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Control of exhaled SARS-CoV-2-laden aerosols in the interpersonal breathing microenvironment in a ventilated room with limited space air stability

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Abstract

The Coronavirus Disease 2019 (COVID-19) highlights the importance of understanding and controlling the spread of the coronavirus between persons. We experimentally and numerically investigated an advanced engineering and environmental method on controlling the transmission of airborne SARS-CoV-2-laden aerosols in the breathing microenvironment between two persons during interactive breathing process by combining the limited space air stability and a ventilation method. Experiments were carried out in a full-scale ventilated room with different limited space air stability conditions, i.e., stable condition, neutral condition and unstable condition. Two real humans were involved to conduct normal breathing process in the room and the exhaled carbon dioxide was used as the surrogate of infectious airborne SARS-CoV-2-laden aerosols from respiratory activities. A correspondent numerical model was established to visualize the temperature field and contaminated field in the test room. Results show that the performance of a ventilation system on removing infectious airborne SARS-CoV-2-laden aerosols from the interpersonal breathing microenvironment is dependent on the limited space air stability conditions. Appropriate ventilation method should be implemented based on an evaluation of the air condition. It is recommended that total volume ventilation methods are suitable for unstable and neutral conditions and local ventilation methods are preferable for stable conditions. This study provides an insight into the transmission of airborne SARS-CoV-2-laden aerosols between persons in ventilated rooms with different limited space air stability conditions. Useful guidance has been provided to cope with COVID-19 in limited spaces.

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Introduction

The outbreak of the coronavirus disease has raised global concern on the human-to-human transmission of the Severe Acute Respiratory Syndrome Coronavirus-2 (SARS-CoV-2) (Li et al., 2020; Paules et al., 2020). According to the World
Health Organization (World Health Organization, 2020), as of October 30, 2020, more than 44,888,869 cases had been confirmed, including 1,178,475 deaths. This emphasizes that the challenge of the reemergence of the SARS-CoV-2 or future epidemic threats similar to COVID-19 and that effective control method should be in place beforehand.

To control the spread of COVID-19, people are asked to keep social distance and self-isolate at home (Duan et al., 2020). Infected people with mild symptoms have also been asked to self-quarantine at home. This may raise the possibility of a second attack rate of the SARS-CoV-2 to the family members (Kucharski et al., 2020). It has been found that households have a higher infection risk of COVID-19 than in any other population level (Shereen et al., 2020; Yu et al., 2020; Shen et al., 2020). People undiagnosed or asymptomatic might be with others in the same room without any preventive measures, which may aggravate the situation (Qu et al., 2020; Amoatey et al., 2020). Besides households, other limited spaces, such as cabins (Albrecht et al., 2020), cruises (Yoshimura et al., 2020) and hospital wards (Liu et al., 2020), are also reported to be the high-risk locations for SARS-CoV-2 transmissions (Ai et al., 2019), which emphasizes the importance of implementing engineering and environmental methods to control the airborne SARS-CoV-2 aerosols transmission and manage the risks of infectious diseases in limited spaces (Morawska and Cao, 2020).

One of the reported transmission pathways of SARS-CoV-2 is airborne respiratory aerosols carrying viruses via respiratory activities (Morawska and Milton, 2020), for example, breathing (Gao and Niu, 2007; Hayashi et al., 2002), coughing (Gupta et al., 2009; Vuorinen et al., 2020), and sneezing (Shereen et al., 2020; Seepana and Lai, 2012; Scharffman et al., 2016). These aerosols may travel and suspend in the breathing microenvironment with exhaled flows. The trajectory of the exhaled infectious airborne SARS-CoV-2-laden aerosols in the breathing microenvironment depends on the aerosols' size and engineering and environmental controls, such as airflow pattern and indoor temperature distribution (Bourouiba, 2020; Li et al., 2007; Tang et al., 2006). The majority of aerosol particles in exhaled breath are smaller than 5 μm (Fennelly 2020), and the submicron region of the diameter of aerosols with SARS-CoV-2 dominates from 0.25 to 1.0 μm (Liu et al., 2020), within which the airborne aerosols normally do not settle (Tellier 2006) and suspend in the air and follow the air stream (Tang et al., 2011). According to the Reynolds analogy (Reynolds, 1961; Silver, 1950) and the extended Reynolds analogy (Hinze, 1987; Gong and Deng, 2017), the mechanism of heat and mass transfer and shear stress for incompressible flows shared similar characteristics, therefore, for the exhalation flow, it is expected that gas transport process is associated with particle transport process. This allows tracer gas to be a good surrogate of the exhaled airborne aerosols carrying SARS-CoV-2 in studying the transmission of the COVID-19. Bhagat et al. (2020) suggested that concentration levels of CO₂ can be used to indicate the potential presence of SARS-CoV-2 in the air and Zemouri et al. (2020) adopted CO₂ as the indicator to study the transmission of SARS-CoV-2 in dental clinics.

Ventilation has been recognized as an effective engineering and environmental method for regulating airflow and controlling airborne transmission in limited spaces (Kaushal et al., 2004). However, in some circumstances, additional ventilation systems may not be as efficient as they are expected in reducing the airborne cross-infection risk. For example, displacement ventilation would yield thermal stratification in the room, which may confine the exhaled contaminant in a finite layer near the breathing height (Qian and Zheng, 2018), but higher ventilation rates often mean a higher energy cost for mechanical ventilation. In this regard, advanced strategies, such as the combination of ventilation systems and other engineering and environmental control systems should be developed to control the transmission of COVID-19 and reduce the risk of cross-infection.

In recent years, limited space air stability has gained attention (Gong et al., 2010; Wang et al., 2014; Xu et al., 2015; Deng and Gong, 2020). According to Gong et al. (2010), the air condition in limited spaces can be divided into stable, neutral and unstable by the vertical distribution of temperature in the limited spaces. Xu et al. (2015) reported that the contaminant concentration in the exhaled flow was dependent on the limited space air stability conditions. In the stable condition, the exhaled contaminants would be trapped in a confined layer near the release height and disperse along the initially released direction; whereas in the unstable condition the exhaled contaminants tended to disperse quickly from its original expelled place (Gong and Deng, 2017). Most recently, it has been found that the unstable condition may greatly reduce the contaminant level in the breathing microenvironment of an individual in a ventilated room (Deng and Gong, 2021). However, little is understood in terms of the effect of the combination of ventilation methods and limited space air stability on controlling the airborne SARS-CoV-2 aerosols transmission and reducing the possibility of COVID-19 infection in the breathing microenvironment between persons.

The present study proposed an advanced engineering and environmental control system by applying limited space air stability conditions together with a ventilation system in a room and investigated the effect on the transmission of exhaled infectious airborne SARS-CoV-2 aerosols in the breathing microenvironment between two persons both experimentally and numerically. Two real human subjects participated in the experiments to conduct normal breathing process by inhaling through the nose and exhaling by the mouth. A numerical model was established based on the experimental settings to give a visual illustration of the flow field. Also, the influence of ventilation rate on the distribution of temperature and aerosols concentration was examined based on the simulation results. The results can further improve the understanding of the transmission mechanism of exhaled airborne SARS-CoV-2 aerosols in the breathing microenvironment between persons.

1. Methods

1.1. Experimental setup

Experiments were carried out in a full-scale test room (4.0 m × 3.8 m × 2.4 m) installed with an air carrying energy
radiant air-conditioning system in Hunan, China. The schematic view of the test room is shown in Fig. 1a. Two test subjects (two real humans with an average height of 1.62 m and an average weight of 50.0 kg), regarded as the SARS-CoV-2 carriers, presented in the room to perform a normal breathing activity by inhaling through the nose and exhaling by the mouth face to face with a relative distance of 1.0 m. Such combination of breathing mode and the relative position between two persons stands for the worst situation in terms of exposure risks (Ai et al., 2019; Liu et al., Olmedo et al., 2012; Pantelic et al., 2015; Yang et al. 2015; Nielsen et al., 2008). Fig. 1b shows the location of the breathing microenvironment between two test subjects. The engineering and environmental control system in the test room was realized by the implementation of three limited space air stability conditions, i.e., stable condition, neutral condition and unstable condition in a total-volume-ventilated test room with bottom-supply and top-exhaust. The ventilation system provided the test room with an average flow rate of 268 m³/hr, which approximated to 7.4 air changes per hour (ACH). The temperature at the supply vent was 25°C. The measured temperature at the exhaust vent was 22.9°C for the stable condition, and 23.5°C for the neutral condition and 26.7°C for the unstable condition. CO₂ released from the exhalation process was used as the tracer gas to illustrate the transmission of the exhaled SARS-CoV-2 aerosols as it gave a good representation of the behaviour of bioaerosols (Noakes et al., 2009; Li et al., 2013; Gao et al., 2009, 2011) and was accurate enough to study the dispersion of human exhaled aerosol nuclei (Ai et al., 2020). The stable condition, neutral condition and unstable condition were realized by adjusting the temperature of the radiant air-conditioning system above the ceiling and the electric blankets on the floor. Specifically, the stable condition was formed by turning on the radiant air conditioning system at 19°C to cool down the test room, and then the temperature of the radiant air conditioning system was set to 30°C. The unstable condition was realized by turning on the electric blankets at 33°C and the cooling mode of the radiant air conditioning system at 22°C. The neutral condition was created by adjusting the temperature of the radiant air conditioning system and the electric blankets simultaneously and the measured temperature for the floor and the ceiling was 23°C. One experiment run was divided into two parts. Part A was a 30-min tracer gas release period with two test subjects conducting breathing activities. At the end of part A, the test subjects were asked to left the room, and the experiment was carried on for another 30 min (part B) to test the efficacy of the engineering environmental system on the concentration of tracer gas decay. All together three cases, namely, stable case, neutral case and unstable case, were investigated.

The concentration of tracer gas in the breathing microenvironment was measured by nine gas sensors (Senseair, Inc., Delsbo, Sweden) (Fig. 2b) suspended along with L₅, L₆, L₇ (see Fig. 1) at 1.10 m, 1.50 m and 1.70 m. The sampling frequency of the CO₂ sensors was 2 s with an accuracy of ± (70 ppm CO₂ ± 3% m.v.). Fig. 2a shows the data acquisition system. An ambient CO₂ meter (Testo, Inc., Titisee-Neustadt, Germany) (Fig. 2e) with an accuracy of ± (50 ppm CO₂ ± 2% m.v.) was used to measure the concentration at the supply before each experiment to eliminate the impact of background concentration on the experiment results. The temperature at the ceiling and the floor was measured by an infrared thermometer (Testo, Inc., Titisee-Neustadt, Germany) (Fig. 2f). The room temperature was recorded simultaneously by twenty-five mini data loggers (Testo, Inc., Titisee-Neustadt, Germany) (Fig. 2c), distributing along five poles (L₁-L₅) for selected heights (0.1 m, 0.6 m, 1.1 m, 1.7 m, 2.3 m) (see Fig. 1). The flow rate of the ventilation system was measured by a wire anemometer (Testo, Inc., Titisee-Neustadt, Germany) (Fig. 2d) at the supply.

1.2. Numerical model setup

1.2.1. Geometry model and grid generation

To give a good visual illustration of the real physical phenomena, numerical simulations using CFD method were conducted. The numerical model was developed based on the actual room size of the experimental setup (see Fig. 3). The global
Fig. 2 – Photographs of (a) data acquisition system, (b) CO₂ sensors, (c) temperature mini data loggers, (d) wire anemometer, (e) ambient CO₂ meter, (f) infrared thermometer.

Fig. 3 – Computational domain of two CSPs standing in a room of 4.0 m × 3.8 m × 2.4 m.

origin (x, y, z = 0.0 m) was located at point O. Two computer-simulated persons (CSPs) (Bjørn, 1999) were placed in the middle of the ventilated room to represent the test subjects in the full-scale experiments. The diameter of each nostril was 8.0 mm and the opening area size of mouth was 110.0 mm². Temperature and concentration were monitored at the same locations as those in the experiment settings. Fig. 4 illustrates the interpersonal breathing microenvironment between CSP A and CSP B, as well as the monitoring points of concentration.
The geometry model was meshed with a hybrid mesh method. The computation domain was divided into an occupied zone that enclosed the CSPs and the remaining room. The occupied zone was meshed with unstructured tetrahedral cells, and the rest area was meshed with structured hexahedral cells. The interface between the occupied zone and the rest region was treated with the matching method. This hybrid method maintained a preferable mesh quality. Grid independence was checked over three grid resolutions: 1937,399 (Grid 1), 2324,634 (Grid 2), and 5551,878 (Grid 3). Comparisons of velocity profile along L5 for Grid 1, Grid 2 and Grid 3 are presented in Fig. 5a, from which we can see that Grid 2 and Grid 3 exhibited better grid independences. Considering the computational accuracy and efficiency, Grid 2 was used for further analysis. The computational grid on the cross-section of \( z = 2.0 \) m is presented in Fig. 5b.

### 1.2.2. Governing equations

The governing equation of continuity, momentum, and energy is as follow:

\[
\frac{\partial}{\partial t}(\rho \phi) + \text{div}(\rho \mathbf{U} \phi) = \text{div}(\Gamma_\phi \text{grad} \phi) + S_\phi
\]  

(1)

where, \( \phi \) is the common variable. When \( \phi = 1 \), the equation becomes the continuity equation; when \( \phi \) represents the air velocity components \( u, v \), and \( w \) (m/sec); the equation becomes the momentum equation; when \( \phi \) represents temperature \( T \) (°C); the equation becomes the energy equation; \( \rho \) is the density of air (kg/m\(^3\)); \( \Gamma_\phi \) is the effective diffusion coefficient and \( S_\phi \) is the source term.

### 1.2.3. Boundary conditions

As the dynamics of the inhalation flow close to the nose and the mouth are similar (Haselton and Sperandio, 1988), the same sinusoidal velocity (Villafruela et al., 2013) was applied to the boundary condition for mouth and nose of CSPs. Fig. 6 shows the respiration flow during one breathing cycle for two CSPs. Detailed boundary conditions are listed in Table 1.

T was the temperature; \( v \) was the velocity; \( C \) was the concentration of the tracer gas; \( t \) was the time.

### 1.2.4. Turbulence model

Reynolds averaged Navier-Stokes (RANS) model was employed in the simulation. RNG k-\( \varepsilon \) and enhanced wall function were considered in the simulation. The Semi-Implicit Method for Pressure-Linked Equations-Consistent (SIMPLEC) velocity-pressure coupling algorithm and the second-order upwind spatial discretisation scheme were used for steady and transient computations. The transient computations were initiated from a fully converged steady-state result. Each transient simulation was performed for 60 sec with a time step of 0.01 sec, containing sixteen breathing cycles. Simulations of three conditions of limited space air stability, i.e., stable condition, neutral condition and unstable condition, at two ventilation rates (3.0 ACH and 7.4 ACH) were conducted in the ventilated room (Cases 1-6). Two reference cases (Cases 7 and 8) were simulated with the absence of limited space air stability conditions, i.e., the floor and ceiling were considered as adiabatic wall, to compare with the numerical results of Cases 1-6 and to highlight the effect of limited space air stability conditions. Detailed case descriptions are documented in Table 2.

### Table 1 – Boundary conditions of the CFD simulation.

| Boundary | Settings |
|----------|----------|
| Supply   | Velocity inlet: \( T = 25^\circ C \); \( C = 440 \) ppm; \( v = 1.796 \) m/sec or \( 0.73 \) m/sec |
| Exhaust  | outflow  |
| Sidewall | Adiabatic wall |
| Ceiling  | \( T = 26^\circ C \) (stable condition), \( 23^\circ C \) (neutral condition), \( 25.5^\circ C \) (unstable condition) |
| Floor    | \( T = 21^\circ C \) (stable condition), \( 23^\circ C \) (neutral condition), \( 33^\circ C \) (unstable condition) |
| CSP      | \( T = 34^\circ C \) (Fanger, 1972) |
| Mouth    | Velocity inlet: \( C = 45,000 \) ppm (Berlanga et al., 2017); \( T = 34^\circ C \) (Melikov, 2004); \( v = 4.5 \sin(1.79t) \) |

### Table 2 – Cases descriptions.

| Cases | Limited space air stability\( T_c \)/(°C); \( T_f \)/(°C); Ventilation rate (ACH) |
|-------|--------------------------------------------------|
| Case 1 | Stable, \( 26 \)/\( 21 \)/3.0 |
| Case 2 | Neutral, \( 23 \)/\( 23 \)/3.0 |
| Case 3 | Unstable, \( 25.5 \)/\( 33 \)/3.0 |
| Case 4 | Stable, \( 26 \)/\( 21 \)/7.4 |
| Case 5 | Neutral, \( 23 \)/\( 23 \)/7.4 |
| Case 6 | Unstable, \( 25.5 \)/\( 33 \)/7.4 |
| Case 7 | – / – / 3.0 |
| Case 8 | – / – / 7.4 |
Fig. 5 – (a) Grid independence test: comparison of the air velocity along L5 with different grid numbers, (b) computational grid on the cross-section of z = 2.0 m.

Fig. 6 – Plot of the sinusoidal respiration process.

2. Results and discussion

2.1. Experimental results

2.1.1. Variation of the concentration in the exhaled mainstream direction

The concentration level in the breathing microenvironment is a result of the breathing flow and the room global flow. Fig. 7 shows the concentration of the tracer gas obtained at measuring points a1, b1, c1 along the centerline of exhalation flow, i.e., the exhaled mainstream direction. The relative positions of the measuring points are illustrated in Fig. 1b. Measuring points a1 and c1 were placed in the vicinity of the mouth of two test subjects, respectively, therefore the concentrations at these two points were mainly affected by the breathing flow. As shown in Fig. 7, the measured concentration at measuring point a1 was higher than that at measuring point c1. This reflected an individual difference between the test subjects. Measuring point b1 was located in the middle of the centerline, 0.5 m away from each test subject, so the concentration at measuring point b1 was more likely to be influenced by the general airflow that was driven by the environmental control system in the room (Villafruela et al., 2016). As shown in Fig. 7, during part A, the concentration along the exhaled mainstream direction for the stable case (Fig. 7a) was the highest among three cases, covering a level from 750 ppm to 1500 ppm, whereas it ranged between 500 ppm and 1000 ppm for neutral and unstable cases (Figs. 7b and 7c). Particularly, the concentration at measuring point b1 for the stable case was around 800 ppm while it was 600 ppm for neutral and unstable cases, which indicated that the performance of environmental control system on removing SARS-CoV-2-laden aerosols from the breathing microenvironment in a ventilated place would be different when the air stability condition differed.

At the beginning of part B, the concentration dropped sharply in all three cases due to the absence of the test subjects. Then it gradually settled down to a rather steady and flat distribution, with 600 ppm for the stable case, and 500 ppm for the neutral and unstable cases at the end of the experiments (t = 60 min).

In the neutral case, the temperature of the ceiling and the floor were both at 23 °C, so the temperature field was solely regulated by the ventilation system. While in the unstable case, the temperature of the ceiling and the floor was 25.5°C and 33°C, respectively. Such an air-conditioning arrangement of a chilled ceiling and a heated floor would intensify the air mixing in a ventilated room (Kaye and Hunt, 2010; Hunt and Linden, 1999), however, little difference of concentration level was observed between neutral and unstable cases (Figs. 7b and 7c). This suggested that the air environment in the breathing microenvironment had been already fully mixed by the ventilation flow at the ventilation rate of 7.4 ACH. This characteristic can be further observed from the numerical results in Section 2.2.

Previous studies have found that the stably stratified air may confine the exhaled contaminants at a certain height in the breathing microenvironment and thus cause high exposure risks to the occupants (Gong and Deng, 2017; Deng and Gong, 2021). Here in this study, the same phenomenon was observed when the ventilation system was combined with a stable condition. For the stable case (Fig. 7a), the temperature of the ceiling and the floor was 26°C and 21°C, respectively. A stably stratified air environment was therefore produced. Though the supplied air entered the room with a relatively high velocity and brought turbulent mixing into the occupied area,
the measured concentration in the stable case was still noticeably higher than that of neutral and unstable cases, which led to an assumption that the mixing effect caused by the high ventilation rate can be counteracted by the confinement effect associated with the stable condition, and then lead to the accumulation of SARS-CoV-2-laden aerosols in the breathing microenvironment.

The results suggested that the performance of a ventilation system on removing exhaled SARS-CoV-2-laden aerosols from the breathing microenvironment was dependent on the limited space air stability conditions. From the experiment results of Fig. 1, we found that unstable and neutral cases were preferable in removing the exhaled SARS-CoV-2-laden aerosols from the breathing microenvironment and reducing the risk of cross-infection.

2.1.2. Spatial distribution of the concentration in the breathing microenvironment

Results of the spatial distribution of the concentration at heights of 1.1 m, 1.5 m and 1.7 m in the breathing microenvironment at the end of experiment part A and the end of experiment part B are plotted in Fig. 8. During part A (Fig. 8a), the concentration was the highest in the vicinity of two test subjects (L6 and L7). As the distance from the test subjects increased, the concentration dropped distinguishably at 1.5 m and 1.7 m heights, reaching the lowest values at L5. A contrary pattern appeared at height of 1.1 m, where the concentration increased with distance and peaked at L5. This reflected a consecutive fall-out of the exhaled aerosols from the upper part of the breathing microenvironment to the lower part, which has also been reported by Bourouiba et al. (2014). Fig. 8b and 8c illustrates the concentration distributes along x-axis and y-axis at the end of experiments. The concentration level of the stable case was in the range of 560 - 600 ppm, whereas it was 480-500 ppm for the unstable case and 490-520 ppm for the neutral case. It is clear that in the presence or absence of the test subjects, the distribution of the concentration at different heights for unstable and neutral cases was generally lower than that for the stable case. This highlighted the fact pointed out earlier that the exhaled SARS-CoV-2-laden aerosols tended to be confined in the breathing microenvironment in the stable case while it dissipated more effectively in neutral or unstable cases.

2.2. CFD simulation results

2.2.1. Validation of the numerical model

As shown in Fig. 9, Temperature profiles of experiment and CFD results were compared for stable, neutral and unstable cases. The temperature was obtained along pole L1-L5 (Fig. 1a) at heights of 2.4 m, 2.3 m, 1.7 m, 1.1 m, 0.6 m, 0.1 m, 0.0 m at the ventilation rate of 7.4 ACH. The average discrepancy between the experimental and numerical data for stable, neutral and unstable cases were 4.9%, 3.03%, 2.53%, respectively, which can be considered as acceptable results (Mendez et al., 2008). Also, the tendency of the numerical results was in agreement

Fig. 7 – Variation of concentration with time in the exhaled mainstream direction of (a) stable case, (b) neutral case, (c) unstable case.

Fig. 8 – Spatial distribution of concentration in the interpersonal breathing microenvironment along the x-axis at (a) 30 min and (b) 60 min, and along the y-axis at (c) 60 min.
Fig. 9 – Comparison of the numerical results of vertical temperature profiles with experimental data (a) stable case, (b) neutral case and (c) unstable case.

with that of the experiment results. Therefore, the established numerical model was used for computing the flow field in the breathing microenvironment.

2.2.2. Temperature distribution for stable, neutral, unstable and reference cases

The temperature fields for stable, neutral, unstable and reference cases are illustrated in Fig. 10. Selected representative results are displayed on the cross-section of \( z = 2.0 \) m at the ventilation rate of 3.0 ACH and 7.4 ACH when the CSPs had breathed for 60 sec.

Fig. 10g shows the temperature field of the ventilated room at 3.0 ACH in the absence of limited space air stability conditions (Case 7). The temperature field was stratified in the room, presenting a typical feature of displacement ventilation (Awbi, 2015). Studies have found that this stratification may insert a lock-up effect on the exhaled contaminants in the breathing microenvironment (Bjørn and Nielsen, 2002). When the ventilation rate increased to 7.4 ACH, a greater volume flux entered through the supply vent and thus decreased the vertical temperature difference in the room (Fig. 10b). This was also reported by Gladstone and Woods (2001).

As seen in the neutral case (Fig. 10c, Case 2), a two-layer temperature stratification developed. Compared with the reference case at 3.0 ACH (Fig. 10g, Case 7), the temperature stratification of the neutral case was reduced. This was mainly because in the neutral case, the temperature of the ceiling and the floor were both 23 °C, so the viscosity of the top air was similar to that of the bottom air, which to some extent prevented the supplied cooler air from ascending. Besides, the buoyancy of heat source over the floor generated turbulent convection and disturbed the stratification, so a weakly stratified temperature gradient was established throughout the room.

When the ventilation rate increased to 7.4 ACH (Fig. 10d, Case 5), the temperature field of the neutral case showed a rather uniform temperature distribution of 25 °C in the occupied area. This demonstrated that the neutral condition was more sensitive to the increased ventilation rate than a pure ventilation system. This also confirmed our experimental results in Section 2.1.1 that the incoming ventilation flow at 7.4 ACH brought turbulent mixing into the occupied room, resulting in an equivalent concentration of the neutral case to the unstable case.

Comparing Fig. 10a and Fig. 10g, we found that an enhanced temperature stratification was achieved by the implementation of the stable condition. The intensive temperature gradient helped to confine the exhaled aerosols and could lead to a relatively high infection risk for people in such environments. It should be noted that though increasing the ventilation rate raised turbulence in the room, a stratified temperature distribution was maintained for a stable air environment (Fig. 10b). This proved the assumption that we made earlier in this paper (Section 2.1.1) that the mixing effect of the increased ventilation rate had to some extent been counteracted by the confinement effect of the stable condition. In other words, the stratification flow pattern of a stable environment was less easy to be disrupted by the increased ventilation rate than the other two kinds of limited space air stability conditions. It can be inferred that when the limited space is in a stable condition, increasing the ventilation rate may not always decrease the possibility of cross-infection of COVID-19 as the exhaled SARS-CoV-2-laden aerosols may still be trapped in the breathing microenvironment by the stably stratified air.

When the ventilation system with an unstable condition was considered, the presented airflow patterns in Fig. 10e, 10f indicated more mixed air environments than in the pure displacement ventilation cases (Fig. 10g, 10h). The cooled ceiling and heated floor created intensive convection and accelerated the air entrainment. When the ventilation rate was 3.0 ACH, the room temperature distributed uniformly at 29 - 29.5 °C. When it increased to 7.4 ACH, the mixing became more vigorous, with an obvious supply current appeared in the right bottom corner. The room average temperature was decreased by 1 °C.

2.2.2. Decontamination efficacy of stable, neutral, unstable and reference cases

Representative results when two CSPs had breathed for 45 sec were chosen in this section, corresponding to the exhalation process of the 12th breathing cycles. The concentration was normalized by \( C = C_i/C_0 \), where \( C_i \) was the instantaneous concentration in the room and \( C_0 \) was the initial concentration from mouths (Table 1). The normalized CO2 concentration, according to the Wells-Riley equation (Riley et al., 1978) and CO2-
Based on the risk equation (Rudnick and Milton, 2003), it is possible to estimate the probability of airborne transmission of viruses or pathogens in limited spaces. Figures 11 and Appendix A Figs. S1, S2 compare the distribution of normalized concentration \( C \) on the cross-section of \( z = 2.0 \) m and \( y = 1.5 \) m when ventilation rate was 3.0 ACH and 7.4 ACH for stable, neutral, unstable and reference cases. According to Bivolarova et al. (2017), ventilation rate would not affect the difference in concentration between tracer gas and aerosol particles, thereby the characteristics of the distribution of tracer gas illustrated in Fig. 11, and Appendix A Figs S1, S2 can well represent the aerosols dispersion in the interpersonal breathing microenvironment.

When the ventilation rate was 3.0 ACH, for the neutral case (Fig. 11b), most of the exhaled SARS-CoV-2-laden aerosols was confined in the upper breathing microenvironment. The exhaled mainstream from CSP A showed a tendency to deflect upwards and flow above CSP B. For the stable case (Fig. 11a), the mainstream of the exhalation flows was completely trapped in the release height and penetrated horizontally towards each other. Two exhalation flows from CSP A and CSP B reinforced in the middle of the breathing microenvironment and resulted in the highest infection risk. When compared with the reference case of 3.0 ACH (Fig. S2a, Case 7), the trajectory of the exhaled SARS-CoV-2-laden aerosols of the stable case (Fig. 11a, Case 1) was quite similar but was less dispersed to the upper part of the room. This indicated a confinement effect on the aerosol transmission in a stable condition. For the unstable case (Fig. 11c), the exhaled SARS-CoV-2-laden aerosols deviated from the mainstream direction soon after they were expelled from the mouth, so the infection risk was greatly reduced due to the dilution by ambient air.

Figs. 11d - 11f and Fig. S2c show the plane view of the distribution of concentration at the exhalation height (1.5 m) when the ventilation rate was 3.0 ACH. Comparing the contour level of \( C = 0.01 \) of Figs 11d, 11e and Fig. S2c, we found that in the stable case, most of the exhaled SARS-CoV-2-laden aerosols were accumulated in the interpersonal breathing microenvironment, whereas, in the neutral and the reference cases, the breathing microenvironments contained less SARS-CoV-
2-laden aerosols. For the unstable case (Fig. 11f), the concentration in the breathing microenvironment was close to that of the surrounding, with $C = 0.01$ distributing dispersively at 1.5 m height. This reflected a better decontamination efficacy of the unstable case when the ventilation rate was 3.0 ACH.

Appendix A. Fig. S1 and Fig. S2b, d show the distribution of exhaled SARS-CoV-2-laden aerosols when the ventilation rate increased to 7.4 ACH. The expanded contaminated area of the reference case (Figs. S2b, d) revealed that the intensified turbulent mixing by the increased ventilation rate accelerated the transmission of the exhaled aerosols. As shown in neutral cases (Figs. S1b, e) and unstable cases (Figs. S1c, f), the contaminated area expanded to the entire room, larger than that of the reference case both vertically and horizontally. However, in stable cases (Figs. S1a, d), the transport of the exhaled aerosols seemed rather inert to the increase of ventilation rate. The distribution of the SARS-CoV-2-laden aerosols remained suspended in the breathing microenvironment in a way as is shown in Figs. 11a, d, with a slight expansion out of the interpersonal breathing microenvironment. The infection risk was the highest in this case. It should be noted that although the neutral and unstable cases had larger contaminated areas than the stable case, the SARS-CoV-2-laden aerosols less accumulated in the interpersonal breathing microenvironment.

### 2.3. Implications for reduction strategies of SARS-CoV-2-laden aerosols

The study demonstrated that the performance of a ventilation system on removing infectious airborne SARS-CoV-2-laden aerosols from the interpersonal breathing microenvironment is dependent on limited space air stability conditions. Overall, unstable and neutral conditions were more effective in reducing the exhaled SARS-CoV-2-laden aerosols concentration than the stable condition in the interpersonal breathing microenvironment in a displacement ventilated room. Appropriate ventilation method should be implemented based on an evaluation of the air stability condition. In floor heating or ceiling cooling rooms where unstable or neutral conditions are often established. The diffusion of the exhaled aerosols would be accelerated by the convective movement of the indoor air, so total volume ventilation methods, such as mixing ventilation and displacement ventilation, are preferable for diluting the concentration of the infectious SARS-CoV-2-laden aerosols in the breathing environment and thereby reduce the infection risk for people. In ceiling heating or floor cooling environments where stable conditions are normally formed, the exhaled SARS-CoV-2-laden aerosols tend to be confined in the breathing microenvironment and penetrate along the exhaled mainstream direction, resulting in a high infection risk for people nearby. In such circumstances, total volume ventilation methods are less efficient. We thus recommend local ventilation methods to be implemented into limited spaces to directly remove the infectious SARS-CoV-2-laden aerosols from the interpersonal breathing microenvironment. Local ventilation systems, for example, push and pull ventilation system and personalized ventilation system, are the ventilation methods that are used for transporting contaminants or heat from the occupied zone (Olander et al., 2001; Huang et al., 2016; Luo et al., 2018). These systems are based on local capture of contaminants (Biegert and Raillo, 2001). The location of

**Fig. 11 – Distribution of concentration at $t = 45$ s on the cross-section of $z = 2.0$ m of 3.0 ACH (a) Case 1, (b) Case 2, (c) Case 3, and on the cross-section of $y = 1.50$ m (d) Case 1, (e) Case 2, (f) Case 3.**
the exhaust opening inside the space should be in the main direction of the expected emission direction, normally in the back wall. Here under stable conditions, the exhaust opening is suggested to be placed in the windward of the mainstream of the exhaled contaminants to effectively remove the exhaled SARS-CoV-2-laden aerosols from the breathing microenvironment.

3. Conclusions

This paper presented a combined analysis of the transmission of SARS-CoV-2-laden aerosols in the interpersonal breathing microenvironment with both experimental and numerical results. We have shown that limited space air stability greatly affected the distribution of exhaled SARS-CoV-2-laden aerosols in the ventilated room. The following conclusions are made.

1. In the presence or absence of the test subjects, unstable and neutral conditions were generally more effective in removing exhaled SARS-CoV-2-laden aerosols from the interpersonal breathing microenvironment in a displacement ventilated room. Compared with the stable case, neutral and unstable cases had a relatively larger dispersion area of SARS-CoV-2-laden aerosols in the room, but the interpersonal breathing microenvironment was less concentrated with exhaled aerosols. Neutral and unstable cases can contribute to a reduced infection risk for people in limited space.

2. The performance of a ventilation system on removing infectious airborne SARS-CoV-2-laden aerosols from the interpersonal breathing microenvironment is dependent on the limited space air stability conditions. Compared with a pure ventilation system, the stable case presented a more stably stratified temperature field, so the flow field was less likely to be affected by increasing the ventilation rate. As a result, when the ventilation rate increased, most of the exhaled SARS-CoV-2-laden aerosols remained in the interpersonal breathing microenvironment, resulting in relatively high infection risk. The neutral case was found to be more sensitive to the increased ventilation rate than a pure ventilation system. In the neutral case, the temperature field maintained a stable stratification when ventilation rate was 3.0 ACH, whereas it turned into a mixed temperature distribution in the occupied area at increased ventilation rate, thus diluted the concentration of SARS-CoV-2-laden aerosols in the interpersonal breathing microenvironment. Unstable conditions provided a fully mixed temperature field for both ventilation rates and thus the least contaminated interpersonal breathing microenvironment.

3. Suggestions about air distribution method were given based on the evaluation of the air stability conditions in limited spaces. For unstable and neutral conditions, total volume ventilation methods are suitable for diluting the concentration of SARS-CoV-2-laden aerosols, whereas local ventilation methods are preferable for stable conditions to directly remove the infectious SARS-CoV-2-laden aerosols from the interpersonal breathing microenvironment.

The insights and suggestions provided by this study will be useful for providing practical guidance on controlling the transmission of infectious SARS-CoV-2-laden aerosols and reducing the infection risk of COVID-19.

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Appendix A Supplementary data

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.jes.2021.01.025.

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