The effect of air supply rate on indoor infection probability in mixing ventilation

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Abstract. SARS-Cov-2 has caused enormous damage to society and put human health at a hazardous level. Optimizing air distribution patterns is one of the most useful manners to minimize the infection risk of susceptible individuals. Mixing ventilation is widely used, but the effect of air supply rate on indoor infection probability has not been studied yet. Three air supply rates, including 576, 864 and 1152 m^3/h were adopted to study this problem in a simulated room, with dimensions of 5m×5m×2.7m. The Computational Fluid Dynamics (CFD) method was used to consider indoor flow fields under three cases. The infection probability was calculated by the revised Wells-Riley model. The results showed that the overall infection probability decreased as the air supply rate increased. Meanwhile, the infectious air exhaled by the infector would flow along with the supply airflow in a certain direction, resulting in a non-uniform distribution of infection probability in the room. Increasing air supply rate and optimizing workstation layout may be two useful manners to reduce infection probability in mixing ventilation rooms.

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1 Introduction

Since the outbreak of the COVID-19, human health and the global economy have been seriously threatened. Previous research showed that the virus could spread through the air [1-2]. Consequently, controlling the spread of the virus indoors is an important method to prevent cross-infection [3]. Effective ventilation can potentially reduce the risk of airborne transmission [4]. At present, mixing ventilation is widely used in many residential and public buildings due to its prominent advantages, such as ease of design and its ability on handling large thermal loads [5]. However, mixing ventilation systems can not achieve well-mixing state in the real situations. The Wells-Riley model is the commonly used method to evaluate the infection probability. However, the traditional Wells-Riley model was proposed based on well-mixing and steady-state assumptions, which could not accurately predict the infection probability under non-uniform rooms [6]. Shao et al. revised the traditional Wells-Riley model to improve its prediction accuracy in non-uniform conditions. This paper aims to study the effect of air supply rate on indoor infection probability based on the revised Wells-Riley model in a mixing ventilation room.

2 Method

2.1 Geometry and grid meshing

This paper adopted CFD method to study the airborne transmission of the virus indoors. The geometry model was built according to a typical office room, with dimensions of 5m × 5m × 2.7m. The mixing ventilation inlet was simulated using the N-point model, with dimensions of 0.4m × 0.4m. The direction of the air supply was at an angle of 30° with the ceiling. The exhaust outlet was located below the sidewall, with dimensions of 0.4m × 0.4m. An infector and a susceptible person were added in the room, 1.5m away from each other. The geometry model is shown in Fig. 1. The octree method was used to generate meshes in the ICEM CFD 19.2 software. The finer meshes were adopted around the inlet, outlet and occupants to improve the simulation accuracy. The total number of grids was 5199034, and the mesh quality was above 0.2.

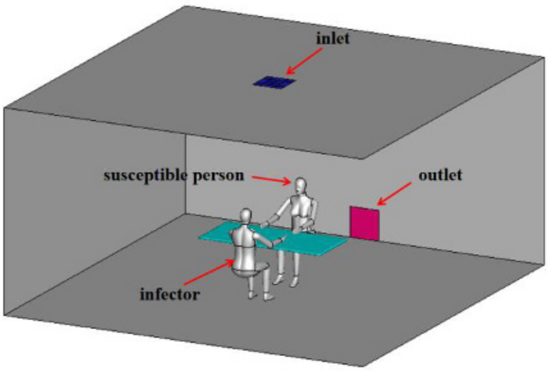

Fig. 1. Geometry model.

2.2 Simulation setup and boundary conditions

The steady-state simulation was used, and the RNG-K epsilon turbulence model was chosen to simulate indoor flow fields. The Boussinesq assumption was adopted to consider the effect of buoyancy force. The "semi-implicit method for pressure-linked equations" (SIMPLE) algorithm was applied to couple pressure and velocity fields. The second-order upwind discretization scheme was employed to ensure simulation accuracy. Solutions were considered convergent when the residual reached 10^{-3} for all equations (except for the energy equation, the residual level should be below 10^{-6}). Furthermore, the data of indoor detection points no longer change with iteration. CO_2 was used as tracer gas to simulate the infectious air exhaled by the infector. The inhalation of the infector and the breath of the susceptible individual were not considered. The total loads of the room were 2KW, including two persons (80W/person) and the other loads uniform distributed on the four sidewalls. Three air supply rates were simulated, 576m^3/h (case 1), 864m^3/h (case 2) and 1152m^3/h (case 3). It was worth noting that the room was conditioned by the all fresh air system, no recirculation air was used. The specific boundary conditions are shown in Table 1.

Table 1. Boundary conditions.

Boundary	Simulation setup
Inlet	Velocity inlet (2m/s, 3m/s, 4m/s), 18°C, mass fraction of CO_2: 0
Outlet	outflow
Nose	Velocity inlet (0.48m/s), 35°C, mass fraction of CO_2: 0.04
Human	Constant heat flux (58W/m^2)
Sidewalls	Constant heat flux (34W/m^2)
Floor, ceiling	Adiabatic walls, no slip

2.3 Calculation of infection probability

The revised Wells-Riley model proposed by Shao et al. was used to calculate the indoor infection probability [6]. More details about the calculation equations could be found in Shao's published paper. In this study, the quantum generation rate was set as 30quanta/h. The pulmonary rate of the infector was set as 0.3m^3/h, and all of the virus-laden air was exhaled through infector's two noses. The intermittence of the exhalation was not considered in this study, and it was simplified as continuous exhalation. The exposure time was considered to be 3h. Furthermore, the effect of wearing masks on the infection probability of the susceptible person was not taken into account.

3 Results

3.1 Temperature and velocity distributions

It is necessary to study the indoor flow fields since the airborne transmission of the virus is highly influenced by air distribution. As the only variable was air supply rate under three cases, the temperature and velocity distributions in case 3 were analyzed as an example.

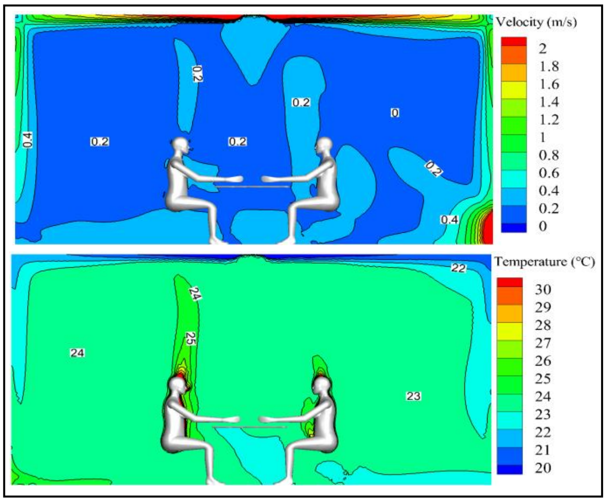

Fig. 2. Temperature and velocity distributions in case 3.

As shown in Fig. 2, the temperature distribution was almost uniform in the occupied zone. However, the temperature on the side near the exhaust outlet was slightly lower than that on the side away from the exhaust outlet. It was because the thermal loads on the side near the exhaust outlet were easier to be timely exhausted, rather than mixed with room air. The fresh air supplied from the inlet would attach the ceiling, rather than directly blow to the occupied zone. Meanwhile, the velocity in the occupied zone was not above 0.2m/s. The average temperatures for the occupied zone were 28℃, 25℃ and 23℃ for case 1, case 2 and case 3, respectively.

3.2 CO_2 and infection probability distributions

The CO_2 and infection probability distributions at the middle of the room under three cases are shown in Fig. 3. Notably, the display scale in Fig. 3 is chosen to be relatively small to better show the CO_2 and infection probability in the whole room. The maximum displayed in Fig. 3 may not be the actual maximum. As shown in Fig. 3, the exhaled air would flow toward the ceiling under the buoyancy effect, and moved together with the supply air after reaching the ceiling level. This phenomenon was most obvious in case 3, causing a higher CO_2 concentration in the left side of the room than that in the right side of the room. Meanwhile, the overall CO_2 concentration in the room decreased with the increase of the air supply rate. Under three cases, the area with the lowest CO_2 concentration in the room was the area where fresh air flowed through on the right side of the room. Furthermore, this area would become larger with the increase of the air supply rate. It was similar to the CO_2 concentration, the infection probability on the left side of the room was substantially higher than that on the right side of the room. Meanwhile, the infection probability in the whole room decreased with the increase of air supply rate, and the area with high infection probability decreased too. The infection probability of the susceptible person decreased as the air supply rate increased, around 4%, 3% and 2% for case 1, case 2 and case 3, respectively.

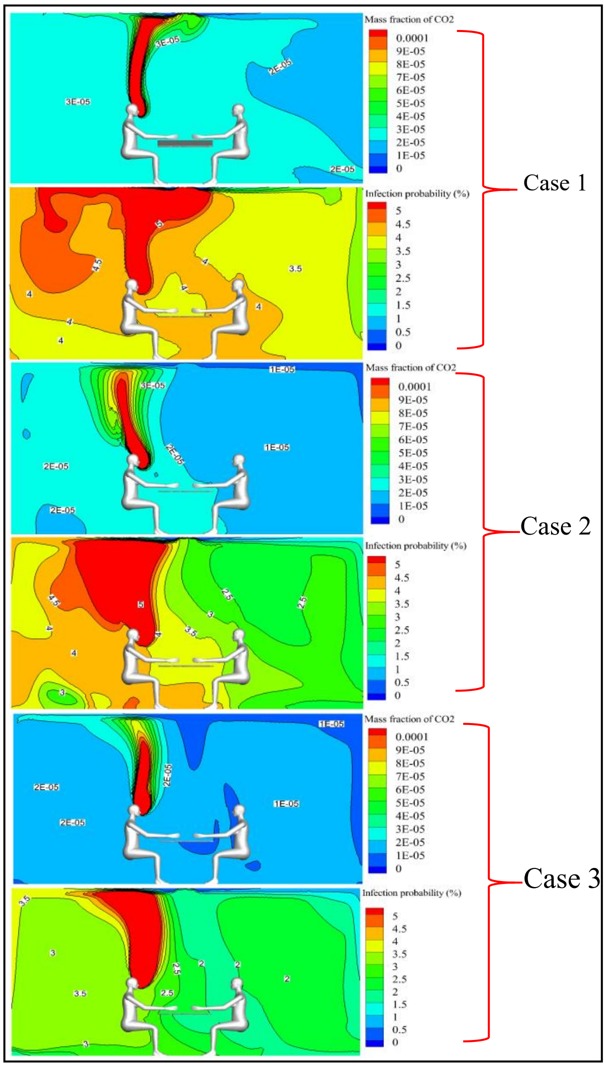

Fig. 3. Mass fraction of CO_2 and infection probability.

4 Discussion

It could be found that the distributions of CO2 and infection probability calculated by the revised Wells-Riley model could match well in this study. Compared with the well-mixing assumption in the traditional Wells-Riley model, the revised Wells-Riley model could accurately predict the infection probability in non-uniform conditions. In this study, the air supply temperature and thermal loads were constant under three simulation cases. Consequently, the room air temperature decreased as the air supply rate increased, resulting in a stronger thermal plume around the susceptible person. The effect of the thermal plume would protect the susceptible person from infection. Furthermore, the virus-laden air exhaled by the infector could flow more easily to the ceiling level (Fig. 3). It indicated that decreasing the room set point

temperature might be a useful manner to reduce the risk of indoor cross-infection. However, energy consumption should be carefully considered in real applications. It was worth noting that the virus concentration in the air supply inlet was considered as 0, which might be a little different from the actual scenario. The effect of air supply rate on indoor infection probability in recirculation air systems should be studied in the future.
From the results, indoor air distribution has an obvious impact on the infection probability. In mixing ventilation, the diffuser style can substantially affect the air distribution. Most diffusers used in the real scenarios are similar to those used in this paper. The virus-laden exhaled air may flow with the supply air in a certain direction, especially in those rooms with low room air temperature. It means that the relative positions between the occupants and air supply inlets are important while considering the infection probability in real situations.

5 Conclusion

The air distribution pattern has an important influence on infection probability. It is an effective way to reduce the infection probability by increasing the air supply rate under the same temperature and thermal load conditions. In mixing ventilation rooms, the virus-laden air exhaled by the infector can flow with the supply air in a certain direction, resulting in a non-uniform distribution of infection probability.

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