

INTERVENTION OF PERSONALIZED VENTILATION ON INTERPERSONAL AIRBORNE DISEASE TRANSMISSION

Yijing Ren^{1,*}, Shihai Pan¹, Na Li¹, Chunwen Xu¹

¹ College of Pipeline and Civil Engineering, China University of Petroleum, Qingdao, China

Abstract. Personalized ventilation (PV) has been integrated to reduce the risk of interpersonal infection exposure in the office environment. Some studies showed that PV systems may increase occupants' risk of airborne infection. Therefore, the aim of this study is to investigate the intervention of PV on interpersonal airborne disease transmission in office environment. A three-dimensional computational fluid dynamics model (CFD) was developed and experimentally validated in a clean chamber. Then the validated CFD model was used to calculate the diffusion of exhaled droplets under different particle size. Results showed at the size of $0.7\mu\text{m}$ particles, compared to pure mixing ventilation, the personal ventilation of 6L/s reduced the inhalation fraction (IF) from 0.121% to 0.092%, and the reduction ratio of IF is 23.96%. As of $5\mu\text{m}$, the IF also decreased from 0.165% to 0.102%, and the reduction ratio of IF is 38.18%. The percentage of $50\mu\text{m}$ particles deposited on the ground rises from 6.29% to 43.22% of exhaled particles. Therefore, the personalized ventilation can reduce the risk of inhalation in exposed person, and for large size particles, the number of particles falling on the floor increased greatly, which lead to the risk of resuspension increases. The results may be helpful for maximizing the effect of PV in interpersonal airborne disease control.

1 Introduction

Airborne diseases have been one of the main causes which leads to huge economic losses and casualties all over the world every year [1]. Therefore, the way to reduce casualties caused by airborne diseases and control their spread through effective methods is one of the urgent problems to be solved in the current epidemiology and multidisciplinary fields. Building indoors is a place where people gather for a long time. The spread of indoor air diseases can be effectively reduced with good building ventilation in buildings [2-5]. As a potential form of airflow organization, the personalized ventilation (PV) can directly send the treated fresh air to the breathing zone. Previous study has shown that compared with traditional ventilation, PV can significantly reduce the risk of airborne disease transmission in indoor environments [6]. Meanwhile, PV has shown its advantages in air quality through the coupling with other background ventilation methods with reasonable design. But, some studies showed that PV systems may increase occupants' risk of airborne infection [7,8]. Therefore, the aim of this study is to investigate the intervention of PV on interpersonal airborne disease transmission in office environment with the aid of computational fluid dynamics model (CFD).

2 Method

2.1 System description

In this study, the physical model was developed by Space-Claim2021R1, which was $5.0\times 3.5\times 2.5\text{ m}$ (L×W×H) as shown in Fig.1.

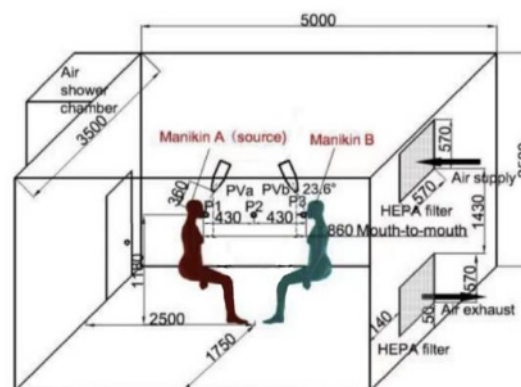


Fig. 1. Physical model used in ANSYS.

It was conditioned by a mixed ventilation (MV) system assisted by PV-system. The two openings installed two high efficiency particulate air filters (HEPA filters, 99.5%). The air-change rate (ACR) was set as 2h^{-1} , and the supply air temperature was $16.5\pm 1.0^\circ\text{C}$. The PV system was equipped with HEPA filters to supply fresh air, and two PV nozzles were 0.36 m from nose and clamped with vertical angle 23.6° . PV-a was placed in front of the source manikin and the PV-b was in face to the exposed manikin. To simulate the exposure of an person to particles exhaled by an infected person, numerical models of thermal manikins were developed. Two manikins had clear facial features. Each one has a

Corresponding author: S20060038@s.upc.edu.cn

mouth area of 1.2 cm² and a nose area of 3.57 cm². Manikin A was served as the infected person and manikin B served as the exposed person. Two manikins were face-to-face in sitting postures, and the relative distance of two mouths was 0.86 m.

2.2 Continuous phase

This study used ANSYS Fluent 2021R1 to simulate the flow field and the variables distribution (airflow temperature and velocity) inside the office space. Due to the presence of PV and background ventilation, the office environment had high turbulence effects, so the Realizable k-ε model with full buoyancy effects and enhanced wall treatment was employed to predict the indoor turbulent flow fields [9].

In the room, the density change of the air is mainly due to the temperature, and the variations are small. Therefore, the Boussinesq approximation was used to deal with the buoyancy effect. The SIMPLE algorithm was used to solve the velocity-pressure coupling fields. Except for the pressure equation used in the standard scheme, the other equations were discrete adopted the second-order upwind scheme. Meanwhile, for the steady flow, the scaled residuals was lower than 10⁻⁴.

2.3 Discrete phase

After calculating the indoor flow field in steady state, the solver was changed to transient. A time step of 0.1s was considered to be sufficient. In this study, the 5µm and 50µm particles generated by the breathing process were considered, and the evaporation process of the particles was ignored. The discrete phase models of DPM (Discrete Phase Model) based on Lagrangian method and DRW (Discrete Random Walk), which considered the impact of local turbulence intensities on particles, were used to track the trajectory of particles.

2.4 Boundary conditions

The breathing cycle was 4s, and the first two seconds of each breathing cycle was manikin A exhaled through mouth, and the last 2s was manikin B continuously inhaled through noses.

In the steady state, set the average velocity of the breathing process to the boundary condition of the respiratory airflow. Transient calculations were performed on the basis of steady-state calculations, and the curve of human real breathing flow over time could be fitted with a sinusoidal function. The mouth of the manikin A is used as a particles release port, and the density of particles was 2165kg/m³. The detailed boundary conditions were shown in Table 1:

Table 1. Boundary conditions for the CFD model.

Boundary	Boundary type	Used conditions in the CFD model
Supply (Mixing ventilation)	Velocity-inlet	V (constant): 0.075 m/s Temperature: 16.6 °C DPM condition: Reflect

PV inlet	Velocity-inlet	V (constant): 6L/s(2.96m/s) Temperature: 25.8 °C DPM condition: Reflect
Exhaust	Out-flow	DPM condition: Escape
Thermal manikin A	Wall	Temperature(head): 29.1 °C Temperature(body): 31.1 °C DPM condition: trap
Thermal manikin A mouth	Velocity-inlet	V (steady, constant): 2.36 m/s V (transient, UDF): 3.84sin(π/2) m/s Temperature: 32.6 °C DPM condition: Reflect
Thermal manikin B	Wall	Temperature(head): 28.1 °C Temperature(body): 30.3 °C DPM condition: trap
Thermal manikin B nose	Velocity-inlet	V (steady, constant): 2.5 m/s V (transient, UDF): 4.07sin(π/2) m/s Temperature: 30.5°C DPM condition: Reflect
ceiling, walls, floor, PV pipe	Wall	zero heat flux DPM condition: trap

2.5 Meshing and Verification

The unstructured-poly-hexcore-prism meshes were generated by using ANSYS Fluent Meshing 2021R1. The mesh was shown as Fig. 2. To contain the viscous sublayers, 15 prism layers were generated near the thermal manikin surfaces. The meshes around two manikins' heads and in the breath zone between the exposed person and the infected one were encrypted. The height of the first layer of the human body surface and the boundary layer of each wall was 0.003m, y⁺<5.

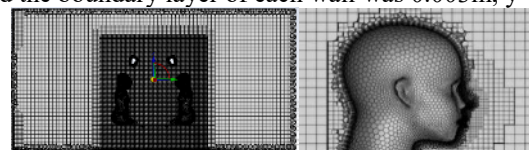


Fig. 2. Details of the grid arrangements around the manikins.

For this grid division, three different numbers of grids were selected, including 1.05 million, 2.27 million, and 3 million, and the grid independence was verified for the three forms of grid numbers. Select the temperature fitting curve on the Z (x=0, y=0) axis at the center of the model for comparison, and the comparison results are shown in the figure 3.

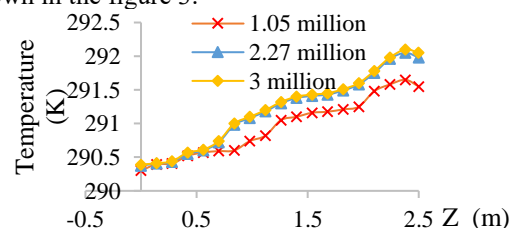


Fig. 3. Comparison of temperature changes on the same monitoring line with different grid numbers.

It was shown that 2.27 million grids can meet the calculation requirements, so 2.27 million grids were selected for numerical calculation. The inhalation fraction (IF) was used to indicate the proportion of the particles inhaled by exposed people to the total amount of particles exhaled by infected people. Comparing the inhalation fraction with the experimental results, it was found that the numerical simulation can basically consistent with the experimental results. So it was believed that the numerical simulation method can be used in this study.

3 Results

Gravity plays a key role in particle diffusion. Personalized ventilation system will have different intervention effects with different particle sizes. The specific simulated conditions were shown in Table 2.

Table 2. Parameters of CFD cases.

case	Particle size	Ventilation condition
1	0.7 μm	MV
2	5 μm	MV
3	50 μm	MV
4	0.7 μm	MV+PVAB
5	5 μm	MV+PVAB
6	50 μm	MV+PVAB

As shown in Fig. 3 and Fig. 4, both 0.7 μm and 5 μm particles were partially suspended near the breathing zone of the exposed person. It can be seen that the diffusion of 0.7 μm and 5 μm particles in mixed ventilation was similar. Particles was firstly affected by personalized ventilation airflow and spread to the back of the source manikin. Over time, slowly move in the direction of the exposed manikin. Compared with 0.7 μm , personalized ventilation had a weaker diffusion effect on 5 μm . With the same diffusion time, 5 μm of particles diffused farther away.

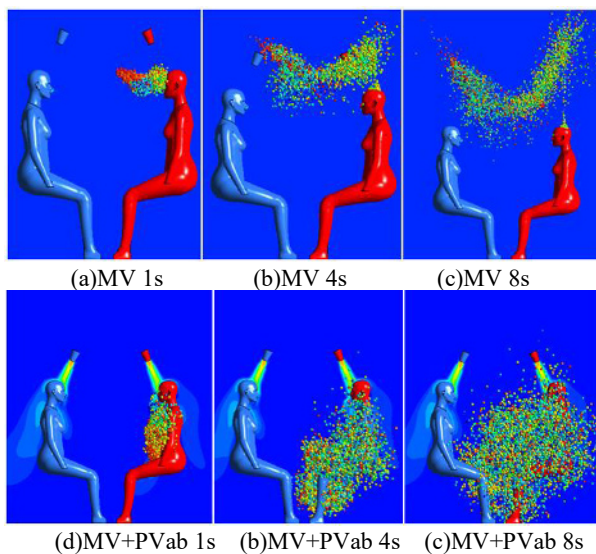


Fig. 4. Contours of particles distribution with 0.7 μm particles.

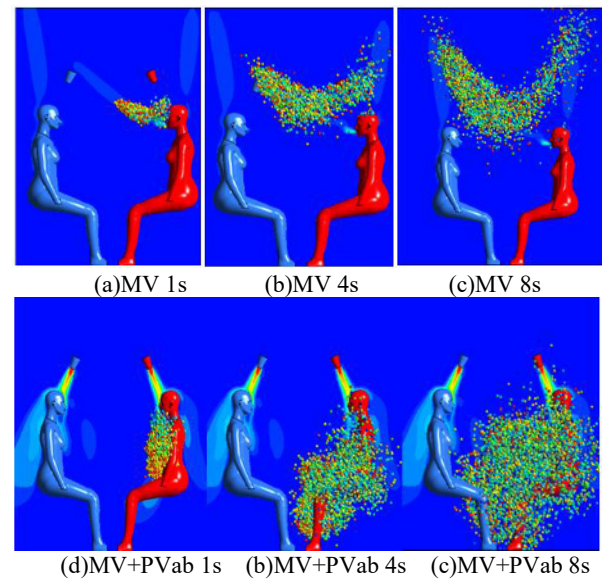


Fig. 5. Contours of particles distribution with 5 μm particles.

The results showed that at the size of 0.7 μm particles, compared to pure mixing ventilation, the personal ventilation of 6L/s reduced the IF from 0.121% to 0.092%, and the reduction ratio of IF is 23.96%. As of 5 μm , the IF also decreased from 0.165% to 0.102%, and the reduction ratio of IF is 38.18%. Therefore, the personalized ventilation can reduce the risk of inhalation by exposed persons, and the rate of IF decline by personalized ventilation increased with the increasing particle size.

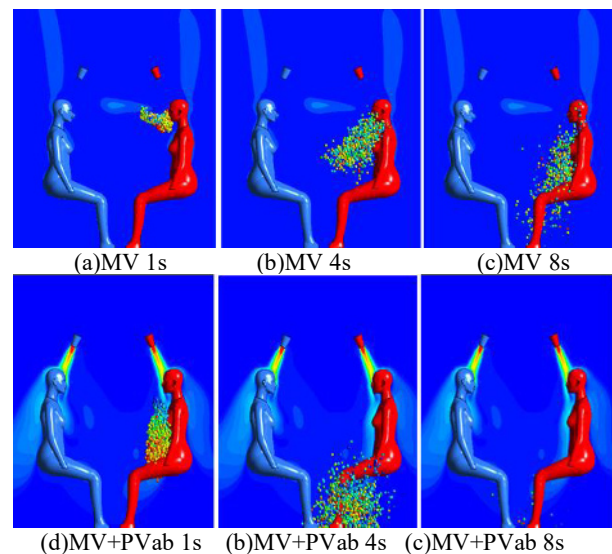


Fig. 6. Contours of particles distribution with 50 μm particles.

As shown in Fig. 6, 50 μm particles almost settled on the infected person's body and ground. The exposed person did not inhale particles. The percentage of 50 μm particles deposited on the ground rises from 6.29% to 43.22% of exhaled particles. The percentage of particles deposited in the source manikin's legs decreased from 90.15% to 54.78%. This may cause more serious secondary suspension problems, so when using personalized ventilation, there should have some ground disinfection measures.

4 Conclusion

Personalized ventilation (PV) has been integrated to reduce the risk of interpersonal infection exposure in the office environment. A 3D CFD model was developed and experimentally validated in a clean chamber. Then the validated CFD model was used to calculate the diffusion of exhaled droplets under different particle size. The results showed that with the increase of particle size, the diffused particles decreased and the increase of the number of particles settling on the infected person's body and ground. Therefore, the personalized ventilation can reduce the risk of inhalation by exposed persons, and the rate of IF decline by personalized ventilation increased with the increasing particle size. And for large size particles, the number of particles falling on the floor increased greatly, which lead to the risk of resuspension increases. The results may be helpful for maximizing the effect of PV in interpersonal airborne disease control.

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