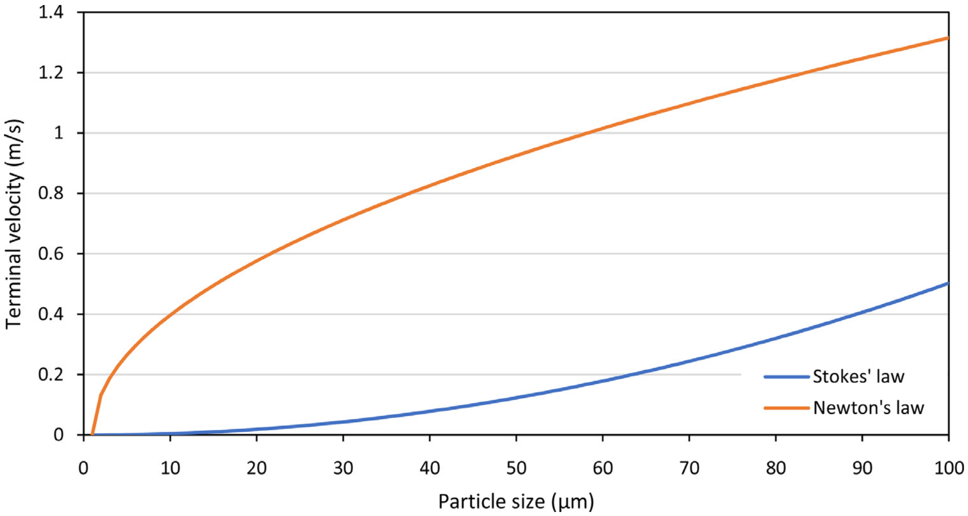

Fig. 3. Terminal velocity profile against particle size following Stokes' and Newton's laws.

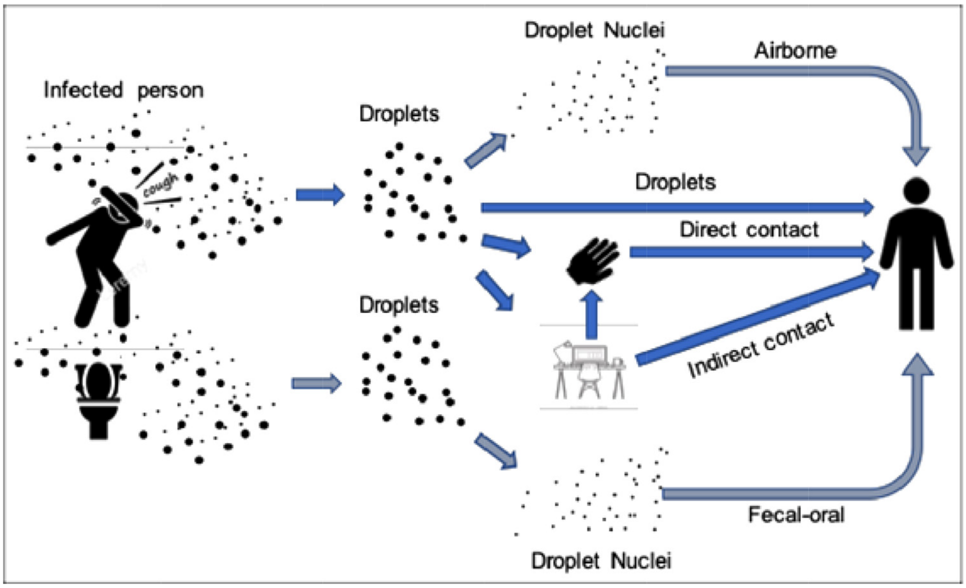

Fig. 4. Illustration of the different transmission routes of viruses such as SARS-CoV-1, MERS-CoV, and SARS-CoV-2 (dark blue colour). (Figure: courtesy Francesco Franchimon) [25]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Respiratory Syncitial Virus, Rubella, Tuberculosis and Varicella, can spread by droplet nuclei [32].

Measles and tuberculosis for example are proven to be preferentially airborne transmitted diseases [29]. But the fact that these diseases have been controlled with widely available drugs and vaccines resulted in a decrease in research effort into airborne transmission mechanisms. Recent SARS-CoV-1 and MERS-CoV outbreak have given a new impetus to research on this subject. Indeed, SARS-CoV-1 is thought to be transmissible by direct, indirect, and droplet contact, the Amoy Garden case identifies a strong possibility of airborne transmission. During the outbreak, the virus spread from a faulty dried-out bathroom drainage system and rose to a extraction fan, then was carried by the wind into the adjacent building infecting several occupants [7,16,25,28,31,33]. Ribonucleic acid, RNA, and even viable viruses have been detected in aerosols in healthcare facilities for some respiratory viruses such as seasonal and avian influenzas virus, MERS-CoV and respiratory syncytial virus [34]. In the case of MERS-CoV, samples taken in hospitals and isolation wards in South Korea confirmed the airborne transmission. Some patients of the same ward were infected, even though they were standing more than two meters away from the source. Air samples and surrounding areas, including regularly disinfected accessible and inaccessible surfaces, were all contaminated by MERS-CoV [35]. This experimental data challenges the previously recognised transmission routes, acknowledging the high possibility of airborne transmission as an opportunistic route at close range and even long range when the conditions were favourable and concentrations at the source were high.

2.2.3. Airborne SARS-CoV 1 and 2

SARS-CoV-2 shares the same modes of transmission as the SARS CoV-1 and, although the viability and virality of an air sample has not been proven at the time of writing, it cannot be ruled out. The airborne route, being opportunistic [25], is by its nature difficult to interpret. Air samples take time before being tested after which the concentration might be too low, through dilution, to establish with confidence the presence of viable virus on droplet nuclei. RNA detection is also not usually enough to interpret the risk of airborne transmission [34]. A number of studies indicate airborne or droplet borne transmission [14], and to the authors' knowledge, there is no study yet demonstrating the lack of infection in a situation where only airborne transmission is permitted (and with particles in high concentration). This would be the only definitive way to disprove the mode of transmission [36].

Recent superspreading events also support the argument for airborne transmission. During a choir rehearsal in Mount Vernon (Washington), although precautionary care was taken to suppress direct contacts and keep distance between the singers, 53 out of the 61 participants caught the disease [28] and at least two people were reported to have died [37]. The aerosol stability of SARS-CoV-2 was recently tested in laboratory conditions. A three-jet Collison nebulizer created contaminated aerosols ($< 5\,\mu$m) fed into a Goldberg drum. In this environment, the SARS-CoV-2 remained viable with a half-life between 1.1 and 1.2 h (95% credible interval 0.64–2.64 h) as shown in Fig. 5. The researchers compared the results with SARS-CoV-1 and found similar half-life results (95% credible interval 0.78–2.43 h). The reduction in infectious concentration (titre) during the 3-h long tests was from $10^{3.5}$ to $10^{2.7}$ TCID50 (Fifty-percent tissue culture infective dose) per litre of air for SARS-CoV-2. This reduction was similar to that observed with SARS-CoV-1, from $10^{4.3}$ to $10^{3.5}$ TCID50 per Litre of air [27].

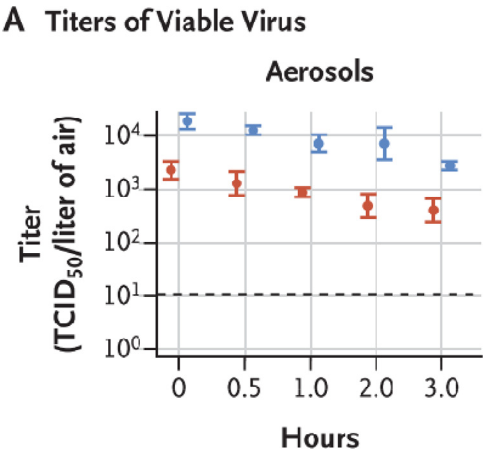

Fig. 5. Evolution of the concentration of aerosolized viable virus expressed in 50% tissue-culture infectious dose (TCID50) per litre of air. Titration on Vero E6 cells was used to quantify the samples from three experiment replicates. In blue, SARS-CoV-1 and in red SARS-CoV-2 Source: The NEW ENGLAND JOURNAL of MEDICINE [27]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

As much as it is difficult to affirm that the experimental conditions genuinely reflect real world transmission, the results show at least that the virus can remain viable outside the human body and remain able to infect other hosts. It also establishes a strong correlation with SARS-CoV-1 for which many more examples of airborne transmission have already been documented. If the transmission routes of SARS-CoV-2 are shared with those of the Coronaviridae family, the opportunistic airborne route is a serious threat and adequate mitigating measures must be taken urgently [13,14,23].

2.2.4. Infected particles - generation and interaction with the human body

In order to better understand how to combat airborne transmission, one must understand the relation between the particle emission and deposition mechanisms. Droplets can be generated from different places in the respiratory tract of the infected person with various resulting diameters. Once deposited on the uninfected individual they then infect the conjunctiva or mucous membranes in the upper respiratory tract of the new host [13,26,38]. Small particles can be generated during speech in the alveoli of the lungs and vocal cord vibration by a fluid film burst mechanism [7,39]. It was reported that vocalization emits 10 times more particles than breathing, and some speech super-emitters can (for reasons unclear yet) expel 10 times more particles than average [6]. This could be an explanation to the Mount Vernon choir outbreak: the higher concentration of infected particles added to the need for extra deep breathing required for singing facilitates airborne transmission. Coughing and sneezing also generate large numbers of particles, the majority of which are inhalable ($< 100\,\mu$m in size): 78.6–96.0% for coughing and 98.9% for sneezing. Furthermore, between 7.1 and 46.7% of cough expelled particles and 18.8% of particles produced by sneezing were under $4\,\mu$m in diameter [38]. These smaller particles penetrate deeper and can deposit further in the respiratory tract. Generally, particles above $10\,\mu$m do not reach the alveoli whereas particles above $20\,\mu$m deposit in the upper respiratory tract as shown in Fig. 6 [5,13,26,28,34,38].

Transmission that occurs in the lower respiratory tract, shown in Fig. 6 due to smaller particles potentially leads to aggravated symptoms and a higher mortality rate, whereas deposition in the upper respiratory track by larger aerosols necessitates a larger number of viruses for the host to develop symptoms [29]. This is due to the fact that the nasal and tracheobronchial regions have an additional defence system. The nasal tracts are covered by a mucus layer that entraps deposited particulates. The continuous movement of cilia pushes the captive infected particles up to the gastrointestinal track where they cannot infect the host [5,38]. Research studies have shown that small particles still present a substantial risk of infection [26], and it was reported that for some respiratory diseases, a single virus can cause illness. In the case of SARS-CoV-2, a minimum required viral load has not yet been confirmed [5,7,29]. Once the virus finds a susceptible cell, it can infect individuals through binding its pike proteins to the cell wall then uses the cell to replicate before bursting it. Thereafter, it releases more viruses that can either contaminate other cells, be destroyed by the immune system or be expelled from the body and potentially transmit to a new host [23].

2.2.5. Contagion

Studies have shown that the ensuing incubation period is on average 5.1 days, but can range from 2 to 10 days [23]. The virus remains detectable for a median of 20 days [40,41]. A critical specificity of SARS-CoV-2 is the serial interval (or the time lapse) between an infection of a host and the transmission to a susceptible uninfected person. An average of 5.8 days, with a 95% credible interval between 4.8 and 6.8 days, and median of 5.2 days, with credible interval between 4.1 and 6.4 days, were reported [41]. The small-time delay and possible overlap between the end of the incubation period and the secondary infection shows that pre-symptomatic transmission is very likely. It is believed that the infectiousness starts 2.5 days before the first symptoms of the disease and peaks when the symptoms are starting [5,41]. This would be the major cause of the rapid spread of the pandemic. The speed of the spread is represented by the basic reproduction, Ro, number which is the average number of susceptible persons infected by a single host [24]. For SARS-CoV-2 Ro is estimated to range between 1.4 and 6.49 (mean, 3.23; median, 2.79) [23]. Furthermore, the Ro is rapidly evolving and other studies have found values of Ro between 1 and 4 before intervention to limit the spread [42]. The basic reproduction number corresponding to pre-symptomatic transmissions alone is estimated to be 0.9, with 95% credible interval between 0.2 and 1.1. A Ro value superior to 1 means the virus will spread exponentially, indicating these transmissions are almost sufficient to sustain the pandemic [24]. At the beginning of the

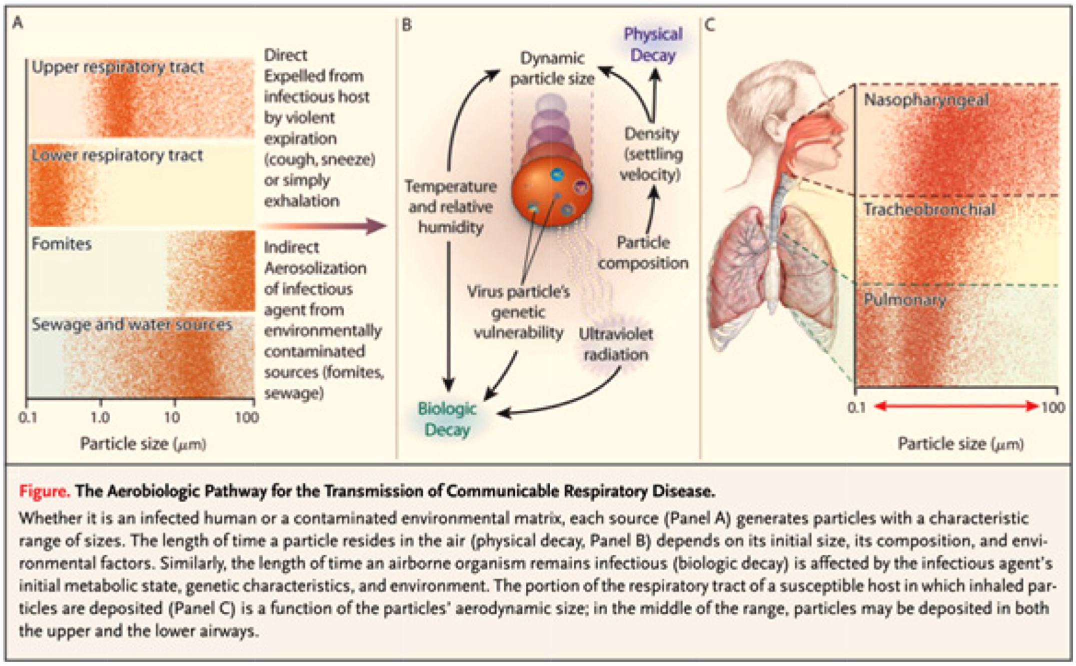

Figure. **The Aerobiologic Pathway for the Transmission of Communicable Respiratory Disease.**

Whether it is an infected human or a contaminated environmental matrix, each source (Panel A) generates particles with a characteristic range of sizes. The length of time a particle resides in the air (physical decay, Panel B) depends on its initial size, its composition, and environmental factors. Similarly, the length of time an airborne organism remains infectious (biologic decay) is affected by the infectious agent's initial metabolic state, genetic characteristics, and environment. The portion of the respiratory tract of a susceptible host in which inhaled particles are deposited (Panel C) is a function of the particles' aerodynamic size; in the middle of the range, particles may be deposited in both the upper and the lower airways.

Fig. 6. Particle size relation with generation and deposition locations [29].

Wuhan outbreak, the contribution of pre-symptomatic cases accounted for 46% of all infections, with 10% for asymptomatic cases, and it is now widely accepted that seemingly healthy people can spread the virus, though uncertainty remains over how much they have contributed to the pandemic. Though estimates vary, models using data from Hong Kong, Singapore and China suggest that 30–60% of spreading occurs when people have no symptoms [24,41,43]. As the body starts to build antibodies against the virus, the concentration begins to decrease, and the infectiousness of the disease declines significantly after 10 days [24]. When a significant portion of the population stops being susceptible to the virus, the Ro falls below 1 and the number of new infections drops below the sustaining rate. This can be achieved through vaccination or by building immunity after recovering from the disease - thus the state of herd immunity may be achieved [24]. Although mutation from the virus and decay of the immune system memory could still pose a challenge to achieving this goal.

2.2.6. *Ventilation as the means of slowing down infection rate*

In order to supress or slow the progression of the pandemic, efforts must be made to reduce Ro. Precautionary measures must consider the entire population since pre-symptomatic and asymptomatic transmissions are a critical factor in the spread of SARS-CoV-2. If the virus can spread from seemingly healthy carriers or people who had not yet developed symptoms, the public-awareness campaigns, airport screening and ‘stay-home-if-you’re sick’ policies might not stop it. More targeted measures are required including a considered re-design of Indoor Environments, especially aspects handling the air buildings’ ventilation systems [44]. Both the airborne and or droplet borne routes cannot be ignored. Pre-symptomatic and asymptomatic hosts do not cough or sneeze extensively [5,7,40]. When doctors in Wuhan, China, where the new virus first emerged, studied 138 early cases, they concluded that 41% of patients had most likely contracted the disease in the hospital [40]. Therefore, the hypothesis stating that infection through small particles plays a more important role in the transmission along with the direct and indirect (fomites) routes can be used. Thus, ventilation plays an important role in reducing the risk of transmission through dilution and removal of the infected particles within the indoor environment [25]. Preparedness to fight airborne disease is essential and SARS-CoV-2 offers the chance to research and apply mitigating ventilation solutions which could prove life-saving now and in the future when another virulent and deadly pandemic arises [29].

3. Current ventilation mechanisms in high occupancy buildings

3.1. *Ventilation recommendations and standards*

ASHRAE standard 62.1:2019 defines acceptable Indoor Air Quality as “air in which there are no known contaminants at harmful concentrations, as determined by cognizant authorities, and with which a substantial majority (80% or more) of the people exposed do not express dissatisfaction” [45].

If airborne infectious particles are to be counted as harmful even in small concentrations, as explained in the previous section, either the amount of fresh air supplied to a room needs to be dramatically increased or the ventilation strategy needs to be reconsidered to protect the occupants. This paper focuses on high occupancy buildings such as schools or office spaces where the occupants are static most of the time. Current standards already have predetermined values to meet the acceptable indoor air quality. For example, the ASHRAE standards dictate a minimum ventilation rate of 5 L/s per person or 0.9 L/s.m^2 in educational facilities. For office buildings, the minimum values are 2.5 L/s per person or 0.06 L/s.m^2 [45]. Having said that, due to variability in ventilation methodologies, similar ventilation rates may translate to significantly different indoor transmission outcomes. Fresh air can be provided in a number of ways, relying on many different technologies and having different extraction, dilution and air distribution effectiveness. The British standards BS EN 16798-3:2017 defines 4 basic types of ventilation systems (Table 2):

Table 2
British standard classification of ventilation systems [44].

Description	System type
Fan assisted air volume flow in only one direction. This system is balanced by air transfer devices within the building envelope.	Unidirectional ventilation system
Fan assisted system operates in supply and exhaust directions.	Bidirectional ventilation system
Natural ventilation relies on natural driving forces.	Natural ventilation system
Hybrid systems rely on natural and mechanical mechanisms. Any combination of the ventilation mechanisms can be used depending on the situation.	Hybrid ventilation system

Several factors play a role after a ventilation solution is selected that affect the final system performance and Indoor Air Quality. The poor initial design of a selected ventilation solution could be due to various reasons such as error in sizing, reduced performance due to lack of maintenance, lack of operator knowledge or the intentional reduced use in order to save energy or reduce noise and all can be detrimental to the occupants’ health. Several studies have demonstrated that in classrooms, the ventilation rates have often failed to reach the minimum standard required. The peak CO$_2$ concentration, which can be used as an indicator of the ventilation rate in occupied spaces, often exceeded the recommended levels. In a study, the reported CO$_2$ measurements in several thousand classrooms has shown that all classroom averages exceeded 1000 ppm (0.1%) which is an indicator of a ventilation rate lower than 7 L/s/person at default occupancy. In many instances, the average CO$_2$ levels were above 2000 ppm with peak concentrations between 3000 and 6000 ppm [46]. This discrepancy between the building standards and reality demonstrated the need for a thorough reconsideration of ventilation design and ventilation systems specified in high occupancy buildings well before the impact of coronavirus. In the light of SARS-CoV-2 pandemic there is an even more desperate need to address the ventilation design and effectiveness. Improved ventilation has been noted to deliver a positive health impact with a noticeable reduction in illnesses and absences. In particular, reduced respiratory health effects, such as mucosal and allergy symptoms are significantly reduced with increased ventilation rates [46]. A study based on Californian schools demonstrated that an increase in the ventilation rate by 1 L/s/person resulted in a 1.6% reduction in illness related absences [47]. Poor ventilation has also been linked to many adverse health effects: transmission of infectious diseases, acute respiratory symptoms and impaired cognition performance [48–50].

The European guideline, INDOOR AIR QUALITY & ITS IMPACT ON MAN report N 11, proposes the following equation to calculate the required ventilation rate to ensure adequate Indoor Air Quality [51]:

$$Q_h = \frac{G}{C_i - C_o} \times \frac{1}{\in_v} \tag{5}$$

where

Q_h= ventilation rate required for health (l/s)
G= pollution load of chemical (μg/s)
C_i= allowable concentration of chemical (μg/l)
C_o= outdoor concentration of chemical at air intake (μg/l)
$\in_v$= ventilation effectiveness.

It expresses the dilution of the said pollutant as a function of the ventilation rate effectiveness which can be engineered to suit the room, occupant type, and the risk at hand. In the case of infected particles, the recommendations from REHVA, the Federation of European Heating, Ventilation and Air Conditioning Associations, are to supply as much outside air as possible. According to REHVA, mechanical ventilation should be activated more often (24/7 when possible with lower rates during quiet times) and at least to start ventilating before and after busy hours while the density of occupancy needs to be decreased when possible This will increase the distance between people and lower the pollutant emission rate. With or without mechanical ventilation, window airing should be used to boost the air exchange rate. Toilet windows on the other hand need to remain closed and mechanical extraction activated at all times to create negative pressure and prevent contaminated particles from entering other parts of the building though doors or by an unforeseen route through nearby open windows [25].

3.2. Ventilation and COVID-19

Prior to COVID-19, densely packed open-plan offices were already suspected of making employees sick [52]. Viruses and other pathogens are not the typical pollutants and even small and temporary exposure has been proven to lead to infections. Studies of viral infections spread through indoor spaces document clearly that mechanically induced, mixing airflow can pose a greater risk of infection spread as it pushes turbulent air deep into rooms, possibly picking up infected droplets along the way [53]. Further research by the University of Oregon demonstrated how air conditioning or hybrid ventilation can spread the pathogens much farther than 6 feet, even when the host is positioned a long distance from the fan driven system [53,54]. It appears that it is not just the rate of supply of fresh air that needs to be considered but also the air flow dynamics and air distribution pathways through occupied spaces that urgently need review, which include the type of airflow, velocity, its turbulence and its direction.

Keeping Indoor Environments virus-free plays a key part in reducing or slowing the transmission of various airborne infections. Since viruses have an approximate diameter of 150 nm, they can be easily carried by aerosol droplets in the air and linger afloat for many minutes and sometimes hours. An inappropriate or inadequate ventilation strategy can dramatically increase the risk of disease transmission.

A research study conducted by a team of scientists at the Defence Science and Technology Laboratory on the aerosol survival of SARS-CoV-2 in artificial saliva and tissue culture media and high humidity found that COVID-19 could be transmitted via airborne droplets in addition to physical contact with droplets deposited onto surfaces [55]. The study used the SARS-CoV-2 England variant which was suspended in the air using tissue culture media at medium and high relative humidity, 40–60% and 68–88%. The outcome of the study has shown that the virus was still detectable after 90 min.

Taking the above-mentioned publications into account, ventilation and comfort strategies have been categorised by airflow characteristics and their potential impact on pathogen spread through occupied spaces in the next section.

3.3. Ventilation strategies

Considering the dynamics of droplet and aerosol spread indoors, various ventilation and air conditioning strategies can be grouped into three main categories:

- Recirculating ventilation (frequently called mixing or hybrid ventilation) and conditioning systems that either move the indoor air around (typical split AC or VRF system or even a ceiling fan) or mix indoor air with outdoor air before pumping it into the room (such as hybrid or 'heat recycling' ventilation systems that have been lately installed in many schools). This ventilation method generally produces turbulent air flows with stale air either partly or fully recirculated back into the affected rooms.
- Mixing ventilation systems that are designed to distribute fresh air throughout the occupied space ensuring all occupants experience similar air quality, with air supplied through specific ventilation outlets or diffusers. They are predominantly mechanical systems such as large, centralised Air Handling Units (AHU) or smaller, localised Mechanical Ventilation systems with Heat Recovery (MVHR). This ventilation method generally produces turbulent, mixing air flows within rooms.

Table 3
Classification of ventilation strategies by airflow dynamics.

Recirculating ventilation (and comfort systems)	Split air conditioning systems	Room air is processed by the wall or ceiling mounted fan unit and recirculated at speed to ensure furthest reach within the space
	Ceiling fans	Room air is recirculated downwards (or upwards) at speed to ensure wind chill cooling and sufficient spread within the space
	Hybrid ventilation systems	Room air is mixed with external air and recirculated into the space with the help of a fan to ensure farthest distribution and mixing
Mixing ventilation systems	Air handling units (AHU)	Outside air is conditioned and supplied to occupied spaces through ducts using floor or ceiling diffusers. Stale air is mixed with fresh and then disposed of through various outlets thanks to positive pressure from AHUs.
	Mechanical ventilation with heat recovery (MVHR)	Balanced supply and extract systems, mostly localised, that both supply and extract air from the same space. These systems provide heat recovery option to reduce ventilation related heat loss.
	Positive input ventilation	Localised fanned systems supplying fresh air (and relying on façade openings for exhaust using positive pressure). Similar airflow dynamics to AHUs listed above.
Displacement ventilation methods and systems	Continuous extract ventilation	Localised or centralised fan driven systems extracting stale air (relying on building fabric openings such as windows or louvres to let fresh air in utilising negative pressure).
	Natural ventilation measures (Predominantly windows)	Building integrated measures designed to displace stale air and supply fresh air using buoyancy including elements such as windows, passive stacks or solar chimneys.
	Natural ventilation systems	Natural Ventilation products or systems utilising buoyancy in their operation including roof cowls, wall mounted IAQ responsive louvres or IAQ controlled window openers.

- Displacement ventilation systems that remove contaminated indoor air and supply fresh outside air in a predominantly even, buoyancy assisted fashion, effectively displacing it with no or little disruption. They are primarily passive systems such as Natural Ventilation cowls, façade louvres or automatically opening windows. This ventilation method generally produces a laminar airflow within rooms (outside of very windy conditions).

Typical ventilation measures are listed and grouped in the table below, complete with a brief description (Table 3):

4. Ventilation solutions in detail

4.1. Recirculating ventilation strategies

The recirculating approach has been popular choice for new schools in recent years for both ventilation and comfort provision, mainly due to its low capital cost and simplicity.

4.1.1. Hybrid ventilation systems

Some recirculating systems are used for ventilation with the recirculated stale air mixed with fresh, outside air, in order to increase the temperature of the air supplied to the classroom, necessary to reduce discomfort in absence of a heat exchanger. The diagram, shown in Fig. 7, illustrates the concept of hybrid ventilation:

The mixed, partly recirculated, air is fan driven in such a way as to reach far into the classroom up to 8 m from the system and to supply enough fresh air, mixed with stale air for comfort, to maintain CO_2 levels below an average of 1000 ppm. As this requires fresh air flows rate in a range of 150 l/s, when combined with stale air it may reach a volume flow rate of 300 l/s or higher which, considering the small size of the air diffusers, can generate substantial air velocities in occupied spaces - leading to high air turbulence. According to a recent study and modelling conducted by the University of Oregon, this type of airflow has the potential for high spread of coronavirus infected droplets within densely occupied spaces, even with just one person exhaling the virus droplets [53,54]. Apart from the recirculation itself, the transmission appears to be facilitated by the type and velocity of turbulent airflow designed to reach deep into the occupied space as shown in Fig. 8.

4.1.2. Recirculating comfort systems (Air conditioning)

This covers most of the Air Conditioning systems used commercially with the mode of operation similar to the Hybrid Ventilation systems mentioned above with the exception of containing no fresh air in its supply path – all is constantly recirculated. Air is pulled into the system from the room, conditioned, either cooled or heated, and then supplied back into the room at high enough velocity to reach to the end of the occupied space. Since the systems are designed to ensure that conditioned air gets to every area of the room, providing comfort, the pathogens picked up by the circulating air can travel much further than 2 m [53,54,58]. A typical AC airflow can be illustrated by the Computational Fluid Dynamics picture in Fig. 9.

4.1.3. Recirculating ceiling fan

Ceiling Fan is another recirculating comfort system and is designed to either reduce air stratification in the room, bringing the warm air down from the ceiling, or to introduce enough air movement to cool the occupants through wind chill effect. Both actions are designed to improve comfort while displacing the need for more power-hungry AC or excess space heating. As it can be seen in the CFD snapshot in Fig. 10, ceiling fans also ensure that air within the room is fully mixed. As much as there can be various iterations of the above approach, the unifying factor is that ceiling fans continuously mix air within spaces where they serve, such as classrooms, lecture theatres or offices. Consequently, any contaminated droplets and aerosols sneezed, coughed or exhaled can travel significant distances within the rooms and reach occupants who are much farther away from the infected host than 2 m [59].

The research carried out by *Jaakkola* et al. [61] shows the importance of the introduction of fresh air into any occupied room, with recirculation of the air posing a significant risk with many of the air borne diseases not just being carried from person to person by the airflow but also entering the ventilation system itself, possibly being trapped in the air filter. However, many of the pathogens may escape filters causing further infections and droplets can be carried for long distances across spaces by fan induced turbulent airflow without having to enter the recirculating system. Since the vast majority of air conditioners in high occupancy buildings utilise air recirculation, it raises the question over their safety and indicates the need for further research into such comfort, ventilation and indoor air quality provision so that the occupant safety can be improved, especially in the light of the COVID-19 pandemic [61].

4.2. Mixing ventilation

4.2.1. Air handling systems (or Air handling units, AHUs)

Air Handling Units are generally located in the basement or lower floors of a building such as office blocks (US) or on top of the building (UK). AHUs are tasked to supply hundreds of m^3 of air per second across the whole building and generally dehumidify, heat and cool the incoming fresh air as required. The air is supplied through floor or ceiling grills generating positive pressure within the building, it then moves across the ventilated space mixing with existing, stale air along the way and is exhausted through various building fabric openings, exhaust ducts or atria created for that purpose as shown in

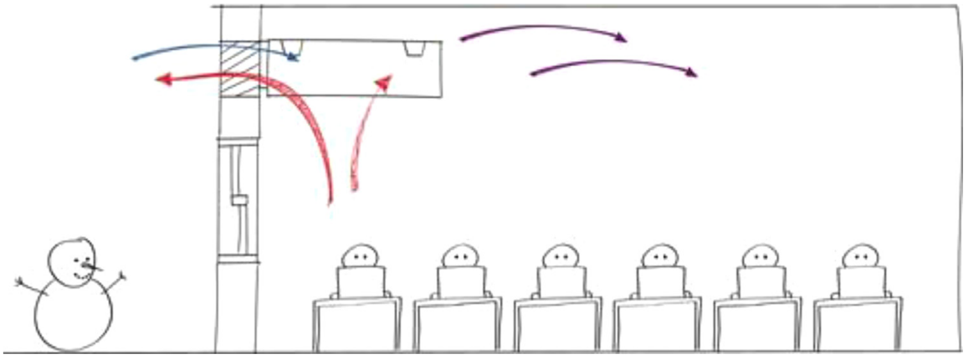

Fig. 7. NVHR® by Breathing Buildings [56].

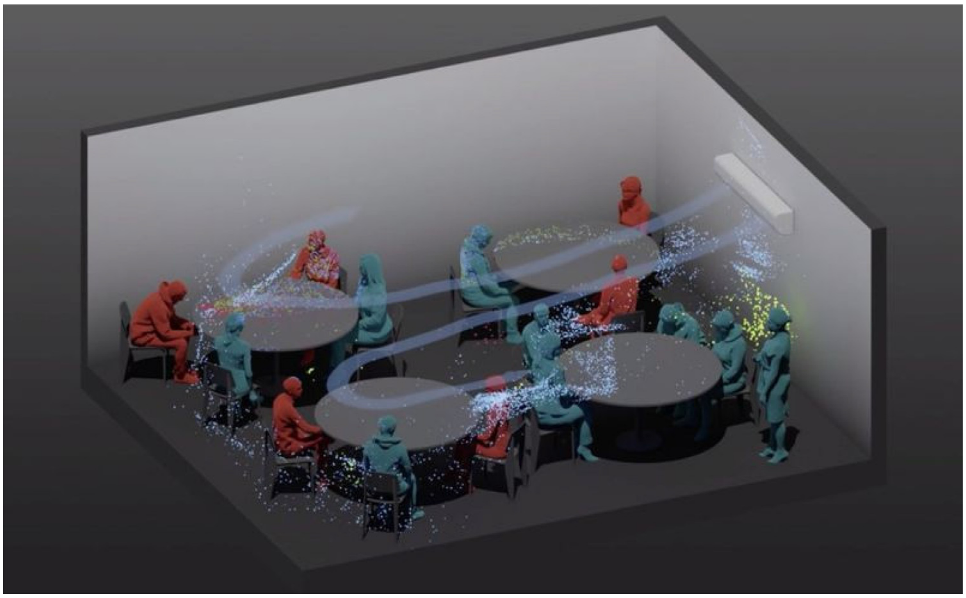

Fig. 8. Computer modelling by the University of Oregon showing the potential spread of coronavirus in a restaurant with an air recirculating unit [57].

Fig. 11. In some cases, buildings can utilise a hybrid solution combining both natural ventilation principles (even natural free cooling) and mechanical assistance.

A CFD study of a simplified room, with one simulated occupant, using a positive pressure mixing ventilation system can be seen in Fig. 12. However, as the fresh air is supplied, a significant degree of mixing will occur within the occupied space. The general design of AHU ductwork, as well as deep floor plan offices exacerbate the fan induced mixing throughout occupied spaces leading to increased risk of long-distance droplet movement.

4.2.2. MVHR (Mechanical ventilation with heat recovery)

These balanced ventilation systems are generally localised and mounted within the ceiling void of the room or classroom they serve, extracting air from the occupied space, passing it through the air to air heat exchanger to recover the heat and warm up the incoming fresh air, as shown in Fig. 13. As much as both air flows are channelled through the same box, there is generally no mixing between the two paths. These systems allow for higher thermal efficiencies due to heat recovery but with an electrical penalty of two fans running constantly. A typical classroom MVHR ventilation arrangement

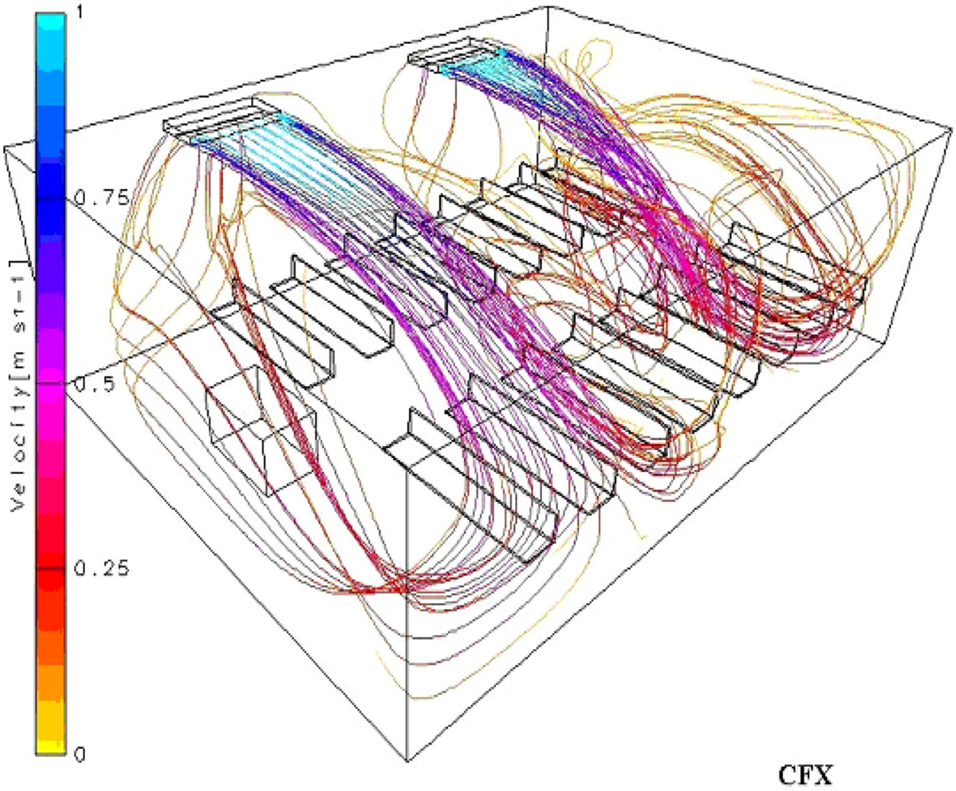

Fig. 9. CFD of a typical split AC in a typical lecture room [59].

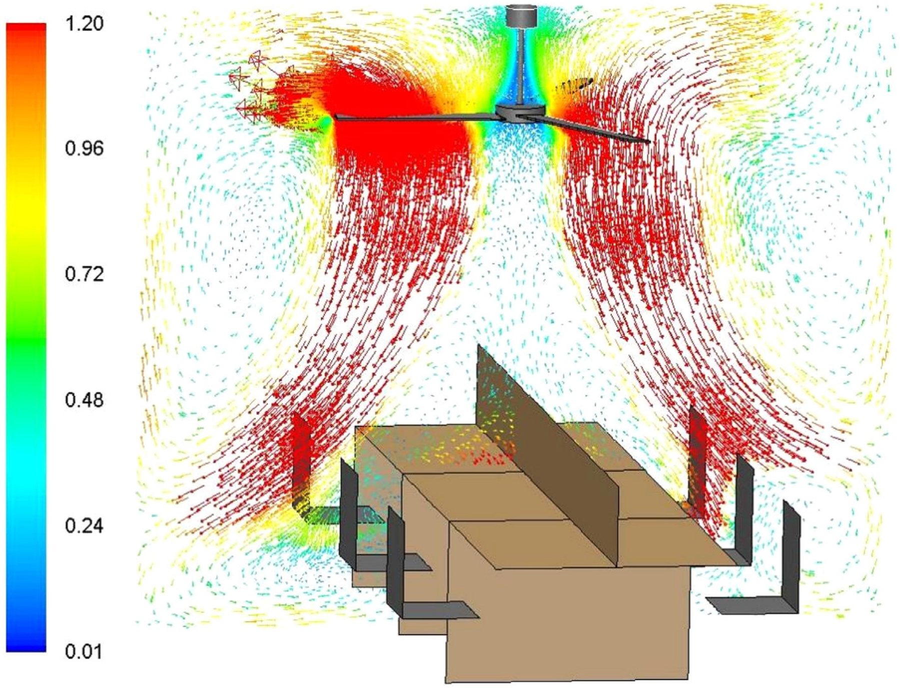

Fig. 10. CFD of a typical comfort ceiling fan in an office [60].

can be seen in Fig. 14 constructed through simulation software, whereby an air plume generated by supply airflow in façade mounted MVHR system.

MVHR systems have been documented to deliver adequate Indoor Air Quality as well as expected comfort levels. Their design is to deliver fresh, tempered air to every area of the ventilated space, as it can be seen on a CFD of the façade mounded MVHR below, which, in case of the risk of infection, appears to have similar airflow flow characteristics as recirculating ventilation modelled by the University of Oregon. More turbulent air flow at higher velocity is much more likely to mix with existing air and carry larger droplets further into the room, possibly spreading virus contaminated droplets around the room and leading to a higher risk of infection spread.

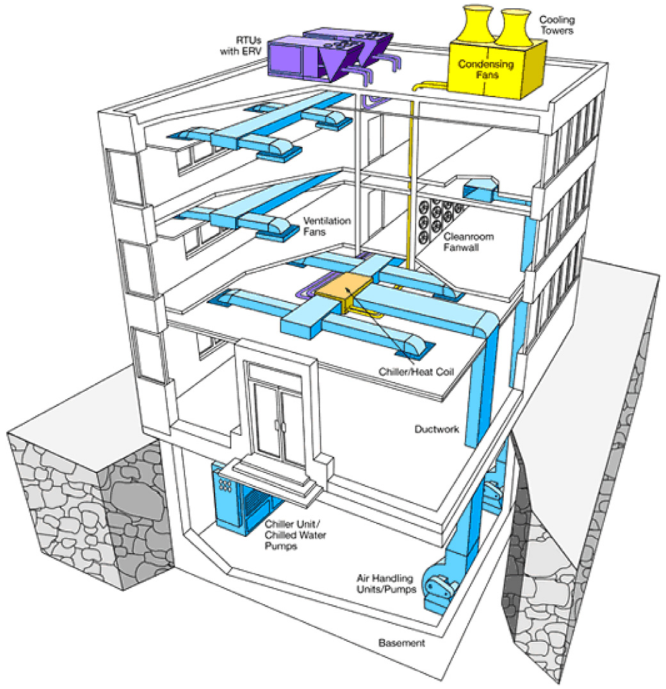

Fig. 11. Typical AHU ventilation arrangement with supply ducts located in ceiling voids [62].

As this is specific to air delivery design rather than the system characteristics, it may be possible to reduce the risk of infection by a careful redesign of the ductwork, its size as well as inlet and outlet location and sizing. It may also be theoretically possible to use MVHR as displacement ventilation in some cases if a complete change of installation design is possible. As much as this is an important area for further research, specific ventilation ductwork design or ventilation design guidance are outside the scope of this paper.

4.2.3. Positive input ventilation (PIV)

PIV is very similar in its airflow characteristics to positive pressure Air Handling Units described beforehand with the main difference being the local placement of the fan powered unit or system. The unit supplies the air into an occupied area with enough velocity to evenly distribute it throughout the space. Due to its design, it has similar air mixing characteristics as AHUs.

4.2.4. Summary of mixing ventilation systems

Although mechanical ventilation usually comes with better controllability, it can increase both capital and operating costs which are some of the drawbacks. The need for higher maintenance and the loss of performance when not effectively managed also need to be factored in. It was demonstrated that the severity of symptoms associated with sick building syndromes can be linked with the cleanness of the air filters and HVAC system. The occupants' symptoms were recorded by questionnaire before and after cleaning a part of the HVAC system and changing the filters. In the renovated section, the severity of the symptoms decreased while they remained identical in the untouched section. When using dirty filters, which is often the case in many high occupancy buildings equipped with such mechanical ventilation, the emissions from the used filters were found to increase with the outdoor airflow rate. Increasing the ventilation did not improved the air quality, while raising the operation costs [66]. The main difference between mixing and displacement ventilation can be seen in Fig. 15.

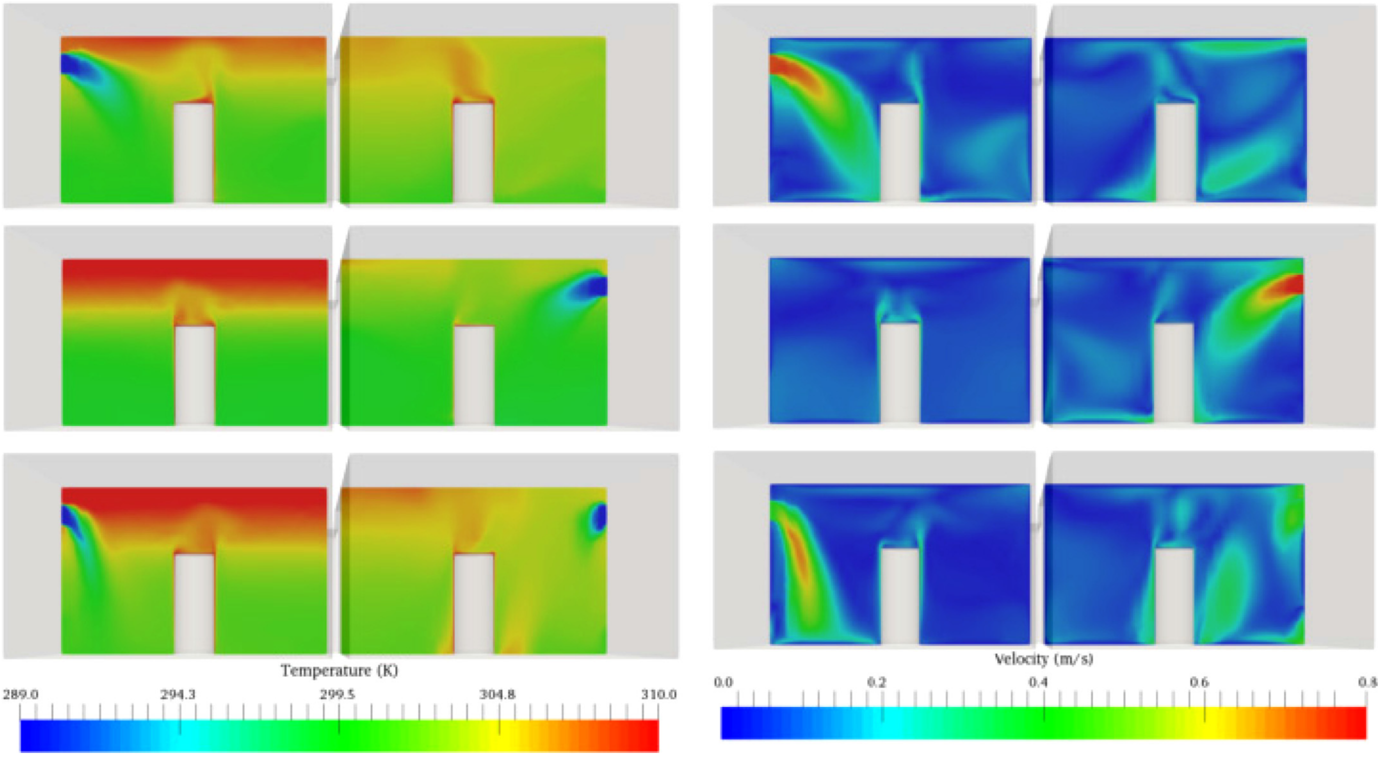

Fig. 12. Temperature and velocity distribution under the three mixed-ventilation systems scenario [63].

Fig. 13. Classroom MVHR system by Nuaire [64].

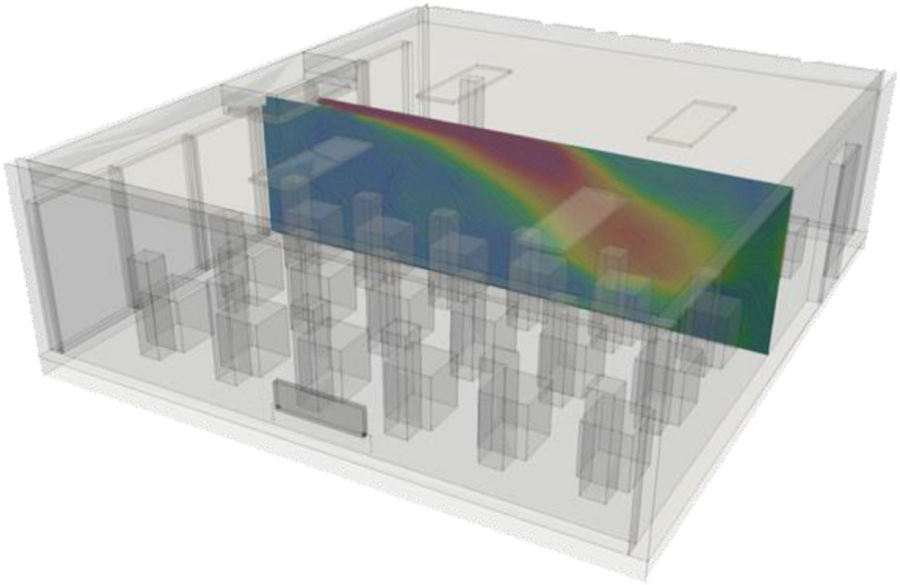

Fig. 14. Air plume generated by supply airflow in façade mounted MVHR system [65].

As much as the risk of recirculation is significantly lower or negligible within the ductwork, virus contaminated droplets can still be carried for long distances across occupied spaces by fan induced turbulent airflow. It may be theoretically possible, however, to design the air distribution ductwork and room diffusers in such a way as to reduce in-room mixing and thus the risk of airflow induced infection spread. Furthermore, there is even a possibility of adapting existing building services with COVID-19 specific office floor alterations. Further research into the possible development of such comfort, ventilation and indoor air quality provision is urgently needed so that designers, engineers and facilities managers can ensure occupant safety, especially in the light of the COVID-19 pandemic.

4.3. Displacement ventilation solutions

Displacement ventilation systems can be broadly divided into mechanical and natural. Mechanical displacement systems can service the entire building, often using a simplified version of Air Handling Units with centralised extract systems or with specific rooms, office floors or classrooms using localised extract systems. Continuous extract ventilation is more frequently used in domestic buildings and is currently used predominantly in bathroom areas in high occupancy buildings. Natural displacement ventilation approaches can include whole building integrated systems, room specific systems, ventilation products, such as passive ventilation cowls or specific wall integrated louvres. They can also rely on windows, either automated or manually operated, in which case they may be placed at the opposing ends of the room and at different heights with the exhaust located at a high level close to the ceiling, providing maximum displacement ventilation benefit. Brief examples of each approach are listed below:

4.3.1. Natural ventilation measures

Conventionally, the most economical way to provide ventilation was to rely on natural forces acting on air, taking advantage of atmospheric pressure differentials such as wind pressure moving air sideways or making use of the buoyancy of warmer air moving upwards. Fig. 16 shows three different Natural Ventilation examples: (1) the first illustrates the stack effect. Air enters the building envelop through interstices or ventilation apertures, the thermal load of the building (occupants or equipment) warms it, lowering the air density. The warmer stale air is naturally buoyant and moves upwards to the ceiling of the room or to the next floor through open staircase or elevator shafts. Exhaust openings at the top of the building release the stale air back to the atmosphere. (2) Cross ventilation relies on the pressure difference created by the wind. The windward facade acts as an obstacle which slows the wind down. On the leeward façade, the air is accelerated to the ambient wind speed creating a negative pressure. Therefore, fresh air infiltrates through one façade and exfiltrates through the opposite wall. A natural Ventilation compliant internal floor plan facilitates the air movement posing as little resistance to the airflow as possible while the external shape of the building can be used to maximise the driving pressure difference. (3) The third example is a solar chimney: Often also used as a staircase, its walls

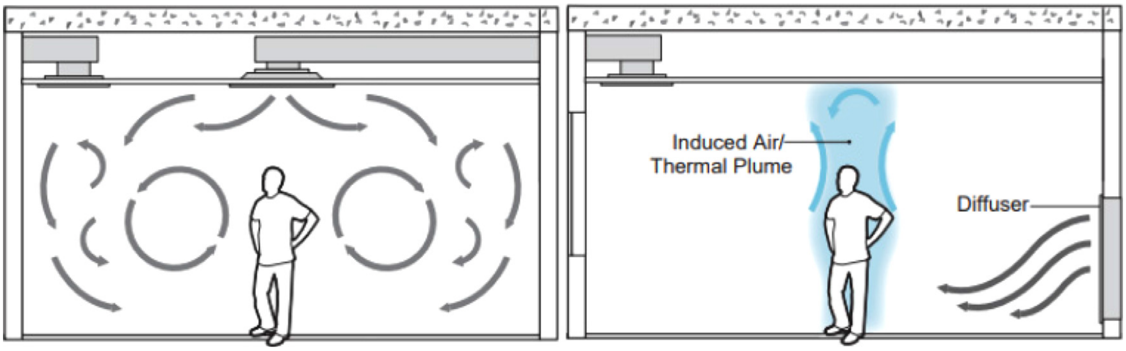

Fig. 15. Mixed vs. displacement ventilation system [63].

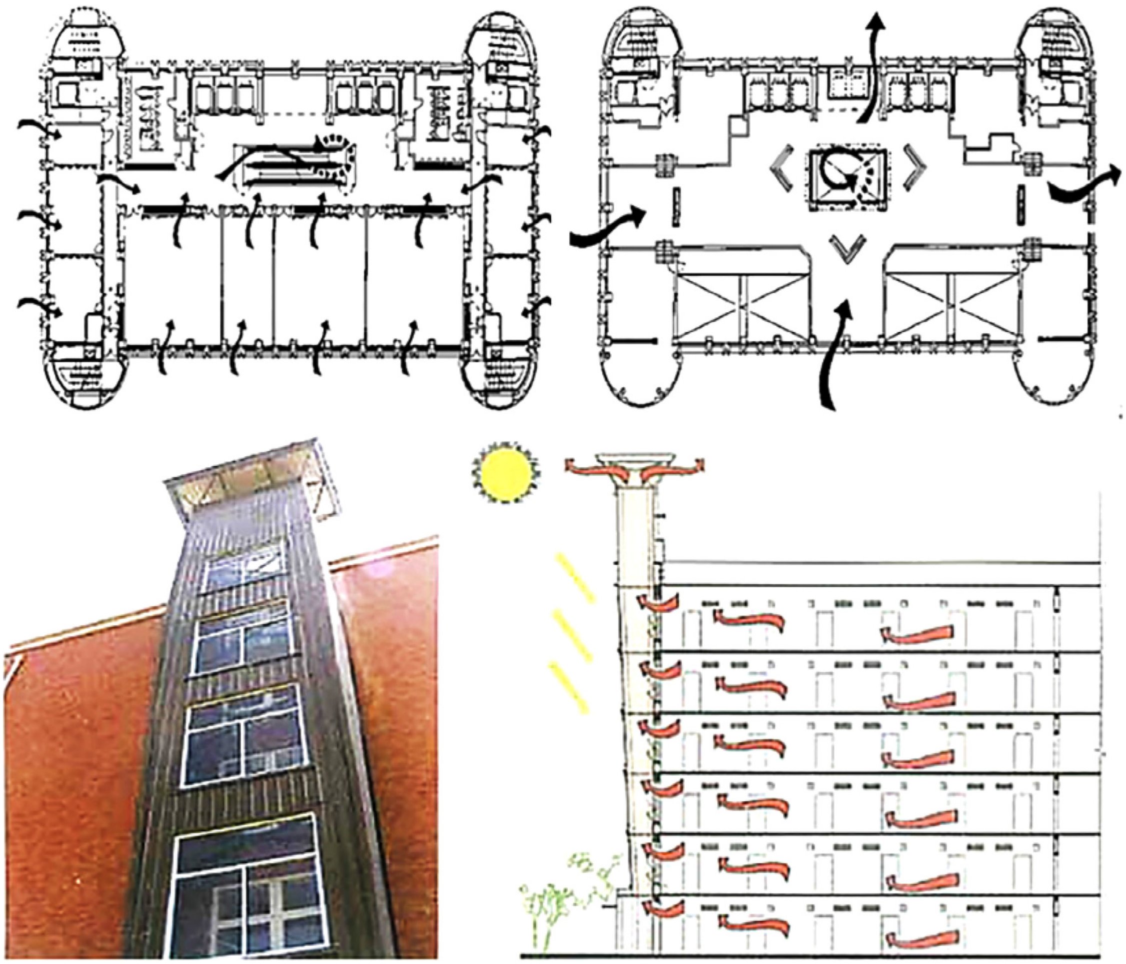

Fig. 16. Drawings of different natural ventilation solution: the top left drawing illustrates the stack ventilation principle. The top right drawing is a wind floor with cross ventilation, the bottom picture and drawing show a solar chimney [67].

are covered in radiation absorbent glass or other heat inducing façade material. The sun warms the wall and the air inside, boosting the stack effect. The warmed stale air floats to the exhaust opening faster while drawing air from all connected floors, increasing the ventilation rate [67].

Even though Natural Ventilation methods, including operable windows that are either manual or automatic, are one of the simplest methods of providing ventilation they frequently suffered the most from drawbacks such as bad design and implementation. Main design issues included calculating full window area as an opening, which in reality is often less than 1/10th of the window, locating windows in the wrong area or at the wrong height. As much as varied height cross ventilation can be effective, a row of short windows at mid height will generate almost no air movement, no solar shading and window related overheating, cold draughts, noise, incompatibility with interiors such as blinds or with the user behaviour.

The study by the University of Oregon [54,58] observed that Natural Ventilation with a plentiful supply of fresh air dilutes and removes contaminated air much more effectively than fan driven, recirculated air movement, significantly reducing the risk of infection, as shown in Fig. 17. However, ventilation design that requires the stale air to move across the entire floor plan, or through common areas such as hallways and staircases before being exhausted from the building, is understandably more likely to spread infection than when the stale air is exhausted at the source, directly to the outside. Considering the research conducted so far, if designed and implemented appropriately, natural ventilation measures, or a combination of localised mechanical exhaust and large cross section natural inlets, can provide an adequate displacement ventilation solution, significantly reducing the risk of infection.

A frequently quoted drawback of natural ventilation measures is the perceived lack of control and dependence on external factors such as wind speed and air temperature to provide fresh air. Moreover, the need to reduce the internal airflow resistance and maintain large openings and air pathways in large, building-integrated natural solutions reduces the possibilities for noise dampening or provision of adequate temperature management. In noisy, hot or cold environments, this ventilation strategy is often rejected in favour of mechanical ventilation solutions which are simpler to design and do not require familiarity with building physics.

4.3.2. Natural ventilation systems

As opposed to building integrated ventilation methods or measures such as opening windows, the natural ventilation systems are products that can include roof mounted cowls and/or façade integrated elements. They can be designed or sized specifically for the application, be it a classroom or a sports hall. The systems rely on either the roof cowls to both supply fresh and extract stale air or on façade elements entirely, in which case, they would be placed at the top and bottom of each space to maximise the stack effect. Some natural ventilation products can include heat recovery or comfort cooling. Most of these systems can ensure displacement ventilation with little contaminated air mixing, as long as used with appropriate internal air dividers, as illustrated in Fig. 18. Various examples are listed below:

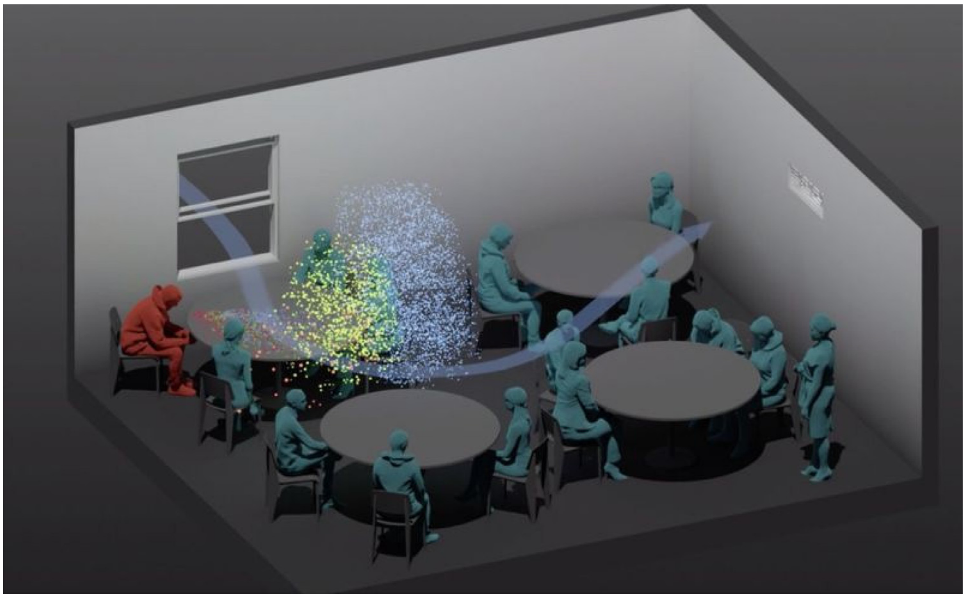

Fig. 17. The simulations showed how fresh air from an open window could carry the virus to a vent, University of Oregon [68].

Roof mounted natural ventilation systems: these have been available for many decades and successfully used in schools and other low-rise high occupancy buildings. Their use has declined in recent years due to comparatively higher capital costs than simple mixing systems and the lack of a heat recovery function, although overall energy consumption is reduced due to the lack of fans and the associated electricity use and heat recovery systems have recently become available. These systems are available from several UK manufacturers.

Roof mounted natural ventilation systems with heat recovery: these are relatively new additions to the natural ventilation product range, even though the addition of heat recovery to Natural Ventilation has been researched considerably with several academic publications considering heat transfer with heat pipes or thermal wheels in order to improve natural ventilation whilst saving energy. Their operation is broadly similar to the standard roof cowl systems in terms of air movement, and can also include façade integrated ventilation for boost, with the addition of heat recovery capability which reduces ventilation related heat loss, further increasing energy efficiency. An example of this mechanism is shown in Fig. 19: Ventive Windhive (Natural Ventilation with Heat Recovery) systems (Fig. 19). Numerous academic papers covered the use of Natural Ventilation systems, both with and without heat recovery, and demonstrated that, when appropriately sized and designed, they work very effectively [69–71].

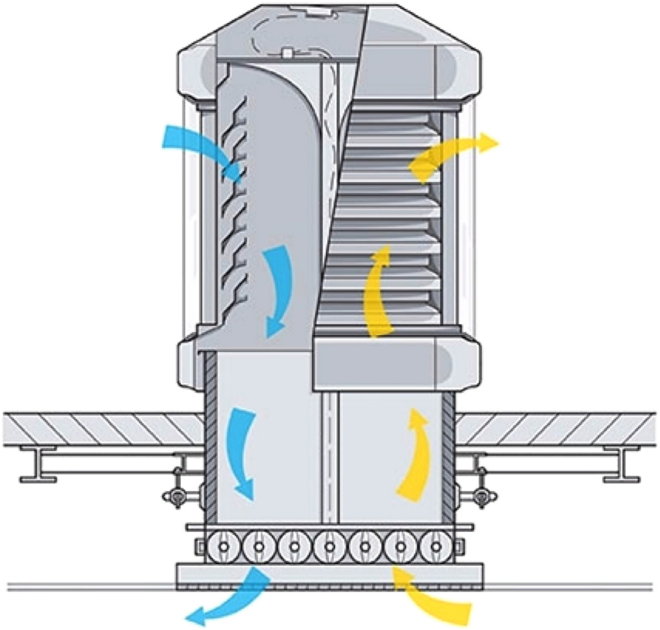

Fig. 18. Monodraught Windcacher X-Air [68].

Façade mounted natural ventilation systems: these could be stand alone or have additional heating: These are generally automatically actuated façade openings with a room matching grille on the inside and a weather louvre on the outside, located at both high and low level in the room. Depending on CO_2 concentrations, one or both dampers would open automatically to provide the required, buoyancy driven airflow. In some cases, these systems may include a heating coil, to reduce the cold drafts that could be generated during winter in the absence of a heat recovery function. If required, they can also include a bank of acoustic attenuators to reduce external noise transfer to the indoors as shown in Fig. 20.

Intelligent façade mounted systems with heat pump: latest technology developments include the addition of a heat pump to façade mounted Natural Ventilation systems to provide both the heat recovery feature. This feature is implemented by transferring heat from the exhaust vent to the supply vent with the help from a low power compressor as well as heat pump driven summer cooling as shown in Fig. 21. The general operation is the same as for the twin façade system noted above – fresh air is supplied at low level with the exhaust mounted at high level. However, unlike the above, the incoming air is tempered to improve occupant comfort using the exhausted air energy – either warmed in winter or cooled in the summer. The usual electrical consumption of the compressor is, in part, offset by the reduced electrical consumption due to the absence of fans. The other potential benefit of the system is that the summer cooling tends to boost natural ventilation by heating the exhaust air above the ambient temperature enabling the natural ventilation equipment to maintain adequate air flows all year round.

4.3.3. Hybrid displacement ventilation (Mechanically assisted)

A school in Grong in Norway implemented hybrid bidirectional ventilation, shown in Fig. 22, for the provision of the required Indoor Air Quality based on a balance between supply and exhaust air.

Fig. 19. Ventive Windhive (Natural ventilation with heat recovery) systems.

Underground ducts connect the basement of the building to the wind tower. The mechanism in which this ventilation strategy works relies on air entering the tower further down the school field either naturally or using a fan, depending on the available buoyancy. The air is then driven under the school through a duct entering the rooms through the lower level then rising due to buoyancy, leaving the building through the chimney-like stack. The ventilation rate for each room is controlled by the degree of opening of the exhaust damper and the optional extraction fan. This type of system is simple mechanically, and offers fresh air either naturally, during winter, or using fans when buoyancy is too weak to drive the airflow, with compressor driven heat recovery that utilises a centralised concept for ventilation [72].

4.3.4. Mechanical extraction ventilation

A study in a school in New-Zealand highlights the positive effects of a better ventilation strategy on airborne particles. Two adjacent classrooms were monitored and compared, one with continuous mechanical extraction ventilation solutions and the other where the occupants were relied on to open windows. The levels of inorganic airborne particles were monitored to show how they were removed from the breathing space. The first room was equipped with a unidirectional ventilation system consisting of a fan assisted solar roof prototype with a double-layer roof made of a polycarbonate layer over a steel corrugated north-facing roof, where outdoor air was passed between the two layers, while the other classroom had no specific ventilation system with manually operable windows as the only means of ventilation. The goal of the study was to assess the air quality and the effect of ventilation on reducing respiratory and cardiovascular diseases associated with poor air quality. Air samples were measured to identify the number of inorganic particles sizing under 10 μm. The exhaled airborne particle concentration and dilution provided by the ventilation system follow the same trend, since, at this size, aerodynamic forces prevail over gravitational forces as explained in Section 2.1. The ventilated system provided 32.3 L/s of tempered outside air, or approximately 0.6 air change per hour, for a classroom volume of 200 m^3. The unidirectional ventilation system reduced the average CO_2 concentrations by 27%, from 1345 ppm to 980 ppm, and average moisture content by 12%, from 9.08 g of water per kg of dry air to 7.98 g of water per kg of dry air. The actively

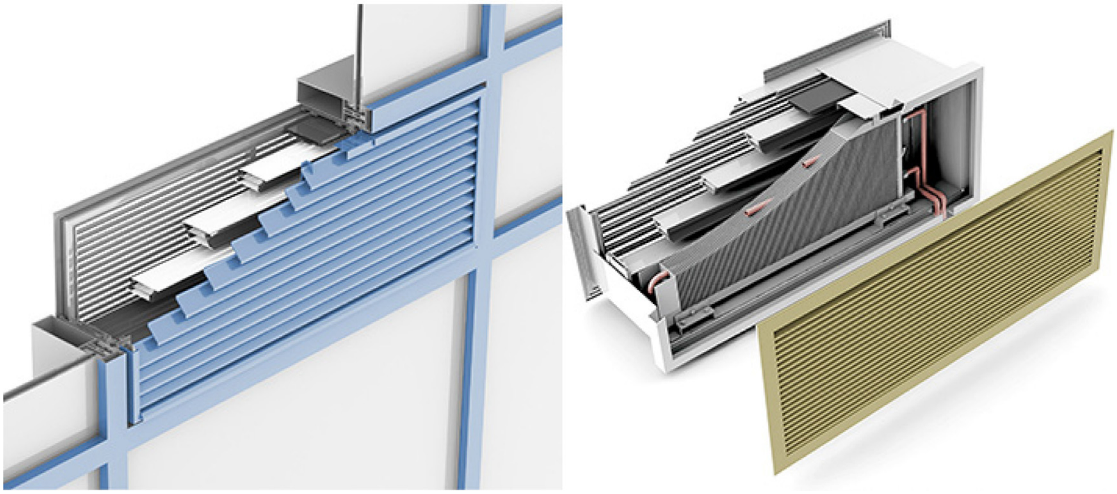

Fig. 20. Passivent aircool and thermal aircool.

Fig. 21. Ventive active (Natural ventilation with heat recovery, heating and cooling).

ventilated classroom had on average a 66% lower concentration of airborne particles sizing under 10 μm than the unventilated classroom as shown in Fig. 23 [73].

Displacement ventilation systems, such as natural ventilation, naturally assisted extraction ventilation and continuous mechanical extraction ventilation, appear to be the most promising ventilation solution in terms of reducing the spread of viruses and other pathogens indoors This is mainly due to the lower air flow velocity, non-turbulent air flow characteristics and a much lower likelihood of air mixing occurring within the ventilated spaces. This observation is investigated further using Computational Fluid Dynamics in the next section.

5. Airflow characteristics in natural displacement ventilation systems using CFD

Two of the above listed displacement ventilation systems have been selected for further analysis of room specific airflow dynamics and its potential impact on exhaled droplet and pathogen distribution through occupied spaces to assess their impact on the potential spread of infection: (1) Roof mounted Natural Ventilation with Heat Recovery and (2) The Façade mounted Naturally Intelligent Ventilation system with heat pump. Due to their similarity to each group of the Natural Ventilation Systems mentioned above, we consider the

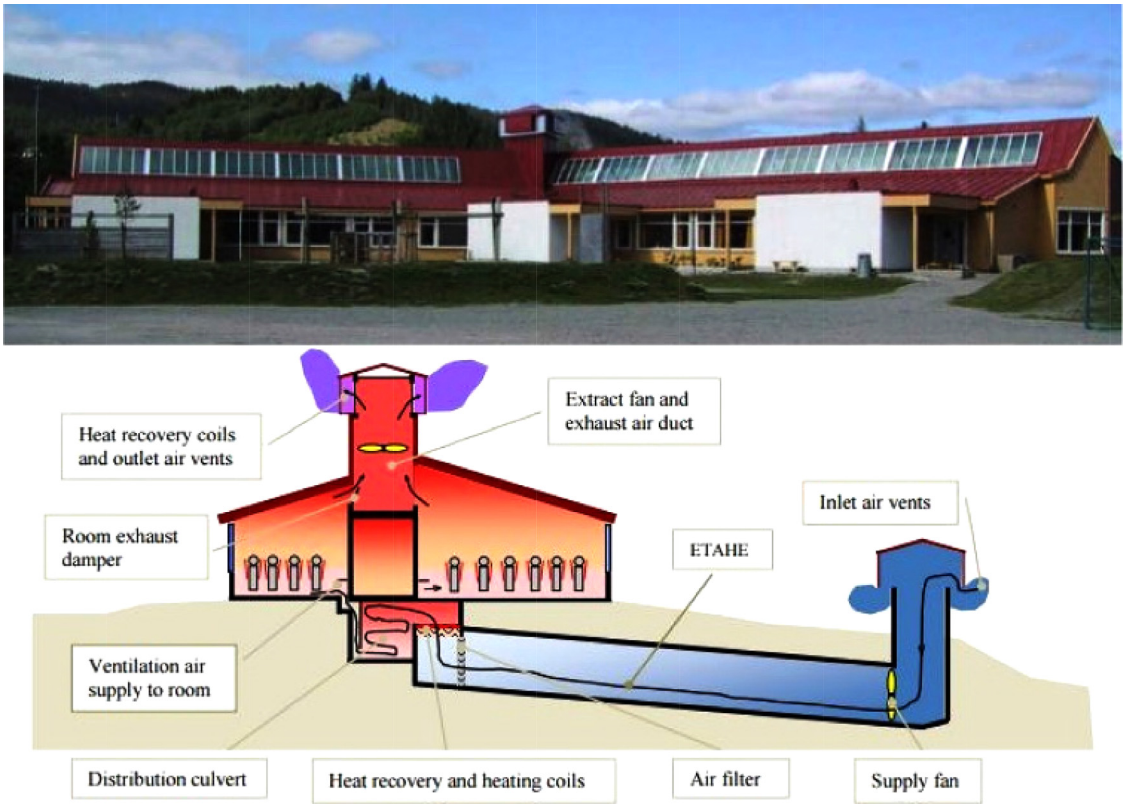

Fig. 22. Photo and schematic of a ventilation mechanism implemented in a school [72].

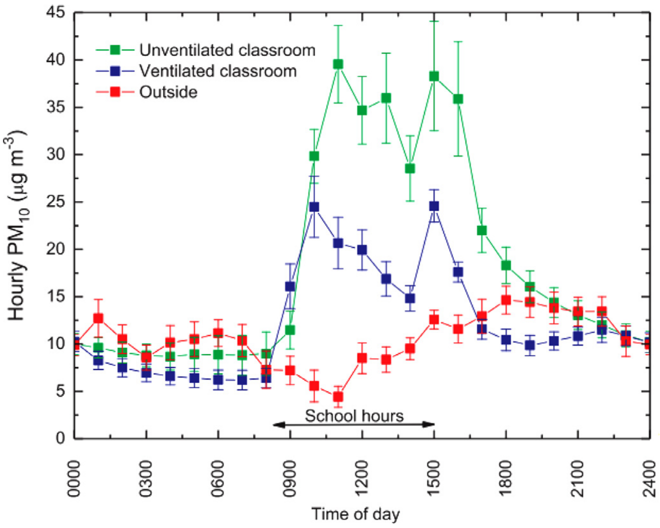

Fig. 23. Weekday plot of inorganic particles <10 μm (PM$_{10}$). Error bars show the standard error of the data measured during the 3 weeks test [73].

results of the CFD modelling to be representative across the roof mounted and façade Natural Ventilation range.

Both of the selected systems appear thermally and physically well designed to be able to passively ventilate occupied spaces whilst recovering heat through either passive or active methods, using wind speed, wind pressure and air buoyancy to drive the air flow. Under normal circumstances, a natural ventilation strategy has many benefits over mechanical or fan-powered systems, including lower carbon emissions, reduced operating costs, and ease of installation. According to the research mentioned above, it also appears to have measurable advantages when it comes to reducing the risk of infection spread indoors – this is further investigated below.

To aid in the assessment of expected airflow and classroom comfort levels achieved in-situ for two displacement systems, a Computational Fluid Dynamics study has been carried out. The CFD study aims to quantify the steady state performance within a school classroom for the following two Natural Ventilation systems with Heat recovery: Ventive Windhive and Ventive Active. The overall ventilation performance will be quantified in terms of the simulated CO$_2$ concentration levels within the classroom alongside more specific modelling results of the temperature and, most importantly, air velocity and airflow characteristics.

5.1. Geometry description

The global setting for the analysis of the two ventilation systems is that of a fully enclosed classroom, with dimensions 3000 h x 7000d x 8000 w (mm), where: h is height, d is depth and w is width. The classroom is occupied by 30 seated students with corresponding chairs and tables as shown in Fig. 24 for the Ventive Windhive system.

To enable a true representation of the Natural Ventilation system's working environment an additional region is included to represent the outside ambient with dimensions 10,000 h x 10,000 d x 10,000 w (mm). Although the two ventilation systems will be modelled in the same working environment, the configuration and set-up of each unit is different, and therefore each will be presented separately for clarity.

The Windhive system, shown in Fig. 24, is a roof-mounted unit, with the indoor diffuser located at an arbitrary central location such that it is not positioned directly above any person.

The Ventive Active system, shown in Fig. 25, has a different buoyancy driving set-up utilising the external wall of the classroom with the supply unit located no more than 200 mm from the floor level and the extract unit located at the top of the room (preferably 2.4 m from the finished floor level or higher).

5.2. Model description

Following the finalisation of the geometry an idealised room specific 3D model of each set-up was created using CAD software before being imported into Star-CCM+ v13.06. To help reduce the computational expense of the simulations in terms of mesh and physics several modelling assumptions were made, these are listed below:

- Simplified geometry for the children and desks to act as the sole obstacles in the classroom
- U value of 0.5 W/m^2/K applied to the walls to account for an average heat flux
- Each child assumed to act as a heat source producing 70 W (equating to a total heat source of 2100 W)
- Wind, solar gain and equipment loads including lighting and airtightness are ignored
- Grill losses located on the Invent Active and Passive are accounted for through specification of a porous medium with an effective opening of 85% and a porous inertial (α) and viscous (β) resistance of 1.77 and 1.71 m/s, respectively
- To achieve a realistic outside ambient a small constant velocity field ([0.1] m/s) is active across the length of the domain, in order to account for natural wind and to help initiate a flow solution. This is adopted also for the additional ambient region within the Invent Passive simulation to account for the open window.
- Ambient and initial temperature field is equal to 10 °C
- Initial classroom CO$_2$ level is set at 450 ppm whilst the ambient/environment is equal to 400 ppm
- Each child is presumed to provide a CO$_2$ release rate of 0.035 m^3/h equating to a bulk class CO$_2$ supply of 1.05 m^3/h

The aim is to complete two independent CFD simulations, one for each of the Natural Ventilation systems. Each simulation will operate with a multi-component gas as the working fluid, separated such that the CO$_2$ and other components of air are modelled independently.

The chosen software package for all simulations is that of the commercial CFD package, Starccm+ V 13.06, supplied by SIEMENS. This is a well validated CFD code that is widely used throughout both industry and academia.

5.3. Mesh details

To provide a solution domain suitable for the CFD solver the 3D model must be discretised into a series of smaller fluid volumes by successively splitting nominally hexahedral cells until a desired cell size is achieved. The accuracy of a given simulation is largely controlled by the size and quality of the cells and therefore a number of refinement regions in areas of interest were created. It should also be noted that a grid independent solution is achievable, at this point further reduction of the cells will only account for a higher computational cost instead of improved accuracy.

All meshes presented here have been generated using a trimmed cell mesh with local refinement regions and prism layers to account for the near wall effects. Each mesh is illustrated below with the total number of cells for each specified.

The total number of cells used for the Windhive model is 9.5 million. An image of the mesh for Windhive is shown in Fig. 26.

The total number of cells used for the Invent Active model is 7.7 million. An image of the mesh for Windhive is shown in Fig. 27.

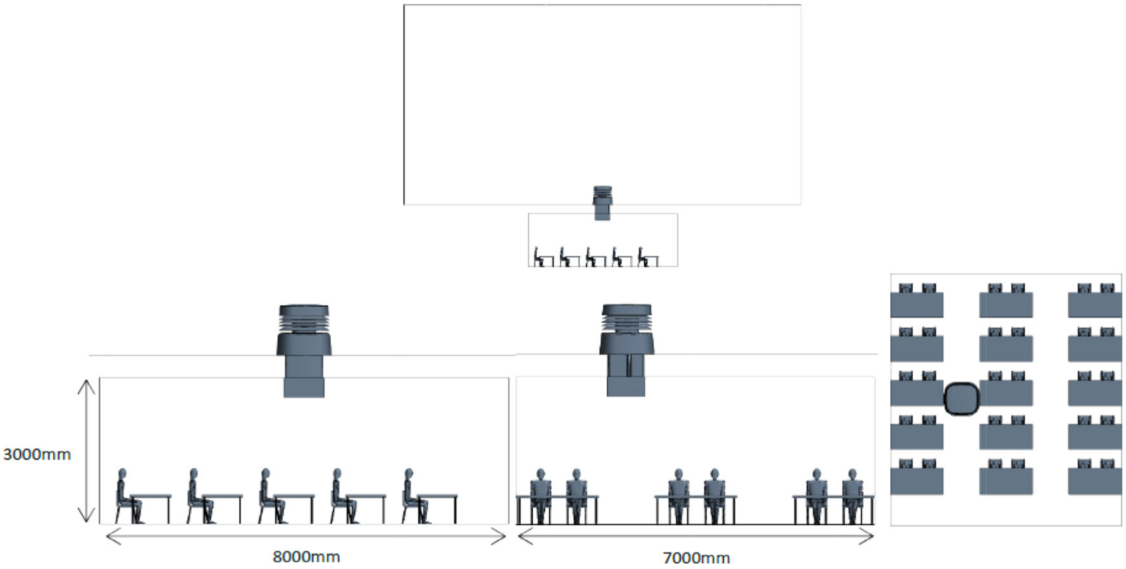

Fig. 24. Image showing classroom geometry for Ventive Windhive.

5.4. Simulation results and discussion

Fig. 28 shows the velocity scenes for the two cases for vertical and horizontal cross-sections. For both systems it can be seen that the greatest flow speeds are experienced at the inlet and outlet locations, with both the Ventive Windhive and Ventive Active showing the greatest velocities regarding the inlet stream. It also provides a top down projection of a 1 m velocity slice, directly in-line with the heads of the seated students. This image shows more clearly the locations and magnitude of the incoming air stream of the Windhive. It must be noted that the Ventive Active's inlet is below this point.

Table 4 indicates the mass and volume flow rates calculated at the inlets and outlets of the two respective systems. The greatest flow rate is provided by the Windhive (150 l/s) even without the wall purge opening whilst the Active is somewhat lower in the fully passive operation mode (113 l/s). The stated flow rates relate to values of 4.8 l/s (Ventive Windhive), and 3.6 l/s (Ventive Active) per person with reference to 30 children and 1 teacher.

An important factor aiding in achieving a desired level of CO_2 within a room is the total rate of air change in one hour. Based on a classroom area of 165 m^3 the estimated number of air changes per hour for the two configurations (based on the inlet flow rates provided in Table 4) are calculated as:

- Windhive = 3.3 air changes per hour
- Ventive Active = 2.5 air changes per hour

Stagnation regions are possible for such systems according to the model whereby Fig. 28 shows the velocity profiles. However, people within such environment tend to stand up and move around slightly which will induce further air movement within the stagnated air regions.

The CEN Report CR 1752 Ventilation for buildings states that if seated occupants are the only source of pollution then the CO_2 concertation should be below 800 ppm for category A, 1000 ppm for category B and 1500 for category C, where the outdoor ambient level is quoted as 350 ppm. Category A represents a high level of expectation, recommended for fragile and sensitive persons like young children, elderly, sick or handicapped persons. Category B is the normal level of expectation that should be considered for new buildings or renovations. Category C represents moderate level of expectation that may be used for existing buildings [74].

Expectedly the Windhive configuration provides the most air changes over a given period due to its higher flow rates, and this correlates to a more favourable mass fraction of CO_2, as shown in Figs. 28 and 29. Although it should be noted that despite having a lower rate of air change, the Ventive Active reduces the levels of CO_2 comparably to the Windhive. Both these systems appear to be able to maintain the initial CO_2 conditions through the regular exchange and circulation of air throughout the room.

The distinct airflow profiles of both Natural Ventilation systems shown above are of great interest in relation to spread of coronavirus and other pathogens indoors. The supplied fresh air is observed to distribute evenly at low level (well below the breathing, and

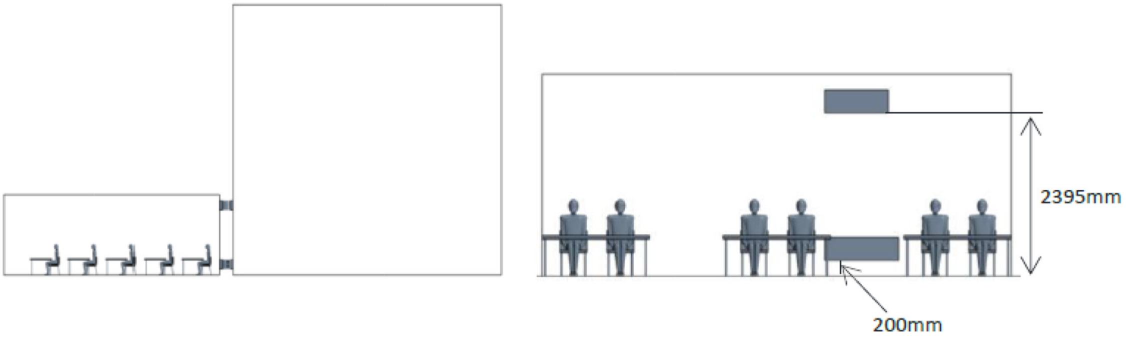

Fig. 25. Image showing classroom geometry for the Invent Active.

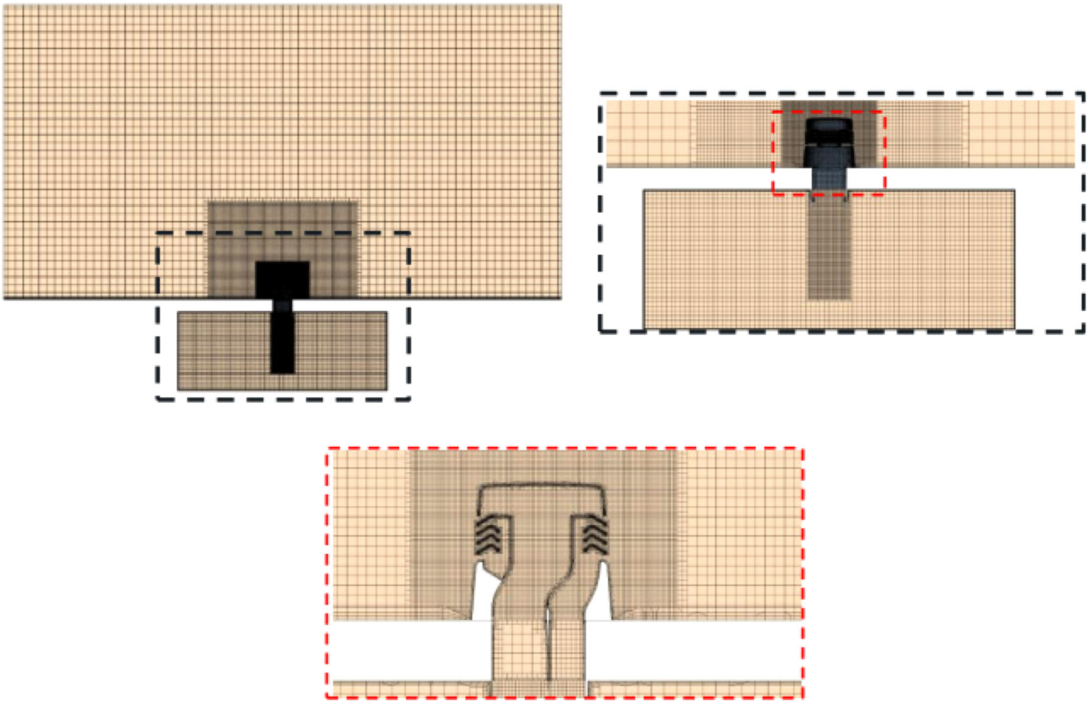

Fig. 26. Image showing the mesh for Winhive system.

especially exhaling, area) at a higher volume but lower velocity than fan induced ventilation (thus is much less likely to pick up heavier droplets already dropping to the floor) while the stale air appears to move steadily upwards before being exhausted out of the building, with no observed mixing indoors. This, in combination with the low observed CO_2 levels (which are a good proxy for contaminated, exhaled air) as well as the prior research listed above (where, unlike mechanical and recirculating ventilation, the cloud of droplets and particles is not pushed around the room but instead travels in a fairly direct line from window to the exhaust vent, resulting in fewer people being exposed to it), indicates that Natural Ventilation has a much lower risk of spreading the droplet and aerosol borne infection indoors than other ventilation methods. This displacement and stacking effect in interesting also since it protects the occupant regardless of the configuration off the room: For example, younger children often sit around large table instead of rows. By moving the stale air upward the concentration at the breathing level is reduced as well as the infection risk.

6. Discussion

Airborne disease transmission is highly contagious in enclosed environments and especially in buildings with inadequate or inappropriate ventilation systems. The theory shows that small droplets of less than 10 μm in diameter have the potential to remain in the air for hours since their terminal velocities would be at 3 mm/s, depending on various characteristics and conditions at the time. With the unprecedented pandemic of the COVID-19 spreading through the society at an extremely fast pace, many academics and industry professionals are raising the question of whether the current ventilation strategies are outdated and inadequate for such contagious diseases. Even though the widely accepted mechanism of SARS-CoV-2 transmission to the date of writing this article has been through droplet borne pathways, the WHO is accepting the possibility that the deadly virus could be transmitted through the air. Many research studies have shown that with appropriate ventilation, the risk of transmission is greatly reduced, further emphasizing the need for research

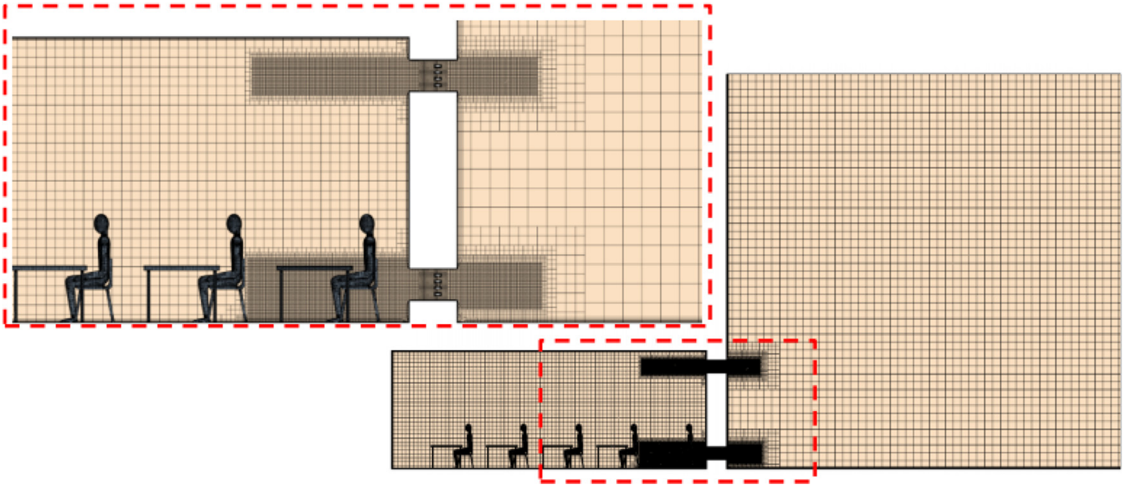

Fig. 27. Image showing the mesh for the Invent Active system.

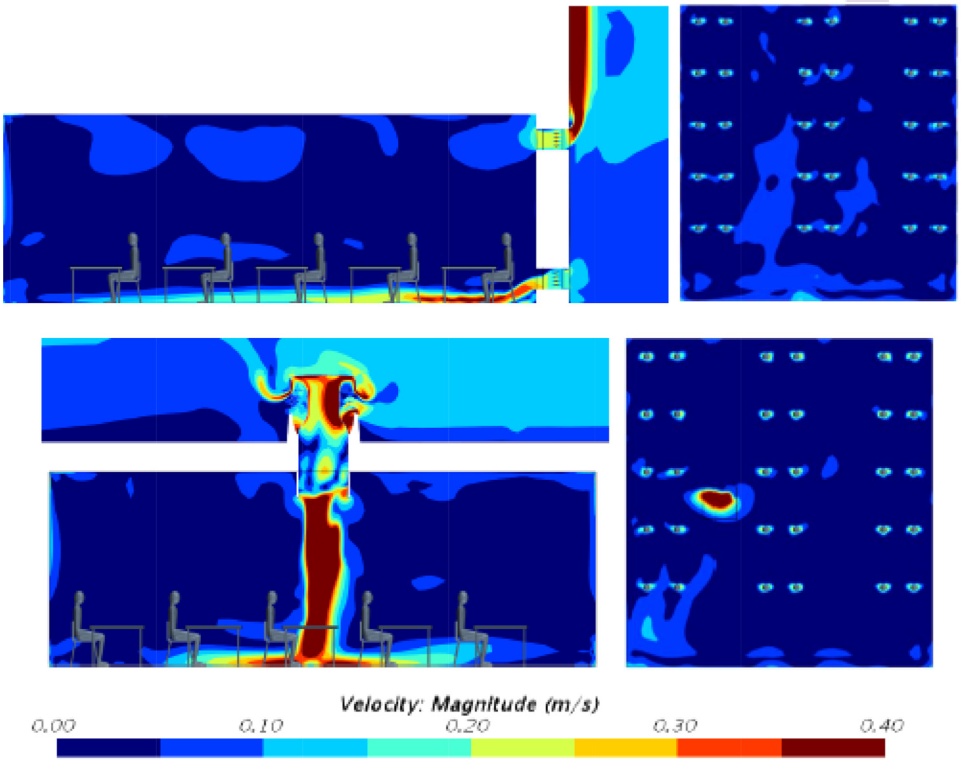

Fig. 28. Velocity profiles for; top) Ventive Active, Bottom) Ventive Windhive. Slices taken along the classroom centreline from a side perspective and at a height of 1 m with the camera angled from above.

into and adaptation of current ventilation methodologies. Furthermore, an insufficient ventilation rate and inappropriate ventilation strategy (mixing of in-room or recycled air, poor mechanical ventilation maintenance) have been linked to degraded health outcomes for the users of high occupancy buildings. This includes facilitated airborne transmission of diseases, sick building syndrome, increased sickness absence and reduced cognition.

This paper has reviewed widely used ventilation strategies adopted in high occupancy buildings such as schools and offices. The currently accepted approach to reducing airborne disease transmission recommended by various industry associations (ASHRAE, CIBSE) as well as the World Health Organisation is to increase the ventilation rate using plentiful fresh air to dilute the contaminant to a safe level. In many schools and other high occupancy buildings, the target ventilation rates are rarely met. The benefits of better health and attendance and resultant economic outcomes largely outweighed the capital investment of installing, renovating, or retrofitting appropriate ventilation solutions, even before the COVID-19 pandemic. As can be seen above, the most commonly used ventilation approaches are inadequate when it comes to lowering airborne transmission risks. Different strategies were reviewed with CFD examples to consider their impact on the pathogen propagation indoors. It seems beyond doubt that recirculating ventilation strategies should be avoided as they limit and prevent the dilution of harmful particles while also facilitating the distribution of stale, possibly contaminated air throughout occupied spaces. As the occupancy of the room increases (expressed in time and number of people), so does the exposure. Mixing ventilation approaches are also disadvantageous as they may increase the range of infectious particles within the room and the range of sizes of particle that can sustainably remain airborne. Displacement ventilation with a generously sized natural inlet is preferred as it can move stale, contaminated air directly to the exhaust of the room in a laminar fashion whilst the concentration of small droplets and airborne particles in the indoor air is significantly reduced. The mode of ventilation can be achieved by either fully natural ventilation or natural supply with a mechanical extraction strategy. Natural displacement ventilation offers many other advantages such as reduced power consumption and low maintenance costs. On the other hand, some natural ventilation systems may lack controllability or a heat recovery, both of which can be addressed through careful system selection (ensuring sensor-based responses as well as automatic actuators for the supply and exhaust openings) and good design practice. Mechanical solutions have an energy consumption penalty due to the use of fans and may require larger capital investment and maintenance costs. If balanced mechanical systems are to be considered, a significant, research based, re-design effort is required with larger ductwork and openings to avoid high air velocity and in-room mixing ventilation dynamics which currently can defeat the purpose of ventilation by increasing the concentrations and the range of the infectious particles. It has also been demonstrated that the use of filters can prove detrimental when not properly maintained and regularly cleaned or changed. On the other hand, the use of mouth and nose covering, such as 3 ply masks for example, directly impact the quantity of droplets and particles emitted by the occupants in the indoor volume. In practice, the constant use of these masks can reduce the comfort level of the occupants and may be difficult to enforce in high occupancy buildings since it relies on the cooperation of each individual and following procedures. Whereas, the implementation of a natural displacement ventilation systems passively offers an additional form of transmission risk reduction.

Table 4
Mass and volume flow rates calculated at the inlets and outlets of the respective systems.

Utility	Mass flow rate (kg/s)	Volume flow rate (l/s)
Ventive Windhive	0.178	150
Ventive Active	0.136	113

Two Ventive natural displacement ventilation systems were chosen for study using CFD simulations. The large air volume combined

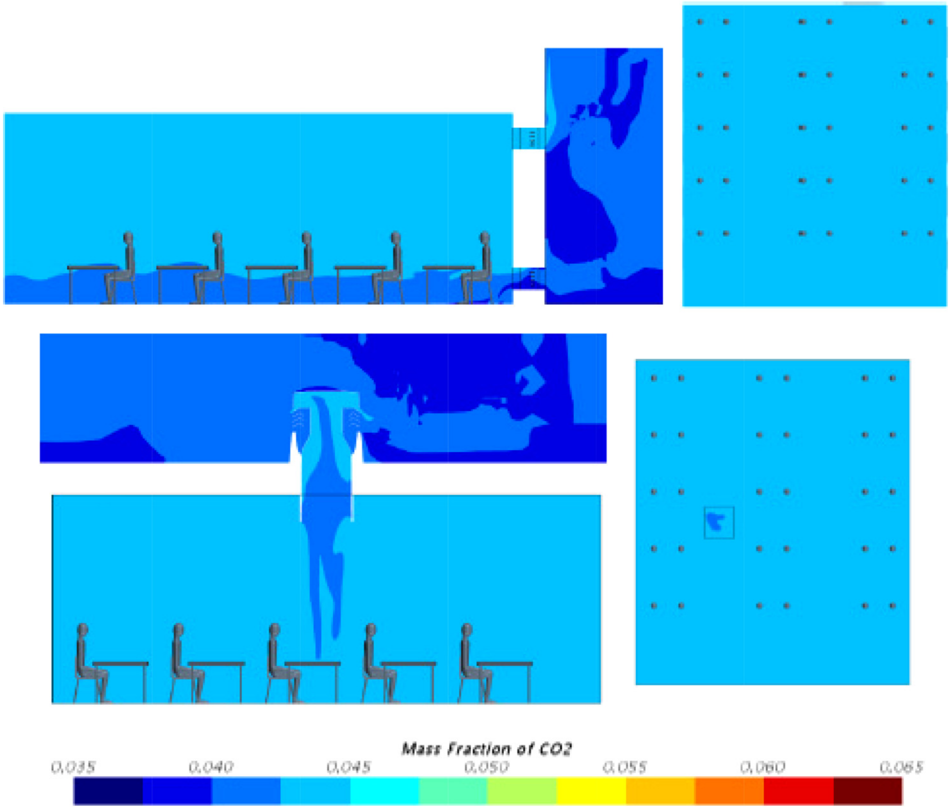

Fig. 29. CO_2 mass fraction for, top: Ventive Active, Bottom: Ventive Windhive.

with low airflow speed allow sufficient quantities of fresh air to be supplied into the space, distributing evenly through the bottom of the room and gradually displacing the stale air to the top of the space thanks to the buoyancy-driven stack effect. The advantages of this type of ventilation strategy are that it can significantly reduce the risk of airborne disease transmission. It provides large volume ventilation at low air speed, which facilitates a stratification effect. This stratification effect along with the appropriate placement of air inlets and outlets allow a natural and almost universal upward flow of air to the top of the room and out through the appropriate exhaust vents. This restricts the horizontal movement of airborne particles which contain pathogens that are produced when infected individuals breath, speak or cough, capturing the smaller droplets to migrate almost upwards, while allowing larger droplets to fall out of breathable level air, vastly reducing the risk of disease transmission via indoor air. The large volume of fresh air supplied into rooms lowers the concentration of other contaminants in the room and increases the IAQ to desired levels. As an added benefit, in both closely studied systems, the heat recovery capability and dynamic, connected controls both increase comfort levels, making the high air refresh rate more bearable for occupants, and enable remote adaptation of ventilation provision, which improves the response of facilities managers to risk levels.

7. Conclusion

Building Services of high occupancy buildings must be better adapted as a matter of urgency to facilitate the reduction of disease transmission resulting from inappropriate or inadequate ventilation. The COVID-19 pandemic has exposed areas requiring urgent development to protect both our health, wellbeing and the economy by providing safe indoor environments for employees or students. This paper has demonstrated possible routes for indoor disease transmission, the mechanisms in which diseases can spread, facilitated by conventional ventilation systems, the gaps in current knowledge and technologies and areas of interest for future research and development. Although many cases of disease transmission can be reduced by social distancing or wearing the recommended PPE, the air surrounding us indoors requires much better management to safely remove air borne pathogens. Many of the current ventilation strategies that rely on centralised air distribution and ceiling level supply or recirculation can provide the optimum conditions for rapid disease spread in high occupancy buildings. On the other hand, displacement ventilation strategies, such as the natural ventilation or naturally assisted ventilation explored above, can provide an effective starting point for reclaiming our buildings for safe use. However, significant gaps remain in the knowledge needed for the development of more personalised ventilation mechanisms at an economic level to allow for adaptation of already installed ventilation systems to help mitigate the risk of infections in existing buildings.

Declaration of Competing Interest

None.

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