Simulation study on the effect of air supply and exhaust terminals to coughed droplet diffusion in NPI ward

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Abstract. The numerical (CFD) method is applied in this paper to investigate the nonuniformity of temperature and airflow filed, the spatial and temporal distribution of coughed droplet under stratum ventilation and mixing ventilation in the negative pressure isolation (NPI) ward. The influence of exhaust terminals number and location on the diffusion process of coughed droplet is analyzed under heating mode. The results show that the relative pollutant concentration in the breathing area of stratum ventilation is lower than that of mixing ventilation. When the air exhaust terminals are high from the ground and the number are small, it is more conducive to reduce the infection risk of medical staff. The deposition rate and suspension rate of stratum ventilation are higher than that of mixing ventilation, and the escape rate is lower. When the number of exhaust outlets is large and the location is high, the nonuniformity coefficient is the smallest and the deposition rate is the largest, which are 0.668, 0.029 and 91.4% respectively. The escape rate is higher when the number of exhaust outlets is small and the location is high, and the suspension rate is higher when the number of exhaust outlets is large and the location is low, which are 27.9% and 1.11% respectively.

1 Introduction

COVID-19 broke out in the spring of 2020, by December 2021, there were more than 200 million confirmed cases of COVID-19, including more than 5 million deaths. Although the epidemic has been basically brought under control in China, the global epidemic prevention and control situation is still very severe, with daily new cases in the United States, Europe and other countries at a high rate [1]. NPI ward has been widely used in the prevention and treatment of respiratory infectious diseases. The droplets produced by patients' breathing activities are an important source of virus in NPI ward [2]. In NPI ward, good airflow organization is an important measure to prevent cross infection of medical staff.

This paper takes the experimental platform of NPI ward of Chongqing University of Science and Technology as the research object, and analyzed the influence of the ventilation mode (stratum ventilation and mixing ventilation) and the position and number of exhaust terminals on the droplet transmission under the heating condition in winter by using the CFD simulation method, and to explore the applicability of floor ventilation in NPI ward.

2 Research method

2.1 Physical model

Fig. 1(a) show the internal structure of NPI ward, with 4.8m×4.5m×2.4m, excluding buffer room and toilet. For mixing ventilation (MV), the air supply outlet is located at the top of the ceiling. For stratum ventilation (SV), the air supply outlet is located in the middle of the side wall, the centre is 1.5m away from the ground, air supply outlet sizes are 0.51m×0.51m. The exhaust terminals are 0.18m and 1.02m away from the ground, and there are eight exhaust terminals with a size of 0.34m×0.14m. There were two beds in the ward, one patient lying on his back in each bed, the doctor standing on one side of the bed, and the nurse standing at the end of the bed. Medical staff and patients are replaced by dummies made of paper boxes. The head was simplified as a cube with the side length of 0.2m, the mouth as a square with the side length of 0.02m, and the trunk as a cuboid with the side length of 0.5 m×0.2 m× 1.4 m. A 100W bulb was placed inside the dummy as the heat source, and the heat flow density of the human body was 43 W/m². The ceiling is equipped with 4 lighting lamps, each of which is 30W, and the heat flux is 83W/m². The size of the door crack is 0.9m× 0.015m.

The layout of survey points is shown in Fig. 1(b). L1-L7 represent survey lines, and five survey points (0.1m,0.6m,1.1m,1.5m and 2.2m) with different heights are set for each survey line, with a total of 35 survey points used to measure the temperature and wind speed in the ward. P1-P5 is the indoor wall temperature measurement point, where P1-P4 1.5m from the ground,
P5 is located in the ceiling. Experimental test and measurement instruments are shown in Table 1.

| Instrument               | Parameter        | Precision | Measuring range |
|--------------------------|------------------|-----------|-----------------|
| TSI 8380 Air volume hood | Air quantity     | ±3%       | 42~4250m3/hr    |
| GSP-6 Temperature detector | Temperature | ±0.5℃     | 0~50℃          |
| SWEMA Universal anemometer | Wind speed   | ±0.03m/s±3% | 0.05~10.00m/s  |

2.2 Mathematical model

The CFD software ANSYS Fluent 19.0 is used to simulate the indoor flow field and droplet diffusion process, select the pressure base solver, set the gravity in the Z direction to -9.81m/s, and open the energy equation. Reynolds-averaged NS model (RANS) is selected for time-averaged treatment of turbulence pulsation term, and the general form of fluid flow control equation is:

\[
\frac{\partial(\rho\phi)}{\partial t} + \frac{\partial(\rho u_i \phi)}{\partial x_i} = \frac{\partial}{\partial x_j} \left( \Gamma_\phi \frac{\partial \phi}{\partial x_j} \right) + S_\phi
\]

(1)

Where \(\Gamma_\phi\) is the diffusion coefficient corresponding to variable \(\phi\), and the last \(S_\phi\) term is the source term of function \(\phi\) [3]. RNG k-ε model is used as turbulence model because it performs well in indoor ventilation system [4]. The standard wall function is used for near-wall treatment [5]. The discrete ordinates (DO) radiation model is applied to simulate the radiative heat transfer among the surface of occupants, lights and other indoor surfaces [6].

Finite volume method (FVM) is used to discretize the equation into algebraic equation. Coupling with pressure and velocity adopts SIMPLE algorithm. Second-order upwind scheme is adopted for pressure, momentum and energy. First-order upwind scheme is adopted for physical quantities such as turbulence kinetic energy, turbulent dissipation rate and radiation. Boussinesq model is adopted to consider buoyancy effect, and the criterion for judging the convergence of each physical quantity is that the residual error of energy equation reaches 10^{-6} and the residual error of other physical quantities reaches 10^{-3}. Using discrete phase model to simulate the spray process of droplets [7].

2.3 Boundary conditions

Design value of air supply volume is 470 m³/h, and air exhaust volume is 580 m³/h to keep indoor pressure at -5pa. In NPI ward, the indoor design temperature is 20℃-26℃, and the indoor design temperature for heating in winter is 22℃ [8]. Wall surfaces, doors and windows of the room are constant temperature surfaces, and the ceiling is 22.2℃ and other wall surfaces are 21.6℃.

With a cough airflow speed of 10m/s and a release time of 1s, the droplet pollutants caused by breathing will not be considered after coughing. With the droplet density of 700 kg/m³, the droplet size obeys Rosin-Rammler distribution, the minimum particle size is 1.0x10^{-7}m, the maximum particle size is 2x10^{-4}m, the average particle size is 1.6x10^{-4}m, the distribution index is 3.42, and the number of particle sizes is 14. The mass flow rate of droplets is 1.03x10^{-6}kg/s [9]. The droplet temperature is 35℃ [10].

2.4 Grid independence test

Non-structural hexahedron mesh is used to discretize the volume of NPI ward, and the mouth, lamp and human body are locally encrypted. Selecting 430,000 coarse meshes, 1.3 million medium meshes and 3.2 million fine meshes, the maximum mesh sizes are 30 mm, 50 mm and 70 mm respectively. Case 6(Table 3) is taken as an example for simulation calculation, as shown in Fig 2. The results show that 1.3 million medium grid is accurate enough.
2.5 Model validation

In working condition 1 (Table 3), for example, the temperature and speed of 35 measuring points in the room were measured through experiments, and the simulated data of wind speed and temperature were compared. The results are shown in Fig 3. The maximum errors of wind speed and temperature of the survey line are 9.5% and 7% respectively, and the error range is less than 10%. The simulation results are basically consistent with the experimental test results.

2.6 Design condition

In this paper, a total of 8 simulation conditions are designed, as shown in Table 2, in which two kinds of air distribution, the number of two kinds of exhaust terminals and the height of two kinds of exhaust terminals are considered to explore their influence on the diffusion law of indoor droplets.

Table 2. Simulation conditions

| Conditions | Design temperature | Number of exhaust terminals | Exhaust terminals height | Air distribution |
|------------|--------------------|----------------------------|--------------------------|------------------|
| 1          | 22°C               | 4                          | 0.18m                    | MV               |
| 2          |                    | 4                          | 1.02m                    | SV               |
| 3          |                    | 2                          | 0.18m                    | MV               |
| 4          |                    | 2                          | 1.02m                    | SV               |
| 5          |                    |                            |                          |                  |
| 6          |                    |                            |                          |                  |
| 7          |                    |                            |                          |                  |
| 8          |                    |                            |                          |                  |

2.7 Performance evaluation

Non-uniformity coefficient is used to analyze the indoor air flow field [11]. Pollutant concentration fraction and relative pollutant concentration breathing zone are used as evaluation indexes to analyze the variation of the average concentration of indoor droplets and the concentration of breathing zone with time under different air distribution [12]. The deposition rate, escape rate and suspension rate were used as evaluation indexes to analyze the "fate" of cough droplets in NPI wards [13].

1) Non-uniformity coefficient

The difference of indoor temperature and wind speed at each point can be expressed by "non-uniformity coefficient". The smaller the non-uniformity coefficient, the better the uniformity of airflow distribution. And that calculation of the uneven coefficient of temperature and wind speed are shown in formula (2) to (4):

(ku)" = u/u                           (2)

Among them:

ku = (T - T) / n,  u = (u) / n           (3)

σT = √(∑(T - T)^2) / n,  σu = √(∑(u - u)^2) / n   (4)

Where kT represents the coefficient of temperature unevenness; ku represents the uneven coefficient of wind speed; T represents the average temperature, K; u represents the average wind speed, m/s; σT represents the root mean square deviation of temperature; σu represents the root mean square deviation of velocity; Ti represents the temperature of the measuring point, K; ui represents the wind speed at the measuring point, m/s.

(2) Contaminant concentration fraction: the ratio of indoor average pollutant concentration to initial droplet concentration:

Cp = c / cex                           (5)
Relative pollutant concentration in breathing zone: ratio of average pollutant concentration in breathing zone to initial droplet concentration:

\[ C = \frac{C_p}{C_{\text{ex}}} \]  

(6)

Where \( C_v \) is the indoor average concentration; \( C_p \) is the average concentration of pollutants in respiratory area; \( C_{\text{ex}} \) is the initial concentration of droplets.

3) Deposition rate: the percentage of the number of settled particles to the total number of exhaled droplets of patients:

\[ R_T = \frac{N_T}{N} \times 100\% \]

(7)

Escape rate: the percentage of droplets discharged from the room through the air outlet to the total number of droplets exhaled by patients:

\[ R_E = \frac{N_E}{N} \times 100\% \]

(8)

Suspension rate: the percentage of the number of droplets suspended in the room to the total number of droplets exhaled by the patient:

\[ R_S = \frac{N_S}{N} \times 100\% \]

(9)

Where \( N_T \) represents the number of droplets "captured" indoors; where \( N_E \) represents the number of droplets removed through the exhaust vent; where \( N_S \) represents the number of suspended indoor droplets; \( N \) represents the total number of droplets generated indoors.

3 Results and discussion

3.1 Non-uniformity coefficient analysis

Wind speed and temperature non-uniformity coefficients under eight working conditions are shown in Fig 4. Wind speed and temperature non-uniformity coefficients of working condition 2 are the largest, which are 0.982 and 0.04 respectively. The non-uniformity coefficient of condition 5 is the lowest, which is 0.668 and 0.029 respectively. The results show that the non-uniformity coefficient of mixing ventilation is lower than that of stratum ventilation, the non-uniformity coefficient is lower when the number of exhaust terminals is large, and the non-uniformity coefficient is lower when the position of exhaust terminals is high.
3.2 Changes of mean concentration and relative concentration of breathing zone

Fig. 5(a) shows the trend chart of indoor pollutant concentration fraction changing with time under eight different working conditions. Indoor pollutant concentration fractions of eight kinds of airflow organizations are almost the same at the end of 300s, which is close to 0, indicating that all eight kinds of airflow organizations can eliminate indoor pollutants within 0-300 s. On the basis of 95% indoor pollutant removal, the time required for eight working conditions is 120s, 130s, 70s, 80s, 25s, 90s, 20s and 30s respectively. Condition 7 has the highest efficiency and Condition 2 has the lowest efficiency.

Fig. 5(b) shows the trend of the relative pollutant concentration in the respiratory area of patients after coughing with time. From the figure, it can be seen that the concentration of droplets in breathing zone gradually decreases with time, and after 150s, the concentration difference under various working conditions gradually decreases. During 0-150s, the concentration in the respiratory zone of working condition 1 is the highest, and that in working condition 8 is the lowest. Comparison shows that the relative pollutant concentration in the breathing zone of stratum ventilation is lower than that of mixing ventilation, and the exhaust terminals located at the upper part of the hospital bed are better than those located at the lower part of the hospital bed. The working conditions of two exhaust terminals are better than those of four exhaust terminals.

3.3 Droplet deposition, escape and suspension in NPI ward

Fig. 6(a) shows the deposition rates of NPI ward walls (walls around the room and ceilings), floors and patient areas (bed surfaces and patient surfaces) under different working conditions. As can be seen from the figure, a large number of droplets are deposited in the affected area, among which some droplets with larger particle size are greatly influenced by gravity and deposited on the floor. When the particle size is small, the main deposition position changes with the ventilation conditions, and finally they are captured by the wall surface and excluded from the outdoor. In working conditions 1-8, the deposition rate in the patient area has reached more than 65%, which indicates that the concentration of droplets in the patient area is high, and the medical staff should try to reduce the stay time and walking time in the patient area, so as to reduce the infection risk and the secondary diffusion of droplets.

Fig. 6(b) shows the deposition rate under different working conditions. From the figure, it can be seen that the deposition rate of stratum ventilation is higher than
that of mixing ventilation, the deposition rate of four exhaust terminals is higher than that of two exhaust terminals, and the deposition rate of exhaust terminals with a height of 1.02m is higher than that of 0.18m. In which, the highest deposition rate is 91.4% under the condition of 1.02m height of four exhaust terminals of stratum ventilation, and the lowest deposition rate is 72.2% under the condition of 0.18m height of two exhaust terminals of mixing ventilation.

Fig. 6. (b) Deposition rate under different working conditions

Fig. 7 shows the escape rate of droplets within 300s and the indoor droplet suspension rate under 8 working conditions. In which the highest escape rate of working condition 7 is 27.9%, and the lowest escape rate of working condition 2 is 7.6%. Indoor droplet suspension rate is 0.04% in working condition 7 and 5, and 1.11% in working condition 2. The escape rate of mixing ventilation is higher than that of stratum ventilation, and the escape rate of fewer exhaust terminals and higher positions is higher. In stratum ventilation, the suspension rate is higher than that in mixing ventilation, and the suspension rate is higher with more exhaust terminals and lower positions.

4 Conclusion

From the point of view of non-uniform coefficient, mixing ventilation is lower than stratum ventilation; When the number of exhaust terminals is large and the position is high, the non-uniformity coefficient is small.

Relative pollutant concentration in the breathing zone of stratum ventilation is lower than that of mixing ventilation, and the relative pollutant concentration in the breathing zone is lower when the position of exhaust terminals is higher and the number is smaller.

Compared with mixing ventilation, the deposition rate and suspension rate of stratum ventilation are higher and the deposition rate is lower. When the number of exhaust terminals are large and the position are high, the deposition rate is high, when the number of exhaust terminals are small and the position are low, the escape rate is high, and when the number of exhaust terminals are large and the position are low, the suspension rate is high.

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