Analysis of viral aerosol distribution characteristics in typical body positions of patients under local exhaust air

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Abstract: In this paper, CFD numerical simulation and experiment were used to simulate the diffusion process of human exhaled aerosol particles, and the influence of human lying down, sitting and standing posture on the diffusion of aerosol particles under local exhaust air conditions was studied. The results show that different body positions have significant effects on local exhaust air effect. Only 13.2% of the aerosol particles could be removed by local exhaust air in the lying state. The exclusion rate in sitting posture was 25.4%; The exclusion rate for standing posture was 20.6%. Local exhaust air alone is not enough to prevent infection. It is recommended to adopt the combination of mixed ventilation and local exhaust air, which may have a better effect on preventing cross infection, indoor particulate matter transmission and controlling pollution.

1. Introduction

At the end of 2019, the COVID-19 epidemic broke out and quickly swept the world. As an emergency medical treatment facility, the makeshift hospital played an important role in preventing and controlling the COVID-19 epidemic. Most of the renovation objects of makeshift hospitals are high space buildings such as gymnasiums. The requirements of indoor air flow area are different from those of makeshift hospitals. Gymnasiums mainly meet the needs of competition, while makeshift hospitals need to effectively control pollution. Source, keep the indoor infectious area in a negative pressure state as much as possible, and ensure the safety of indoor air. Therefore, after being modified for the treatment and isolation of patients, it is necessary to adapt the indoor wind environment. Poor temperature distribution and flow field characteristics will cause personnel virus aerosol particles to stay inside the makeshift hospital, greatly increasing the risk of cross-infection between patients and between patients and medical staff .[1] In the post-epidemic era, makeshift hospitals in China have been gradually closing down. Nevertheless, it is vital to acknowledge that there is a likelihood of future outbreaks and the emergence of new infectious ailments. Therefore, such make-shift hospitals will continue to play a critical part not only in managing the COVID-19 crisis but also in responding to other infectious diseases and public health emergencies on a large scale.[2]

Local exhaust air is a ventilation method used to collect and remove pollutants from a specific area. Research has demonstrated that compared to the overall ventilation system, the local exhaust air system can directly extract the air surrounding the pollution source, leading to a more effective removal of pollutants.[3] Hospital ward patients are typically found in varying positions, such as lying, sitting, or standing, which is especially evident in makeshift hospitals. Sun and Ji conducted a study on the transmission and diffusion of particulate matter of different sizes exhaled by people lying and sitting on beds in rooms with mixed ventilation and displacement ventilation.[4] Melikov and Kaczmarczyk measured indoor air quality in a floor-ventilated room. The research findings revealed that the distribution of pollutants is significantly impacted by different body positions.[5] Yin et al. conducted a study to analyze the distribution of aerosol particles that patients generate while breathing and coughing in different positions (lying and sitting) and under two ventilation methods in the ward. The results showed that in wards with displacement ventilation, pollutant concentration was higher when patients were lying down than when they were in a sitting position. However, there is a scarcity of research that systematically analyzes how human posture affects the dispersal of aerosol particles in the same ventilation conditions.[6]

In this context, this article is based on the local exhaust air method, starting from the perspective of the effect of different positions of the human body on the distribution of particulate matter, and takes a demonstration makeshift hospital as a research object, through experiments and numerical simulations to analyze the distribution of virus aerosol particles in the makeshift hospital. To study the diffusion mechanism in the epidemic to provide a basis for the transformation and construction of makeshift hospitals in the future.

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2. Computational method

Since the air flow in hospitals is generally turbulent, and the RNG k-Ɛ model has fast computation speed and accurate results, this model was selected for the solution, and the wall function method was used to simulate the flow in the near-wall area.[7]

This article chooses to use the Lagrangian method to solve the particle motion equation to obtain the particle motion trajectory. The motion equation is expressed as

$$\frac{dx_{pi}}{dt} = u_{pi} \tag{1}$$

$$\frac{du_{pi}}{dt} = F_D + G + F_a \tag{2}$$

In the expression,u_{pi} represents the particle velocity, m/s; F_D represents the drag force, G represents the gravitational force, m/s^2; F_a represents other additional forces besides the drag force and the gravitational force acting on the particle of unit mass, mainly including pressure. Gradient force, Basset force, additional mass force, Brownian force, Saffman force and thermophoretic force. In Lagrangian simulation analysis, Saffman force plays a very important role in the movement of particles. In an indoor environment, changes in air temperature and the effect of heat plumes from the human body on particle motion will cause particles to be affected by thermophoretic forces. And some studies[8] have shown that in addition to gravity and drag force, the additional forces on particles are Brownian force, thermophoretic force, and Saffman lift force. Therefore, in this study, to simplify the calculation, only Brownian force, thermophoretic force, and Saffman lift force were considered.

3. Simulation setup

ANSYS SCDM software was used to create physical models of bed areas, patients, beds, air vents, etc. To save computing power and time, and to improve calculation accuracy, the models were set up symmetrically, and the human body model was simplified to a square man. To eliminate the influence of the height of the baffles on the overall diffusion of the particles, all the 1.2 m high baffles used in the makeshift hospital were replaced with 2 m high baffles. The final model is shown in Figure 1 and the model dimensions are shown in Table 1.

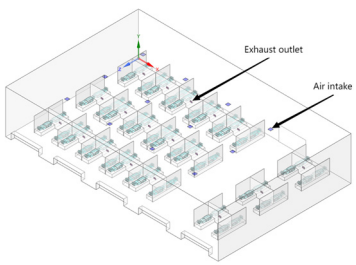

Fig. 1.Geometric model

Table 1.Physical model dimensions

Model	Model size
Bed area	37.5m×30m×6m (L×W×H)
Hospital bed	1.95m×0.9m×0.4m (L×W×H)
Door	3.8m×2m
Nurses' station	3.9m×0.9m×0.75m (L×W×H)
Baffle	2m (H)
Mouth of a person	2cm×3cm
Bed spacing	1.5m
Air intake	0.4m×0.4m
Exhaust outlet	0.2m×0.3m

To ensure the accuracy of the CFD simulation results, certain assumptions are made: First, the walls and baffles are assumed to be insulated walls. Second, the ward is assumed to have good air tightness, and the leakage air volume in the room is not taken into account. In addition, the human body surface temperature is set to 31°C, while the exhaled air flow temperature is set to 35°C.[9] Based on the experiment, the respiratory velocity is set to 0.3m/s, the exhaled particle density is set to 914kg/m^{-3}, and the total release rate is set to 0.085μg/s. To maintain negative pressure in the hospital bed area, the exhaust air volume should exceed the supply air volume. Considering the elevated floor height, the exhaust air volume in the hospital bed area should be calculated to be at least 156m^3/(person·h).[10] In this study, there are 144 patients in the hospital bed area. The exhaust air volume is calculated to be 21600m^3/h based on the number of beds. Normally, the fresh air volume is set to 70% to 90% of the exhaust air volume. For this article, we plan to use 80% as the fresh air volume, which is 17280m^3/h. The specific boundary condition settings are shown in Table 2

Table 2. Numerically simulate boundary condition parameter settings

Boundary	Boundary type	Parameter settings
Air intake	Velocity inlet	V=1.25m/s
Exhaust outlet	Velocity inlet	V=-1.3m/s
Mouth of a person	Velocity inlet	V=0.3m/s

4.Experimental setup

4.1 Experimental Overview

The experiment was conducted in a makeshift hospital in a city in Liaoning Province, China. The hospital has two floors. The first floor has a construction area of 3039.8m^2, a height of 6m, and a bed area of 37.5m×30m. Figure 2 is the bed area of the makeshift hospital, the height of the baffle is 2m; bed 1.95m×0.9m, the height is 0.4m, and the distance between the beds is 1.5m. In the inside of the hospital bed area, as shown in Figure 3, a warm body dummy in a lying position is used to simulate a real patient in the hospital, wherein the warm body dummy is developed by self-development, and a resistance wire with good thermal conductivity is used to evenly wind around the outside of the dummy to simulate human body heat production, and the temperature of the body model is about 31°C. In addition, the outer surface of the resistance wire is covered with a layer of aluminum foil to ensure the uniformity of heat production of the dummy model

Fig.2. Inside the makeshift hospital

Fig. 3. Homemade heating dummy

4.2 Experimental setup and test equipment

The aerosol generation system, Model 7388AGS, is capable of producing aerosol particles with a diameter ranging from 0.1 to 10μm. As illustrated in Figure 4. The solute used is Diisooctyl sebacate (DEHS), which is colorless, odorless, and non-toxic, with a density of 914kg/m^3. Isopropanol alcohol serves as the solvent for DEHS, with a solution mass fraction of 60%.[11] Breathing aerosol particles are expelled from the manikin's mouth through a tube at a velocity of 0.3 m/s.[12] The aerosol monitor used in this experiment is the Dust Trak8530. It is capable of measuring the concentration of aerosols with diameters of 1μm, 2.5μm, 4μm, and 10μm in real time. In this particular experiment, the Dust Trak8530 is used to monitor the concentration of 1μm aerosol particles indoors. Figure 5 shows the setup of 9 monitoring points positioned above a human body model at heights of 0.8m (lying breathing height), 1.2m (sitting breathing height), and 1.7m (standing breathing height). Concentration data were monitored at 120 s and 240 s, and continued for 30 s. Before each experiment, the room was ventilated until the concentration of 1 μm particulate matter at the experimental point had decreased to the initial concentration

Fig.4. Aerosol generation system

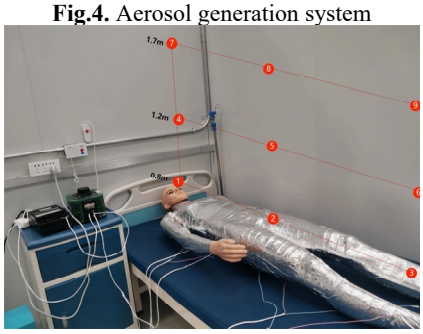

Fig. 5. Distribution of measurement points

5. Results and discussion

5.1 Model validation

In order to verify the correctness of the CFD computational model, the experimental data were used to verify the mathematical model selected in this paper, and the physical model was established according to the relevant physical parameters of the on-site ward. Since the site is not ventilated, there are no air intake and exhaust outlet in the ward during the simulation. Other settings are the same as in section 3 of the text. Since it is not easy to directly compare the simulation results with the experimental results, dimensionless concentrations[13] are introduced for comparison, defined as

$$C(\%) = \frac{\overline{C(x,t)}}{C_0} \tag{3}$$

In the formula, C(x,t) is the average concentration of aerosol particles at measurement point x at time t, and C_0 is the initial concentration of exhaled aerosol particles. The dimensionless concentrations of the experimental and simulation results are shown in Table 3. The experimental results show that the simulated values are in good agreement with the experimental values. For points 1 to 9, the maximum difference in C(%) is less than 5%, indicating that the mathematical model used in this article can more accurately simulate the diffusion of particulate matter in the ward

Table 3. Dimensionless concentration

C (%)	point1	point2	point3	point4	point5	point6	point7	point8	point9
Experiment 120s	0.05	0.02	0.07	0.01	0.08	0.05	0.06	0.04	0.12
Simulation 120s	0.04	0.12	0.1	0.02	0.09	0.02	0.07	0.01	0.09
Experiment 240s	0.09	0.07	0.06	0.22	0.17	0.02	0.05	0.08	0.04
Simulation 240s	0.09	0.05	0.07	0.05	0.08	0.14	0.04	0.09	0.05

5.2 Distribution of particulate matter

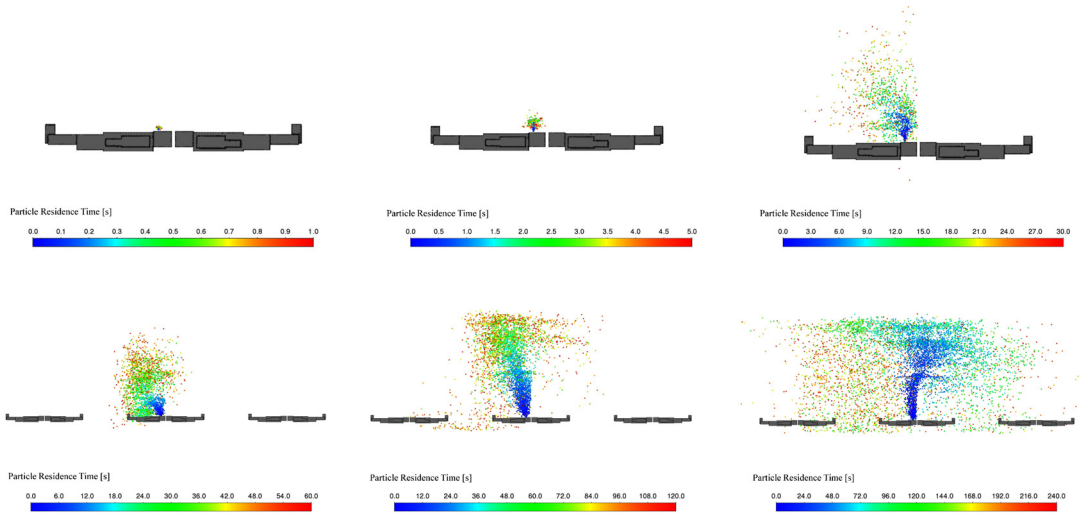

Fig. 6. Distribution of exhaled aerosol particles in the human body from 1s to 240s lying flat in the local exhaust air state

In hospitals, patients spend most of their time at rest, so the distribution of aerosol particles when lying flat is very important. Figure 6 shows the distribution of aerosol particles exhaled from a single human body while lying flat in the case of local exhaust air. In the case of local exhaust air, some particulate matter adheres to objects such as the human body, baffles, walls, floors, and ceilings, while other particulate matter is expelled through the exhaust vent. At t=120s, particulate matter begins to diffuse to the opposite side and is influenced by the opposite exhaust air and the thermal plume from the human body. At t=240s, the particulate matter at the top has not been exhausted in time, resulting in the diffusion of particulate matter from the top to the other side of the baffle. A total of 432 particles were tracked by simulating the aerosol particles exhaled by all people, of which 57 were expelled through the exhaust vents. By calculation, it is concluded that the proportion of aerosol particles excluded by the local exhaust air is 13.2%.

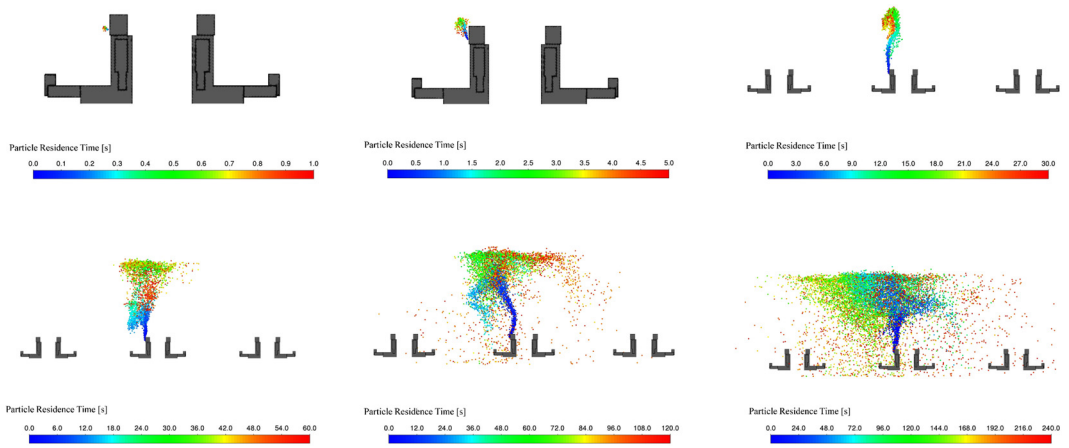

Fig. 7. Distribution of aerosol particles exhaled by the human body in a seated position under local exhaust air for 1s to 240s

As shown in Figure 7, when the patient is in a sitting position, aerosol particles initially move a certain distance in the direction of breathing. A small fraction of these particles are then captured by the thermal plume and move upward. After 30 seconds, a large number of particles move upward due to the influence of thermal plumes and temperature gradients. At t=60s, some of the particles reach the ceiling and begin to accumulate. Other particles are affected by gravity and begin to settle. At t=120s, the influence of the heat plume on the particulate matter becomes more obvious, and the particulate matter is almost separated into two parts, one part reaches the top and gradually forms the "particle layer", and the other part floats on the top of the human leg and makes irregular movement until it gets rid of the influence of the heat plume. At t=240s, the "two-part" phenomenon disappears, and the particulate matter gradually spreads throughout the room.

In the sitting position, 432 particles were tracked, 110 escaped through the exhaust, and the proportion of excluded particles was 25.4%

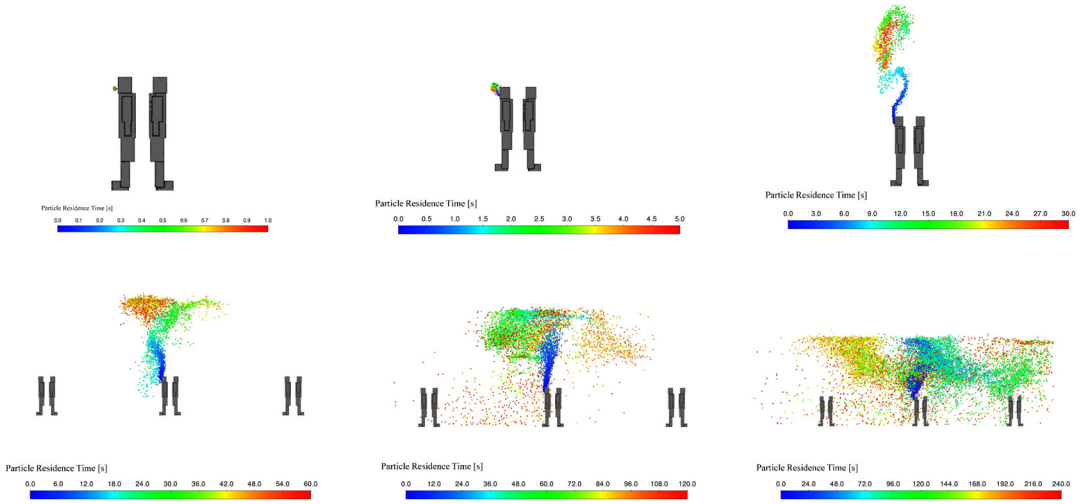

Fig. 8. Distribution of aerosol particles exhaled from a standing human body at 1 s to 240 s with local exhaust air

Figure 8 shows the distribution of particulate matter in the standing state, in the standing state, the movement of aerosol particles in the first 30 seconds is basically the same as the movement in the sitting state, and in t=60s due to the absence of the influence of the leg thermal plume, the particulate matter will continue to sink downward, after 60 seconds, the particulate matter will gradually spread throughout the room and accumulate at the top of the room, forming a "particle layer".

5.3 Velocity analysis near human body

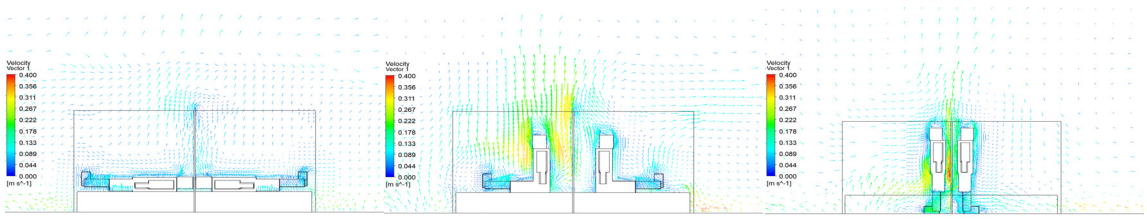

Fig. 9. Velocity vector near human body

Figure 9 shows the speed near a lying, sitting, and standing body, respectively, with arrows indicating the direction of the speed. A uniform speed scale is used for ease of comparison. As can be seen from the figures, the speed of the flat body is less than that of the sitting and standing positions. It can be concluded that the influence of the human heat plume on particulate matter is small in the lying position. In the sitting position, the airflow in front of the chest is faster. This may be caused by the bending of the legs, which increases the thickness of the thermal plume in the chest, thereby increasing the influence of the thermal plume and causing it to accelerate the surrounding airflow. Therefore, we can infer that when sitting, the aerosol particles over the legs of the human body move upward. Figure 7 also shows this well.

As can be seen in Figure 9, regardless of the posture of the human body, the baffle plays a role in guiding and possibly accelerating the movement of the airflow. This is evident in both the sitting and standing vector images.

6. Conclusions

In this paper, Lagrange method was used to study the influence of typical body positions on the movement and removal efficiency of 1μm particles in a makeshift hospital under local exhaust air, and the following conclusions were drawn:

1. When local exhaust air is used, the posture of the human body has a great influence on the efficiency of particle removal. Specifically, the effect of particle removal is better in the sitting position, while the effect is poor in the lying position.

2.The presence of the baffle effectively prevents the lateral transmission of viral particles, but it also directs or even accelerates the airflow exhaled by the surrounding human body.

3.If only local exhaust air is used, regardless of the patient's posture, particles will accumulate at the top of the room to form a "particle layer". These particles can spread

over time, increasing the risk of infection in the surrounding population.

Therefore, relying solely on local exhaust air is not enough to control pollution. It is suggested that the combination of mixed ventilation and local exhaust air is adopted to control pollution and prevent cross-infection, which may have better effect.

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