

Study on vent spacing of multi-vent module-based adaptive ventilation for reducing contaminant diffusion

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Abstract. Infectious respiratory diseases are known to have high levels of airborne transmissibility. However, traditional ventilation methods based on perfect mixing often lead to the diffusion of airborne pathogens. Multi-vent module-based adaptive ventilation (MAV) is a ventilation method designed to meet the needs of different indoor scenes and reduce air mixing. MAV combines multiple groups of multi-vent modules. The vent spacing of a single module is also an important factor, but the influence of the change of vent spacing on the effect of MAV in contaminant diffusion control has not been studied. Computational Fluid Dynamics (CFD) is applied to study the influence of air vent spacing of a single MAV module on contaminant diffusion control in a simple office. Three different vent spacing of 1.5m, 2.0m and 2.5m and four vent layout modes is selected. The results show that when the vent distance is 2.0m, the MAV system has the best control effect on contaminant diffusion. Up to 61.5% of the contaminants are limited in the control area.

1 Introduction

Since entering the 21st century, infectious respiratory diseases have had a serious impact on human society. There are three common transmission routes for respiratory pathogens (such as SARS-CoV-2): droplet, contact and aerosol (or airborne) transmission. Airborne transmission is the primary transmission route of SARS-CoV-2, via inhalation of droplets/nuclei exhaled by an infected individual [1]. Respiratory droplets, which are released during breathing, speaking, coughing or sneezing, can carry pathogens and be suspended in the air for various lengths of time, and transmit the virus from person to person [2]. Studies on cough aerosols and exhaled breath from patients suffering from various respiratory tract infections have shown that particle size distribution is surprisingly similar between such patients, i.e. smaller particles ($<5\ \mu\text{m}$) predominate [3]. Most particles in exhaled breath have a diameter smaller than $4\ \mu\text{m}$, with a median of $0.7\text{--}1.0\ \mu\text{m}$ [4]. Biological aerosols can result in full-spectrum diseases at doses much lower than those required for large droplet transmission [5], which indicates that the infection risks and transmission ranges are higher. Respiratory diseases such as SARS-COV-2 are most likely to spread indoors, such as in homes or workplaces [6]. Thus, the rational use of HVAC systems is of great importance for environmental control to reduce infection risk and to improve human wellbeing in the pandemic [7]. Multi-vent module-based adaptive ventilation (MAV) is a new ventilation method that results in a smaller contaminant diffusion area and lower contaminant diffusion speed [8]. It is composed of several groups of multi-vent

modules and can divide the indoor environment into subzones and flexibly switch inlets and outlets to adapt to different requirements. However, there is still a lack of research on the influence of vent spacing on multi-vent modules. Different vent spacings may affect the control effect of the MAV system on contaminant diffusion. Therefore, this paper selects three vent spacings of 1.5m, 2.0m and 2.5m and four typical MAV module modes. Meanwhile, an infected person continuously releases contaminants by breathing. The computational fluid dynamics (CFD) method was used to simulate the contaminant diffusion of an infected person in different vent spacings and MAV modes. The results show that when the vent spacing is 2.0m, the MAV module has the best control of contaminant diffusion. In this case, up to 61.5% of the contaminants are limited to the control range of the MAV module. The study also found that when the two air inlets are switched over the infected person at the same time, the contaminant control effect of the MAV module will be weakened.

2 Methodology

2.1 Physical Model

The office size selected in this study is $5\ \text{m (L)} \times 5\ \text{m (W)} \times 3\ \text{m (H)}$. Compared with the general two-person office, it is larger to avoid the excessive impact of the wall on the droplets exhaled by the patient. There is a desk in the office with a height of $0.7\ \text{m}$. Two computer monitors are on the desk. There are two people

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sitting face to face in the room, one of whom was infected. One MAV module is used in the room, and four air vents are set on the ceiling. As shown in Fig. 1, there are three kinds of air vent spacing, which are 1.5 m, 2 m and 2.5 m respectively. The four air vents are arranged in a rectangle and are coloured in orange. Any two of them are air inlets, and the remaining two are air outlets. The size of a single air vent is $0.2\text{m} \times 0.2\text{m}$, and the air supply velocity is 1.5m/s .

For this study, a Poly-Hexcore mesh was generated. The grids around the occupants, vent grilles, and nostrils were refined to fit the dramatic gradients of the velocity field. The total number of cells was set to be approximately 2.5 million, which was determined via refinement of the mesh until the flow field solution was grid-independent.

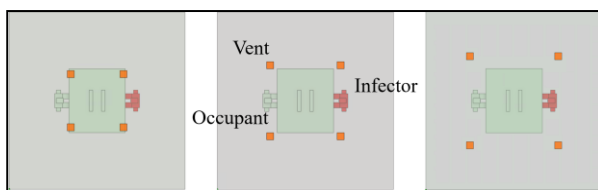


Fig. 1. Schematic diagram of room vent: 1.5m, 2.0m, 2.5m

2.2 Boundary conditions and case setting

In order to speed up the calculation, the manikin is simplified into four parts: head, trunk, arm and leg. Each manikin was 1.4 m tall, and the height of nostrils is about 1.2m. The nostril cross-sectional area is $0.5\text{ cm} \times 2.0\text{ cm}$. The exhaled airflow is seen as a cone starting at the nostril. The apex angle of the cone is 22° , and the axis of the cone is 30° to the vertical direction. Breathing is simplified as a continuous exhalation process. The velocity of exhaled airflow is 1 m/s and the temperature is 310K . The heat source intensity of the occupants was 40 W/m^2 , where the radiation and latent heat were not considered. Fig. 2 shows the occupants and furniture in the office. Those infected were coloured red.

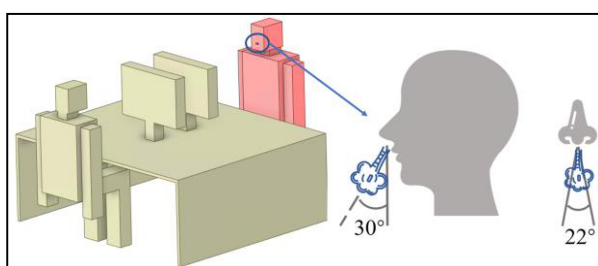


Fig. 2. The model of office and occupants

The supplied air had a temperature of 296K and a velocity of 1.5 m/s . A velocity inlet boundary condition was applied to the air supply grilles, whereas a pressure outlet boundary condition was set for the exhaust grilles.

Table 1. lists the details of the boundary condition settings.

Surface	Boundary condition
wall/ceiling/floor	wall; adiabatic ;Trap DPM

occupants	wall; heat flux 40W/m^2 ; Trap DPM
nostril	velocity-inlet; velocity 1m/s ; temperature 310K ; escape DPM
air supply	velocity-inlet; velocity 1.5m/s ; escape DPM
air exhaust	pressure-outlet; 0 Pascal; escape DPM

2.3 Numerical model and case setting

The calculation was divided into two parts: one was the steady-state calculation of the flow field for a given ventilation mode and boundary conditions, and the other is the calculation of steady-state solver with the transient particle release. The realisable K- ϵ model was used to simulate the air distribution in the room. The SIMPLEC algorithm was used to decouple the pressure and velocity. The convection and diffusion terms in the governing equations were discretised using the second-order upwind scheme. A standard wall function was adopted to model the turbulent flow in the near-wall region.

In the second step, the DPM model was used to calculate particles. Pascal and Oesterle [9] compared results using 1×10^4 , 2×10^4 and 4×10^4 particles in a simple shear flow and concluded that 2×10^4 were sufficient. Approximately 18 particles were released in each time-step, which was 0.1 s during breathing. Calculations were performed for 1200 time-steps, which spanned a total of 120 s , during which time 21600 particles were released by the infector.

2.4 Case setting

As shown in Fig. 3, four vent layouts were selected, which were recorded as Mode A - D.

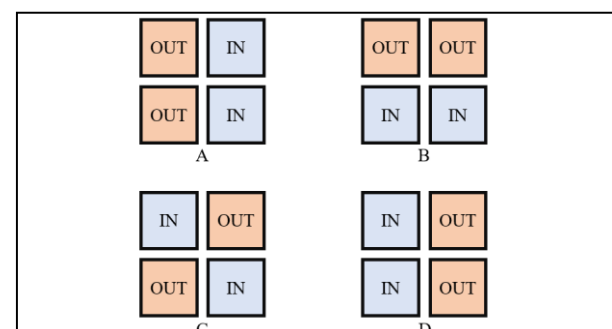


Fig. 3. Four different vent layouts

At the same time, the four modes were applied to three vent spacing respectively. Therefore, 12 cases can be obtained. Table 2 shows all 12 cases.

Table 2. Case list

Case	Vent spacing	MAV Mode	Case	Vent spacing	MAV Mode
1	1.5m	A	7	2.0m	C
2	1.5m	B	8	2.0m	D

3	1.5m	C	9	2.5m	A
4	1.5m	D	10	2.5m	B
5	2.0m	A	11	2.5m	C
6	2.0m	B	12	2.5m	D

3 Results and discussion

The purpose of the MAV system is to control the diffusion of contaminants. Therefore, in this paper, different from the conventional evaluation of ventilation methods, it is more important to leave particles in the control area. Therefore, the room in this study can be divided into three zones. The upper zone of more than two meters high, the central zone of $3\text{m} \times 3\text{m}$ in the centre of the room, and the outer zone surrounds the central zone. Fig. 4 shows three areas of the room. In addition to staying in the above three areas, particles may also be trapped by walls, interior decoration, or escaped from outlets. The walls are also divided into two areas at a height of 2m.

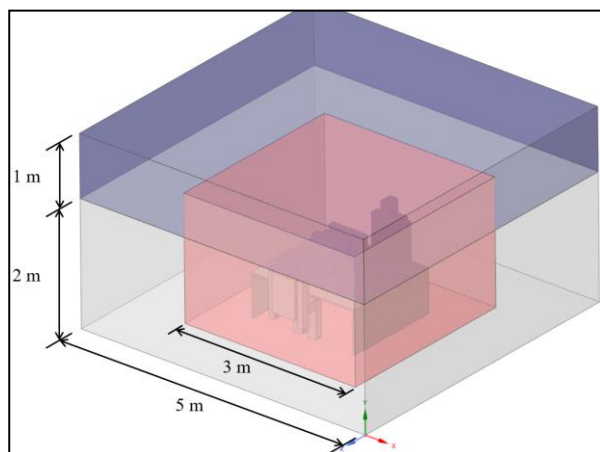


Fig. 4. Three different zones of the office.

3.1 Droplet diffusion characteristics at different time

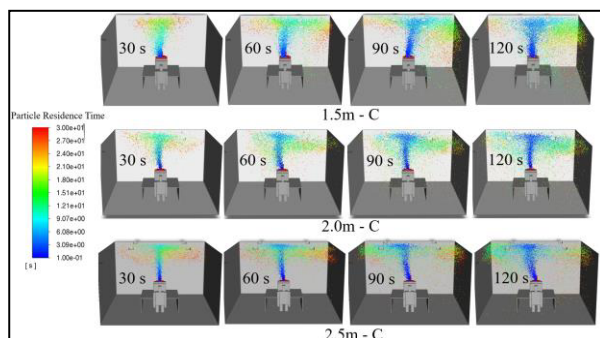


Fig. 5. Distribution of particles at different times and three vent spacings.

Fig. 5 shows the variation of particle distribution with time for three different air vent spacings. The MAV

mode C in Fig. 3 was chosen as the air outlet layout. As can be seen from the figure, after the infected person exhales the pollutant moves upwards with buoyancy, which is mainly influenced by the thermal plume around the body and the exhalation temperature. From 0s to 30s, the upward flowing contaminants spread to the sides near the ceiling, with the greater the spacing between the vents, the greater the spread. From 30s to 60s, particles continue to diffuse outwards. At 60s-120s, at 1.5m vent distance, the contaminants are entrained by the airflow and blown downwards due to the close horizontal distance between the air supply and the infected, which is considered harmful to the health of the occupants in the central area. However, with a 2.5m vent spacing, the air vent spacing is larger and therefore the particle dispersion area is greater. At the same time, more particles fall around, making it less likely that the MAV module will have the effect of controlling the spread of contaminants.

3.2 Classification of particles

120 seconds after the infected person starts releasing the contaminant, it can be seen to spread fully in the room. Depending on the position of the particles at this point and their eventual fate, they can be divided into three categories. Particles that are captured by the area below 2 m from the walls or in the peripheral areas are likely to be out of the control of the MAV module. Particles in the upper area or discharged by the air vents are more difficult to diffuse into other areas. Particles captured by tables, monitors or occupants themselves as well as particles in the central area do not spread for the time being but have the potential to cause contagion by other means. The three types of particles mentioned above are referred to as safe particles, escaped particles and particles to be determined. Fig. 6 shows the ratio of the three particle categories in each case. The number of particles in each case is 21600

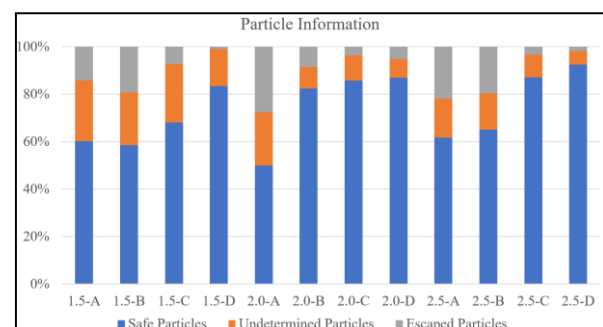


Fig. 6. Particle information

It can be seen that regardless of the vent spacing, a single MAV module can confine more than 50% of the contaminants to a safe area without spreading outwards. The average number of safe particles is highest when the vent spacing is 2.0m. The two cases with vent spacing of 1.5m and 2.5m have similar numbers of fugitive particles, while the main difference is in the pending particles. the 1.5m case has more pending particles, with up to 25.6% of the particles being captured by tables and figures, or suspended in the inner zone.

We believe that the higher the number of safe particles, the more effective the MAV is at controlling the spread of pollutants. This avoids the spread of contaminants into the control area outside the MAV module. At the same time, we should ensure the health of occupants other than infected persons in the control area of the module. Therefore, the specific fate of the particles is also very important.

3.3 Ultimate fate of particles and optimum air vent spacing

Fig. 7 shows the final fate of particles that can be controlled by the MAV module in different cases (located above 2m or in the central area or captured by a surface such as a table). The more particles that are controlled means that fewer particles will affect the outside of the module, which gives an indication of the effectiveness of the MAV module in controlling the diffusion of contaminants. However, for the occupants in the controlled area of the module (e.g. the two occupants in this simulation), more particles in this fraction means a higher risk of infection. Therefore, the final fate of this fraction of particles is very important.

Clearly, when particles escape from the outlet or are suspended in the area above 2m, the impact on the occupants in this control area is relatively small. When more particles are suspended in the central area, the risk of infection to occupants within the control area is higher. In other words, fewer light blue sections in Fig. 7 mean higher occupant safety in the control area.

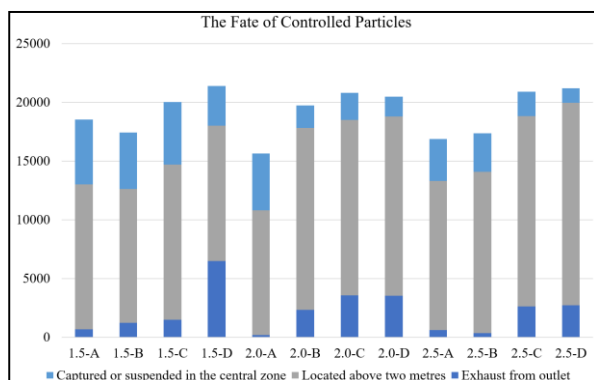


Fig. 7. The Fate of Controlled Particles

The average number of suspended particles in the central area is lowest when the air outlet spacing is 2.0m. According to Fig. 6 and Fig. 7, when the vent spacing is 2m, the MAV module not only provides maximum control of contaminants spreading outwards, but also protects the health of the occupants in the control area of the module.

Furthermore, we can note that, regardless of the ventilation spacing used, the effect is always the worst when MAV mode A is used, with particulate matter being difficult to get out of the outlets. This is because the two air inlets above the infected person interfere with the process by which the contaminants rise with the thermal plume. This makes it take longer for the particles to reach the upper area and then be exhausted. Mode D, on the other hand, is more effective because

the two outlets above the infector help the contaminants to move upwards quickly and at the same time help them to be exhausted as quickly as possible.

4 Conclusion

In this study, the effect of MAV module vent spacing on its pollutant dispersion control effectiveness was investigated. The results show that the best control is achieved when the vent spacing is 2.0m and also provides maximum protection for occupants in the control area of the module.

When the vent spacing is 2.0m, up to 96.2% of particles are controlled, with an average value of 88.7%.

MAV mode C (cross alignment of inlets and outlets) is the best MAV strategy when the location of the infected person is uncertain or the patient is asymptomatic. In addition, it is important to avoid having two air inlets above the same occupant. This may significantly reduce the performance of the MAV.

Acknowledgements

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References

- Greenhalgh, T., Jimenez, J. L., Prather, K. A., Tufekci, Z., Fisman, D., & Schooley, R. (2021). Ten scientific reasons in support of airborne transmission of SARS-CoV-2. *The lancet*, 397(10285), 1603-1605.
- Bartzis, J. G., Efthimiou, G. C., & Andronopoulos, S. (2015). Modelling short term individual exposure from airborne hazardous releases in urban environments. *J. Hazard. Mater.*, 300, 182-188.
- Fennelly, K. P. (2020). Particle sizes of infectious aerosols: implications for infection control. *The Lancet Resp. Med.*, 8(9), 914-924.
- Bake, B., Larsson, P., Ljungkvist, G., Ljungström, E., & Olin, A. C. (2019). Exhaled particles and small airways. *Resp. Res.*, 20(1), 1-14.
- Tellier, R. (2009). Aerosol transmission of influenza A virus: a review of new studies. *J. R. Soc. Interface*, 6(suppl_6), S783-S790.)
- Qian, H., Miao, T., Liu, L., Zheng, X., Luo, D., & Li, Y. (2021). Indoor transmission of SARS - CoV - 2. *Indoor Air*, 31(3), 639-645.
- Ding, J., Yu, C. W., & Cao, S. J. (2020). HVAC systems for environmental control to minimize the COVID-19 infection. *Indoor Built. Environ.*, 29(9), 1195-1201.
- Zhang, H., Zhang, W., Zhang, W., Xuan, Y., & Yue, Y. (2022). Multi-vent module-based adaptive ventilation to reduce cross-contamination among indoor occupants. *Build. Environ.*, 108836.

9. Pascal, P., & Oesterlé, B. (2000). On the dispersion of discrete particles moving in a turbulent shear flow. *Int. J. Multiphas. Flow*, 26(2), 293-325.