Characteristics of aerosol dispersion in isolation wards under the mixing and perforated ceiling air supplying ventilation strategies

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Abstract. In this paper, a numerical simulation study of the airflow organization and aerosol diffusion process in a typical isolation ward is carried out to explore the effects of mixing ventilation (MV) and perforated ceiling air supplying ventilation (PCV) strategies on aerosol diffusion and deposition in the ward. Furthermore, the effects of aerosol particle size (5μm, 20μm) and aperture ratio of perforated plate on aerosol distribution were studied in this paper. The simulation results show that: compared with the MV case, PCV results in a more uniform flow field and temperature field in the ward, and can increase the discharge speed of aerosol particles, which can effectively reduce the risk of cross-infection among medical staff; by counting the proportion of aerosol deposition, discharge and suspension on each surface in the ward, it can be found that small-sized aerosol particles (5μm) are more likely to diffuse and suspend in the ward under the influence of the flow field, while large-sized aerosol particles (20μm) are more likely to be deposited on the ground and on the bed under the influence of gravity; when using PCV, reducing the porosity of perforated plate can accelerate the deposition and discharge of aerosol particles, reduce the suspension of particles in the ward, and reduce the risk of virus infection in the air.

1 Introduction

Since 2019, the novel coronavirus pneumonia (COVID-19) epidemic has been widespread, and medical staff in medical institutions are facing a high risk of infection. The new coronavirus is mainly transmitted from person to person through respiratory droplets (>5-10 μm in diameter) and direct contact[1,2]; at the same time, the evaporation of respiratory droplets will produce small-sized aerosol particles that can move with the air flow, so the new coronavirus may be transmitted through aerosol particles (diameter <5 μm)[3,4]. On the other hand, the isolation ward is an important occasion for the treatment of patients with new coronary pneumonia. Research[5] has shown that there is an association between ventilation strategies in wards and virus transmission. Due to the limited space in the isolation ward and the highly contagious novel coronavirus, medical staff may be infected during the treatment of patients. Therefore, the ventilation strategy of the isolation ward must reduce the risk of infection as much as possible. The air-conditioning design method for this type of room is quite special. For example, the ward needs to be in a negative pressure state to avoid the spread of polluted air to other clean spaces; it is also necessary to minimize the exhalation of the patient's gas into the breathing area of other people.

Common ward airflow organization forms include mixed ventilation(MV), displacement ventilation(DV) and perforated ceiling air supplying ventilation (PCV). Previous studies have carried out some studies on the propagation characteristics of aerosol particles under these different air distribution forms. Using experiments and numerical simulations, Awbi [6] found that displacement ventilation and mixed ventilation have similar ability to remove pollutants, but displacement ventilation can make the indoor temperature distribution more uniform. Akimoto et al. [7] conducted experiments on floor air supply, displacement ventilation and mixed ventilation, and found that the indoor temperature stratification of floor air supply and displacement ventilation is more obvious than that of mixed ventilation. Yang et al. [8] simulated displacement ventilation and mixed ventilation and found that displacement ventilation can remove pollutants more effectively when the pollutants are below the breathing area. Gao et al. [9] found through simulation that for displacement ventilation rooms, if the vertical temperature difference is too large, aerosol particles may stay in the breathing area for a long time. Qian et al. [10] found that local areas with higher pollution levels would be formed in the room under the condition of displacement ventilation through tracer gas experiments. Li et al. [11] used tracer gas experiments and found that the upper return air is more conducive to removing aerosols than the lower return air.

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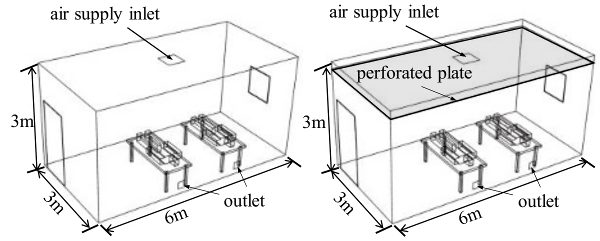
The above studies show that the air distribution has a great influence on the concentration distribution of indoor aerosol particles, and a reasonable air distribution can reduce the suspended amount of indoor particles. However, there are few studies on the ward airflow organization and the diffusion characteristics of aerosol particles in isolation wards under the perforated ceiling air supplying ventilation strategy, which deserves further research and evaluation. Based on the above purposes, this paper firstly compares and analyzes the flow field, temperature field and particle concentration distribution in the ward under the two strategies of MV and PCV; then, under the condition of PCV, the effect of perforated plate opening rate and particle size on the particle discharge efficiency in the ward was discussed. This article can provide a reference for the design of air-conditioning airflow in isolation wards and how to avoid cross-infection among medical staff.

2 Research object

The research object in this paper is the negative pressure ward shown in Fig.1, and the size of the ward is 6 × 3 × 3 m^3. The door size is 1×2 m^2 and the window size is 0.8×0.8 m^2. There are two beds in the isolation ward, with a size of 1.9×0.8×0.6 m^3. The air supply volume is 500 m^3/h, the exhaust air volume is 600 m^3/h, and the infiltration air volume through the gaps of doors and windows is 100 m^3/h. To simplify the model, the width of the door and window gaps in this article is set to 2 mm. The human body is appropriately simplified, the height is 1.7 m, the surface area of the human body is 2.15 m^2, and the human mouth is simplified to a square with a side length of 0.01 m.

When MV is used, as shown in Fig.1(a), the air supply inlet is arranged in the center of the ward, with a size of 0.5 × 0.5 m^2; the return air outlet is arranged on the underside of the head of the bed, 100 mm from the ground, with a size of 0.2×0.2 m^2. When PCV is used, the size of the supply air inlet and return air outlet of the ward is the same as that of the MV, but a perforated plate needs to be added at a distance of 0.2 m from the roof of the ward. The thickness of the perforated plate is 0.02 m, and the length and width are 6 m and 3 m, as shown in Fig. 1(b).



(a)MV (b) PCV

Fig. 1. Schematic diagram of the geometric models of different air supply modes

3 Research methods

3.1 Numerical model

In this paper, ANSYS Fluent v19.2 is used to solve the equations of fluid flow and particle motion. Air is assumed to be an ideal incompressible gas, and natural convection due to temperature gradients is calculated using the bossinesq assumption.

In order to explore the diffusion characteristics of particles, this paper adopts the unsteady calculation method of coupling discrete phase and continuous phase. For the continuous phase, the RNG k-ε model coupled with the enhanced wall function is used to simulate the turbulent flow; for the discrete phase, the DPM (Discrete Phase Model) model based on the Euler-Lagrangian method is used to simulate the motion of aerosol particles. The random walk model is used to track the trajectory of particles.

In order to simplify the model, this paper uses the porous medium model to replace the perforated plate, that is, the perforated plate is set as the porous medium fluid region. In the simulation, the drag coefficient of the porous medium is set as the drag coefficient of the perforated plate. According to the research on the resistance coefficient of perforated plates by Li Quanwei[12], the resistance coefficient(C) of air passing through perforated plate with different opening ratios (β) (the opening diameter is 6 mm) can be expressed as:

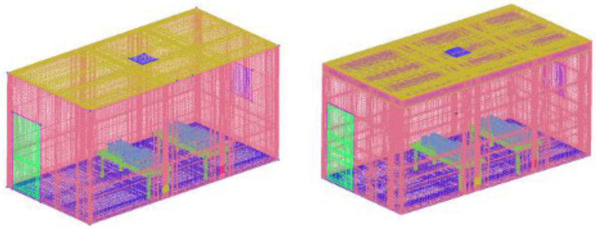
$$C = \frac{1.16\beta^{-2.03}}{\Delta n} \quad (1)$$

In formula (1), Δn is the thickness of the perforated plate.

In this paper, the resistance coefficient of the porous medium is adjusted to correspond to the different opening ratios (0.1~0.5) of the perforated plate.

3.2 Computational domain and grid

In this paper, ICEM CFD software is used to mesh the ward models with two air supply strategies. Mesh refinement is performed in areas with large velocity and composition gradients, such as around the human body, near the mouth, near the wall, etc. In particular, for PCV, mesh refinement of the porous media area is also required. After completing the grid independence verification, it can be determined that the number of grids in the MV and PCV are 2.32 million and 3.49 million, respectively, as shown in Fig.2.



(a)MV (b) PCV

Fig. 2. Schematic diagram of grid of two air supply modes

3.3 Boundary conditions

According to the research results of Duguid et al. [13], the particle size of droplets generated by breathing behavior is mainly distributed between 2 and 100 μm. After the aerosol particles are ejected from the human body, evaporation and diffusion will occur. However, under common indoor temperature and humidity fields and airflow fields, the evaporation of 20-80 μm droplets into 5-20 μm droplet nuclei takes only a few seconds. Therefore, typical particles with diameters of 5 μm and 20 μm were selected for the study in this paper. In the simulation, it is assumed that each particle does not agglomerate, and the evaporation of droplet particles is ignored.

The walls, ceilings, doors, and windows around the ward are set as constant temperature walls, and the temperatures are 25 and 30 °C, respectively. The air supply inlet, door and window gaps, and human mouths use speed inlets. The wind speeds of the three are 0.556m/s, 0.148m/s, and 1.4m/s, respectively, and the temperatures are 22°C, 28°C, and 38°C, respectively; the air outlet adopts the free outflow boundary condition. Since the particle size of the particles is small, it is considered that the particles are trapped when they reach the wall surface, so the wall surface is set to a trap condition. Human body heat dissipation adopts constant heat flux density. According to the specification, when the room temperature is 24 °C, the heat dissipation of an adult man while sitting is 108 W, and the heat flow of the human body is 50 W/m2. The particle size is 5 μm and 20 μm, and the density is 1000 kg/m3. The particles were released from 0 s, and the release time step was 0.01 s.

Except that the pressure term adopts the staggered pressure (Pressure Staggering Option, PRESIO) discrete format, the other control equations are discrete using the second-order upwind style, and the Couple algorithm is used to solve the pressure-velocity coupling. The convergence criteria of the simulation include two aspects: (1) the residuals of the energy equation and other equations are 10^{-6} and 10^{-4} respectively; (2) the temperature and velocity at the outlet basically do not change with the iteration, that is, the variation range is less than ±1°C, ±0.1 m/s.

3.4 Simulation cases

In this paper, the influence of air supply strategy, particle size, and perforated plate opening ratio on the flow and particle diffusion characteristics in the ward will be studied through the six working cases shown in Table 1.

Table 1. Simulation cases

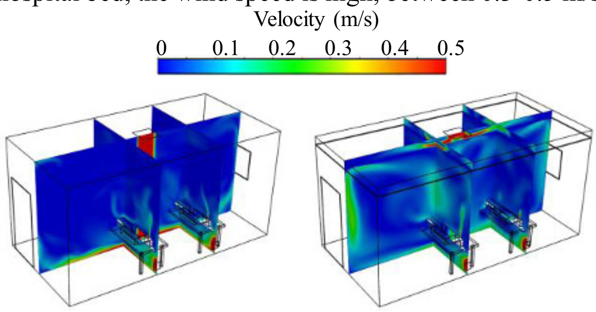
Working case	Air supply strategy	Plate opening ratio	Particle size (μm)
Case1	MV	\	5
Case 2	MV	\	20
Case 3	PCV	0.5	5
Case 4	PCV	0.2	5
Case 5	PCV	0.1	5
Case 6	PCV	0.1	20

4 Discussion of results

4.1 Effect of ventilation strategy

4.1.1 Analysis of flow field

Fig.3 shows the flow field in the ward under MV (Case 1) and PCV (the opening rate is 0.1, Case 5). It can be seen from Fig.3(a) that when the MV is adopted, after the cold air enters the ward from the air supply inlet, it can almost reach the bottom of the room, and then spread to the surroundings. The wind speed below the air supply intlet in the ward is relatively large, and the wind speed decays slowly, basically between 0.4-0.5 m/s; the air velocity near the floor of the ward is between 0.3-0.4 m/s, and the wind speed in most areas of the ward is low, between 0-0.1 m/s. Since the patient's body temperature is higher than the ambient air temperature, there is a rising thermal plume on the patient's surface with a maximum velocity of about 0.1 m/s. The hot jet produced by the patient's breathing is ejected from the mouth, and its velocity decays rapidly under the influence of the surrounding airflow. The infiltration wind of doors and windows has little effect on the flow field in the ward. Due to the existence of the return air outlet in the lower part of the hospital bed, the wind speed is high, between 0.3-0.5 m/s.



(a) Case1 (b) Case5

Fig. 3. Comparison of the flow field in the ward under MV (Case 1) and PCV (Case 5)

It can be seen from Fig.3 (b) that when the perforated plate is used for ventilation, the flow field in the ward changes significantly compared with the MV. Due to the resistance of the perforated plate, after the cold air comes out from the air supply inlet, it cannot directly enter the room, but goes down slowly through the perforated plate. The wind speed in most areas of the ward is between 0.1-0.2 m/s. In this form of air supply, because the cold air is slowly falling from the top of the ward, the heat plume on the patient's surface is not obvious; and the jet at the patient's mouth is also suppressed to a certain extent, and the speed attenuates faster. Similarly, due to the existence of return air vents in the lower part of the hospital bed, the wind speed in this area is high, between 0.3-0.5 m/s.

4.1.2 Analysis of temperature field

Fig.4 shows the temperature field in the ward when MV (Case 1) and PCV (the opening ratio is 0.1, Case 5), respectively. It can be seen from Fig.4(a) that when MV is used, the cold air can reach the bottom of the ward, and the temperature stratification in the ward is more obvious.

The overall temperature distribution is low in the lower part and high in the upper part, that is, the temperature at the top is higher, between 26-28 °C, and the temperature at the bottom is lower, between 22-24 °C.

It can be seen from Fig.4(b) that when an perforated plate with a opening ratio of 0.1 is used for ventilation, the cold air enters the perforated plate and the ceiling cavity from the air supply inlet, and then passes through the perforated plate to reach the ward. Therefore, the air temperature in the cavity is lower, the temperature is between 22-24 °C, and the temperature in the room is between 24-26 °C. Fig.4 shows that the temperature distribution in the room is more uniform under the PCV compared to the MV.

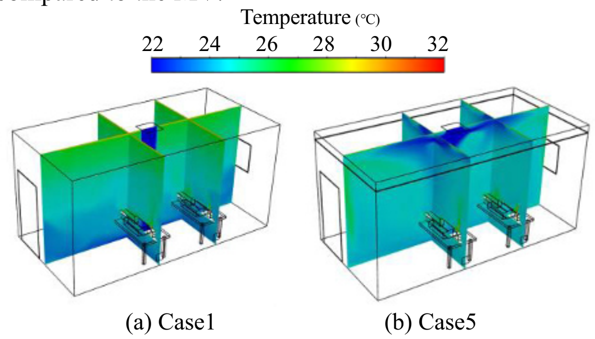


Fig. 4. Comparison of the temperature field in the ward under MV (Case 1) and PCV (Case 5)

4.1.3 Analysis of particle concentration

Fig.5 shows the distribution of aerosol particle concentration in the ward under the MV and PCV strategies when the steady state is reached. It can be seen from the figure that under MV, after the aerosol particles are exhaled from the human mouth, they first diffuse upward, and then gradually spread horizontally to the entire ward. As a result, the concentration of aerosol particles was higher throughout the ward, with the highest concentration in the area above the patient's head. When the perforated plate is used for ventilation, the diffusion range of aerosol particles is significantly reduced. The particulate matter is mainly concentrated in the area above the human head, and the concentration of aerosol particulate matter in other areas of the ward is significantly reduced. This shows that the concentration of indoor suspended aerosol particles is reduced when the perforated plate is used for air supply. It can be speculated that the removal rate of aerosol particles is faster than that of MV. Therefore, the particle removal efficiency is higher, which is more conducive to reducing the risk of cross-infection among medical staff.

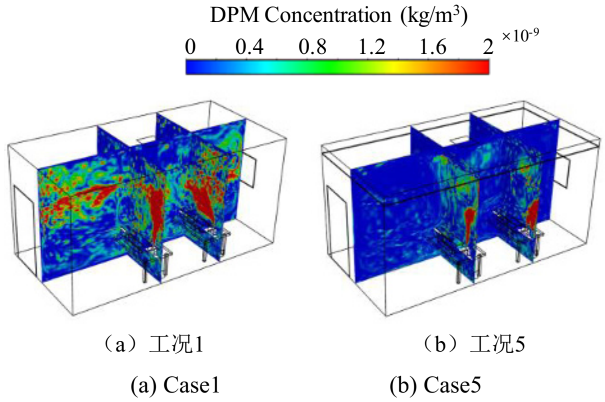


Fig. 5. Concentration field of particulate matter in the ward under MV (Case 1) and PCV (Case 5)

4.2 Influence of particle size

Fig.6 shows the change in the amount of particulate matter in the ward over time. It can be seen from the figure that whether MV or PCV is used, the variation law of particles with different particle sizes over time is basically the same, that is, the concentration/number of particles in the room will eventually reach a steady state and will not change. No matter which air supply form is used, compared with the small particle size (5 μm) particles, the large particle size (20 μm) reaches a steady state in a shorter time, and the final number of suspended particles in the ward is less.

When the steady state is reached, the ratio of aerosol deposition, discharge and suspension on each surface of the ward can be counted (the ratio of each statistic to the total number of particles released at the current moment), and the results are shown in Table 2. By comparing Case 1 and Case 2, it can be seen that the proportion of small-sized particles falling on ceilings, doors, walls and windows is higher than that of large-sized particles, while larger-sized particles fall more on floors, beds and patients, and the small-sized particles discharged through the return air outlet and finally suspended in the room are also more than the large-sized particles. This is mainly due to the fact that small-sized particles are more easily affected by airflow to reach various positions in the room and suspend in the ward, while large-sized particles are quickly deposited by gravity and are not easy to diffuse. This phenomenon is similar for the PCV strategy.

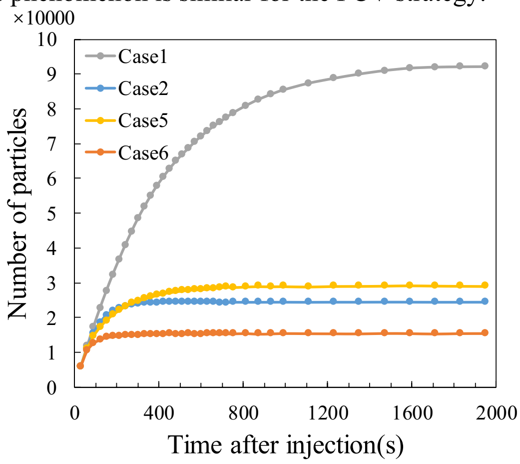


Fig. 6. Effect of particle size on removal rate

Table 2. The proportion of aerosol deposition, discharge and suspension on each surface of the ward

Position	case1	case2	case5	case6
ceiling	0.44%	0.00%	2.35%	0.07%
door	0.22%	0.08%	0.30%	0.11%
floor	7.90%	24.51%	14.80%	34.80%
patient	2.54%	10.76%	2.95%	3.36%
wall	8.61%	6.24%	8.10%	5.68%
Patient bed	5.37%	7.99%	5.12%	6.83%
window	0.14%	0.01%	0.04%	0.01%
exhaust	45.90%	38.07%	51.68%	41.32%
suspend	28.88%	12.35%	14.65%	7.83%

In addition, comparing Case 1 and Case 5, it can be seen that when the perforated plate is used for ventilation, the concentration of indoor suspended particles is lower, and the discharge efficiency is higher. In other words, under MV, the suspension ratio is 28.88% and the discharge ratio is 45.90%, while under PCV, the suspension concentration is only 14.65% and the discharge ratio is 51.68%. This shows that the PCV is more likely to discharge indoor particulate matter, so that the indoor suspended concentration is lower.

4.3 Influence of porosity

In order to study the effect of the perforated plate opening ratio (0.5, 0.3, 0.1) on the diffusion of aerosol particles in the ward under the PCV, the number of aerosol particles in the ward at different times under three working Cases(case3-5) was counted, as shown in Fig.7. The figure shows that, over time, the number of aerosol particles in the ward will eventually reach a dynamic equilibrium steady state. In the steady state, the number of indoor aerosol particles will characterize the removal ability of PCV with different opening ratios to aerosol particles. In other words, the higher the number of particles, the weaker the removal ability.

It can be seen from Fig.7 that when the opening ratio is different, the time to reach equilibrium is also different, that is, the smaller the opening ratio, the shorter the time for the number of aerosol particles to reach equilibrium. In addition, with the decrease of the open porosity, the number of finally suspended aerosol particles in the ward gradually decreased, indicating that reducing the open porosity can accelerate the deposition and discharge of particles. This shows that when the PCV strategy is adopted, reducing the opening rate can accelerate the discharge of aerosol particles from the room, reduce the transmission path of particles in the room, and reduce the risk of cross-infection.

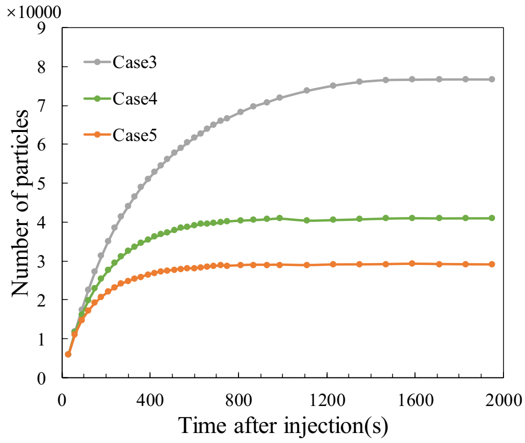


Fig. 7. Influence of open porosity on removal rate

5 Conclusion

In this study, a numerical simulation study was carried out on a typical isolation ward with MV and PCV strategies, and the effect of airflow organization on the diffusion and deposition of aerosols in the ward was discussed. According to the simulation results, the following conclusions can be drawn:

(1) Compared with mixing ventilation, when the perforated ceiling air supplying ventilation is adopted in the ward, the distribution of flow field and temperature field in the ward is more uniform;

(2) Compared with mixing ventilation, when the perforated ceiling air supplying ventilation is adopted, the discharge speed of aerosol particles is faster and the number of indoor suspended particles is less. Therefore, it can effectively reduce the risk of cross infection of medical staff through the air of the ward;

(3) Small particle size is more easily affected by the flow field, so it is easier to suspend in the ward, while large particle size is easier to deposit on the ground and patient bed;

(4) When adopting the perforated ceiling air supplying ventilation strategy, reducing the opening ratio can accelerate the deposition and discharge of particles, so as to reduce the proportion of suspended particles in the air.

Acknowledgement

This paper is supported by the Wuhan Science and Technology Program (No. 2020020601012229).

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