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Distribution of droplets/droplet nuclei from coughing and breathing of patients with different postures in a hospital isolation ward

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\textbf{ABSTRACT}

Suspected and confirmed cases of infectious diseases such as COVID-19 are diagnosed and treated in specific hospital isolation wards, posing a challenge to preventing cross-infection between patients and healthcare workers. In this study, the Euler-Lagrange method was used to simulate the evaporation and dispersion of droplets with full-size distribution produced by fluctuating coughing and breathing activities in an isolation ward. The effects of supply air temperature and relative humidity, ventilation rates and patient postures on droplet distribution were investigated. The numerical models were validated by an aerosol experiment with an artificial saliva solution containing \textit{E. coli} bacteria conducted in a typical isolation ward. The results showed that the small size group of droplets (initial size $\leq 87.5$ μm) exhibited airborne transmission in the isolation ward, while the large size group (initial size $\geq 112.5$ μm) were rapidly deposited by gravitational effects. The ventilation rate had a greater effect on the diffusion of droplet nuclei than the supply air temperature and relative humidity. As the air changes per hour (ACH) increased from 8 to 16, the number fraction of suspended droplet nuclei reduced by 14.2% and 6.4% in the lying and sitting cases, respectively, while the number fraction of escaped droplet nuclei increased by 16.2% and 14.6%. Regardless of whether the patient was lying or sitting, the amount of droplet nuclei deposited on the ceiling was highest at lower ventilation rates. These results may provide some guidance for routine disinfection and ventilation strategies in hospital isolation wards.

\textbf{1. Introduction}

Since December 2019, novel coronavirus disease 2019 (COVID-19) caused by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) has spread rapidly around the world. Following that, the emergence of SARS-CoV-2 variants such as Delta and Omicron variants accelerated the spread of COVID-19, putting humans at greater health risk \cite{1,2}. COVID-19 can be transmitted through droplets, contact with contaminated surfaces, and aerosols in relatively close environments \cite{3,4}. When virus-laden droplets are released into the air through human respiratory activities, they quickly evaporate and become droplet nuclei. Larger droplets will be rapidly deposited after being released due to gravity, whereas smaller droplets or droplet nuclei can spread over long distances as a result of indoor airflow. Contact with contaminated surfaces or inhalation of airborne infectious aerosols may pose a potential risk of cross-infection due to the long survival of surface-deposited or aerosol viruses \cite{5}. Suspected and confirmed cases of COVID-19 are placed in a specific hospital negative pressure isolation ward environment for diagnosis and treatment, which poses a challenge to prevent cross-infection between patients and healthcare workers (HCWs). According to information collected by the International Council of Nurses (ICN), more than 90,000 HCWs worldwide have been infected in the fight against COVID-19 \cite{6}. A previous study demonstrated that the human coronavirus (HCOV) could be capable of transmission by contaminated surfaces in healthcare environment \cite{7}. Zhou et al. \cite{8} detected SARS-COV-2 RNA on the surfaces of pagers and in drawers in the isolation ward where the COVID-19 patient was placed 28 days after discharge. The study by Zhang et al. \cite{9} found that 7 of the 31 high-frequency contact sites were positive in three isolation wards of patients with COVID-19. The above findings suggest that despite prolonged exposure, there is still a risk of environmental contamination and cross-infection in isolation wards. In order to clarify the degree of contamination in different locations of the isolation ward environment so as to determine the focus of disinfection reduce the cross-infection risk, it is necessary to study the distribution of exhaled droplets from patients in isolation wards.

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Numerous studies have shown that the design features of isolation ward environments, especially the ventilation, can enhance the airborne control of respiratory infectious diseases. The experiment study by Qian et al. [10] showed a uniform distribution of droplet nuclei in an isolation wards when mixed and downward ventilation was applied, while a high concentration layer of droplet nuclei was formed due to thermal stratification under displacement ventilation, increasing the individual exposure levels. A study by Aganovic et al. [11] showed that personalized ventilation could be built into hospital ventilation systems in decreasing cross-infection in isolation wards. Nielsen et al. [12] proposed that personalized ventilation could be built into hospital ventilation systems in decreasing cross-infection in isolation wards. Cho [14] used beds to minimize cross-infection. Lu et al. [13] proposed stratum ventilation, which could reduce the concentration of contaminant in the breathing zone and minimize the exposure risk of HCWs. The virus spreads by droplets produced by infected patients’ exhalation activities. As a result, the thermos-fluid boundary characteristics of exhaled droplets, such as expiratory velocity, temperature, and size distribution, are critical for understanding droplet transmission. Wan et al. [15] injected water test droplets containing non-volatile content as a substitute for cough droplets and found that the droplets smaller than 10 μm and could not assess the droplets or droplet nuclei deposition [12]. In addition, the effects of ventilation parameters such as supply air temperature and relatively humidity on droplet distribution in isolation wards were rarely studied except for ventilation modes.

To comprehensively investigate the distribution for exhaled droplets in the isolation ward, Euler coupling with Lagrangian method was applied to investigate the evaporation and dispersion of virus-laden droplets with the full-size spectrum generated by fluctuating coughing and breathing activities. Two patient positions, lying and sitting, were considered and the effects of supply air temperature, supply air relative humidity, and ventilation rate on droplet distribution were analyzed in this paper. Furthermore, an aerosol experiment with an artificial saliva solution containing E. coli bacteria was conducted in a typical isolation ward to validate the numerical models. The results of this study are expected to guide ventilation design and disinfection in isolation wards, and have important significance for controlling the spread of respiratory diseases such as COVID-19.

2. Methods

2.1. Numerical models

The airflow field in the isolation ward was solved using the Reynolds-averaged Navier-Stokes (RANS) equations. The Realizable k-ε model with enhanced wall treatment was applied considering its successful applications in simulating indoor airflow [17,18]. The following was the general form of the governing equations for continuity, momentum, energy and turbulence quantities:

\[ \frac{\partial (\rho u)}{\partial t} + \nabla \cdot (\rho u u) = \nabla \cdot (F_\varphi \nabla \psi) + S_\varphi \]

where \( \rho \) is the air density, \( u \) is the air velocity vector, \( \varphi \) represents the transported quantity, \( F_\varphi \) is the effective diffusion coefficient of \( \varphi \), and \( S_\varphi \) represents the source term. The Boussinesq approximation was used to treat the thermal buoyance flows. The SIMPLE algorithm was employed for the velocity-pressure coupling. The staggered scheme PRESTO! was applied to solve pressure values at cell faces and the second order upwind was taken to discretize the momentum, energy, \( k \) and \( c \) equations.

After the droplets were expelled from the patient’s mouth or nose, the water in the droplets would evaporate rapidly in the air. The Species Transport model was used for the transport and diffusion of mixture of water vapor and air in the turbulence. The model is formulated by the following general equation:

\[ \frac{\partial}{\partial t} (\rho Y) + \nabla \cdot (\rho VY) = - \nabla \cdot J + S_Y \]

where \( Y \) is local mass fraction of water vapor species, \( J \) is the diffusion flux of water vapor species, \( S_Y \) is the source term of water vapor species. At boundaries such as the supply air inlet, nose or mouth, the respective fluid mass fractions of the mixture of air and water vapor were calculated from the relative humidity.

The rate of vaporization was governed by gradient diffusion, which was related to the gradient of the vapor concentration between the droplet surface and the air phase [19]:

\[ \frac{dN}{dt} = c(C_1 - C_\infty) \]

where \( c \) is the mass transfer coefficient, \( C_1 \) and \( C_\infty \) represent molar concentration of water vapor at droplet surface and in the air, respectively. During the transport of the mixture, the changes in the respective fluid mass fractions in the mixture can be calculated according to the general formulæ (2) and (3).

The individual trajectory of each droplet was obtained by solving the momentum equation of the particle based on the Lagrangian frame. This equation could be expressed as:

\[ \frac{d\mathbf{u}_p}{dt} = F_{\omega}(u - u_p) + \frac{\mathbf{g}(p_{\infty} - p)}{p_{\infty}} + F \]

where \( u \) and \( u_p \) are the velocities of air and particles respectively, \( F \) represents the additional forces on the particles. Considering indoor airflow and droplet size, only thermophoretic force, Brownian force and Saffman’s lift force were included in this study. The formula for calculating the thermophoretic force was as follows:

\[ F_\omega = -\frac{6\pi \mu c_{\omega} K_\omega (K + C_1 K_s)}{\rho \nu (1 + 3 C_1 K_s) (1 + 2K + 2C_1 K_s)} \nabla T \]

where \( K_\omega \) is Knudsen number = 2a/dp, \( a \) is the mean free path of the fluid, \( K \) is \( k/K_B \), \( k \) is fluid thermal conductivity, \( K_\omega \) is particle thermal conductivity, \( C_1 \) is 1.17, \( C_s \) is 2.18, \( C_\omega \) is 1.14, \( T \) represents the local fluid temperature, \( \mu \) is fluid viscosity, \( d_p \) is the particle diameter. Other additional forces were negligible, since they were two orders of magnitude smaller than the drag force [20,21]. The particle shape was
This study investigated the effect of different supply air temperatures, relative humidity and ventilation rates on droplet distribution in the isolation ward. Considering the requirements for thermal comfort of patients in the Chinese national standard "Requirements of Environment Control for Hospital Negative Pressure Isolation Ward" (GB/T 35428–2017) [22], three specific supply air temperatures and relative humidity were selected as the research objects, respectively. Ventilation rates of 8, 12 and 16 ACH were chosen based on the isolation ward ventilation rate requirements. Two typical patient positions, lying and sitting, were chosen based on the effect of different release sources on droplet spread. Specific parameter settings selected and the patient postures considered were shown in Table 1. Grille diffusers were used in the isolation ward, which were openings covered with very fine net. The ratio of the effective area to the gross area was 0.9228, with a sufficiently small difference. Therefore, the diffusers were assumed to be openings in the simulations and the velocity-inlet was adopted as the boundary condition of the diffusers [13,14,23–26]. Supply air velocity was obtained according to the ACH, and turbulence intensity was 5% [27]. The primary ceiling diffuser had the same air supply parameters as the secondary ceiling diffuser. In order to create a mainstream area of clean airflow under the diffusers and thereby protect HCWs from infection, the diffusers supplied the airflow in a vertical downward direction [22].

Based on experiment measurements [28,29], the convective heat load of the thermal manikin was taken as 36W, which corresponded to a heat flux of 24W/m². The other solid walls of the isolation ward were assumed adiabatic. The physical process of indoor radiation was not simulated in this study, including human radiation heat loss [23–25,30–32]. An additional simulation case including radiation was performed, and the results showed that ignoring the physical process of radiation had little effect on indoor airflow compared to simulating only convection. The steady-state airflow in the isolation ward was first solved, followed by transient simulations of droplets released by one cough from 0s to 0.5s and continuous breathing from 0.5s to 250s. The time-dependent airflow velocity for coughing and breathing were quantified based on existing experimental measurements [33,34] and implemented into the simulation by User Defined Functions (UDFs), as shown in Fig. 3. In this study, starting from 0.5 s and decreasing
gradually, several time steps were tested for transient simulation of indoor airflow. Time steps of 0.01 s and 0.1 s were found to be accurate enough to capture the changes in the airflow field during coughing and breathing, respectively. Therefore, the time step was set to 0.01 s for coughing process, and 0.1 s for the breath processes. The temperature of the coughing and breathing airflow was 33 °C and the relative humidity was 90% [35, 36]. Due to the large initial size range of droplets released by coughing, a full-size range of droplet for coughing was included in this study. The number fraction of each initial diameter was set based on experimental data from real coughs [37], as shown in Fig. 3. Droplets with each initial diameter were modelled separately and a corresponding number of droplets were injected individually for each initial diameter. A total of 4950 droplets were released during the coughing process. The initial diameter of the droplets released by breathing was

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Fig. 2. Unstructured grids of domain, prism layers around the patients, mouth and nose, (a) the patient lying case; (b) the patient sitting case.
0.4 μm and 520 droplets were released in each breathing cycle [38–41]. Notably, the droplets were only released during exhalation. Taking into account evaporation, the initial droplets contained 98.2% water and 1.8% solids [37]. When the exhaled droplets evaporated completely, the equilibrium diameter of the particles shrank to 26% of the initial diameter. For the discrete phase boundary conditions, air supplies and exhaust were set as reflect and escape boundaries, respectively, and other surfaces were set as trap boundaries. The different boundary conditions used in the numerical simulations were summarized in Table 2. All simulation cases were performed utilizing the commercial CFD software ANSYS FLUENT 2021 R1.

### 2.4. Experimental method

To verify the accuracy of the numerical models, an experiment was conducted in a full-size isolation ward laboratory with a thermal manikin at the Department of Power Engineering, North China Electric Power University (NCEPU). The configurational of the isolation ward experimental cabin was shown in Fig. 4(a). The experimental cabin of the isolation ward had a same dimension as that of the computational models of isolation wards in Fig. 1. It was worth noting that the two air supplies in the isolation ward experimental cabin were the same size, both 0.24 m × 0.135 m. The airflow rate was 350 m³/h. The temperature and relative humidity of supply air was 26 °C and 46.5%, respectively. The airflow velocity was measured with an anemometer (TSI 9535), which had a measurement range of 0–30 m/s and an accuracy of ±3%. Experimentally prepared artificial saliva containing *Escherichia coli* (*E. coli*, ATCC 13706) was aerosolized to simulate the process of droplet production by patient exhalation. *E. coli* was round and white in ordinary agar medium, which had obvious identification. In addition, the biological safety level of *Escherichia coli* was 1, and it was usually used in bioaerosol diffusion experiments in wards [42].

![Fig. 3. Boundary condition for coughing and breathing (a) cough velocity, (b) breath velocity, and (c) size distribution for cough droplets.](image-url)

**Table 1**

| Case No. | Supply air temperature (°C) | Supply air relative humidity (%) | Ventilation rate (ACH) | Supply air Velocity (m/s) | Posture |
|---------|-----------------------------|---------------------------------|------------------------|--------------------------|---------|
| Case 1  | 18                          | 50                              | 12                     | 0.25                     | Lying   |
| Case 2  | 23                          | 50                              | 12                     | 0.25                     | Lying   |
| Case 3  | 28                          | 50                              | 12                     | 0.25                     | Lying   |
| Case 4  | 23                          | 30                              | 12                     | 0.25                     | Lying   |
| Case 5  | 23                          | 70                              | 12                     | 0.25                     | Lying   |
| Case 6  | 23                          | 50                              | 8                      | 0.17                     | Lying   |
| Case 7  | 23                          | 50                              | 16                     | 0.34                     | Lying   |
| Case 8  | 18                          | 50                              | 12                     | 0.25                     | Sitting |
| Case 9  | 23                          | 50                              | 12                     | 0.25                     | Sitting |
| Case 10 | 28                          | 50                              | 12                     | 0.25                     | Sitting |
| Case 11 | 23                          | 30                              | 12                     | 0.25                     | Sitting |
| Case 12 | 23                          | 70                              | 12                     | 0.25                     | Sitting |
| Case 13 | 23                          | 50                              | 8                      | 0.17                     | Sitting |
| Case 14 | 23                          | 50                              | 16                     | 0.34                     | Sitting |

**Table 2**

| Boundary | Condition |
|----------|-----------|
| Primary diffuser | Velocity-inlet: Case1-Case14 Inlet temperature: Case1-Caese14 Inlet relative humidity: Case1-Caese14 DPM condition: Reflect |
| Secondary diffuser | Velocity-inlet: Case1-Caese14 Inlet temperature: Case1-Caese14 Inlet relative humidity: Case1-Caese14 DPM condition: Reflect |
| Exhaust | Pressure-outlet: –15Pa DPM condition: Escape |
| Thermal manikin | Wall: Heat flux: 24W/m² DPM condition: Trap |
| Nose | Velocity-inlet: UDF of breath velocity Inlet temperature: 33 °C Inlet relative humidity: 90% Duration time: 0.5–250 s DPM condition: Trap |
| Mouth | Velocity-inlet: UDF of cough velocity Inlet temperature: 33 °C Inlet relative humidity: 90% Duration time: 0–0.5 s DPM condition: Trap |
| Ceiling, walls, floor, bed, bedstand | Wall: Adiabatic DPM condition: Trap |
lying on a bed with its mouth 0.88 m above the floor and the average surface temperature was $34 \pm 1 ^\circ C$. The bioaerosols were injected at a rate of 0.5 m/s, producing droplets with an average initial diameter of 1 $\mu$m. The droplets were injected continuously for 13 min. Aerosol collection of *Escherichia coli* was performed at 10 min using four Anderson six-stage samplers with a collection time of 3 min. After the collected agar plates were placed in a constant temperature incubator at $37 ^\circ C$ for 24 h, the CFU of *Escherichia coli* on the agar plates were counted and the concentration of *Escherichia coli* aerosol was calculated. The above experimental procedure was repeated three times to reduce experimental accidental error. The locations of airflow velocity measuring points and bioaerosol sampling points in the experiment were shown in Fig. 4(b).

3. Results and discussion

3.1. Verification of mathematical models

Based on the boundary conditions in the experiment, the same numerical methods as the above simulation were used to simulate the experimental scenario. Of note is that the patient in this simulation exhaled continuously from the mouth at a constant rate of 0.5 m/s. The temperature and relative humidity of the exhalation were 26 $^\circ C$ and 100%, respectively. Table 3 summarized the key parameters of the experiment and corresponding simulation. Fig. 5 compared the measured and simulated airflow velocity. The simulated airflow velocity was selected for the two straight lines of Line 1 and Line 2 in Fig. 4(b).
Because the two straight lines had full-size lengths in the X and Z directions of the isolation ward and passed under each of the two air supplies, the airflow velocity distributions on the two straight lines had a large scale and were representative for turbulence model validation. The results showed that the airflow velocity increased abruptly to more than 1 m/s when passing below the air supplies, while the airflow velocity at other locations was below 0.2 m/s. The simulated airflow velocity agreed well with experimental data, indicating the accuracy of the turbulence model in predicting the airflow field in the isolation ward.

To verify the accuracy of the Lagrangian method for bioaerosol diffusion calculations, experimental and simulated bioaerosol concentrations were compared by a normalized concentration that was defined as:

\[ N_{Bi} = \frac{C_{Bi}}{\bar{C}} \]  

(6)

where, for the experiment, \( C_{Bi} \) is the bioaerosol concentration at measuring point \( B_i \), and \( \bar{C} \) is the average concentration of bioaerosol at the four measuring points; for the simulation, \( C_{Bi} \) is the average bioaerosol concentration at measuring point \( B_i \) in the last 3 min of the total simulation time of 13 min, and \( \bar{C} \) is the average of \( C_{Bi} \) at the four measuring points. Fig. 6 compared the experimental and predicted normalized concentrations. For the experimental values, the mean and standard deviation of the normalized concentrations were calculated for three identical experiments. The results showed that the normalized concentrations at the measuring points B2 and B3 were relatively lower compared to the measuring points B1 and B4. This was due to the fact that the measuring points B2 and B3 were located below the air supplies, while the measuring points B1 and B4 were closer to the patient. B1 was closer to the exhaust and located in the downstream of the airflow, resulting in the highest normalized concentration. There were small differences in the normalized concentrations between the simulated and experimental values, and the general trend of the bioaerosol distribution in the experiments and simulation was approximate. As a result, it can be concluded that the Lagrangian method is accurate in simulating bioaerosol diffusion.

| Table 3 | The key parameters for the experiment and simulation. |
|---------|-----------------------------------------------------|
| Content | Experiment | Simulation |
| Velocity of exhalation | 0.5 m/s | 0.5 m/s |
| Temperature and relative humidity of exhalation | 26 °C, 100% | 26 °C, 100% |
| Breathing time | 780 s | 780 s |
| Total time | 780 s | 780 s |

3.2. Airflow distribution in patients’ micro-environment

Since the airflow diffusion mechanism in the patient’s micro-environment was similar in the same posture, Case 2 and Case 9 were chosen for airflow distribution analysis. The instantaneous airflow distribution above the lying patient in Case 2 was shown in Fig. 7. An updraft caused by the combined effects of the ventilation system and the buoyant thermal plume of the patient can be observed at \( t = 0 \) s. The maximum value of vertical velocity was about 0.21 m/s, which was similar to the experimental and CFD results of the thermal plume generated by a single person in traditional indoor spaces [45, 46]. The strong coughing airflow and the thermal plume merged and ascended after cough at \( t = 0.5 \) s, and the airflow velocity reached more than 0.3 m/s. At \( t = 1.5 \) s, the patient was breathing in through the nose. It can be seen that the cough-jet still had a significant effect on the airflow of the local environment, while the inhalation had less effect on the surrounding airflow. At \( t = 3.5 \) s, the airflow exhaled by the patient through the nose rose with the thermal plume, and the maximum airflow velocity was also more than 0.3 m/s. Fig. 8 showed the instantaneous airflow distribution around the sitting patient in Case 9. Similarly, an ascending thermal plume can be seen above the head of the patient. The rising thermal plume was interrupted by the forward airflow created by the cough at \( t = 0.5 \) s. A new vortex can be observed in front of the patient due to the strong influence of the cough-jet and the breakup of the thermal plume. This is consistent with the results simulated by Yan et al. [30]. When the patient exhaled, the effect of the cough airflow persisted even as it gradually dissipated. In
addition, it can be seen that the downward airflow exhaled through nose rose together with the thermal plume due to thermal buoyancy.

3.3. Droplet/droplet nuclei transport

Fig. 9 and Fig. 10 showed the spatial distribution of droplets and droplet nuclei in Case 2 and Case 9, respectively. Coughing droplets were injected vertically upward and forward, respectively, for the patient lying on the bed and the patient sitting on the bed. At \( t = 1 \) s, droplets with different initial diameters produced by coughing could be seen, while at \( t = 10 \) s, droplets with an initial diameter greater than 50 μm disappeared. Among them, droplets with a diameter of 50–100 μm were reduced in size to less than 50 μm due to evaporation and became droplet nuclei, while droplets larger than 100 μm were deposited on the patient or bed under the effect of gravity. In Case 2, the droplet nuclei spread upward as they were affected by the combined effects of the exhaled airflow and the thermal plume, and then spread around after approaching the ceiling. Subsequently, the droplet nuclei moved down with the indoor airflow and were discharged from the exhaust. It was worth noting that most of the droplet nuclei accumulated in the upper part of the isolation ward resulting in a high concentration area. The spread of droplet nuclei was similar in the case of the patient sitting, and
Fig. 9. Spatial distribution of droplets/droplet nuclei from a single cough and continuous breathing in Case 2 (23 °C, 50%, ACH 12, Lying).

Fig. 10. Spatial distribution of droplets/droplet nuclei from a single cough and continuous breathing in Case 9 (23 °C, 50%, ACH 12, Sitting).
there was still a high concentration area of droplet nuclei near the ceiling. However, in the sitting case, the distribution of droplet nuclei in the isolation ward was more uniform than in the lying case. This was because the sitting patient was closer to the two air supplies, and the droplet nuclei generated by coughing and breathing spread more homogeneously under the carrying effect of the supply airflow.

To better understand the dispersion of droplets with different sizes in the isolation ward, the number fraction was adopted to characterize the removal rate of droplets, as shown in Fig. 11. The number fraction was defined as the ratio of the number of suspended droplets or droplet nuclei to the total number of droplets injected for each particular size. It was worth noting that the droplets with the initial diameter of 0.4 μm were generated by continuous breathing, and its number fraction was obtained by dividing the number of suspended droplets or droplet nuclei

![Fig. 11. Number fraction of suspended droplet groups with different initial sizes: (a) in case 2; (b) in case 9.](image-url)
by the total number of droplets injected at the current moment. A “Perfectly mixed” curve was employed to indicate the decay of a “gas-like” contaminant perfectly mixed with the indoor air. This curve was expressed as $y = e^{(-0.0033x)}$, and the constant 0.0033 was the air change rate of the isolation ward (12 hr$^{-1}$ = 0.0033s$^{-1}$) [15]. The results showed that the number of suspended droplets or droplet nuclei gradually decreased with increasing time. The larger the initial size, the greater the decay rate of the number fraction. The decay trend of droplets with initial sizes smaller than or equal 87.5 $\mu$m was similar to that of perfectly mixed gaseous contaminant, indicating that they exhibited airborne transportability. However, as the initial size increased, the effect of gravity became increasingly important. The number fraction of droplets larger than or equal 112.5 $\mu$m dropped rapidly, suggesting that their removal was dominated by gravitational effect. In the experimental study by Wan et al. [15], the droplets were injected vertically upward, similar to the case in which the patient was lying on the bed in this study. In their study, droplets smaller than 45 $\mu$m behaved airborne transmission, while droplet of 87.5 $\mu$m and 137.5 $\mu$m dropped rapidly due to the dominance of gravitational effects. The difference with the present study could be due to the different airflow patterns and the fact that the upward thermal plume generated by the patient was not considered in the study of Wan et al., which counteracted part of the gravitational effect during the upward movement of the droplets.

In the case with the patient lying on the bed, the number fraction of droplets smaller than 45 $\mu$m was larger than the perfectly mixed curve. This indicated that droplets smaller than 45 $\mu$m were not uniformly distributed in the isolation ward, resulting in a lower removal performance of ventilation. The number fraction of droplets larger than 45 $\mu$m was smaller than the perfectly mixed curve because the deposition of droplets played a more important influence in the diffusion process. It could be observed that the number fractions of droplets of 1.5–12 $\mu$m were near the perfectly mixed curve in the case of the sitting patient. This suggested that the removal of droplet was similar to that of the perfectly mixed gas, as the droplets were more homogeneously distributed in the isolation ward. However, as the initial size increased, the effect of deposition became more significant. Since the diffusion paths and number fraction decay of droplets and droplet nuclei were similar, the transport analysis of droplets and droplet nuclei was not repeated for other cases except Case 2 and Case 9.

3.4. Effects of temperature and relative humidity

In order to quantitatively assess the distribution of droplet nuclei in the isolation ward, the number of suspended, deposited and escaped droplet nuclei was recorded at different moments, as shown in Fig. 12 (a–c). Fig. 12 (d) showed the number fraction of suspended, deposited, escaped and nose-inhaled droplet nuclei at 250s. The number fraction was defined as the proportion of suspended, deposited, escaped and nose-inhaled droplet nuclei to the total number of releases, respectively. The results showed that the number of suspended, deposited and escaped droplet nuclei in the isolation ward increased consistently with the temperature and relative humidity.

**Fig. 12.** Distribution of droplet nuclei: (a) suspension, (b) escape, (c) deposition, and (d) number fraction of droplet nuclei at 250s. All cases have the same ACH of 12, but different supply air temperature and relative humidity. For lying cases, Case 1: 18 °C, 50%, Case 2: 23 °C, 50%, Case 3: 28 °C, 50%, Case 4: 23 °C, 30%, and Case 5: 23 °C, 70%; for sitting cases, Case 8: 18 °C, 50%, Case 9: 23 °C, 50%, Case 10: 28 °C, 50%, Case 11: 23 °C, 30%, and Case 12: 23 °C, 70%.
time due to continuous breathing. The number of suspended droplets was higher in the lying cases than in the sitting cases, while the number of escaped and deposited droplet nuclei demonstrated the opposite results. For example, at 250s, the number fractions of suspended, escaped and deposited droplets were 79.5%, 9.5% and 7.4% for Case 2, while the number fractions of suspended, escaped and deposited droplets were 63.6%, 21.5% and 7.6% for Case 9, respectively. This was related to the distribution of droplet nuclei in the isolation ward in both postural situations. When the patient was lying, most of the droplet nuclei gathered near the ceiling and ventilation had a poor performance in the exclusion of droplet nuclei. As the spatial distribution of droplet nuclei was more uniform when the patient was sitting, the removal of droplet nuclei was more effective.

The distribution of droplet nuclei varied similarly with time for different air supply temperatures and relative humidity conditions. For the lying cases, the maximum differences in the number fractions of suspended, escaped and deposited droplet nuclei were 1.6%, 1.3% and 1.1% for the three air supply temperature conditions and 1.4%, 0.8% and 1.2% for the three relative humidity conditions, respectively; for the sitting cases, those were 0.6%, 0.5% and 2.4% for the three air supply temperature conditions and 1.3%, 0.4% and 2.6% for the three relative humidity conditions, respectively. This indicated that the supply air temperature and relative humidity had little effect on the distribution of droplet nuclei in the isolation ward. The evaporation process of the droplets was directly influenced by temperature and relative humidity, however, the time for droplets to evaporate into droplet nuclei was very short [47,48]. Moreover, the time scale of diffusion was much larger than that of evaporation, therefore the droplet diffusion over a longer time was less influenced by temperature and relative humidity [19,49].

Fig. 13 showed the number of droplet nuclei deposited at various locations at 250s. The air supply temperature and relative humidity had less effect on the deposition of droplet nuclei at different locations. The number of droplet nuclei deposited on the ceiling, floor and bed was lower in the lying cases than in the sitting cases, but there was no significant difference in the number deposited on other locations. Regardless of whether the patient was lying or sitting, the highest number of droplet nuclei was deposited on the ceiling, above 1100, while the lowest number was deposited on the bedstand, below 100. As a surface with a high probability of contact by patients, the bedstand played an important role in contact transmission. Despite the small number of droplet nuclei deposited on the bedstand, the process of evaporation occurred when the ACH was increased from 8 to 16, the number fraction of suspended droplet nuclei decreased by 14.2% and 6.4% in the lying and sitting cases, respectively, while the number fraction of escaped droplet nuclei increased by 16.2% and 14.6%. The number of inhaled through the nose decreased as the number of suspended droplet nuclei decreased. The number fraction of droplet nuclei inhaled through the nose decreased by 2.2% and 4.6% when the ACH was increased from 8 to 16 for the lying and sitting cases, respectively. The number of deposited droplet nuclei did not show a significant linear law with the increase of ACH. The highest number of deposited droplet nuclei occurred when the ACH was 12 and the number fraction was 7.4% at 250s for the patient lying case. At 8 and 16 ACH, the number of deposited droplet nuclei was comparable, with a number fraction of 4.6% and 4.9%, respectively. The highest number of deposited droplet nuclei was observed in the patient sitting case when the ACH was 8, and the number fraction was 11.4%. ACH of 12 and 16 had a number fraction of 7.6% and 7.9%, respectively. Overall, the increased ventilation rates facilitated the elimination of droplet nuclei in the isolation ward by exhaust air and reduced the deposition and suspension of droplet nuclei.

Fig. 15 showed the number of droplet nuclei deposited at various locations at 250s for different ventilation rates. The ventilation rate had a significant impact on the number of droplet nuclei deposited on the ceiling. In the lying cases, the highest number of ceiling deposition was 1545 occurring in Case 2 with an ACH of 12, and the lowest was 108 appearing in Case 7 with an ACH of 16; In the sitting cases, the highest number of ceiling deposition was 2157 occurring in Case 13 with an ACH of 8, and the lowest was 951 appearing in Case 14 with an ACH of 16. For the lying cases, the amount deposited on the ceiling in Case 2 was higher than that in Case 6. This may be because the total number of deposited droplet nuclei in Case 2 was greater than that in Case 6. Under the premise of a certain total number of droplets released, the decrease in the number of suspended and inhaled droplet nuclei between Cases 2 and 6 was higher than the increase in the number of escaped droplet nuclei, despite the increase in ACH. For the sitting cases, in contrast to the difference between Case 2 and 6, the reduction in the number of suspended and inhaled droplet nuclei between Cases 9 and 13 was smaller than the increase of the escaped droplet nuclei number. This may explain the lower number of droplet nuclei deposited on the ceiling in case 9 than in case 13. When ACH was increased to 16, the number of droplet nuclei decreased for both the lying and sitting cases. However, the number of droplet nuclei deposited on other locations was less affected by the ventilation rate. This indicated that increasing the ventilation rate did not reduce the contamination of other surfaces in the isolation ward except the ceiling, and therefore surface disinfection remains important at higher ventilation rates.

3.6. Limitations of this study

This study revealed the transmission mechanism and distribution of droplet in a hospital isolation ward and aimed to provide guidance for the ventilation design and disinfection. The exposure risk to HCWs has not been evaluated, considering that HCWs enter the isolation ward with good personal protective equipment. In addition, this study considered only two positions, lying and sitting, and two exhalation activities, coughing and breathing, which were the most common behaviors of
patients in isolation wards. However, patients in isolation wards may perform other arbitrary activities, such as walking, bending, talking, and sneezing. Different droplet distribution would be expected in the isolation ward under different activity conditions of patients. In addition, the position of exhaust would also have an impact on the evolution of different droplet behavior. The effects of these factors should be systematically considered in future studies of droplet dispersion in hospital isolation wards.

4. Conclusion

In this study, evaporation and dispersion of droplets in a hospital isolation ward were investigated using the Euler-Lagrange method. The numerical models were validated by an experiment using *E. coli* bacteria conducted in a full-size isolation ward. The generation, spread, and removal of full-size distributed droplets from coughing and breathing were simulated, and the effects of air supply temperature, relative humidity, and ventilation rates on droplet distribution were analyzed for both lying and sitting patient cases. The following conclusions can be obtained:

1. The coupling of the fluctuating airflow generated by coughing and breathing with the thermal plume was critical to the initial spread of droplets. The small size group of droplets (initial size ≤87.5 μm) exhibited airborne transmission and could stay in the air for a longer time, while the large size group (initial size ≥112.5 μm) were dominated by gravitational effects and underwent rapid deposition after release.

2. Under the same ventilation conditions, the majority of the droplet nuclei were dispersed near the ceiling of the isolation ward for the case with the lying patient, whereas the distribution of droplet nuclei was more uniform for the sitting case. The number of suspended droplet nuclei was higher in the lying case than in
the sitting case, whereas the opposite was true for the number of deposited and escaped droplet nuclei.

(3) The air temperature and relative humidity had less of an impact on the distribution of droplet nuclei in the isolation ward as compared to ventilation rates. The number of suspended droplet nuclei dropped as the ventilation rate rose, but the number of escaping droplet nuclei grew. The number fraction of suspended droplet nuclei reduced by 14.2% and 6.4% in the lying and sitting cases, respectively, as the ACH increased from 8 to 16, while the number fraction of escaped droplet nuclei increased by 16.2% and 14.6%. For the ventilation design of the isolation ward, in order to control the spread of infectious diseases, it was recommended to increase the ventilation rate as much as possible. At the same time, considering energy saving, the design thresholds of air supply temperature and relative humidity could be appropriately reduced on the premise of satisfying human thermal comfort.

(4) The number of droplet nuclei deposited on the ceiling was highest at lower ventilation rates, regardless of whether the patient was lying or sitting. It was recommended to strengthen the disinfection of the ceiling surface of the isolation ward in the routine disinfection.

CRediT authorship contribution statement

Haiyang Liu: Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Data curation, Conceptualization. Zhiyuan Liu: Writing – review & editing, Funding acquisition, Formal analysis, Conceptualization. Yongxin Wang: Writing – review & editing, Investigation, Formal analysis. Chenxing Hu: Writing – review & editing, Funding acquisition, Formal analysis. Rui Rong: Writing – review & editing, Software.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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