Rethinking different ventilation strategies in a post-pandemic era: a CFD assessment

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ABSTRACT

The world has experienced the devastating nature of airborne transmitted diseases through the COVID-19 pandemic. Significant actions were taken in order to reduce the number of new infections, such as quarantines, social distancing, mask wearing, frequent hand washing and surface disinfection. However, all these measures have proven insufficient to eradicate short and long-range infections, confirming the need for engineering tools to control the indoor air quality. Although the role of ventilation design in the minimization of indoor pollutants has been widely discussed, its performance has been linked to energy efficiency. General-volume ventilation strategies have been predominant. However, in a dynamic indoor environment, airflow patterns increase or decrease the risk of airborne transmission at local points, making this consideration an unsuitable option to provide clean air in the breathing zone. The present research demonstrates the purging efficiency of breathing-zone-volume ventilation against the traditional general-volume choice by comparing mixing, stratum and impinging jet ventilation. CFD has been used to predict indoor airflow, simple thermal sensation through draught discomfort and purging efficiency through age of air in a general-purpose building applying RANS modelling. Results show that breathing-zone-volume strategies significantly improve the age of air under cooling mode and sustain or slightly improve it under heating mode. However, draught sensation slightly increases in all the cases. In conclusion, a balance must be reached in this post-pandemic era to satisfy the design triad: purging efficiency, thermal comfort and energy efficiency without sacrificing one of these three elements.

KEYWORDS

Breathing-zone-volume ventilation; Age of air; Air draught; RANS; Steady-state

1 INTRODUCTION

Pandemics and epidemics have historically impacted the development of public health and the surrounding environment: the Bubonic Plague (18th century) contributed to urban planning, the Cholera epidemics (19th century) encouraged sanitary protocols, and the Spanish Flu (20th century) promoted non-pharmacological interventions as mitigation strategies for disease control (Lai et al., 2020). The recent COVID-19 pandemic (21st century) has also exposed the need for prophylactic measures and the value of non-pharmacological interventions such as social distancing, mask-wearing and the control of the built environment (Kwon et al., 2021). Furthermore, pandemics caused by airborne transmitted diseases have increased in the past decade, as evidenced by the SARS-CoV-1 outbreak in 2003 (Asia), MERS-CoV in 2012 (Middle East) and SARS-CoV-2 in 2019 (worldwide), because of technological and demographic changes (Baker et al., 2021). Following history, building design and ventilation control are of the utmost importance to prevent and manage cross-infection and future pandemics.

Within the built environment, portable cleaners and UV light filters have been implemented, as well as an increase in minimum ventilation rates for occupied buildings. Additionally, while the role of ventilation design in the minimization of indoor pollutants – viral or otherwise – has been widely discussed, its performance has often been linked only to energy efficiency (Awbi, 2017). In this context, general-volume ventilation strategies, where the probability of infection may be assumed as independent from the location inside a room, have been predominant. However, in a dynamic indoor environment, airflow patterns increase or decrease the risk of airborne transmission at local points, making the general-volume consideration an unsuitable option to provide clean air in the breathing zone.

In contrast, breathing-zone-volume ventilation targets the circulation of fresh air in the breathing zone and can directly tackle airborne pathogens generated by human respiratory activities, minimizing cross-infection. While this type of ventilation is not new, it has often been overlooked for general-purpose building application in favour of the more conventional general-volume ventilation due to the pre-pandemic focus on energy efficiency, thermal comfort, odour control and such. In this post-pandemic era, a paradigm shift that unlocks newly purposed ventilation systems must occur (Morawska et al., 2021).

The aim of the present research is to demonstrate the application of breathing-zone-volume ventilation, specifically, stratum and impinging jet ventilation, on a general-purpose building. Performance was analysed based on purging efficiency, calculated through the Age of Air (AoA), and thermal comfort, calculated through draught sensation. A conventional general-volume, mixing ventilation strategy has also been analysed as a reference. Computational Fluid Dynamics (CFD) has been used for a RANS, steady-state analysis of the target building under heating and cooling conditions. The overarching objective of this study is to establish the basis of newly-purposed ventilation strategies that focus on infection control as well as generate discussion for future trends.

2 METHODS

The investigation utilized CFD to predict the spatial distributions of airflow and contaminant purging through AoA. The commercial software ANSYS Fluent 2021 R1 was used. Since an accurate prediction is essential to ensure reliable results, quality control and mass balance were carefully monitored while the residuals of the conserved variables were kept at 1×10^{-5}, according to the guidelines of convergence indicated in ANSYS Fluent Manual.

2.1 General-purpose building model

A simplified, empty room with dimensions of 6.0m(length)×6.0m(width) ×3.0m(height) was considered for demonstration (Figure 1). Three cases of ventilation strategies for this empty room were studied: a) mixing ventilation, as the reference general-volume ventilation; b) stratum ventilation; which supplies air to the head (breathing) level, generating a sandwiched airflow, and c) impinging jet ventilation, which delivers fresh air to a room based on a supply duct delivering air impinging onto the floor and extracts it at ceiling level, as the two types of breathing-zone-volume ventilation. Inlets and outlets dimensions, chosen according to commercially available products, are presented in Table 1 while room and mesh design are shown in Figure 1.

This room was equipped with two types of inlets/outlets: V) which refers to the ventilation system transporting outdoor air into the enclosure and subsequently discharging it directly out of the building; and, AHU) which corresponds to the recirculation system (air handling unit), assumed to have 100% filtering. Depiction of this distribution can also be seen in Figure 1.

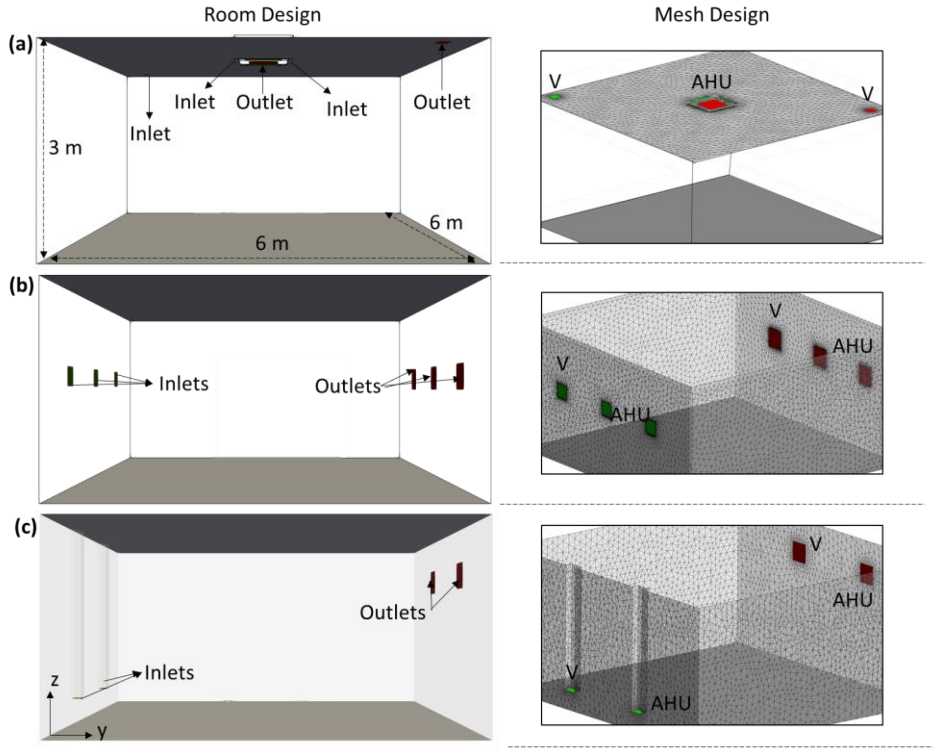

Figure 1: Room and mesh design of the general-purpose building for (a) mixing, (b) stratum and (c) impinging jet ventilation strategies

Table 1: Inlets and outlets dimensions

Cases	Inlet dimensions [m]	Number of inlets	Outlet dimensions [m]	Number of outlets
Mixing	0.2×0.2; 0.6×0.02	1; 4	0.5×0.5; 0.2×0.2	1; 1
Stratum	0.3×0.3	3	0.4×0.4	3
Impinging jet	0.3×0.15	2	0.4×0.4	2

2.2 Airflow and turbulence model

The indoor environment in this study was predicted by CFD, solving the Reynolds-averaged Navier Stokes (RANS) equations under steady state through the SIMPLE algorithm. A second order upwind scheme was chosen for the convection term and buoyancy was treated through the Boussinesq approximation. The renormalization group (RNG) k-ε model was used for turbulence due to previous literature indicating its superior performance (Chen, 1995).
In response to the COVID-19 pandemic, international standards have raised the minimum requirement of outdoor airflow to 10 L/s per person (European Standards, 2019). Therefore, the present study has also set this minimum requirement with an occupancy of two persons. Inlets were set as velocity inlet while outlets were considered as free-slip and the no-slip condition was assumed for all walls. Turbulent intensity was set at 10% and the length scale was defined as $1/7$ of the inlet height. Adiabatic wall conditions were considered for all calculations. During summer, inlet temperature was set at 21 °C and during winter at 25 °C. As a simple thermal comfort analysis, draught sensation was calculated as:

$$D_s = \frac{v_{oc}}{v_{max}} \times 100 \tag{1}$$

Where D_s is the draught sensation, expressed as a percentage from the least (0%) to the highest discomfort (100%), v_{oc} is the velocity magnitude of air in the occupied zone (0.0 to 1.8 m) and v_{max} is the maximum velocity magnitude threshold for discomfort, set in this study at 0.2 m/s.

2.3 Age of air

The age of air is defined as the mean time taken for air molecules arriving within the indoor environment through an inlet to travel to the measurement point. In this study, the mean age of air has been calculated through a user defined function (UDF), based on the ventilation efficiency scales for spatial distribution of contaminants, proposed by Kato and Murakami (1988), where SV3 denotes the age of the supply air and is defined by the following equations:

$$SVE3 = \frac{C'_x(X)}{C_s} \tag{2}$$

$$C_s = \frac{q}{Q} \tag{3}$$

Where $SVE3(X)$ [-] is the Scale for Ventilation Efficiency 3, at position X, $C'_x(X)$ is the contaminant concentration in case of uniform contaminant generation throughout the room, q is the contaminant generation rate and Q is the airflow rate. Further details can be found in the cited literature.

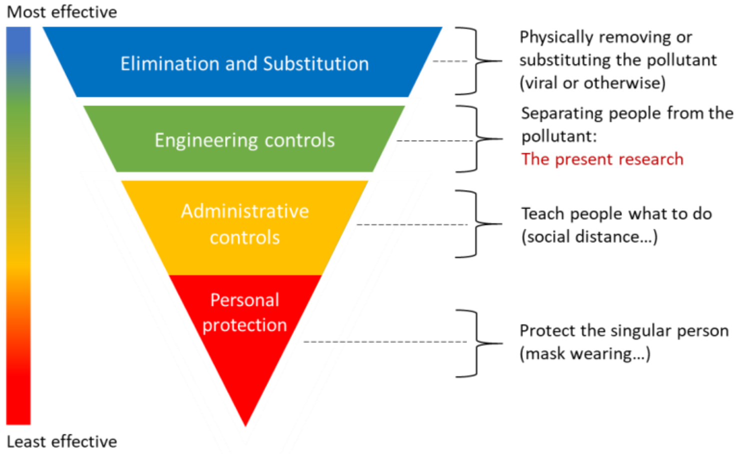

Figure 2: Infection control pyramid adapted from the CDC

3 RESULTS AND DISCUSSION

According to the US Centre for Disease Control (CDC, 2015), building ventilation is an engineering tool to reduce cross-infection and protect human life, ranking second in effectiveness, according to Figure 2. Ventilation should always consider other secondary measures like administrative controls to instruct people on what to do in case of a pandemic, and personal protection for inhabitants like masks, gloves and gowns. However, the following results only consider ventilation as an engineering control, not analysing other elements below

this level in the infection control pyramid. Furthermore, no pharmacological factors are included, such as vaccination effects.
Contours of the air velocity magnitude distribution on representative planes for different ventilation strategies under heating and cooling modes are illustrated in Figures 3 and 4, respectively. During winter, the airflow quickly tended towards the ceiling due to the higher temperature of the air supply when compared to the room air (thermal buoyancy), tending to rise above the breathing zone. The supply jet momentum was high in the direction of the inlets but rapidly lessened its impact as it distributed into the room, diminishing the probability of draught discomfort. Mixing ventilation created a more stagnant air in the occupied zoned, defined between 0.0 and 1.8 meters, while impinging jet ventilation generated more air movement. During summer, the supply jet tended towards the floor, increasing the mixed air in the mixing ventilation case as well as the penetration distance of the jet for the stratum and impinging jet ventilation cases. In all cases, a marked non-homogenous distribution of indoor air can be seen, with higher magnitudes near supply inlets and lower ones near the walls and corners of the room. The AHU of the mixing ventilation system during heating mode (Figure 3) created a Coanda effect, not allowing the filtered air of recirculation system to reach the breathing zone.

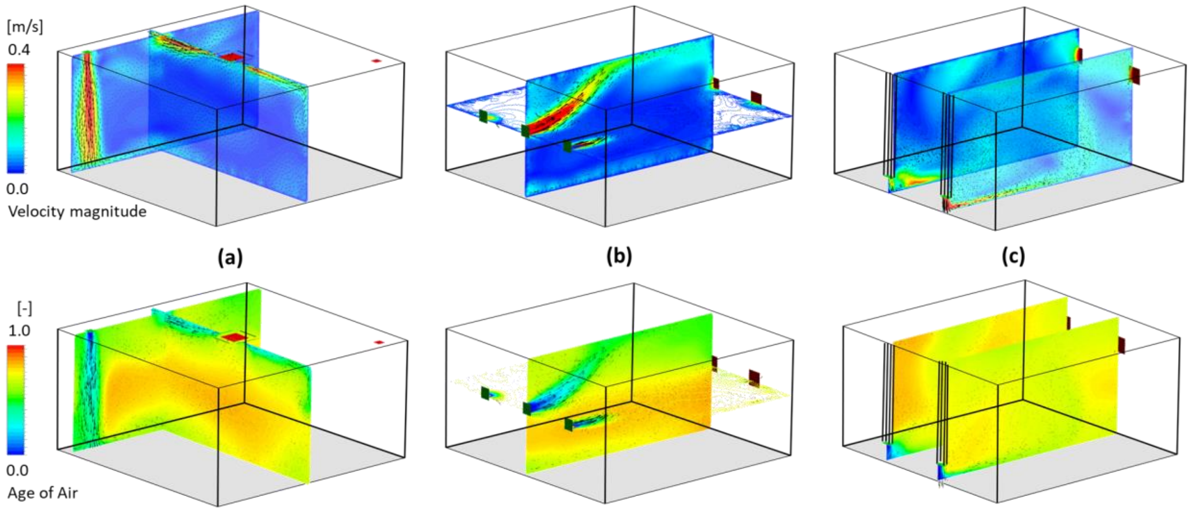

Figure 3: Velocity magnitude and normalized age of air distributions for (a) mixing, (b) stratum and (c) impinging jet ventilation strategies under heating mode

Contours of the normalized age of air also presented in Figures 3 and 4 for heating and cooling mode, respectively. In this study, "new" air was assumed to be injected from both the ventilation and the AHUs. A non-uniformity was present in both heating and cooling modes and, in the case of mixing ventilation, the age of air in the vicinity of the inlet vents was markedly lower than in the vicinity of the outlets and other parts of the room were the penetrating jet had lesser impact. For stratum and impinging jet ventilations, stratification in the age of the air was confirmed, with older air tending above the breathing zone, purging the occupied zone from older air and potential pollutants.
These results mark the relevance of local ventilation efficiency, both locally and horizontally, especially when considering airborne transmission for future ventilation design. In order to compare quantitatively the values of the age of air and draught sensation, this study has chosen as "local" environment the occupied zone (0.0 to 1.8 m) to be on the safety side.
Table 2 presents the results of the different ventilation strategies under heating and cooling mode. The table shows that in heating mode, the values of age of air were either maintained or slightly decreased when compared to the mixing ventilation strategy but the draught sensation increased when stratum and impinging jet ventilation were applied. In contrast, age of air

markedly improved when breathing-zone-volume ventilation was used under cooling mode, with a difference of more than 50% when mixing and impinging jet ventilation were compared. However, draught sensation increased for all cases when compared to the mixing ventilation one.

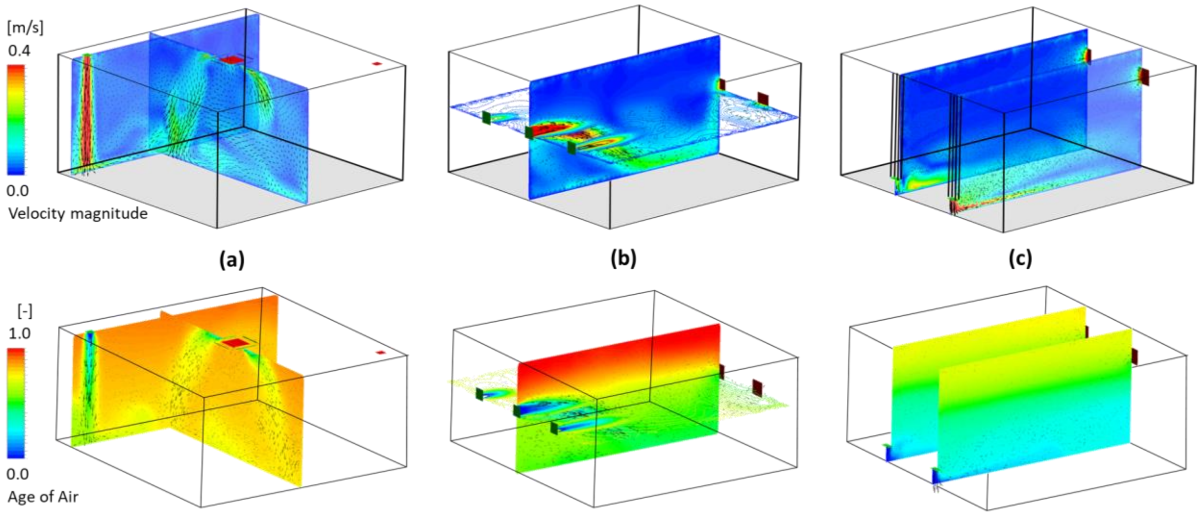

Figure 4: Velocity magnitude and normalized age of air distributions for (a) mixing, (b) stratum and (c) impinging jet ventilation strategies under cooling mode

Table 2: Volume-averaged age of air [-] and draugh sensation [%] in the occupied zone

Cases	Heating		Cooling	
	Age of Air [-]	Draught sensation [%]	Age of air [-]	Draught sensation [%]
Mixing	0.68	12.88	0.74	28.93
Stratum	0.68	13.18	0.57	22.85
Impinging jet	0.63	31.28	0.33	24.11

It was confirmed that cooling mode results regarding age of air and draught sensation were generally better than heating mode results. Horizontal air strategy (stratum) and mixed air strategy in heating mode had similar results because of thermal buoyancy, allowing the warmer air to directly travel to above the breathing zone, minimizing the improvements. Furthermore, the downward flow trend of the mixing ventilation strategy in cooling did not affect the occupied zone in all cases, increasing the age of air and risk of cross-infection.

Results showed that applying breathing-zone-volume ventilation improved the age of the air circulating in the room, particularly under cooling mode; however, thermal comfort, measured through draught sensation, decreased when compared to the reference ventilation. From this point of view, a balance must be reached between thermal comfort and purging efficiency by adjusting the practical parameters of location, ventilation rate and so on.

The change of these parameters can be done by optimizing values established by the multiple guidelines, standards and regulations in the architectural field. Then, one of the coming challenges becomes the in-depth analysis of minimum ventilation requirements. Although this study has maintained the recommended 10 L/s per person in accordance with newly established regulations, is this value still adequate in a post-pandemic era or should it be increased as a prophylactic measure? The second challenge comes through the shift from general-volume to breathing-zone-volume ventilation, knowing the purging efficiency of the latter is higher, while redesigning a thermally comfortable and energy-efficient environment (a paradigm shift).

Furthermore, this study has used AoA to evaluate the indoor environment for potential contaminant behaviour, as usually done in a pre-pandemic era. However, a ventilation index that considers non-homogeneity should be considered, as proposed by Lim et al., 2013 and Ikegaya et al., 2022. Net escape velocity can reflect in detail the probability of airborne infection in a non-uniform environment and will be considered in a future stage.
Finally, while this paper presents the basis for future research, several limitations must be considered: although quality control in the simulations has ben maintained, no experimental validation was carried out. Since this study is intended as an initial demonstration, no parameterisation to optimize outdoor ventilation rate, inlet/outlet location and temperature has been considered. Although a simple thermal comfort analysis has been considered through draught sensation, a more thorough approach is needed in future steps.

4 CONCLUSIONS

The current study investigated the purging effectiveness of general-volume – mixing – ventilation and breathing-zone-volume – stratum and impinging jet – ventilation under heating and cooling mode for a general-purpose building. The recently established international requirement of 10 L/s was set as outdoor airflow condition. This study showed that stratum and impinging jet ventilation greatly improved the age of air in the room under cooling mode, while sustaining – stratum – or improving – impinging jet – age of air under heating mode. Breathing-zone-volume ventilation directly provides fresh air into the breathing zone, lowering contaminants but producing a slightly stronger draught sensation which can impact thermal comfort. Although the occupied zone was able to show somewhat localized results, an exact consideration of local conditions must be used to establish a new ventilation index for non-homogeneous conditions that considers airborne transmissions.
This paper generates critical thinking in the following point: in a post-pandemic era, respiratory infection due to airborne pathogens must be recognized as a risk and consequently, ventilation design should be re-oriented to attack this issue. A balance must be sought between the existing triad in the indoor environment: purging efficiency, thermal comfort and energy efficiency.
Although valuable lessons were learned from previous pandemics, the world was still unprepared for COVID-19. Following historical trends, the next pandemic is not a remote possibility and a re-thought ventilation bedrock must be established to safeguard human health in the indoor environment while keeping a functioning everyday society.

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