Investigation of The Combined Effect of Indoor Air Stability and Displacement Ventilation on Pollutant Transport in Human Breathing Microenvironment

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ABSTRACT

The ventilation system removes pollutants effectively, and the resultant vertical temperature difference in the room greatly affects the indoor air distribution. A reasonable air distribution system is essential to provide a satisfying indoor air quality (IAQ) for the occupants, of which air quality in the breathing microenvironment plays a major role in occupant health, as they are exposed to this region directly. With a view to ultimately optimize the air quality in the breathing microenvironment, indoor air stability, namely, the background temperature effect, integrated with a displacement ventilation system, is analyzed in this study. Experiments were conducted in a full-scale test room with a test subject performing normal breathing activity. The concentration of the carbon dioxide (CO_2) was measured as a proxy for the pollutant concentrations in the breathing microenvironment. The results indicate that the vertical movement of the exhaled air is inhibited in a displacement ventilation system combined with a stable condition, so the inefficient dispersion leads to a severely polluted breathing microenvironment, increasing the infection risk of the occupants. It is also shown that with the same displacement ventilation system, the unstable condition causes the indoor air to undergo significant mixing, which to some extent destroys the stratification resulting from the displacement ventilation. A much greater irregularity appears in the exhaled airflow, so the pollutants travel widely beyond the breathing microenvironment, contributing to a less polluted region. It is concluded that indoor air stability will affect the ventilation systems performance and the unstable condition is advisable for minimizing the amount of pollutants in the breathing microenvironment, reducing the risk of infection and providing a better air quality for the occupants.

KEYWORDS

Indoor air stability; Displacement ventilation; Human exposure; Breathing microenvironment

1 INTRODUCTION

People spend 80-90% of their time indoors, so their health greatly depends on the indoor air quality (Godish & Spengler, 1996). To obtain a high IAQ, ventilation has been considered an effective way to bring fresh air into the room and remove the polluted air. When compared with mixing ventilation, displacement ventilation has the potential to provide higher air quality (Coffey & Hunt, 2007) while consuming less energy, so it is regarded as a promising approach to improve IAQ.

There are many sources of pollutants in indoor environments, the most common of which are the occupants themselves. Human respiration activities generate bio-aerosols that may carry pathogens (Douwest, Thorne, Pearce, & Heederik, 2003), leading to the airborne transmission of infectious substances in indoor spaces (Nielsen, 2009). This is rather remarkable in the occupied zone where human exposure to the indoor pollutant mostly often occurs (Melikov, 2015). When people is in a displacement ventilated room, the temperature gradient confines the vertical movement of the exhaled air, so instead of dispersing, the exhaled air could penetrate a long distance along the initial exhaled direction (Qian et al., 2006). This confinement would lead to pollutants accumulating at a certain height in the breathing zone, which has a negative impact on the occupants health.

Despite in the displacement ventilated room, temperature gradients are also common in the built environment when installed with other HVAC (Heating, Ventilation and Air-Conditioning) systems, for example, radiant air conditioning rooms (Olesen, 2002; Zhou et al., 2019; Schiavon, Bauman, Tully, & Rimmer, 2012; Li, Yoshidomi, Ooka, & Olesen, 2015; Peng, Gong, Mei, Liu, & Wu, 2019). Different vertical temperature or, equivalently, density gradients in a room are referred as the indoor air stability which is defined as a measure of the ability of an air parcel to keep its initial inertia state (Gong & Deng, 2017). The indoor air stability is classified into three categories, namely, stable, neutral and unstable conditions. In the stable condition, buoyancy force inhibits the vertical movement of air and the inertia force dominates the pollutant transport, so pollutants are more likely to maintain the initial inertia state and remain in the mainstream direction. In the unstable condition, the intensified instability of the ambient air would promote the entrainment of the pollutant with the ambient air and thus enhance the vertical movement of the exhaled pollutant. The pollutant is more likely to depart from its original state and dissipates widely. Indoor air stability has been shown to influence pollutant distribution in the indoor environment (Wang, Gong, Xu, & Yang, 2014; Xu, Nielsen, Gong, Jensen, & Liu, 2015a; Gong & Deng, 2017), however, no studies has been concluded with regard to the the feature of air distribution when indoor air stability is combined with the ventilation system.

The purpose of this study is to analyze the combined effect of displacement ventilation and indoor air stability on pollutant transmission in the breathing microenvironment. Exposure intensities (definition is given in 3.3) of different combinations are compared. The results demonstrate that in a displacement ventilated room the indoor air stability has significant effect on pollutant transport in the breathing microenvironment and reduces human exposure to pollutant.

2 METHOD

A whole experiment lasted 1 hour and was divided into two parts. The first part was the 30-minute respiration process. The test subject was asked to perform a steady breathing activity while standing by inhaling through the nose and exhaling through the mouth. The second part was a 30-minute pollutant decay process with no subject presenting in the test room. Figure 1a illustrates the full-scale test room, with length, width, and height equal to 4 m, 3.9 m, and 2.4 m, respectively. To create different indoor air stability conditions, the test room was equipped with an air carrying energy radiant-air-condition system on the ceiling to control the temperature of the top area. Four electrical blankets, with a dimension of 2 m × 2 m, were laid over the floor to control the temperature near the floor. The radiant air conditioning system and the electric blankets were operated at least 6 hours before each experiment was commenced in order to ensure a steady temperature distribution. The walls of the room were considered to be adiabatic. Twenty-five mini data loggers with an accuracy of ± 0.5 °C were distributed evenly on five poles (L1, L2, L3, L4, L5) to record the temperature at heights of 0.1 m, 0.6 m, 1.1 m, 1.7 m and 2.3 m. Two additional loggers were hung at the return and exhaust.

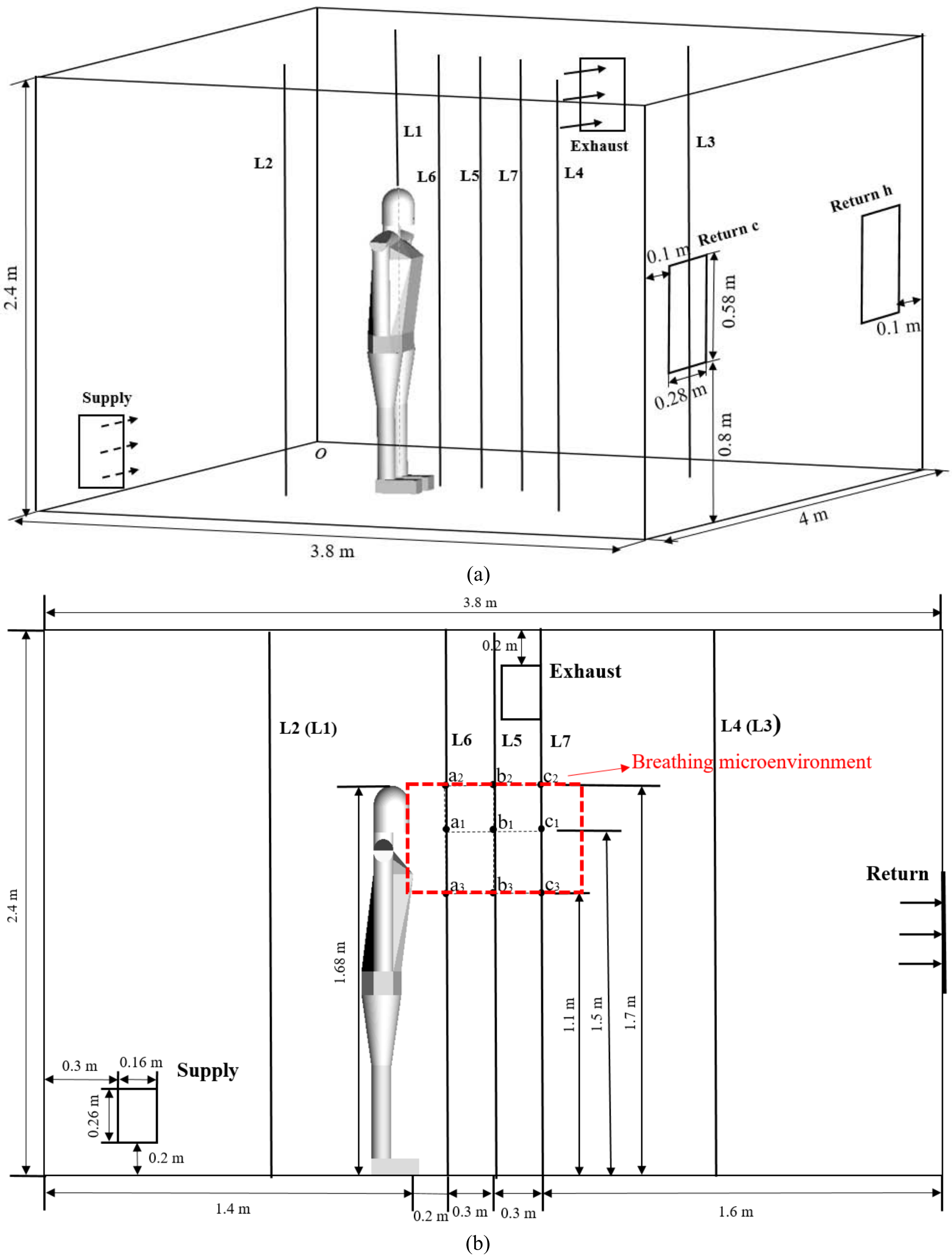

Figure 1: (a) Configuration of the three-dimensioned test room. (b) Layout of the displacement ventilation system and the measuring points

Figure 1b shows the layout of the displacement system. A wall-mounted air supply was installed neat the base of the sidewall with a ventilation rate of 7.75 ACH. The exhaust was of the same size as the supply and was installed near the top of the opposite sidewall. Two air returns were mounsted on the wall on the right hand side. When the radiant air conditioning system was in heating mode, Return h was opened and Return c was closed; when in cooling mode, Return c was opened and Return h was closed.

In this study, the breathing microenvironment was defined as a region, see Figure 1b, which is 1 m in front of the human body between the height of 1.1 m and 1.7 m (Bjørn & Nielsen, 2002; Xu et al., 2015a; Olsen, 2016; Liu, Li, Nielsen, Wei, & Jensen, 2016). CO_2 has been acknowledged as a good indicator in IAQ studies for more than one century (Billings, 1893), and is still being widely used in recent studies (Zhang, Wargocki, Lian, & Thyregod, 2017; Ramalho et al., 2014; Sundell et al., 2011;), so here, the CO_2 concentration from natural respiration was measured to indicate the pollutants level in the breathing microenvironment. Nine CO_2 sensors, with an accuracy of ± 30 ppm, were installed along three poles (L5, L6, L7) at stomach height (1.1m), mouth height (1.5 m) and head height (1.7 m), see Figure 1b. Before each experiment, the background CO_2 concentration was measured by a CO_2 meter. The CO_2 sensors and the CO_2 meter were cross-calibrated before each experiment. The air velocities at the supply, exhaust, and return were measured before each experiment by an anemometer with an accuracy of ± (0.1m/s + 5% of measured velocity).

3 RESULTS AND DISCUSSION

3.1 Temperature distribution in the test room

The measured temperature at different heights are shown in Table 1, which gives a temperature difference between the ceiling and the floor for the stable and unstable condition, respectively. In the stable condition, the floor temperature was 19.8 ℃ and the ceiling temperature was 26 ℃, forrming a temperature difference of 6.2 ℃ in the room; in the unstable condition, the temperature for the floor and the ceiling was 31.0 ℃ and 25.5 ℃, respectively, forming a temperature difference of – 5.5 ℃. The vertical temperature profiles are not a linear function of the height. It might be explained by the existence of heat source in the room (the test subject and the effect of the displacement ventilation.

Table 1: Temperature (℃) at different heights

Indoor air stability	Height（m）						
	0	**0.1**	**0.6**	**1.1**	**1.7**	**2.3**	**2.4**
Stable	19.8	20.5	21.6	23.6	24.2	25.3	26.0
Unstable	31.0	28.2	27.8	27.6	27.2	26.8	25.5

3.2 CO2 concentration distribution in the microenvironment

The CO_2 concentrations in the breathing microenvironment were obtained from the 9 measurement points (between the heights of 1.1 m and 1.7 m) ,see Figure 1. To eliminate the effect of the slight differences of the background CO_2 concentration at the beginning of each experiment, the CO_2 concentrations were normalized as follows

$$C=\frac{C_i-C_0}{C_0} \quad (1)$$

In (1) C_i is the concentration of instantaneous CO_2 (ppm), C_0 is the concentration of background CO_2 of each experiment (ppm). The normalized results are shown in Figure 2.

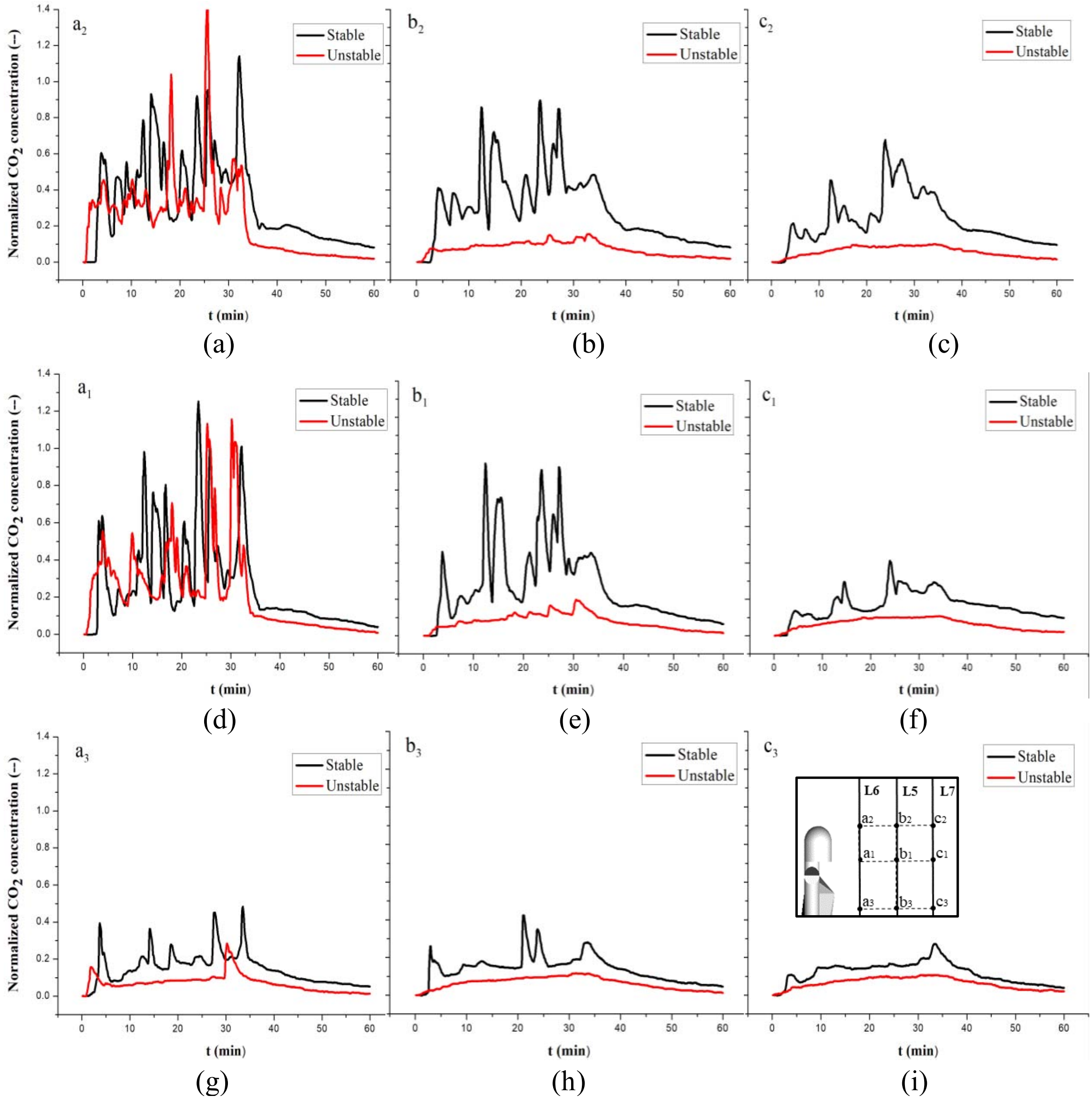

Figure 2: The variation of the normalized CO_2 concentration with time at different measuring points in the displacement ventilated room with stable and unstable conditions

During the first 30 minutes, periodic oscillations of CO_2 concentration were observed. These oscillations are in line with the normal breathing mode found by Villafruela et al. (2016) and Xu et al. (2015b). CO_2 concentration reaches a peak during the exhaling process where a relatively large amount of CO_2 is produced, then it drops significantly. This drop is partly because the test subject re-inhales the exhaled CO_2, and partly because the CO_2 has been dispersed into the ambient environment. This phenomenon is evident at most measuring points in the stable condition, except that point c_3 (Figure 2i) has a rather smooth concentration curve; while in the unstable case, the occurrence of this oscillation is greatly reduced. Only at points a_1 and a_2 (Figures 2d and 2a) can the phenomenon be observed. This indicates that when compared with the unstable condition, the pollutant is more likely to retain its initial state of motion in the stable condition.

As revealed from the concentration distribution at different measuring heights in Figure 2, the CO_2 flow is initially exhaled horizontally from the mouth with a relatively high momentum, and gradually deflects from its initial mainstream direction, turning upwards. The CO_2 concentrations at points a_1 and a_2 (Figures 2d and 2a) are the highest when the distance from the

test subject is 0.2 m (L6). This is mainly due to the fact that CO_2 is released from the test subject themselves, the thermal boundary layer of the human body carries the CO_2 flow towards head height, resulting in a high concentration near the human body, both at mouth height and head height. As the CO_2 flow travels further, in the stable condition, for example, at 0.5 m (L5) from the test subject, the concentration of CO_2 at point b_2 (Figure 2b) begins to exceed that at point b_1 (see Figure 2e), indicating that more exhaled flow has been transported to the upper breathing microenvironment. At 0.8 m (L7), this difference becomes more pronounced. The factors that are responsible for this increase are, firstly, the temperature of the exhaled air is higher than that of the ambient air, so the buoyancy force drives the exhaled air upwards. Secondly, the supplied air in the displacement ventilation system rises up after being heated by the heat source (here the test subject). When this supplied air reaches the breathing microenvironment, the exhaled airflow acquires the vertical momentum from the supplied air and thus bends upward. This upward movement is less obvious in the unstable condition as the CO_2 concentrations drop dramatically and eventually lie in the range within 0.0 and 0.1 with much less fluctuation.
Noticeably, the concentrations of CO_2 within the breathing microenvironment tend to be relatively high in the stable condition and relatively low in the unstable condition, except two abnormal peak values of the unstable condition at point a_2 when the respiration lasts for 19 min and 26 min, respectively. This presumably happens by the occasionally unsteady expiration of the test subject, such as a sudden deep breath or an unavoidable cough. The higher concentration in the stable condition is probably because, in the stable air, the temperature in the upper area is higher than the lower part, the buoyancy of the exhaled airflow decreases as it rises. The exhaled CO_2 will be suppressed and can not be dispersed effectively, causing a more severe polluted area in the breathing microenvironment. The occupants is at a higher risk of getting infected in this stable environment. The confinement of the exhaled flow has been also reported by Bjorn and Nielsen (2002). They concluded this confinement as a 'lock-up' phenomenon as the stably stratified environment can lock the exhaled flow at a certain height, causing a high concentration locally. Conversely, in unstable air, the buoyancy of the exhaled air increases as it rises, increasing the ultimate deviation and propagation distance. Any variation will have a noticeable effect on the state of the exhaled air (Pellew & Southwell, 1940) which would in return cause the disturbance to grow in amplitude in such a way that the exhaled air progressively departs from the initial state. Regardless of the distance from the test subject, the CO_2 concentrations at stomach height (see Figures 2g, 2h and 2i) were always the lowest, which indicates less CO_2 has travelled to the lower part of the breathing microenvironment, which is also found by Licina et al. (2015), Qian et al. (2006) and Olsen et al. (2016).

3.3 Exposure assessment

This breathing mode adopted in this study (inhale through the nose and exhale through the mouth) is normally seen in this cases where people smoke or suffer from a nasal congestion, and the exhaled air normally contains a high concentration of infective aerosols. These pople are regarded as the pollutant sources, meanwhile they are also exposed to the polluted breathing microenvironment as they would re-inhale a fair amount of their exhaled air. To assess human exposure under stable and unstable condition, exposure intensity E, is adopted in this study, which is defined by the National Research Council (National Research Council, 1991) as

$$E=\int_{t_1}^{t_2} C(t)\,dt \qquad (2)$$

In (2), C(t) is pollutant concentration, and t_2 - t_1 is the duration of exposure. Figure 3 plots the exposure intensity in the first 30 minutes of the experiments. In the first 5 minutes after the test subject began to breathe, no significant difference of the exposure intensity between the stable condition and the unstable condition is observed, with E = 6 in stable and E = 4 in unstable. At later times, the differences become more apparent and at the end of the breathing experiments, the exposure intensity is E = 80 in the stable condition and only E = 40 in the unstable condition. It is straightforward to see that the stable exposure intensity is always double that of the unstable condition at different times, which indicates the occupants in a stable environment have a significant greater possibility of being infected if exposing themselves to an indoor environment with existing desease carriers.

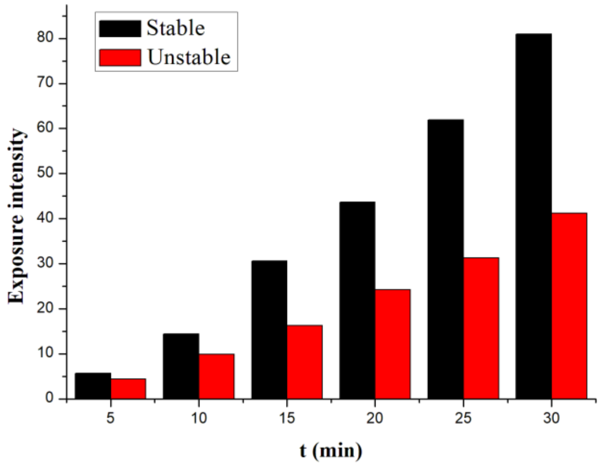

Figure 3: Exposure intensity E from (2) in the microenvironment in a displacement ventilated room for stable and unstable conditions

Figure 3 demonstrates that in the stable condition, the strong stratification inhibits the vertical motion of the airflow, so the movement of the air is confined to a certain region and gradually settles down in the breathing microenvironment, resulting in a higher exposure intensity. People exposed to this area will be at a higher risk of becoming infected. In addition, it may also aggravate the illness condition of the source person as they might re-inhale exhaled air remaining in their breathing microenvironment area (Bjørn & Nielsen, 2002). In the unstable condition, the vertical motion is promoted by Rayleigh-Bernard convection (Getling, 1998)) which is formed by the warm floor and cool ceiling in the test room. This arrangement of heating and cooling causes instability in the background environment, so the airflow experiences an enhanced mixing effect and thus disturbs the air stratification in the breathing microenvironment. As the exhaled air continuously entrains the ambient air, the pollutant has been correspondently well dissipated before it travels further in the breathing microenvironment. The resultant lower exposure intensity is in line with the finding by Olesen et al.(2016), who reported that floor heating would destroy the stratification of the displacement ventilation and thus reducing human exposure.

It is notable that the exposure intensity also depends on the duration of the stay. When people stay in the indoor space for a very short time, the stable condition would not lead to a worse situation of human exposure than an unstable condition would. The negative impact would only be prominent when people stay indoors for a considerable time.

3.4 Limitation of the work

The movement of people can create strong local air movement due to the wake behind the person, which breaks down the stratification of exhaled air (Bjørn & Nielsen, 2002). Tang, Li, Eames, Chan, & Ridgway (2006) pointed out that a person walking forward at about 1 m/s would create a volume flux of 225 L/s, with an attached wake of 76-230 L. Compared with the test room volume here of approximately 36 m^3, the wake could cause a significant mixing in the room. This local airflow is of great value in studying the pollutant distribution in certain areas (Bjørn & Nielsen, 2002). However, the research interest of this study primarily focuses on the pollutant concentration in the breathing microenvironment when the occupant is in a stationary standing posture. With this in mind, the test subject was asked to walk out of the test room as gently as possible (at approximately 0.2 m/s) at the end of the experiments to avoid causing a strong wake. It is thus assumed herein that occupant movement does not affect the pollutant distribution.

4 CONCLUSIONS

A combination of indoor air stability and displacement ventilation has been experimentally studied.

The full scale study has shown that indoor air stability influences the performance of displacement ventilation systems. A displacement ventilation system integrated with a stable condition will cause a more stagnant air environment in the breathing microenvironment. Under such environments, occupants have a larger exposure intensity and are more likely to be infected by the polluted air.

The unstable indoor air caused an instability of the indoor air, and to some extent destroys the stratification associated with the displacement ventilation. The exhaled flow is less likely to keep its initial state and tends to disperse beyond the breathing microenvironment, resulting in lower concentrations in this region. Occupants may have a lower infection risk. In conclusion, the unstable condition is advisable for minimizing the amount of pollutants in the breathing microenvironment, reducing the risk of cross infection and providing a better IAQ for the occupants.

Air distribution under the combination of indoor air stability and displacement ventilation could be affected by moving objects, which is worthy of future investigation.

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