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Distribution characteristics of respiratory aerosols in enclosed environments

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Abstract: This paper studies the spatial concentration distribution and temporal evolution of exhaled and sneezed/coughed droplets within the range of 1.0 to 10.0 μm in an office room with three air distribution methods, including mixing ventilation (MV), displacement ventilation (DV), and under-floor air distribution (UFAD). The simulation results indicate that exhaled droplets with diameters up to 10.0 μm from normal respiration process are uniformly distributed in MV. However, they become trapped at the breathing height by thermal stratifications in DV and UFAD, resulting in a high droplet concentration and an increased exposure risk to other occupants. Sneezed/coughed droplets are more slowly diluted in DV/UFAD than in MV. Low air speed in the breathing zone in DV/UFAD can lead to prolonged human exposure to droplets in the breathing zone.

Key words: respiratory droplets; displacement ventilation; under-floor air distribution (UFAD); transmission; airborne disease

Indoor air plays a significant role in the transmission of airborne infections in enclosed environments, such as open-plan offices, hospital wards, and commercial aircraft cabins. When a contagious individual coughs or sneezes, infectious droplets are dispersed throughout the room, shrink through evaporation, and then remain suspended in the air for an extended period of time. Inhalation of the droplet nuclei may cause infection.

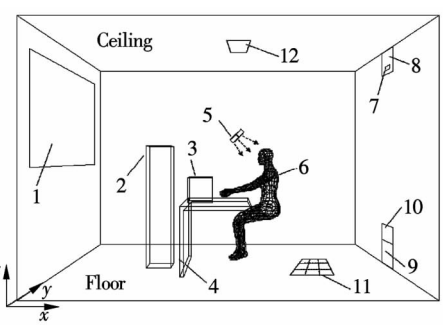
Infection reports in hospitals, high-rise apartments, offices, and transport vehicles indicate a close association between airflow pattern and the transmission/spread of infectious diseases[1]. This suggests a potentially important role of different air-distribution methods in influencing the dispersion of infectious aerosols. To control aerosol dispersion by air currents, specific ventilation systems have been recommended for special circumstances, such as the guidelines for isolation rooms set by the Public Health Service Centers for Disease Control and Prevention[2]. For a typical air-conditioned building room, cool air is usually supplied by mixing ventilation (MV), displacement ventilation (DV), and under-floor air distribution (UFAD). MV creates a well-mixing condition and a uniform thermal environment, while DV and UFAD maintain a vertical gradient of temperature and concentration through low-level supply and up-level exhaust. A number of studies have found that DV and UFAD were more effective than MV in removing non-passive gaseous pollutants. However, their functions in removing expiratory droplets and reducing the risk of indoor cross-infections have been less studied.

By modeling droplet concentration distributions in a real office using an Eulerian-based model, the aim of the present study is to determine the influence of MV, DV and UFAD in the transport of bio-aerosols from human respiratory activities. The spatial variance of droplet concentrations under steady-state exhalation conditions and concentration evolution versus time under transient sneezing conditions are described below.

1 Numerical Simulations

1.1 Case description

The dimensions of the simulated office room are: 4.0 m (length) × 3.0 m (width) × 2.7 m (height) (see Fig. 1). Tab. 1 summarizes the boundary conditions for the window, computer, desk, and the full-scale human body. The heat load in this room is approximately 36 W/m^2 (based on floor area). We compare three air distribution methods (MV, DV, and UFAD) using an air supply temperature of 17 ℃ in MV and 19 ℃ in DV and UFAD, and the air change rate is 5.7 time/h. The normal components of the inlet air velocity in MV and DV are 2.55 m/s and 0.255 m/s, respectively. In UFAD, the floor opening is divided into nine square cells in order to represent the swirling flow from a floor-mounted circular diffuser. All the outer cells have a different supply airflow direction and are responsible for one-eighth of the total supply rate. The angle between the supply airflow and



1—Window; 2—Vertical heat source; 3—Computer; 4—Table; 5—Personalized ventilation air terminal device (circular outlet with a diameter of 20 cm, not activated in the present study); 6—Human body; 7—Mixing ventilation inlet (0.2 m × 0.05 m); 8—Displacement ventilation outlet (0.4 m × 0.3 m); 9—Mixing ventilation outlet (0.4 m × 0.3 m); 10—Displacement ventilation inlet (0.4 m × 0.5 m); 11—UFAD inlet (0.21 m × 0.21 m); 12—UFAD outlet (0.4 m × 0.4 m)

Fig. 1 Configuration of the simulated office

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Tab. 1 The details of numerical methods

Item	Description
Turbulence model	Renormalization k-ε model
Wall treatment	Non-slip, standard logarithmic wall function
Numerical schemes	Upwind second-order difference for the convection term; central difference for the diffusion term with second-order accuracy; SIMPLEC algorithm
Window	Uniform heat flux 150 W
Floor, ceiling, walls	Adiabatic wall
Vertical heat source	Uniform heat flux 100 W
Human body	Fixed skin temperature at 31 ℃
Computer	Uniform heat flux 120 W
Desk	Adiabatic
MV inlet	Airflow rate 51 L/s, turbulence intensity 20%, turbulence length scale 5 mm, temperature 17 ℃
DV inlet	Airflow rate 51 L/s, turbulence intensity 15%, turbulence length scale 5 mm, temperature 19 ℃
UFAD inlet	Airflow rate 51 L/s, turbulence intensity 15%, hydraulic diameter 70 mm, temperature 19 ℃
MV/DV/UFAD outlet	Velocity and temperature: free slip
Nose	For steady exhalation, respiration rate 8.4 L/min, exhaled air temperature 35 ℃, turbulence intensity 10%, hydraulic diameter 10 mm; for sneezing simulation, air velocity 22 m/s, duration 0.5 s

the floor is 30°. The detailed descriptions of this treatment are provided in Ref. [3].

Two physiological processes are taken into account: a steady-state exhalation process and a transient sneezing process. The human body in the computational domain has both a nose and a mouth opening. One previous study[4] found that the exhaled air conditions (exhalation direction, velocity, etc.) from the index patient have a considerable effect on indoor aerosol concentrations and personal exposure. The dynamic respiration cycle is simplified by a steady exhalation process through the human's nostrils. The exhaled air is continuously pushed out through the nostrils at a 45° downward angle at a rate of 8.4 L/min and a temperature of 35 ℃. This rate is consistent with the breathing rate of an adult with a metabolic level that corresponds to the performance of office work. According to PIV (particle image velocimetry) measurements by Zhu et al.[5], sneezed airflow has a similar 45° downward angle from the nose and a velocity at 22 m/s. The sneezing process lasts 0.5 s.

1.2 Airflow and particle modeling

We model the non-isothermal three-dimensional airflow using the RNG (Renormalisation Group) k-ε model. The buoyancy term is included in the y direction momentum equation and the k and ε equation. Air density is defined as a function of temperature using a piecewise-linear relationship. In the transient simulation of sneezing, the time step during a 0.5 s sneezing process is 2 ms. This is small enough to ensure the Courant number less than 1.0. When a sneezing process ends, the time step is gradually increased to 50 ms to reduce the time cost of iteration. To compare the dispersion characteristics of gaseous pollutants and expiratory aerosols, we add CO_2, a tracer gas, with a 5% mass fraction into the exhaled air.

The airborne particles in indoor air can be regarded as dilute systems because the concentration is usually less than 10^8 particle/m^3. This feature suggests that one-way coupling in the simulation is a rational approach. In the present modeling of droplets, both the fluid and particulate phases are treated as interpenetrating continua. However, there are drift fluxes between them caused by gravitational settling. Thus, a gravity vector is added into the convection term of the governing equation for droplet transport:

$$\frac{\partial(\rho C)}{\partial t} + \nabla(\rho(\boldsymbol{U} + \boldsymbol{V}_S) C) = \nabla[\rho(D_p + \varepsilon_p) \nabla C] + S_C \tag{1}$$

where ρ is the air density (g/m^3); C is the particle concentration (g/m^3); $\boldsymbol{U}$ is the air velocity (m/s); $\boldsymbol{V}_S$ is the particle gravitational settling velocity (m/s); D_p is the Brownian diffusion coefficient (m^2/s); ε_P is the particle turbulent diffusivity (m^2/s); and S_C is the source term (g/m^3). The particles are assumed to be spherical with a material density of 1 000 kg/m^3.

To quantify the deposition amount at wall surfaces, we adopt the L&N deposition model[6]. Under the assumption that the deposition flux is one-dimensional and constant in the concentration boundary layer, the L&N model integrates Fick's law across the boundary layer and expresses the non-dimension deposition velocity as a function of droplet properties and local airflow conditions. A previous study validated the drift-flux model combined with wall treatment using the L&N model by comparing it with two sets of experimental data[3].

1.3 Evaluation index

Under steady-state conditions, we inspect normalized concentration values at a number of locations to assess the performance of air distribution types. The particle concentrations are normalized by a value at the human nose. Under the transient conditions where sneezed droplets disperse over time, the droplet cloud spatial volume (CSV) may be of particular importance where the concentration is higher than a fixed value, i.e., infection threshold. CSV displays the size of the polluted zone. In the drift-flux model, CSV is determined by labelling each computational cell by a new variable. The variable is 1.0 if the concentration in a particular cell is greater than or equal to the infection threshold,

otherwise 0. Then CSV can be ascertained by integrating this variable across the computational domain.

2 Results and Discussion

2.1 Airflow fields

The airflow patterns and temperature profiles are illustrated in Fig. 2. The mean temperature at the middle height (1.4 m) is 23 ℃ in all ventilation systems, although the supply air temperature is 2 ℃ lower in MV. As expected, the forced convection in MV drives the well-mixing of air and heat while the natural convection results in temperature gradients in DV and UFAD. Natural convection around the human body is of a particular interest since it interacts with the respiration flows. The upward air speed above the human head reveals that the maximum speeds are 0.30, 0.14, and 0.18 m/s in MV, DV, and UFAD, respectively. The warm thermal plume surrounding the body is the strongest in MV.

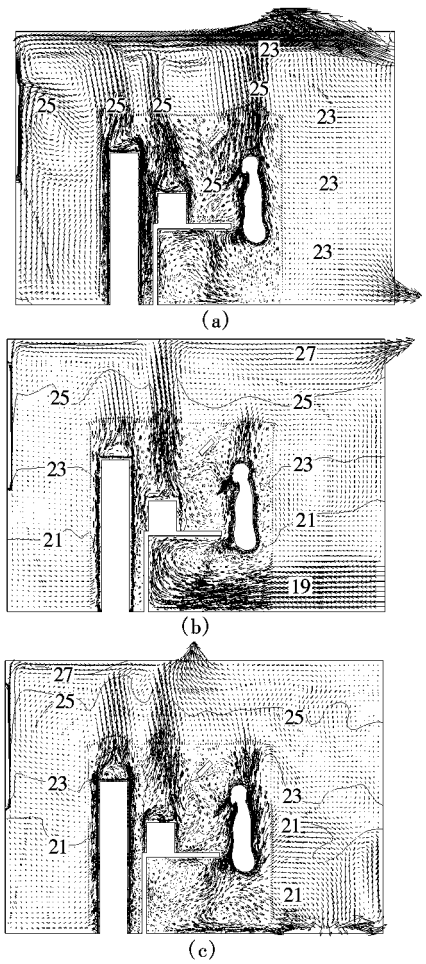

Fig. 2 Air flow patterns and temperature distributions in the middle section ($y = 1.5$ m) of the room. (a) MV; (b) DV; (c) UFAD

2.2 Steady state simulations

Fig. 3 shows the average values of normalized concentrations in horizontal planes across the room at different heights. The concentration in the exhaled air is denoted as 1.0. The droplets are well-mixed in MV in contrast to DV and UFAD where the highest concentration is at between 1.2 and 1.5 m. Note that the average height of the nose is 1.35 m. This middle-height-pollution effect in our study is inconsistent with the two-zone theory of DV which holds that the lower level in a room is the clean zone while the upper level is the polluted zone.

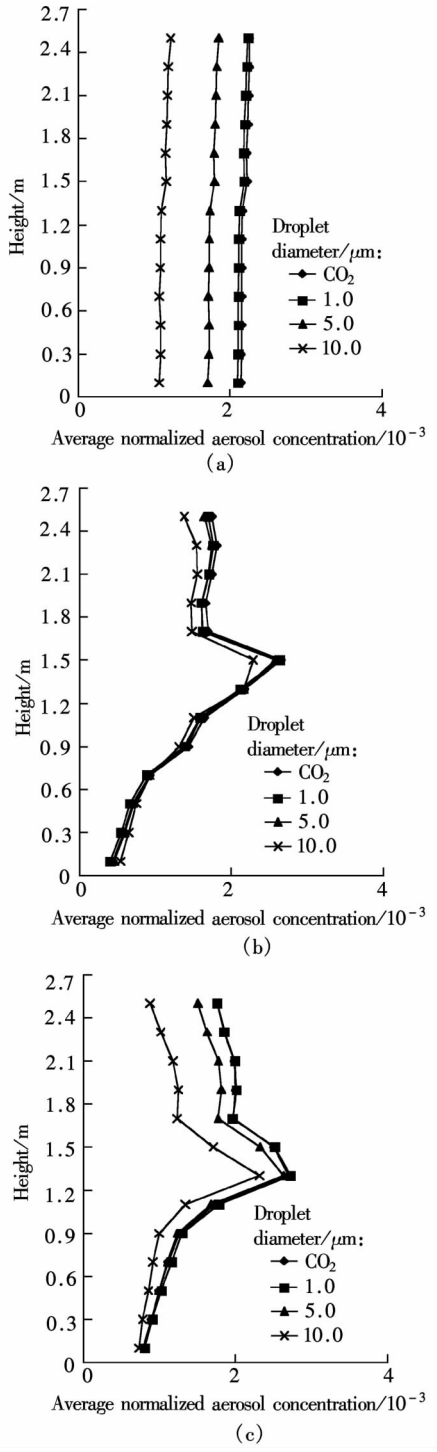

Fig. 3 Average normalized concentrations in planes across the room at different height levels. (a) MV; (b) DV; (c) UFAD

Our findings are in agreement with the experimental results from Qian et al.[4] where full-scale manikins were placed onto two separate beds in a hospital ward with mixing, downward, and displacement ventilation. Using nitrous oxide as a proxy for droplet nuclei, both the smoke visual-

ization and the concentration distribution indicate that the exhaled airstream from a reclined individual penetrates a short distance and is diluted quickly by the room air. In DV, the exhaled air stream travels a long distance and exhibits a high concentration layer at certain heights. Our study implies that the observation of tracer gases may also hold true for respiratory particles smaller than 10.0 μm.

In Ref. [3], particles were uniformly released at the surface of the heat source (the vertical heat source in Fig. 2) without initial momentum at a rate of 0.154 μg/s. The inhaled concentrations of the human in MV, DV, and UFAD were 2.17, 1.50, and 1.68 $\mu g/m^3$ for 5.0 μm particles, and 1.02, 1.40, 1.88 $\mu g/m^3$ for 10.0 μm particles, respectively. The particle source was combined with the heat source so that particles smaller than 5.0 μm would behave as tracer gases with a higher ventilation efficiency in the stratified thermal environments as compared with the uniform environments. However, particles larger than 10.0 μm were too heavy to be carried upwards by the buoyancy effect and remained at the human breathing height, suggesting a higher level of pollution exposure than in MV. The performance of DV and UFAD thus appears to be particle-size sensitive if the particulate matter is produced in heat plumes. Friberg et al. [7] found that DV was less effective in removing large particles (>10.0 μm) because the upward airflow in DV may be insufficient to transport large particles upwards to the ceiling exhaust. In our study a maximum concentration in the breathing height in DV and UFAD appears for both tracer gases and particles. Furthermore, under the indoor furniture and ventilation rate conditions used in our study, MV tends to generate a uniform concentration distribution while, in contrast, exhaled pollutants from occupants are trapped in the breathing zone in DV and UFAD.

The "trap" phenomenon of expiratory pollutants in the thermally stratified environments is undesirable with regard to controlling transmission of respiratory diseases. The accumulation of respiratory droplets can increase the risk of human infection. The key to resolving this problem may be closely linked with the possibility of elevating the trap layer of pollutants to a region above the average breathing height of a human. The location of the trap layer is believed to be affected by the air change rate and the thermal conditions.

2.3 Transient simulations

Fig. 4 shows the dynamic dispersion process in the first 6 s after sneezing. The sneezed air impinges at the desk, is blocked by the computer, and then diverges on two sides. High speed sneezed/coughed airflow shows a feature of orientation. The spatial relationships among indoor furniture and occupants significantly influence the transport of saliva droplets. The "target zone" of the sneezed/coughed jet flow is of high infection risk. Keeping a certain distance between occupants and masking the nose/mouth when sneezing/coughing are reasonable measures to reduce the airborne disease transmissions.

The dilution process of an aerosol cloud is illustrated in Fig. 5. The legends in Fig. 5 indicate the concentration level. For example, "10.0 μm > 10^{-4}" means that, at any points in the volume, the normalized concentration of 10.0 μm droplets is no less than 10^{-4}. The sneezed droplets are most quickly diluted by the room air in MV. For example, for 10.0 μm droplets being diluted to one ten-thousandth, the maximum pollution volume and the corresponding time is 4.3 m^3 and 20 s in MV, 4.0 m^3 and 55 s in DV, and 3.2 m^3 and 40 s in UFAD, respectively. The droplet cloud is diluted quickly in MV as compared with DV. For a single sneeze, a $1:10^4$ dilution of the sneezed droplet concentration has a volume at the order of magnitude of the room space, warning that there is a serious risk of infection if the infection threshold is 10^{-4} or below. Further, people may sneeze and cough repeatedly. The quick dilution in MV has mixed results. It can rapidly dilute the concentration to a level below the infection threshold; however, it can also more quickly transport the droplets a farther distance and lead to infection if the threshold is very low. Given a disease with an infection threshold of 10^{-4}, at 20 s after the sneezing event, the danger zone where the concentration is higher than 10^{-4} is at a volume of 4.3 m^3 in MV. It is 2.5 m^3 in DV and 2.3 m^3 in UFAD. However, at 60 s, the room space with MV is safe, whereas, even at 100 s the indoor air in DV or UFAD is still infectious.

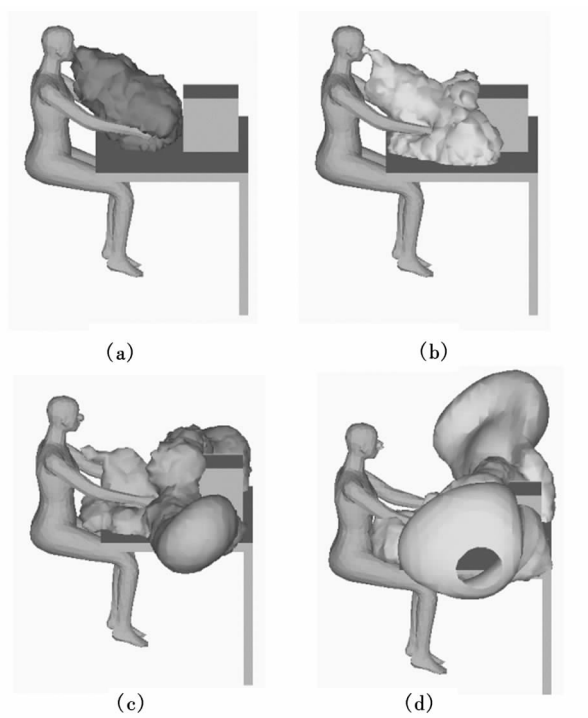

Fig. 4 Shape of normalized concentrations at 10^{-3} for 1.0 μm particles at different times after a sneezing event. (a) 0.5 s; (b) 1.0 s; (c) 3.0 s; (d) 6.0 s

In some studies, mixing time is defined as the shortest time period required to reach a well-mixing condition[8]. Well-mixing is characterized by two requirements: the length scale of the droplet cloud is comparable with the room length scale and the standard deviation of the concentration should be below 10% of the arithmetic mean concentration. During point pulse release of pollutants (i.e. sneezing or coughing) well-mixing conditions may not be

achieved before the pollutants are ventilated outside the room. By validating their simulation against their experiments, Gadgil et al. [9] found that the mixing process depends primarily on the mean airflow in the room and secondarily on the pollutant source location. This finding is in agreement with our results shown in Fig. 5. An examination of the air speed in the breathing height shows a mean value of 0.1m/s in MV, which is about two-times faster than in DV and UFAD. This highlights the importance of indoor air speed levels in the control of cross-infections at similar air change rates. High speed assists droplet dispersion, whereas low speed can cause a local accumulation of droplets over an extended time period.

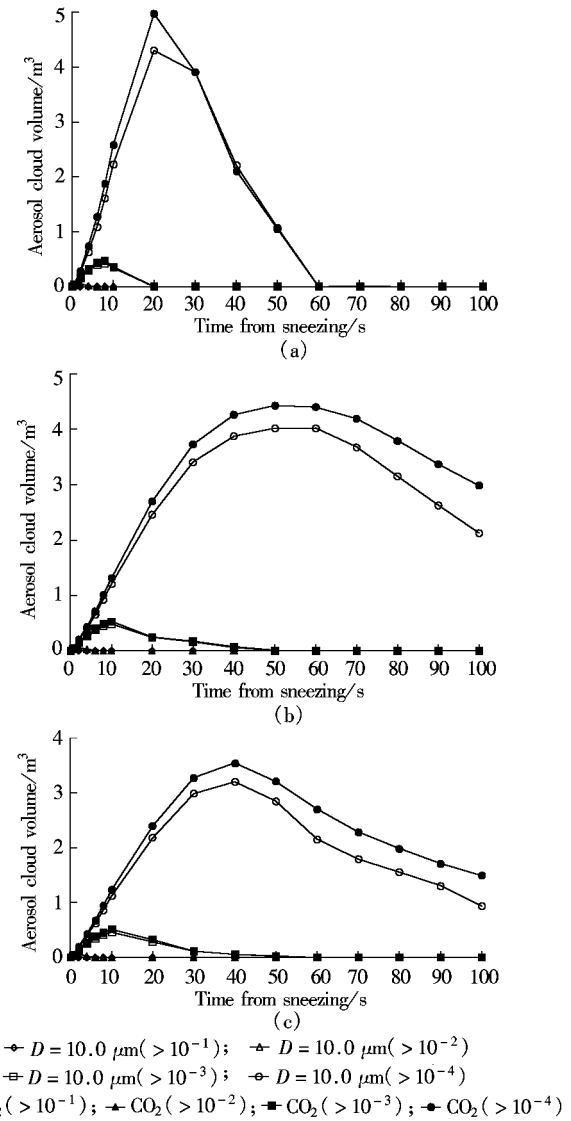

Fig. 5 Evolution of the sneezed aerosol cloud volume. (a) MV; (b) DV; (c) UFAD

3 Conclusions

This study adopts an Eulerian modeling approach to investigate the spatial concentration distribution and temporal evolution of exhaled and sneezed droplets that fall within the range of 1.0 to 10.0 μm. Special attention is paid in comparing the performance of three common ventilation types (i.e., MV, DV, and UFAD) in their abilities to reduce cross-infection risks. The important conclusions are as follows:

1) Respiratory droplets smaller than 10.0 μm disperse similarly to tracer gases. Under steady-state conditions, the exhaled droplets from a normal breathing process can become trapped at the human breathing height in DV and UFAD, thereby increasing human exposure and risk of infection.

2) In DV and UFAD, the distribution characteristics of particulate matter generated from a surface with convective heat versus those from a human nose are entirely different. The trapped layer appears when pollutants are released from the latter.

3) The transient dilution of sneezed/coughed droplets is dominated primarily by the indoor air velocities in the breathing zone. The higher velocity level with MV results in a faster-mixing droplet cloud in the ventilated air than with DV and UFAD. Thermal stratification combined with a lower air velocity at the middle-room-height can cause a longer residence time of the respiratory droplets in the breathing zone, and thus potentially increase the exposure and infection risk.

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人体呼出气溶胶在封闭环境中的分布特性

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摘要:研究了 1.0 ~ 10.0 μm 的呼吸道颗粒物在混合送风、置换送风和地板送风的办公室环境中的浓度空间分布和瞬态演变规律. 仿真结果表明:小于 10.0 μm 的飞沫在混合送风的房间内几乎是均匀分布的. 然而,在置换送风和地板送风中,垂直温度梯度使得小于 10.0 μm 的飞沫在人体呼吸区高度聚集,导致一个较高的浓度水平,因此室内人员被感染的概率比较高. 由咳嗽或者打喷嚏产生的飞沫在置换和地板送风中的稀释(浓度衰减)比在混合送风中慢,这是因为置换和地板送风中人体呼吸区的风速比较小,飞沫在此聚集,不易被气流携带排出室内空间.

关键词:呼吸道飞沫;置换送风;地板送风;传输;空气传播

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