The motion law of aerosols produced by human respiration under the action of thermal plume in ventilated room

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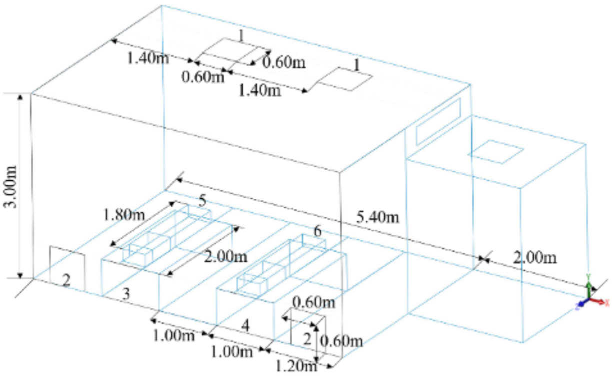
Abstract. To investigate the human exhaled particle motion law under the effects of the thermal plume in a ventilated room, a three-dimensional model of a typical double ward was created. The Large Eddy Simulation was utilized to study the effects of thermal plume of different intensities on particle diffusion, and the removal effects of varied ventilation rates on particles during displacement ventilation were simulated. The results show that the thermal plume formed by a human model at varied room temperatures has a consistent distribution law, and particle diffusion distance and velocity are positively linked with plume intensity. Lower ventilation rates are preferable for particle-removal in the reasonable ventilation mod

COVID-19 has presented a significant danger to global public health since its emergence[1]. SARS-CoV-2 can be transferred by aerosols, according to studies [2], and the quantity of indoor particles is highly correlated with exhaust air volume and air supply position [3]. Currently, research on the environment of hospital wards focuses mostly on the impact of airflow organization on the interior environment and microbiological diffusion [4-6], neglecting the impact of the human thermal plume on the diffusion of particles produced by breathing. How to better restrict the virus's propagation in the air has become a popular concern and a pressing issue that must be addressed. The function of the human thermal plume in the diffusion of aerosol particles will be investigated in this work using numerical modeling, and strategies for eliminating aerosol particles will be studied as a result.

1 Research object

1.1 Physical model

In this paper, an ordinary double ward is utilized as the research object to establish a three-dimensional model with a size of 7.40m (X) × 3.00m (Y) × 3.60m (Z), as shown in Figure 1. The dispersion of aerosol particles at different room temperatures (24 °C, 27 °C, which are common temperature of air-conditioned room in summer, and 30 °C, which is common temperature of no air-conditioned room in summer. [7]) is the focus of this work. Furthermore, the effect of air change rate on particles is simulated using an up-supply and down-return ventilation system (vent 2 is the supply-air inlet, and vent 1 is the return-air outlet). There are three temperature zones in the manikin (head, torso, and lower limbs). The temperatures of the three zones in three room temperatures are given in Table 1.



1-2. Vent 3-4.Sickbed 5-6.Patient
Fig. 1. Ward geometric model

Table 1. Ward geometric model.[7]

Section		Head	Upper body	Lower body	Breathing air
Temperature Setting (℃)	Room temperature for 24℃	33℃	27℃	28℃	35℃
	Room temperature for 27℃	33.5℃	29℃	30℃	35℃
	Room temperature for 30℃	34℃	31℃	32℃	35℃

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1.2 Mathematical model

The governing equation of LES is composed of continuity equation and unsteady N-S equation obtained through filtering function processing:

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_j}(\rho \overline{u_i})=0 \tag{1}$$

$$\frac{\partial}{\partial t}\left(\rho \overline{u_i}\right)+\frac{\partial}{\partial x_j}(\rho \overline{u_i u_j})=\frac{\partial}{\partial x_j}(\mu \frac{\partial \sigma_{ij}}{\partial x_j})-\frac{\partial \overline{P}}{\partial x_j}-\frac{\partial \tau_{ij}}{\partial x_j} \tag{2}$$

$$\sigma_{ij}=\left[\mu\left(\frac{\partial \overline{u_i}}{\partial x_j}+\frac{\partial \overline{u_j}}{\partial x_i}\right)\right]-\frac{2}{3}\mu\frac{\partial u_i}{\partial x_j}\delta_{ij} \tag{3}$$

Where u is the vector form of the velocity, ρ is the density in kg/m^3, and t is the time, P is pressure in flow field, x_i and x_j are cartesian coordinate components ($i, j=1,2,3$), $\overline{u_i}$ and $\overline{u_j}$ are velocity components associated with x_i and x_j , $\overline{u_i}$, $\overline{u_j}$ are the filtered average velocity component, μ is the dynamic viscosity coefficient of the fluid, σ_{ij} is the Strain tensor due to molecular viscosity, δ_{ij} is the Kronecker function, $\tau_{ij}=\rho\overline{u_i u_j}-\rho\overline{u_i u_j}$ is the sublattice Reynolds stress.

1.3 Boundary conditions

Boussinesp is used to estimate air density in this work, and the pressure implicit partition operator approach is employed to solve the problem. To discretize momentum and energy in space, the second order upwind approach is utilized. The transient equation is solved using the implicit second order approach. For the supply-air inlet, the velocity inlet boundary condition is used. The pressure outlet boundary condition is applied to the return-air outlet.

The setting of other boundary conditions are shown in Table 2.

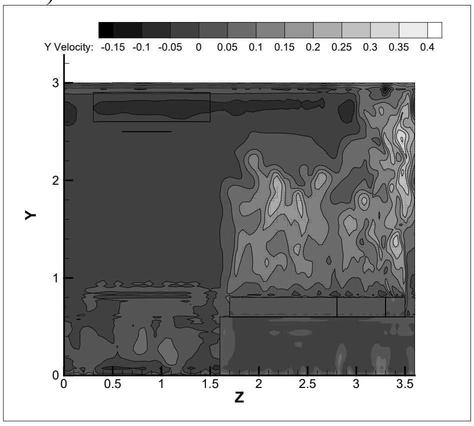
Table 2. Setting of boundary conditions.[7]

Boundary	Setting
Nostril area	1.44cm^2
Respiratory rate	10.00/min
Breathing capacity	5.98L/min
Airflow velocity	0.70m/s
Airflow angle	30°
Particle diameter	0.30-3.00μm
Particle density	1.20×10^{3}kg/m^3
Coefficient of thermal expansion of air	0.36×10^{-2}（L/℃）
Particle release time	0-30s

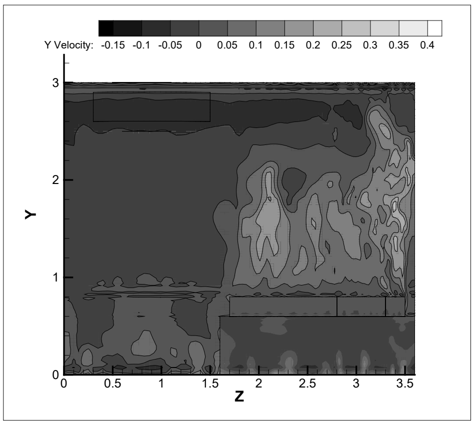
2 Results and discussion

2.1 Influence of thermal plume on particle diffusion

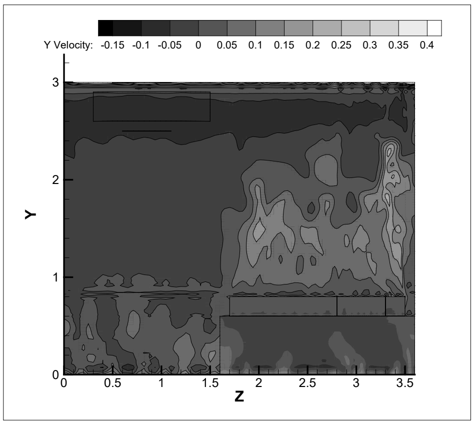
The simulation results for the two manikins are identical, the area where the right manikin's nose is positioned (X=-3.7m) is chosen for examination.



a) Room-temperature for 24℃



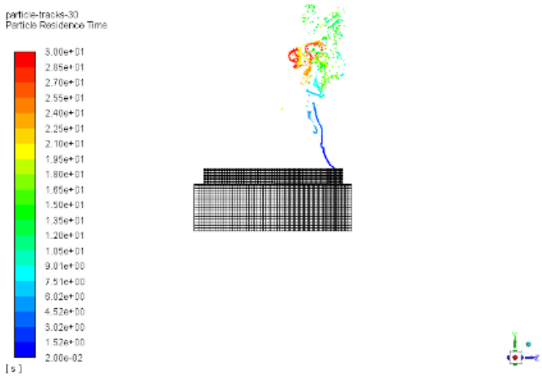
b) Room temperature for 27℃



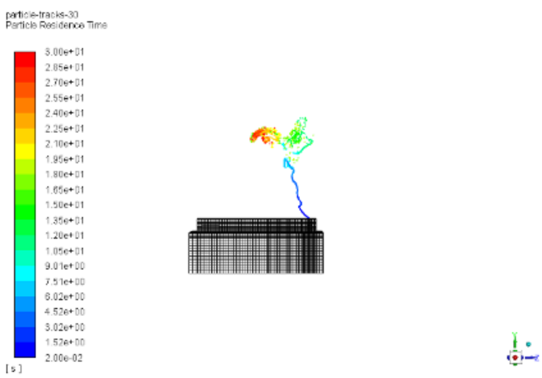
c)Room temperature for 30℃

Fig.2. Velocity contour of the thermal plume at different room temperature

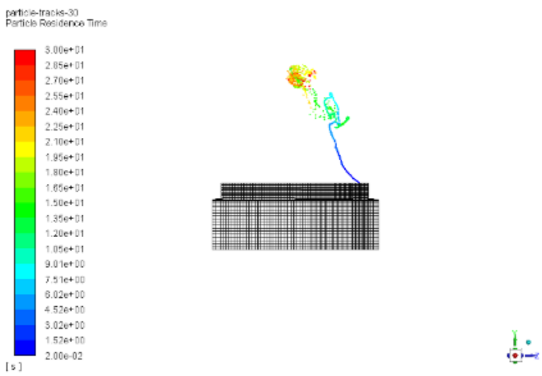
The distribution rules of the thermal plume formed by the manikin at different room temperatures tend to be consistent, as shown in Fig. 2. The thermal plume's velocity increases as the temperature differential



a) Room-temperature for 24°C



b) Room temperature for 27℃



c) Room temperature for 30°C

Fig. 3. Diffusion results from human exhaled particles at different room temperature

between the manikin's surface and ambient temperature grows. The difference between the manikin surface temperature and room temperature has a positively correlated with the velocity of the thermal plume. The maximum velocity of the thermal plume is at a height of 0.90m–1.70m above the manikin, which is the same as the primary particle distribution region, and the maximum values of three kinds of room temperature are 0.35 m/s, 0.27 m/s, and 0.22 m/s, respectively. The diffusivity of particles is positively associated with the velocity of the thermal plume, as seen in Fig. 2 and Fig.3. The simulation findings closely resemble those of Feng et al. [7].

Fig. 4 shows that the lower the room temperature, the greater the particle diffusion height, which is consistent with the thermal plume velocity change rule. The fraction of particles in the height range of 2m-3m is

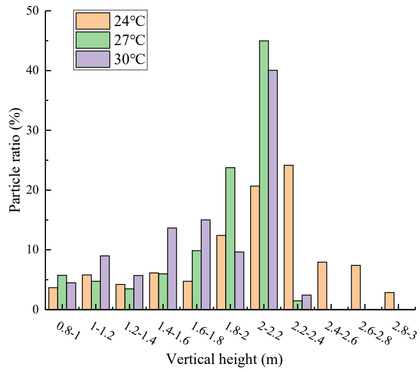


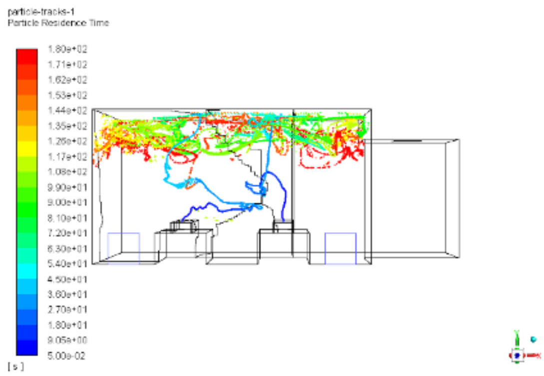
Fig.4. Distribution of particles along the vertical direction at different room temperature

46.43 % and 42.49 % at room temperature of 27°C and 30°C, respectively. The proportion of particles in the height range of 2m-3m is 63.04 % at room temperature of 24°C, and the proportion of particles in the height range is 1.36 times and 1.48 times that of the other two types of room temperature, respectively.

2.2 The impact of air change rate on particles diffusion

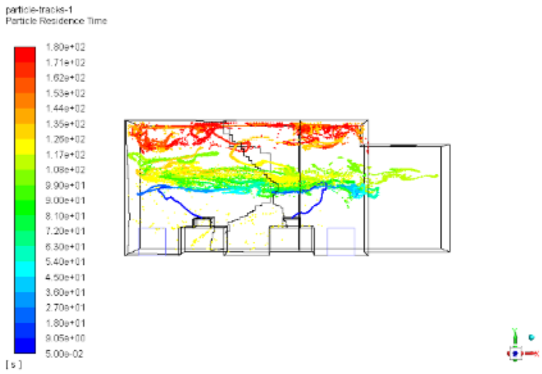
After studying four different air supply forms, it was found that when the number of air change rates was the same, the air supply method of the bottom and top return could better control the diffusion of particles. The diffusion of particles at different air change rates was simulated, and the results are shown in Fig. 5.

Increasing air change times, as shown in Fig. 5 and 6, enhances particle diffusion under the same air supply type. Reducing the number of air changes helps to better regulate the particles near the roof, which aids in particle removal. The model does not account for things like people mobility, and the inside air is less disrupted, which is comparable to what happens on the ward at night. When the ward's interior environmental disturbance factors are low, limiting the frequency of air changes is beneficial not only to the air-conditioning system's energy efficiency, but also to the removal of patients' inhaled particulate matter.

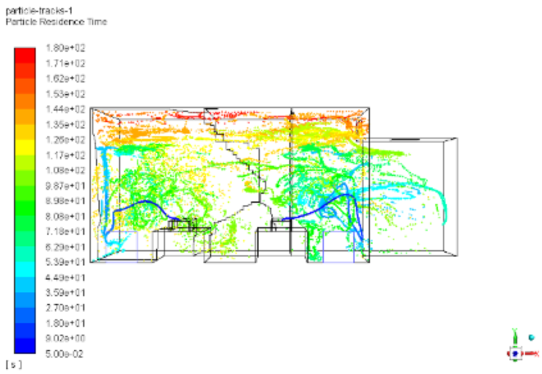


a) 5 ACH

https://doi.org/10.1051/e3sconf/202235605012



b) 10ACH



c) 15 ACH
Fig. 5 Diffusion results of particles at the different air change rates

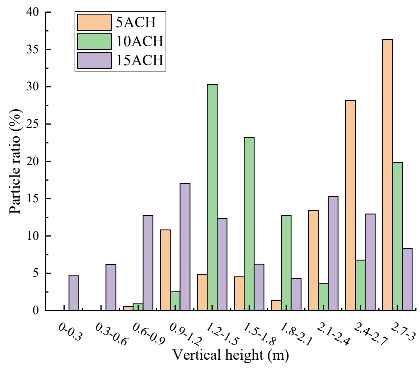


Fig. 6 Distribution of particles along the vertical direction at the different air change rates

3 Conclusions

The influence of air change rate on particle removal during displacement ventilation was simulated in this work, using an ordinary double ward as the research object, and the following conclusions were drawn:

(1) At different room temperatures, the distribution of thermal plumes produced by human body models tends to be constant. The difference in surface temperature and ambient temperature was positively associated with the velocity of the thermal plume and the height of particle diffusion.

(2) When there are few interference factors in indoor environment, such as hospital wards at night, reducing the number of air changes is not only beneficial to reduce energy consumption of air-conditioning system, but also to remove particles exhaled by patients.

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