A CFD approach to reduce the risk of Covid-19 airborne transmission in a typical office.

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Abstract. The Covid-19 virus can spread rapidly in the air and cause the epidemic to rage around the world. This study takes a typical office as the research object and proposes four different partition settings to suppress the spread of the virus in the air based on displacement ventilation. And these strategies are verified by DPM model simulations of two daily situations of indexed person for coughing and talking. This study then employed a modified Wells-Riley model to evaluate the effectiveness of these strategies in mitigating the risk of viral infection. As expected, in the absence of a partition, a susceptible person at the other end of the seat greatly increased the risk of infection. Partitions can significantly reduce the risk of infection (100% → 20%), while partitions with a full-wrapped structure can reduce the risk of infection to less than 1%. For the instantaneous release scenario of coughing, the barrier can capture a large particle diameter (>50 μm) particles, and the smaller particle diameter can be discharged out of the room with the thermal plume. The strategies provided in this study can provide recommendations for indoor epidemic prevention and control in the context of the Covid-19 pandemic.

1 Introduction

The global pandemic of Covid-19 has caused significant economic damage [1]. Airborne infection caused by aerosol is one of the main transmission routes of Covid-19 [2]. Infectious aerosols carrying the virus travel farther. In reality, the droplets produced by the infected person when they cough and speak evaporate into the air and easily become infectious droplet nuclei. The particle size of highly infectious droplet nuclei is mostly around 0-10 μm, which can easily be suspended in the air for a long time [3, 4]. It increases the probability of people being infected and poses a great threat to people's life and health.

And since people spend 90% of their time indoors or in confined environments [5], it is important to choose the right type of mechanical ventilation. The most traditional uniform type of ventilation system used today is mixing ventilation, which works by mixing all the air in a room to create a uniform temperature and dilute contaminants throughout the space. While uniformly mixed air does dilute contaminants, it also sweeps them away from the source and distributes them throughout the room [6]. The high transmission risk of the Covid-19 virus certainly increases the probability of infection for indoor occupants. In contrast, displacement ventilation is designed to prevent indoor air mixing, and in sidewall-supplied displacement ventilation systems, low-velocity supply air is introduced directly into the occupied area [7], then rises as it is heated by the heat source. The heat source in the occupied area (e.g., occupants, computers) creates upward convection in the form of a thermal plume. These plumes carry pollutants away from the surrounding occupied area [8]. In this case, displacement ventilation brings clean air around people's breathing areas. However, in an existing study [9], displacement ventilation has a limited effect on the disturbance of high-momentum respiratory activities, so physical measures are taken to achieve the effect of blocking the aerosol propagation pathway by setting up different styles of partitions.

The Wells-Riley model has been widely used to estimate the risk of infection in perfectly mixed spaces, but it may underestimate the risk of airborne infection in incompletely mixed spaces. Therefore, a model suitable for the distribution of displacement ventilation airflow is needed to calculate the risk of infection. This paper focuses on investigating the effect of appropriate combinations on the probability of Covid-19 aerosol infection in a typical office by simulating displacement ventilation and different forms of zoning combined with fitting a modified Wells-Riley model.

2 Methods

2.1 Space layout of a typical office

The simulation consists of a partition wall displacement ventilation unit. The size of the whole room is 3.47 m×3.05 m×2.74 m. A column diffuser with a height of 0.81 m and a diameter of 0.41 m is set in the middle of the side wall of the office, while an outlet with a diameter of 0.1 m is set in the middle of the roof, regardless of the return air. The internal heat gain consists of two fluorescent lamps, two laptops, and two occupants. To demonstrate the effect of partitions on
particle dispersion in displacement ventilation, four scenarios were set up in this study: no partition, partition A (single-panel partition), partition B (half-wrapped partition), and partition C (full-wrapped partition). Fig. 1. shows the floor plan of the simulation and its contents.

**2.2 CFD settings**

To establish a CFD model for this typical office, the resolution of the minimum generated tetrahedron mesh size is 0.008 m for the global mesh size, and 0.0025 m for the mesh close to the manikin and diffuser (Fig.2.). The inlet velocity and temperature settings follow the ASHRAE standard for displacement ventilation (Fig.2.). The radiation heat transfer between the heat source (e.g., manikin) and the air is not considered in the simulation.

**Table 1. Parameter of the typical office.**

<table>
<thead>
<tr>
<th>Boundary surface</th>
<th>Velocity</th>
<th>Temperature</th>
<th>Particle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Human body</td>
<td>No slip</td>
<td>28 w/m²</td>
<td>Trap</td>
</tr>
<tr>
<td>Lamp</td>
<td>No slip</td>
<td>50 w/m²</td>
<td>Trap</td>
</tr>
<tr>
<td>Desktop</td>
<td>No slip</td>
<td>40 w/m²</td>
<td>Trap</td>
</tr>
<tr>
<td>Office walls</td>
<td>No slip</td>
<td>Twall=296 k</td>
<td>Trap</td>
</tr>
<tr>
<td>Diffuser inlets</td>
<td>0.045 m/s</td>
<td>Tfloor=295.5 k</td>
<td>Escape</td>
</tr>
<tr>
<td>Outlet</td>
<td>Pressure outlet</td>
<td>293 k</td>
<td>Escape</td>
</tr>
<tr>
<td>Mouth and nose of persons</td>
<td>4 m/s (talking) or UDF (coughing)</td>
<td>310 k</td>
<td>Escape</td>
</tr>
</tbody>
</table>

**Fig. 1.** A plan of the test chamber of the office room and its contents (unit of length is m).

**Fig. 2.** Simulation mesh.

Detailed simulation settings are shown in Table 1. In addition, we consider the cough (Fig.3.) and talk of asymptomatic infected persons to simulate to quantify the impact of the displacement ventilation system and partition on Covid-19 infection.

**Fig. 3.** Temporal evolution of the inlet cough velocity [10].

In this study, a 0.2 m×0.4 m×0.4 m breathing zone around the nose location. The commercial CFD program ANSYS Fluent simulates this office model. This simulation uses the steady-state Reynolds-averaged Navier-Stokes (RANS) equation and RNG k-ε turbulence model [11] to solve the airflow and temperature field of the office. The standard wall function is used to describe the near-wall velocity distribution. The numerical method uses the SIMPLEC algorithm to couple the pressure and velocity equations, as well as the second-order discretization scheme of the convection and viscosity terms of the governing equations. When the error of all independent parameters is within 5%, the result can be considered convergent.

After solving the calculation of the steady gas flow field, the discrete phase modeling (DPM) Lagrangian method is used to simulate the particle diffusion. Generally, the particle diameter is small when talking, and the particle size set in this simulation is 0.3–10 μm [12], while the cough is often accompanied by particles with large particle size, so the particle size of the simulated cough is 0.3–1000 μm [13]. For the simulation of particulate matter in this study, talk is a continuous condition, so the particle release process is a whole cycle (i.e. 300 s), while cough itself is an instantaneous release, so the duration of cough in the simulation is 0.61 s.
2.3 Wells–Riley model

Wells Riley model is a method for quantitative assessment of airborne infection risk [14]. It is a simple and rapid risk assessment method for airborne infection, and it is widely used in the study of infectious respiratory diseases [15, 16].

\[ P = 1 - e^{-\frac{Iq}{V \Lambda}} \]  \hspace{1cm} (1)

where \( I \) is the number of infectors, \( I = 1 \); \( P \) is the infection risk probability estimated by the Wells-Riley model; \( p \) is the breathing rate of a typical person; \( V \) is the room volume; \( \Lambda \) is equivalent fresh air change rate in the room; \( t \) is the exposure time.

The equivalent air change rate (\( \Lambda \)) means the equivalent supply flow rate (h\(^{-1}\)) of clean air per unit volume in the room space. In this study, it depends on the equivalent ventilation air change rate (\( \lambda_{vent} \)). As this study consider the situation of a non-uniform indoor environment, a ventilation factor (\( \epsilon_{vent} \)) represents the dilution efficiency in the target location under an uneven environment. This method uses the ratio of exhaust air concentration (\( C_{exhaust} \)) to target location concentration (\( C_i \)) to effectively assess the risk of airborne infection of viruses in spatial and temporal resolution. It is convenient in practical applications with displacement ventilation.

\[ \Lambda = \lambda_{vent} = \lambda_{DV} \epsilon_{vent} \] \hspace{1cm} (2)

\[ \epsilon_{vent} = \frac{C_{exhaust}}{C_i} \] \hspace{1cm} (3)

Where \( \lambda_{DV} \) is the fresh air supply rate of the displacement ventilation system (h\(^{-1}\)) to the breathing zone of susceptible people.

\[ P = 1 - e^{-\int_{0}^{t} \frac{p + q(C_{exhaust} - C_i)}{\lambda_{DV}}} \] \hspace{1cm} (4)

Where \( p \) is the respiratory rate of the susceptible (m\(^3\)/s), \( q \) is the quantum generation rate per asymptomatic infected people (h\(^{-1}\)), and some studies also showed that the quantum production rate of COVID-19 was 142 h\(^{-1}\) for infected people and the breathing rate of a susceptible is 0.54 m\(^3\)/h [17].

3 Results

3.1 Airflow field

The simulated temperature field and velocity field of displacement ventilation in a typical office are shown in Fig. 4. The temperature at the feet and head of the occupants are less than 2 \( ^\circ \)C, meeting the ASHARE replacement ventilation design standard. In addition, due to the low air supply speed of the office diffuser, the formation of temperature stratification mainly depends on the formation of a manikin thermal plume. The airflow velocity provided by the thermal plume is 0.1–0.2 m/s.

![Fig. 4. Vertical thermal and velocity distribution in no partition case.](image)

Under the condition of displacement ventilation airflow distribution, this study simulated the airflow distribution of asymptomatic infected people talking and coughing. Detailed comparisons of velocity vectors and contours in the infected manikin micro-environment were demonstrated in Fig. 5. A continuous and strong ascending thermal plume can be observed from the origin scenario. In the talking scenario, although the speed at the mouth slightly interferes with the thermal plume, the thermal plume still rises slowly along the heating surface near the manikin skin. To a certain extent, the thermal plume interferes with the direction of the speed at the mouth.

![Fig. 5. Comparisons of airflow distribution; origin scenario, with talking, with cough flow at t = 0.1 s.](image)

And coughing scenario showed the local airflow distribution immediately after the cough at t = 0.1s, in which the ascending thermal plume was interrupted by the cough flow and led to a relatively weaker ascending thermal plume above manikin’s head. Due to the breakup of the thermal plume and the strong effects of the coughing, local airflow recirculation was observed in front of the sitting occupant. The disturbance effects of the coughing were significant.

3.2 Infection risk at talking scenario

Because the particles in the talking scenario are continuously released, it means that as time goes on, the more likely the susceptible people in the office are surrounded by covid-19 aerosol. Fig.6 showed the particle distribution when t=60s, and the upward thermal plume of the manikin slightly changes the diffusion direction of particles, exerting force on them. When t=30s, in case 1 without any partition protection, the breathing zone of susceptible people has been filled with particles of covid-19, and susceptible people have a great risk of infection. The remaining cases protected by
partitions, to some extent, block the propagation of particles, and cooperate with the thermal plume to transport particles to the exhaust outlet, reducing the infection risk.

Fig. 6. Comparisons of particle distribution between four scenarios under talking: no partition, single-panel partition, half-wrapped partition, and full-wrapped partition.

To more accurately compare the effect of partition on particle diffusion under different cases, Equation (4) is used to calculate the infection probability.

Fig. 7. Comparisons of infection risk between four scenarios under talking.

It can be seen from Fig. 7, that the infection risk of case 1 without partition increases significantly with the increase of exposure time. After about 3 minutes, the infection risk of susceptible people has reached 100%. The infection probability of case 2 and case 3 increased similarly, and both reached a relatively balanced state after 5 minutes, reaching about 20%. As for case 4, because it is a fully-wrapped structure, the trap of particles is greatly increased, which makes the infection risk of this case the lowest, less than 1%, and the case with the lowest infection risk.

3.3 Effects of cough-jet on particle transport

Particles were released with the coughing process during the first 0.61s. It can be seen from Fig. 8, that since the cough scenario is instantaneous, the distribution of particles in the office depends on the air distribution of the displacement ventilation system when the cough is completed. In addition to case 1, the impact of a coughing jet sends particles quickly to the partitions, so the partitions capture a large number of particles, greatly reducing the risk of infection. At this time, the partition effects in cases 2, 3, and 4 are not significantly different.

Fig. 8. Comparisons of infection risk between four scenarios under coughing.

The distribution of particle diameters in cough cases is different from that in talking, and its distribution range is very wide, it is necessary to consider the influence of partitions on particles of different diameters.

Fig. 9. Particle trajectories after release by an indexed person under case 1 at t=1.5s.

Fig. 9. shows the distribution of different particle diameters, and the distribution of particle diameters with 0–10 μm and 10–50 μm is similar. Because the thermal buoyancy is greater than gravity, these particles are suspended in the air, causing the propagation risk of covid-19. Since the social distance between two occupants is greater than 1.2m (the width of the table), the diameters of the particles greater than 50 μm at this distance will fall on the surface of the obstacle due to gravity and be captured by it, which will not pose a risk to subsequent transmission.

Therefore, in the cough scenario, attention should be paid to the distribution of particles with a particle diameter of 0–50 μm suspended in the air. And more quantitative analysis is required in the future to extend the case in this study.

4 Conclusion
The ascending thermal plume formed on the human body surface under the displacement ventilation system was interrupted by the cough-jet, and local airflow recirculation formed by this led to a relatively weaker ascending thermal plume above the manikin's head. But at a lower mouth inlet speed, such as talking, this will not happen.

(2) In the case of talking, susceptible person exposure to a very high risk of infection in the process of continuous release. Among the four different types of partition settings, the full-wrapped structure is the most effective in reducing the risk of infection, only 0.4%.

(3) For the cough scenario with the instantaneous release, the simplest partition will greatly interfere with the transmission of particles, that is, a single partition can significantly reduce the risk of infection. Research shows that particle diameters more than 50 μm in the social distance will not cause infection risk to susceptible people. However, due to the wide distribution of particle diameters under cough conditions, it is necessary to further study the transmission of particles with different particle diameters.

**References**

1. WHO Coronavirus disease (COVID-19) dashboard.