

Advanced ventilation chair for source control of respiratory infectious diseases

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Abstract. Since the outbreak of the new crown, a large number of people at home and abroad have been infected, causing great damage to human lives, the economy, and the whole society, which has led to a great deal of concern about respiratory infections. Hospitals are at high risk for the spread of respiratory infections, and hospital outpatient rooms are a focal point for the prevention and control of nosocomial infections due to the small space and frequent visit of many people, where effective measures can greatly reduce the risk of the spread of respiratory infections. Airborne transmission is generally controlled by strengthening ventilation and dilution. However, full space dilution ventilation is less effective in removing exhaled droplet nuclei and is limited by the capacity of the ventilation system and other conditions. Therefore, airborne transmission is a weak section in hospital infection prevention and control, and there is an urgent need to develop advanced technical means aiming for source control. In this paper, computational fluid dynamics (CFD) simulation was used to study the interaction between exhaled airflow, thermal plume, and ventilation airflow when patients stayed in the outpatient consulting room for a short period (from a few minutes to more than ten minutes). After comparing the two styles of wearing mask, it was determined that only the top exhaust was the best distribution form. When patient wear face masks, the top exhaust with ventilation volume rate of 20 m³/h can achieve 90% collection efficiency in 30 s. After the patient left, it takes only 15 s to collect most exhaled particles. The air volume and vent dimension is important to the design of ventilation plate, when the design is not reasonable, it can cause up to 50% impact. This paper propose a personalized ventilated chair for airborne transmission which could contribute new solutions and technologies to achieve the goal of significantly reducing hospital infection rates.

1 Introduction

Nosocomial infection is a great threat to the health and safety of medical staff and patients. Compared with other departments of the hospital, the space of physician consultation rooms is relatively small, usually without mechanical ventilation, and the close communication between doctors and patients is frequent and intensive. Therefore, airborne cross infection easily occurs between patient and doctor as well as between patients who visit the same doctor at different times. Therefore, it is an important area of hospital infection prevention and control. Among others, source control is an effective measure to mitigate the risk of airborne transmission. This paper intends to design and study a kind of personalized ventilated chair to effectively collect the exhaled air of patients and then greatly reduce the airborne infection of respiratory infectious diseases in hospitals.

2 Methodology

2.1 Geometry and computational mesh

In this study, the size of the outpatient room is 5×4×3 m. A manikin simulating a patient is located in the middle of the room. The manikin sits on the chair proposed in this paper with a backward tilt of 15°. The upper part of the chair is provided with a ventilation panel, and the left and right sides of the ventilation panel and the top are provided with vents for the supply or collection of airflow. The ventilation panel of the chair is divided into different sections I, II, and III, and the detailed setting of the ventilation panel is shown in Figure 1. The dimensions of single top vent is 0.28×0.1 m, and a single side vent size is 0.07×0.28 m. The whole room adopts up-return and down-supply air distribution, where the volume is set to 30 m³/h and the vent is located in the back wall of the room.

In this model, ICEM software is used to build the model and Fluent Meshing is used to generate the grid. Due to the irregularity of human body boundary, the unstructured grid is used to fill the whole computing domain. More cells are arranged around the human body boundary layer, nose, mouth, and vents.

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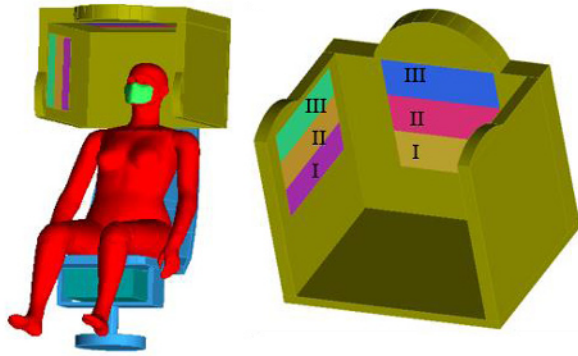


Fig. 1. Schematic diagrams of the ventilation panel

2.2 Boundary conditions

The air supply vent of the room, the air supply vent of the ventilation panel, and the mouth of the manikin are set to velocity-inlet. Non-slip boundary conditions were applied to all walls in the CFD simulations. The heating of equipment and lighting is not considered in the model, and only the human body is considered as the heat source. The manikin is set to a body temperature of 32 °C [1] and the rest are set to adiabatic conditions. The airflow-particle interaction was considered as a two-way coupling, with the droplet evaporation ignored. Aerodynamic diameters of the investigated particles were 0.1, 0.5, 1, and 5 μm. The density of each particle was 1000 kg/m³, with a specific heat capacity Cp of 4182 kJ/(kg·K) [2] and the same initial velocity as the exhaled flow. To reduce the error caused by the random influence of turbulence on the particle trajectory, the discrete random walk model (DRW) was used to simulate particles and to evaluate the effect of turbulent dispersion. Particle generation was set to 60 s and the total mass flow rate was set to 5.24×10⁻¹¹ kg/s [3]. Other boundary conditions are shown in Table 1.

Table 1. Parameter of the model

Description	Type	Velocity (m/s)	Temperature (°C)	Wall type
Room supply vent	velocity-inlet	0.208	24	escape
Ventilation panel supply vent	velocity-inlet	0.21	26	reflect
Room exhaust vent	pressure-outlet	N/A	26	escape
Ventilation panel exhaust vent	velocity-inlet	-0.15	26	escape
Ceiling	wall	N/A	0 Heat flux	reflect
Manikin	wall	N/A	32	trap
Mask	velocity-inlet/porous jump	0.2	34	escape
Mouth	velocity-inlet	2	34	reflect

Chair, wall, floor	wall	N/A	0 Heat flux	trap
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2.3 Grid independence test

To balance computing resources and result accuracy, an appropriate number of cells should be used. We calculated the airflow velocity in the respiratory zone 0.5 m ahead of the human mouth using three types (coarse, medium, and fine) of grids, and the results can be seen in Figure 2. The results show that there is little difference between the three types of grids; the maximum difference of temperature is 0.2% and the maximum difference of velocity is 5%. We then decided to use the 1.3 million grids. In this type of grid, the mesh size of nose and mouth is set to 0.001, the human body to 0.005, vent size to 0.01, chair size to 0.02. The maximum mesh size of the surrounding wall is set to 0.1 and the mesh size of the rest is set as 0.1. We have numbered every case, and the specific information of each case is listed as shown in Table 2.

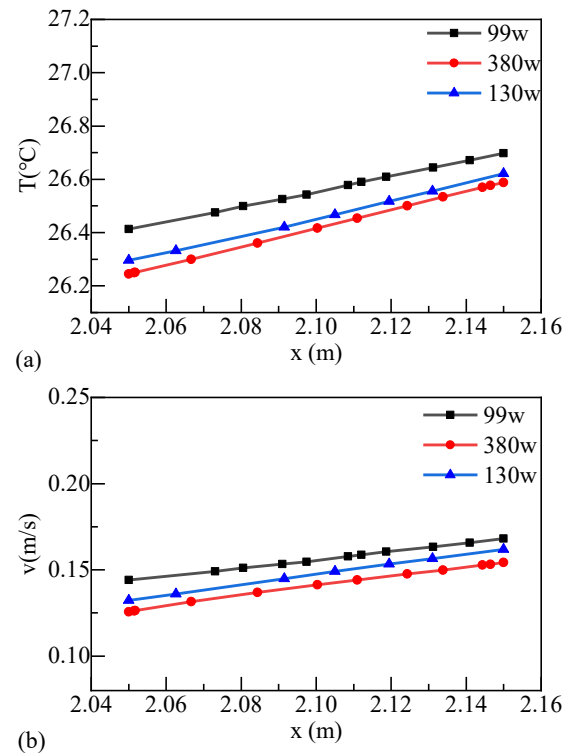


Fig. 2. Grid independence test: comparison of the air velocity with different grid numbers

Table 2. Setting of the case

Case	Distribution type	Distribution on volume (m ³ /h)	Side vent	Top vent	Mask type
A0	A	30	II	II+III	velocity-inlet
A1	A	60	II	II+III	porous jump
A2	A	30	II	II+III	porous jump
A3	A	30	III	I+II	porous jump

B0	B	30	II	II+III	velocity -inlet
B1	B	60	II	II+III	porous jump
B2	B	30	II	II+III	porous jump
B3	B	30	III	I+II	porous jump
C0	C	30	N/A	II+III	velocity -inlet
C1	C	60	N/A	II+III	porous jump
C2	C	30	N/A	II+III	porous jump
C3	C	30	N/A	I+II	porous jump
D0	D	30	II	N/A	velocity -inlet
D1	D	60	II	N/A	porous jump
D2	D	30	II	N/A	porous jump
D3	D	30	III	N/A	porous jump

3 Results and discussion

A total of four forms of air distribution have been studied in this paper, namely A, B, C and D, each of which can be seen in Figure 3.

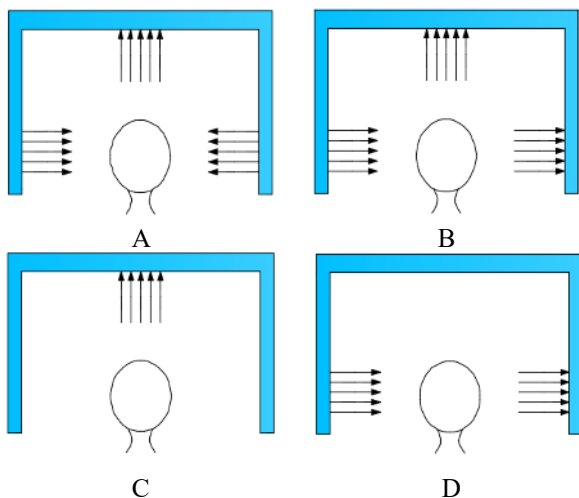


Fig. 3. Schematic diagram of the air distribution forms

The control effectiveness of each form was evaluated separately while ensuring that the air supply volume was constant ($30 \text{ m}^3/\text{h}$) and the air outlet area was kept consistent. The air distribution form is evaluated in terms of the collection efficiency of the exhaled particulate matters, under different mask-wearing forms.

1) Perfectly worn mask

When the patient is considered to be wearing the mask perfectly, i.e., no particles are leaking through the gaps between the mask and the person's face and the only way for particulate matter to escape is through the mask. For this condition, the mask face is set as the velocity inlet, and the velocity at the mask is

approximately 0.2 m/s according to the exhaled flow rate [4]. Assuming that particles are ejected completely from the mask, the effect of each form of air distribution is shown in Figure 4(a).

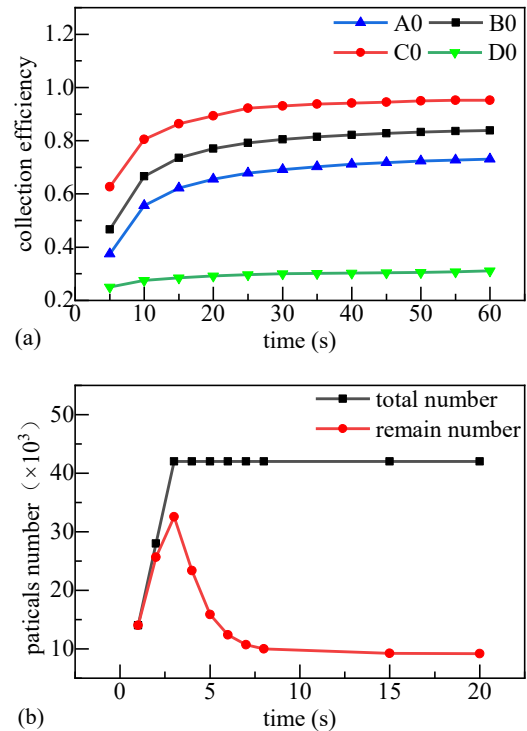


Fig. 4. Schematic diagram of the effect of the air distribution form; (a) continuous particle release, (b) release of 5 s

In this case the left and right vents are set to II, and the top exhaust vents are II and III. As can be seen from the above Figure 4(a), the collection efficiency of air distribution form is $C > B > A > D$, of which form D can hardly form a collection of particles, form A 70% efficiency under this working condition, while form B 80% and form C exceeding 90%, and up to 95%.

The result of continuous release of particulate matter is presented in Figure 4(a), and the result of 5 s release of particulate matter is shown in Figure 4(b). When the pollutant source stops releasing, within 10 s, the chair can remove 76.2% of the particles, but there is still 24.8% of the particles being diffused into the room with the airflow or settled on the seat or floor.

2) Wearing a mask with a gap

Since in actual life, people often wear masks with a gap, and the scenario of imperfectly worn masks was therefore investigated. In this scenario, particulate matter escapes from the left and right sides of a person's face as well as the gap between the nose and the mask, while the particles crossing the mask was simulated using the general mask filtration efficiency. The simulation results are shown in Figure 5(a).

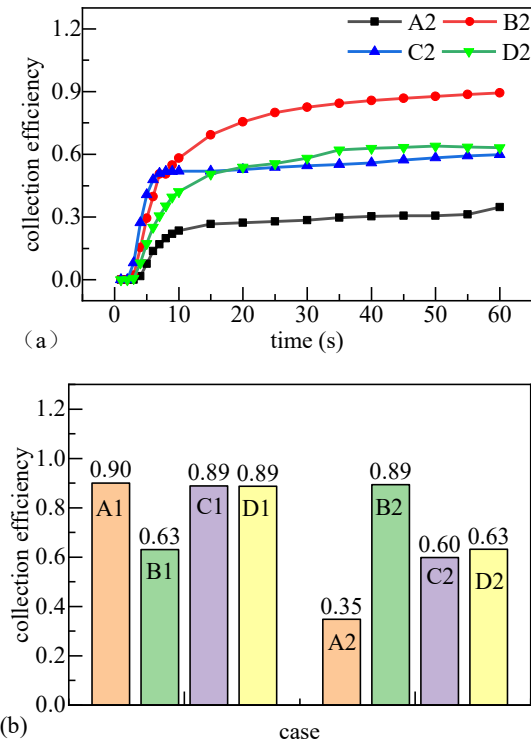


Fig. 5. Schematic diagram of the effect of the air distribution form; (a) 30m³/h of the supply airflow (b) comparison of different air volumes

As can be seen from Figure 5(a), when the left and right ventilation openings are set to II and the top exhaust vents are II and III, B2 has the best collection efficiency, reaching 90% in steady-state, while C and D are slightly less effective, reaching almost 60% and 63%, and air distribution form D is the least effective, collecting only 30% of the particulate matter. In addition, the effect of doubling the ventilation volume on the collection efficiency is shown in Figure 5(b). It can be seen that the efficiency is somewhat improved except for the form B, which can eventually reach 90%. In form B, the overall airflow diffuses outwards due to the two air streams blowing against each other, resulting in a reduction in the efficiency of particulate removal.

By observing the motion status of particles, it was found that particles did not move to the exhaust vent along the shortest path. Therefore, the left and right vents were set as I and the upper exhaust vent set as I and II, and then the influence of air distribution mode on the collection efficiency was explored.

It can be seen in Figure 6 that the efficiency of form C is better than B and A, which can reach 90%, while the effect of form D is poor, which can only reach 54%. Compared with B and A, form C does not need any air supply, but only needs air exhaust, and the efficiency is even better.

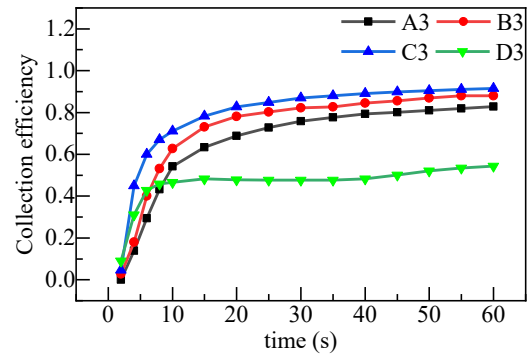


Fig. 6. The collection efficiency of each air distribution form over time

4 Conclusions

This paper discusses the collection efficiency of ventilation chair on exhaled particles of seated person under four forms of local air distribution and the following conclusions are obtained.

- 1) In the case of small particles (<5 μm), the particles move with the airflow, particles with different sizes have similar trajectories, so controlling the airflow pattern is the key to controlling collection efficiency.
- 2) For different mask-wearing results, the best air distribution is the only top exhaust.
- 3) Increasing the air volume can generally enhance the collection efficiency for the forms A and D, but it could also lead to increased disturbance and weaken the efficiency for the form B.
- 4) The position of the exhaust air outlet influences the collection efficiency and the best position should match the trajectory of the exhaled airflow as far as possible.
- 5) The use of the ventilation chair allows the rapid collection of particulate matter; in the case of C, for example, in about 10 s, 60% of the particles can be collected and 90% in the 30 s. While, after the patient left, it takes only 15 s to collect 80% of the exhaled particles.

References

- 1 ZT. Ai, AK. Melikov. *Indoor Air*. 28(4), 500-524 (2018)
- 2 YX. Zhang, GH. Feng, Y. Bi, et al. *Sustain. Cities Soc.* 51, (2019)
- 3 J. Redrow, S. Mao, I. Celik, et al. *Build Environ.* 46(10), 2042-51 (2011)
- 4 P. Prasanna Simha, PS. Mohan Rao. *Phys. Fluids*. 32(8), 081905 (2020)