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The influence of air supply inlet location on the spatial-temporal distribution of bioaerosol in isolation ward under three mixed ventilation modes

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ABSTRACT

The outbreak of COVID-19 and the spread of infectious pathogens through bioaerosols have once again aroused widespread concern worldwide. Isolation ward is an important place to prevent the spread of infectious bioaerosols. However, infection of health care workers (HCWs) in the isolation ward often occurs, so it is urgent to carry out relevant research to reduce the cross-infection between HCWs and patients. In this paper, the temporal and spatial distribution characteristics of bioaerosols under three mixed ventilation modes in a single ward were studied, namely, upper supply side return air of Case 1 and side supply and side return ventilation are Case 2 and Case 3 respectively. The results show that the removal efficiency of bioaerosol in the ventilation mode of Case 3, in which directional airflow is formed from the air supply inlet to the release source and then to the exhaust outlet, is 46.6% and 67.7% higher than that of Case 1 and Case 2, respectively. In addition, ventilation methods based on mixed theory do not guarantee good air quality in the breathing zone (1.3 m to 1.7 m) of HCWs, which may increase the inhalation risk for HCWs. It is hoped that our results can provide some useful suggestions for optimizing the airflow layout of the isolation ward, reducing the risk of cross-infection, and virus elimination.

1. Introduction

Since the 21st century, humans have experienced a variety of infectious diseases caused by airborne pathogens, such as severe acute respiratory syndrome (SARS), Middle East Respiratory Syndrome (MERS), tuberculosis, and airborne diseases have been of great concern around the world [1-6]. Although droplets and contact transmission are considered to be the main routes of transmission of COVID-19, there was evidence that aerosol transmission is also an important route [7,8]. Isolation wards is one of the most effective devices to prevent the spread of infectious diseases outside. But it also carries a higher risk of cross-infection between HCWs and patients. During this outbreak, a large number of health care workers (HCWs) are infected. Effective ventilation strategies were extremely important to reduce cross-infection [9]. Guidelines for the design of isolation ward have been published by different national health boards [10–12]. However, there is still no consensus on standards such as the placement of air inlets and outlet, as well as the number of air changes to minimize the risk of transmitting infection.

Indoor air distribution mainly depends on the location of the inlet and outlet. How to improve the efficiency of ventilation, ensure indoor air quality and reduce the inhalation and contact risk of HCWs has always been the focus of research in the field of health care. Liu et al. studied aerosol diffusion in ventilation rooms with downward air supply, and the results showed that the lower air supply velocity was beneficial to aerosol diffusion control [13]. Qian et al. investigated the downward ventilation system of hospital wards. It was suggested to further study the location of air supply diffuser and exhaust outlet in the downward ventilation system. Airflow structures that efficiently remove pollutants should be designed to reduce the risk of cross-infection in general hospital wards [14]. Lu et al. believed that the air velocity in the occupied area of mixed ventilation was low and had no direction. The mixing of fresh and old air led to the widespread spread of pollutants in the breathing zone. This can lead to a higher risk of infection. It was
also pointed out that the pollutant removal performance of displacement ventilation is more sensitive to the location and direction of pollution sources [15]. Research by Villafruela et al. showed that when other parameters were equal. The position of the air inlets and outlets and the type of air diffuser had a great influence on the ventilation quality and air flow pattern. It also pointed out that the conclusions obtained with one type of diffuser cannot be deduced to other diffusers [16]. Berlanga et al. evaluated four different hospitals mixed ventilation modes and compared them with replacement ventilation modes, and found that replacement ventilation had better performance in hospital room environment [17]. Zhang et al. conducted a comparative study on the mixed ventilation of air supply from the ceiling or the upper side wall and the attached ventilation based on adaptive wall in the negative pressure isolation ward under the same ventilation times, and found that the attached ventilation could reduce the average concentration of pollutants by 15–47% [18]. Wang et al. studied the fate and patient intake ratio of respiratory particles in four-bed wards under air flow modes of impingement jet ventilation and two types of mixed ventilation. The results showed that mixed ventilation was less effective in removing particles and reducing intake in susceptible patients than impingement jet ventilation. It was also pointed out that displacement ventilation has better air quality than mixed ventilation in occupied areas [19]. Bin Zhao et al. analyzed the relationship between infection probability and ventilation efficiency of HCWs in a confined space by combining the Wells–Riley equation [20]. However, the above research focused more on improving the ventilation efficiency of ward. In addition, compared with airborne transmission, the risk of contact transmission caused by bioaerols deposited on all surfaces of ward cannot be ignored, especially in the hospital bed frequently touched by the HCWs and physical contact with the patient.

Deposition of infectious bioaerols exhaled by patients in wards is affected by many factors. The survival potential of bioaerol on a surface depended on the properties of the surface, especially its water content, and also on the type of virus and its tolerance to dry conditions [4]. The New England Journal reported that SARS-COV-2 remained alive in aerosols for three hours during the experiment [21]. Zhao et al. used numerical simulation to predict the concentration and deposition of aerosol particles in displacement and mixed ventilation room, and the results showed that the deposition and concentration of particles with different particle sizes were greatly affected by ventilation method, and the particle sedimentation rate of displacement ventilation room was lower than that of mixed ventilation room with the same particle properties [22]. Therefore, it is necessary to analyze the deposition of bioaerols under different ventilation modes in the ward to guide the disinfection of ward and reduce the risk of contact transmission.

Since the 1970s, Computational fluid dynamics (CFD) method has been introduced into the ventilation system research, and it has been increasingly used in the ventilation system of operating room [23–25], general hospital ward [26–28], isolation ward [29–31] and even subway vehicles [32] and industrial buildings [33]. This paper studied the distribution of bioaerols in a typical single-person isolation ward by CFD method. The accuracy of the mathematical model was verified by comparing the experimental data with the numerical simulation results. The deposition, suspension and removal characteristics of bioaerols in empty rooms and actual rooms under three air supply modes were quantitatively analyzed. The relative positions of the air supply inlet and hospital bed, as well as the relative positions of the air supply inlet, release sources and exhaust outlet on the migration characteristics of bioaerols were considered, and the temporal and spatial distribution of bioaerols were predicted. Meanwhile, the concentration change in the breathing zone of the entire isolation ward was quantitatively analyzed. It is hoped that our results can provide some useful suggestions for optimizing the airflow layout of the isolation ward, reducing the risk of cross-infection, and virus elimination. At the same time, it must be acknowledged that the three ventilation modes studied in this paper cannot represent all situations, which is also the limitation of this study, but the situation studied in this paper is well representative [34]. In our follow-up work, we will continue to carry out relevant studies, hoping to obtain more valuable research results.

2. Case study

As illustrated in Fig. 1, the physical model used in this study is a typical single isolation ward. The size of the isolation ward is 4.226 m length (L) × 2.622 m width (W) × 2.8 m height (H). In order to distinguish the four walls in different directions, X+, X-, Z+ Z- represent the surface of the room except the ground and ceiling. Three ventilation strategies are considered: one up-supply side return (Case 1) and two side-supply side return (Case 2 and Case 3). The air supply of Case 1 is introduced into the isolation ward by two air inlets of the equal size (0.24 m × 0.135 m) located in the ceiling. The air from the two air inlets is sent to the side and the end of the bed, respectively, which is the regions where the health care workers (HCWs) may work. The air supply inlet of Case 2 is diagonally distributed with the exhaust outlet. This mode of air supply maximizes the flow of air through the ward and finally out of the exhaust outlet. And the air supply inlet of Case 3 is located on the side wall opposite the exhaust outlet near the ceiling, and the air supply inlet, the head of the bed and the exhaust outlet are basically on the same plane. Compared with Case 2, the air circulation distance in the ward in this ventilation mode is significantly shortened. To ensure the same air supply speed as Case 1. The size of the air supply inlet of Cases 2 and 3 is 0.27 m × 0.24 m. The exhaust outlet (0.27 m × 0.27 m) in all scenarios is the same, and it is located at the lower position of the side wall on the other side of the hospital bed.

Based on these three ventilation strategies, the effects of different air supply inlets in isolation ward on bioaerol deposition, spatial distribution and removal efficiency were studied. Our previous research found that facility layout may influence aerosol distribution [35]. Therefore, two scenarios were considered: empty room and actual room. In all scenarios studied in this paper, the air supply flow is 430 m³/h, equivalent to 14 air changes per hour (ACH).

According to the research focus of this paper, the internal layout of the isolation ward is simplified accordingly. In the actual room, it contains only a single bed and a patient. Such simplification is considered acceptable.

Grid density and quality affect the accuracy of numerical simulation results [36]. The isolation ward space was meshed by ICEM CFD ANSYS software. The mesh used in the simulation is unstructured tetrahedral mesh, the minimum mesh size is 0.02 m, the mesh quality is greater than 0.3, meet the requirements of calculation. Mesh independence tests were carried out with three different mesh numbers. In order to ensure sufficient refinement of the mesh, regions with large velocity gradient and human body surface were encrypted in three meshes. In these 6 scenarios, the velocity of the vertical center line of the air inlet was used to verify the independence of the grid, as showed in Figs. 2 and 3. The comparison results show that the velocity difference of three kinds of grids is small. Considering the accuracy and computation amount, the grid with medium mesh density is selected for subsequent simulation.

3. Mathematical model

3.1. Model assumptions

In order to simplify the problem of this study, we introduce the following hypothesis:

(1) Indoor air is an incompressible ideal gas [37];
(2) Particles hitting all surfaces are caught immediately and will not bounce, that is, all surfaces are set as trap boundary conditions [38];
(3) When the particle reaches the exhaust outlet, it is considered that the particle is removed, and the exhaust outlet is set as the boundary condition of escape [38];
Fig. 1. Physical model layouts for Cases 1–3.

Fig. 2. Verification of grid independence of actual room (a) Case 1 (b) Case 2 (c) Case 3.
Each surface is adiabatic and the temperature is uniform throughout the room [39];

The evaporation, condensation and breakage of particles are not considered, that is, the size and shape of particles remain unchanged [39].

3.2. Airflow governing equation

Methods for simulating indoor turbulence include direct numerical simulation (DNS), large eddy simulation (LES) and Reynolds average Navier-Stokes (RANS). The application of DNS and LES in turbulence simulation requires high computer memory and computational speed [40, 41]. In recent years, RNG k-ε turbulence model of RANS method has been extensively used in indoor airflow simulation, and has been verified in RANS turbulence model [42]. Compared with other RANS methods, the RNG k-ε model has higher accuracy, calculation speed and stability in indoor environment modeling [43]. Therefore, this study chooses the RNG k-ε turbulence model to calculate turbulence Eq. (1). is the general form of the governing equation:

\[
\frac{\partial (\rho \phi)}{\partial t} + \nabla \cdot (\rho \phi \vec{V}) = \nabla \cdot (\Gamma_\phi \nabla \phi) + S_\phi
\]

where \( \rho \) is the air density, \( \vec{V} \) is the air velocity vector, \( \phi \) represents each of the three velocity components, \( \Gamma_\phi \) is the effective diffusion coefficient of \( \phi \), and \( S_\phi \) is the source term.

In the simulation, the velocity quantity on the wall surface was obtained under the condition of no slip. The air supply inlet was set as velocity inlet with turbulence of 5%. As mentioned above, the air supply rate of the isolation ward is 430 m³/h, which is equivalent to 14 air changes per hour (ACH). The magnitude of the velocity was calculated by the air exchange rate, which was 1.843 m/s. To maintain a negative pressure environment in the isolation ward, the exhaust outlet was set as pressure outlet boundary with a pressure of -15 Pa and turbulence intensity of 5%. Conservative control equations were discretized by the finite volume method. In order to improve the accuracy of numerical calculation, constraint terms and diffusion constraint terms in the second-order upwind discrete control equation were adopted, and the SIMPLE algorithm was used to calculate the flow field.

3.3. Particle tracking governing equation

In order to track the particle trajectories, the Lagrange particle tracking method was used to calculate the particle phase motion, and the discrete random walk model was used to simulate the particle dispersion in turbulence. In the process of simulation, the steady-state calculation of airflow field was carried out first, and then the transient calculation was carried out by adding particles. Its governing equation is:

\[
\frac{d u_{wi}}{dt} = \frac{18 \mu}{\rho_d d_p^2} \left( u_i - u_{wi} \right) + g_i \left( 1 - \frac{\rho}{\rho_d} \right) + F_{wi}
\]

where \( u_i \) and \( u_{wi} \) are the instantaneous velocities of the fluid and particles, respectively; \( \mu \) is the molecular viscosity of the fluid; \( \rho \) and \( \rho_d \) are the densities of the fluid and particles, respectively; \( d_p \) is the diameter of the particles; \( Re \) is the particle Reynolds number; \( C_D \) is the drag coefficient; \( g_i \) is the gravitational acceleration in the i direction; and \( F_{wi} \) is the additional force exerted on the particles.

According to the simulation and experimental results of Chang and Hu, Saffman lift force has a greater impact on particles with a particle size of 2.5–5 μm, while Brownian force has a greater impact on particles with a particle size of less than 0.5 μm [44]. In addition, the ratio of air density to particle density is very small, so compared with other external forces on particles, pressure gradient force, virtual mass force and the Basset force can be ignored in this study [38]. It is assumed that the temperature of the room is evenly distributed and there is no temperature difference, so thermophoretic force is ignored [39]. In the simulation, the size of the patient’s mouth was 0.025 m × 0.025 m, and the respiratory rate was about 10 L/min. The particle size used for simulation in this paper was 2.5 μm, and 900 s were released to stabilize the particle concentration. The simulation was conducted in 1400s, because bioaerosol particles had been basically deposited on the surfaces of the isolation ward or removed at this time. Therefore, this study ignores the influence of Brownian force and only the Saffman lift force was considered.

3.4. Continuous phase flow field verification

To verify the correctness of the mathematical model used in this paper, Yang et al.’s experimental data of full-size airflow velocity field in an ISO-5 clean room was used [45] Fig. 4. shows the layout of the clean room and the location of the measuring points.

Clean room is divided into two parts: a clean ward and bathroom. Overall size of the clean room is 3.3 m (X) × 2.5 m (Y) × 3.1 m (Z), among them, the size of the bathroom was 1.5 m (X) × 2.5 m (Y) × 1.4 m (Z). Air entering the clean room and bathroom was treated by high efficiency filter installed in the ceiling. The size of the air inlet in the clean ward regions was 3.1 m (X) × 1.5 m (Z) + 1.6 m (X) × 1.3 m (Z), and the air supply rate was 6950 m³/h. After the clean air was sent into the ward, part of it was discharged through 5 air outlets at the bottom of the clean ward on both sides (the size of the air outlet is 0.3 m (Y) × 0.75 m (Z)), and a small part was discharged into the bathroom through the door gap between the clean ward and the bathroom. The size of the door gap was 0.02 m (Y) × 0.8 m (Z), and the penetration rate is 100 m²/h. In the bathroom, the dimensions of the air inlet and air outlet were 0.5 m
(X) × 0.5 m (Z) and 1.8 m (Y) × 0.2 m (Z), respectively, and the airflow rates of the corresponding air inlet and air outlet were 325 m$^3$/h and 425 m$^3$/h respectively. In Fig. 4, measuring points were arranged at three heights of 0.8 m, 1.2 m and 1.6 m respectively. The RNG k-ε turbulence model was used to simulate the turbulence and compared with the experimental data. Fig. 5, shows the comparison between simulated and experimental values of airflow velocity. Compared with the measured data of each monitoring point, the numerical simulation results basically accord with the law of flow field. Therefore, it is feasible to use the RNG k-ε model to simulate the flow field in an isolation ward.

3.5. Discrete phase unsteady particle tracking model verification

In this paper, the Lagrangian particle tracking method was used to calculate the motion of the discrete phase. In order to effectively verify the correctness of the model, the experimental data in the literature [46] were compared with the simulated value. Fig. 6(a) shows the physical model of the two-zone full-size room used for verification. The geometric dimension was 5 m (X) × 2.4 m (Y) × 3 m (Z), which was the same as that in the experiment. The room was divided into two equal areas by an open partition board which was located in the middle of the room. The opening was located in the center line of the room and measures 0.95 m (Y) × 0.7 m (Z). Compared with the length of the room, the thickness of the partition can be ignored. The airflow entered the room through the air supply part in the upper part of the room (0.15 m (X) × 0.5 m (Y) × 1.0 m (Z)), and finally discharged through the air exhaust part located in the lower part of the room (0.15 m (X) × 0.5 m (Y) × 1.0 m (Z)). The ventilation rate of the room was 9.216 ACH. In the experiment, and the particle size of smoke was in the range of 0.5–5 μm. In the simulation, particles smaller than 1 μm were included in the range of 1 μm, and the density was 865.0 kg/m$^3$.

The specific process of the experiment is as follows: particles were initially injected into zone 1, and the opening between the two zones was closed before the measurement began. When particles were evenly distributed in zone 1, ventilation and opening were opened, and the particle mass concentration in the two zones was measured. The particle mass concentration (C) is determined by Eq. (3). In the simulation, the total particle mass of injection zone 1 was determined by measured data. The particle mass was evenly distributed in each size group. It was assumed that the initial concentration is uniformly distributed in 5 particle sizes ranging from 1 to 5 μm. The experimental and simulated values of particle mass concentration in zone 1 over time are shown in Fig. 6(b). Since the rebound of particles was not considered in the simulation, which may occur in the experiment, the error between the simulated values and the experimental values was acceptable. Therefore, accuracy of Lagrangian discrete tracking model was verified.

\[ C = \frac{M_s}{V} \]

(3)

Where \( M_s \) is the total mass of suspended particles and \( V \) is the volume of each zone.

4. Results and discussion

4.1. Airflow distribution in isolation ward

The distribution of airflow in the isolation ward directly affects the aerosol migration path. Fig. 7(a) and (b) are the vector diagrams of ve-
Locality streamlines in the central plane of the air supply inlet at the side and tail of the actual room bed in Case 1. This method of air delivery directly around the hospital bed seems to ensure that the air around the HCWs is clean. It can be observed in Fig. 7(a) and (b) that the air flow entered from the air supply inlet of the ceiling and impacted vertically downward to the ground, and then moved to both sides. After moving to the walls on both sides, it continued to move upward along the walls, forming a large vortex in the upper part of the room. Due to the close proximity of the two air inlets, the air flow interacted with each other after hitting the ground, and also formed some small eddies above the ground. Fig. 7(c) and (d) are velocity streamline vector diagrams of the same position of the empty room in Case 1. It can be seen that a large range of vortices are also formed on both sides of the air supply inlets. However, the existence of bed in the actual room destroyed local airflow pattern, resulting in different positions of vortices. The biggest difference is that the ceiling position of the empty room in (f) formed a large local vortex, while there is no such vortex in (b) of the actual room in the same position. Similarly, Fig. 7(c) shows the velocity streamline vector diagram of the central plane of the air supply inlet of Case 2. The airflow moved horizontally to the side wall (Z+ Wall) and down the wall to the ground, creating a vortex above the ground, which was generally a horizontal spiral forward motion. According to Fig. 7(d) velocity streamline vector diagram at the center of air supply outlet of Case 3, after air flow hit the side wall, a small part of air flow formed a small vortex above the room, and most of the air flow down the side wall reached the exhaust outlet and was discharged. Since the air flow pattern in the same position of the empty room in Cases 2 and 3 is basically the same as that in the actual room, it will not be repeated.

### 4.2 Dynamic migration process of bioaerosol in isolation ward

Fig. 8 shows the spatial and temporal distribution of bioaerosols in actual ward under three ventilation conditions. The different colors of
the bioaerosol particles represent the generation time of the aerosol particles. The dynamic migration process of bioaerosol over time is greatly affected by indoor airflow. Fig. 8(a) shows the diffusion of bioaerosols in the actual ward of Case 1. It can be seen that at $T = 20$ s, shortly after the release of the bioaerosol, under the influence of the initial velocity momentum released from the mouth, the bioaerosol first moved to the top of the patient’s head. As time went on, it gradually moved along the X+ wall to the Z-wall. At $T = 200$ s, the bioaerosol has filled the whole room. Influenced by the direction of the initial airflow, the air was sent into the room, hit the ground vertically and then moved horizontally to both sides. Due to the interaction of the two airflow, the vortex was formed near the hospital bed eventually, which made a large amount of biological aerosols exhaled by the patient confined to the vicinity of the patient ($400 < T < 700$ s), which is not conducive to the effective removal of bioaerosols, and also greatly increases the deposition of bed and patient surfaces, increasing the risk of contact transmission. When $T = 1000$ s, the concentration of bioaerosol around the patient gradually decreased because the release of bioaerosol had stopped.

Fig. 8(b) shows the change of spatial distribution of bioaerosol over time in the actual ward of Case 2. Different from Case 1 in Fig. 8(a), at $T = 20$ s, although a small part of bioaerosols moved up and spread to the ceiling, most of them migrated horizontally to one side of the patient’s head, because the air flow in Case 2 was in a horizontal spiral motion, which restricted the direct upward movement of bioaerosols. At $T = 200$ s, it is similar to Case 1 that bioaerosol diffused throughout the room. Bioaerosol concentration was also high in and around the patient’s head throughout the release period.
As can be seen from Fig. 8(c), except in the initial stage of bioaerosol release ($T<60$ s), the diffusion path of bioaerosol was disordered, and the diffusion path of bioaerosol after that was very similar, which indicates that the airflow pattern in Case 3 is very stable. The bioaerosols exhaled by the patient moved upwards, and was impacted by the airflow from the air supply inlet, moving towards the $Z+$ wall. Since the airflow flows directly to the patient, the airflow has a strong ability to carry aerosol particles, and the bioaerosol can be removed from the exhaust outlet in a short time. Meanwhile, it can also be observed that the concentration of bioaerosol in the ward was relatively uniform at all times, and no obvious high concentration regions were formed near the patient. This means that the directional flow of air was good, reducing the possibility of vortex formation in the ward, and thus avoiding the formation of high concentration regions.

Based on the above analysis, it can be concluded that the air supply inlet closer to the hospital bed (Case 1) will complicate the airflow pattern around the hospital bed and form a certain number of vortex regions, so that the aerosol particles exhaled by the patient stay in these vortex regions. Regions with high concentrations of bioaerosols increase the risk of inhalation and exposure to transmission for HCWs. In addition, the formation of a directional flow path (Case 3) from the air supply inlet to the release source and then to the exhaust outlet can not only effectively enhance the ability of the flow to carry bioaerosol particles and accelerate the removal speed of bioaerosol, but also reduce the vortex
near the release source and avoid the formation of high concentration regions.

4.3. Characteristics of deposition, suspension and removal of bioaerosols in isolation ward

Analysis of the deposition, suspension and removal characteristics of bioaerosols in isolation ward is very important to prevent infection of HCWs and ward surface disinfection. The relative position of the air supply inlet, exhaust outlet and release source has great influence on these three characteristics.

Fig. 9 shows the deposition rate of the empty room and the actual room under the three ventilation modes during the simulated calculation of 1400s. The deposition rate was the ratio of the number of particles deposited on all surfaces to the number of particles released. Under the three ventilation modes, whether it is an empty room or an actual room, the deposition rate of Cases 2 and 3 has no noticeable change. The deposition rate of Case 2 is significantly higher than that of Cases 1 and 3, up to 80%. The deposition rate of the empty room of Case 1 is lowest in all scenarios, which was 61.1%. However, the deposition rate in the actual room of Case 1 reached 76.5%, and the deposition rate increased by 15.4%. The reason for this phenomenon may be that the airflow direction of Case 1 was downward, and the air supply of the actual room of Case 1 was relatively close to the patient bed and the patient, which made the airflow pattern near the patient bed more complicated. The spatial migration of biological aerosol particles was hindered, and more aerosols were deposited on the bed and the surface of the patient. This can also be confirmed in Fig. 10. In the empty room, there is no obstruction by hospital bed and patient, and the air supply inlet was very close to the aerosol release source and the exhaust outlet. The downward air-
flow can easily bring most of the aerosol particles to the exhaust outlet for discharge.

It can also be seen from the Fig. 9 that in all scenarios the deposition speed was fast in the period of 0s-300 s, and then tended to be flat in the period of 600 s. At 900s-1000s, there was a short time interval of accelerated deposition speed in the period of 100 s after bioaerosol stopped releasing, and then the deposition rate increased slowly until the end of the simulation.

Fig. 10(a–c) show the deposition rate of bioaerosol particles on each surface in the isolation ward in 1400 s under three ventilation strategies, respectively. The deposition rate was calculated as the ratio of the total number of particles deposited on each surface of the isolation ward to the total number of particles released during the simulation. The deposition rate of each surface in the isolation ward was different due to the location of the air supply inlet. In all three cases, the deposition rate of X+ wall was higher because the release source was closest to X+ wall, which can be easily explained. In Case 1, the deposition rate of ground was the highest, 19.3% and 17.7% respectively in the empty room and the actual room. This is mainly due to airflow patterns and gravity play a dominant role in particle motion. The downward airflow made bioaerosols hit the ground quickly, and a large number of aerosols were deposited on the ground. The deposition rate of all walls in Case 2 was similar, which was due to the symmetrical center of the air supply inlet and the exhaust outlet. After the clean air was fed into the ward through the air supply inlet, it hit the Z+ wall, and then the air flow moved down along the wall to the ground. After hitting the ground, the air flow returned to the Z-wall along the ground. Then the air flow repeatedly carried out this horizontal spiral movement mode and finally discharged from the exhaust outlet. Therefore, the mixing of air in the isolation chamber is relatively uniform, resulting in no difference in the deposition rate between walls. It was just because the air flow repeatedly washed the ground that the deposition rate of ground in Case 2 was lower than Cases 1 and 3. In Case 3, the wall with the highest deposition rate was Z+ wall, with deposition rates of 17.9% and 17.7% in the empty room and the actual room respectively. Aerosol diffusion patterns were also influenced by airflow patterns. Aerosols moved upward after being released from the patient’s mouth and were impacted by air supply in the middle and upper part of the room, changing the trend of upward movement and making aerosols diffuse to Z+ wall, resulting in a higher deposition rate of Z+ wall.

Comparing (a–c) in Fig. 10 shows that the deposition rate of the bed and patient surface in Case 1 are 8.93% and 10.2%, respectively, which were significantly higher than Case 2 (3.45 and 1.73%) and Case 3 (2.9 and 0.84%). As previously analyzed, the distance between the air inlet and the bed was too close, resulting in complicated airflow distribution near the bed and forming a certain vortex regions near the bed. This allowed aerosols to linger in these regions for a longer time, eventually settling on patient and bed. Because health care workers (HCWs) had to be in constant contact with patient and bed, this greatly increased the risk of contact transmission.

Fig. 11 shows the change of bioaerosol particles suspension rate in the isolation ward in 1400s with time under six scenarios. It can be seen that at the end of the simulation (T = 1400), the suspension rate of bioaerosols in the isolation ward was basically 0. On the whole, the change trend of bioaerosol in each scenario is basically the same, and there was little difference in the suspension rate of bioaerosol at ev-
ery point in time. When $T = 100$ s, there was a great difference in the bioaerosol suspension rates in various scenarios. However, as time went on, bioaerosols were gradually deposited on each surface of the ward and discharged from the exhaust outlet, so the difference between the bioaerosols suspension rate at the same time point gradually decreased.

Fig. 12(a) and (b) shows the changes of bioaerosol concentration in the breathing region (1.3m-1.7 m) of HCWs of the three cases in the empty room and the actual room with time. As can be seen from the Fig. 12, in the 900 s of bioaerosol release, although bioaerosol in the breathing zone was slightly different in various scenarios, the concentration of bioaerosol in the breathing zone of the empty room and the actual room basically remained at the concentration level of $10^2$CFU/m$^3$. After the release of bioaerosols stopped, bioaerosols were rapidly diluted due to the influence of ventilation, and the concentration of bioaerosols in the breathing zone also decreased rapidly. By $T = 1400$s, the concentration of bioaerosols in the breathing zone has dropped to an extremely low level. Although the three cases of air supply inlet position is different, but in the breathing zone, the concentration of the aerosol is almost the same, this shows that mixing ventilation mode based on the theory of the hybrid cannot keep breathing zone a good air quality, reduce the inhalation risk of infection of HCWs. It is recommended to study new ventilation methods to reduce the possibility of infection.

Fig. 13 shows the changes in the number of bioaerosol particles removed from the empty room and the actual room in three ventilation methods over time in the 1400s. It can be seen that the largest number of aerosol particles removed in all cases was the empty ward of Case 1, with approximately 140,000 aerosol particles removed in the 1400s. However, the number of aerosol particles removed from the actual room in Case 1 was significantly reduced to only about 85,000, with a reduction in removal efficiency of nearly 40%, but still higher than the number of aerosol particles removed from the empty room and the actual room in Case 2. There was no significant difference in the number of removed aerosol particles between the empty room and the actual room in Cases 2 and 3, indicating that the presence of hospital bed and patient did not have a great impact on the air flow in the isolation ward. However, the number of removed aerosol particles in Case 3 was considerably higher and the removal effect of aerosol particles was better. The results show that the removal efficiency of bioaerosol in the ventilation mode of Case 3 is 46.6% and 67.7% higher than that of Case 1 and Case 2, respectively.

From the perspective of the removal speed of bioaerosol particles, the slope of the empty room in Case 1 in Fig. 13 is the largest, that is, the removal speed of aerosol particles in the empty room in Case 1 is the fastest at the same time point, and the removal speed of Case 2 is the lowest, and the overall removal speed of Case 3 is the fastest. Case 1 in
the actual room, due to the existence of the hospital bed and the patient, the air flow path from the air inlet to the air outlet is blocked, and the ability of the air flow to carry bioaerosol particles is reduced. On the other hand, due to the relative position of the air inlet and the hospital bed, the two downward airflows affect each other, making the airflow pattern near the hospital bed more complicated. The vortices in these regions lead to the retention of a large number of bioaerosol particles. Thus a part of aerosol cannot be well discharged from the exhaust outlet.

From the above analysis, it can be concluded that the relative position of the air supply inlet and hospital bed has a great influence on the removal effect of bioaerosol. If there is not enough space between the air supply inlet and the hospital bed, it may disturb the local airflow path, thus affecting the directional movement of bioaerosol particles to the exhaust outlet. On the contrary, if the relative position of the air supply inlet, the release source and the exhaust outlet are comprehensively considered, the directional airflow path from the air supply inlet to the release source and then to the exhaust outlet is finally formed, which can greatly improve the removal rate and effect of bioaerosol particles.

5. Conclusion

This study numerically simulates the spatial distribution and migration law of the bioaerosol exhaled by infectious patients in the isolation ward in the empty room and the actual room under three ventilation modes. The influences of different positions of air supply inlet in an isolation ward on aerosol spatial distribution were investigated. The following conclusions can be drawn.

(1) Due to the close distance between the air inlet of Case 1 and the hospital bed, vortex regions were formed near the hospital bed, which increased the residence time of bioaerosols in the vortex regions and eventually deposited on the patient’s surface and bed, resulting in an increased possibility of infection among healthcare workers. The result shows the deposition rate of the bed and patient surface in Case 1 is 8.93% and 10.2%, respectively, which are significantly higher than Case 2 (3.45% and 1.73%) and Case 3 (2.9% and 0.84%).

(2) In the layout design of the air supply inlet and the exhaust outlet in the isolation ward, the directional airflow path from the air supply outlet to the release source and then to the exhaust outlet should be formed as far as possible, so as to increase the carrying capacity of the airflow to bioaerosols and improve the removal efficiency of bioaerosol. The results show that aerosol removal efficiency of Case 3 is 46.6% and 67.7% higher than that of Case 1 and Case 2, respectively.

(3) Ventilation based on mixing theory does not appear to be effective in reducing the concentration of aerosol particles in the breathing zone. The results show that there was no significant difference in the concentration of bioaerosol particles in the breathing zone height (1.3–1.7 m) of the entire isolation ward under the three mixed ventilation strategies with different air inlet locations, and the concentration basically remained at 10^3 CFU/m^3. It is suggested to study efficient ventilation method suitable for the breathing zone.

In conclusion, the results of this study can provide useful suggestions for optimizing airflow layout in isolation wards, reducing the risk of cross-infection and key disinfection locations.

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.

CRediT authorship contribution statement

Zhijian Liu: Conceptualization, Methodology, Project administration, Funding acquisition, Funding acquisition, Writing – original draft, Writing – review & editing. Tiansci Wang: Software, Writing – original draft, Writing – review & editing. Yongxin Wang: Software, Writing – original draft. Haiyang Liu: Writing – review & editing, Project administration. Guoqing Cao: Writing – review & editing. Song Tang: Software, Methodology.

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Reference

[1] E.A. Hathaway, C.J. Noakes, P.A. Sleigh, L.A. Fletcher, CFD simulation of airborne pathogen transport due to human activities, Build. Environ. 46 (12) (2011) 2500–2511.
[2] Y. Li, G.M. Leung, J.W. Tang, X. Yang, C.Y.H. Chao, J.Z. Lin, J.W. Lu, P.V. Nielsen, J. Niu, H. Qian, A.C. Sleij, H.J. Su, J. Sundell, T.W. Wong, P.L. Yuen, Role of ventilation in airborne transmission of infectious agents in the built environment - a multidisciplinary systematic review, Indoor Air 17 (1) (2007) 2–18.
[3] N. Mao, C.K. An, L.Y. Guo, M. Wang, L. Guo, S.R. Guo, E.S. Long, Transmission risk of infectious droplets in dry spitting process at different times: a review, Build. Environ. 185 (2020).
[4] L. Morveda, Droplet fate in indoor environments, or can we prevent the spread of infection? in: Proceedings of the 10th International Conference on Indoor Air Quality and Climate (Indoor Air 2005), Beijing, PEOPLES R CHINA, 2005, pp. P9–P23.
[5] J.W. Tang, C.J. Noakes, P.V. Nielsen, I. Eames, A. Nicolle, Y. Li, G.S. Settles, Observing and quantifying airflows in the infection control of aerosol- and airborne-transmitted diseases: an overview of approaches, J. Hosp. Infect. 77 (3) (2011) 213–222.
[6] I.T.S. Yu, T.W. Wong, Y.L. Chiu, N. Lee, Y.G. Li, Temporal-spatial analysis of severe acute respiratory syndrome among hospital inpatients, Clin. Infect. Dis. 40 (9) (2005) 1237–1243.
[7] J.T. Wu, K. Leung, M.G. Leung, Nowcasting and forecasting the potential domestic and international spread of the 2019-nCoV outbreak originating in Wuhan, China: a modelling study, Lancet 395 (10225) (2020) 689–697.
[8] Y. Zhang, O. Han, A. Li, T. Olofsson, L. Zhang, W. Lei, Adaptive wall-based attachment ventilation: a comparative study on its effectiveness in airborne infection isolation rooms with negative pressure, Engineering (2021).
[9] H. Qian, Y. Li, P.V. Nielsen, C.E. Hydegaard, T.W. Wong, A.T.Y. Chwang, Dispersion of exhaled droplet nuclei in a two-bed hospital ward with three different ventilation systems, Indoor Air (2) (2006) 111–128.
[10] C.P.D. Control, Guidelines for environmental infection control in health-care facilities, Morb. Mort. Wkly. Rep. 50 (2001).
[11] J.P. Rydöck, P.K. Eian, C. Lindqvist, I. Welling, E. Lingaaas, Best practice in design and testing of isolation rooms in Nordic hospitals, Nord. Inov. Centre 57 (2004).
[12] J.D. Siegel, E. Rhinehart, M. Jackson, C. Linda, H.C.L. Practices, 2007 guideline for isolation precaution: preventing transmission of infectious agents in health care settings, Am. J. Infect. Control 35 (10) (2007) S65–S164.
[13] Z. Liu, H. Zhu, Y. Song, G. Cao, Quantitative distribution of human exhaled particles in a ventilation room, Build. Simul. (2021).
[14] H. Qian, Y.G. Li, P.V. Nielsen, C.E. Hydegaard, Dispersion of exhalation pollutants in a two-bed hospital ward with a downward ventilation system, Build. Environ. 43 (3) (2008) 344–354.
[15] Y. Lu, M. Olofsson, Z. Lin, Reducing the exposure risk in hospital wards by applying stratum ventilation system, Build. Environ. 183 (2020).
[16] V.J. Manuel, F. Castro, S.J.J. Francisco, S.M. Julien, Comparison of air change efficiency, contaminant removal effectiveness and infection risk as IQA indices in isolation rooms, Energy Build. 57 (2013) 210–219.
[17] F.A. Belargia, T. Odendo, O.A.M. Ruiz, J.M. Villanueva, J.J.F. San, F. Castro, Experimental assessment of different mixing air ventilation systems on ventilation performance and exposure to exhaled contaminants in hospital rooms, Energy Build. 177 (2019) 207–219.
[18] Y. Zhang, O. Han, A. Li, L. Hou, T. Olofsson, L. Zhang, W. Lei, Adaptive wall-based attachment ventilation: a comparative study on its effectiveness in airborne infection isolation rooms with negative pressure, Engineering (2021) (Beijing).
[19] J. Wang, X. Dai, J. Wei, Z. Ai, Y. Fan, L. Tang, T. Jin, J. Ge, Numerical comparison of the efficiency of mixing ventilation and impinging jet ventilation for exhaled particle removal in a model intensive care unit, Build. Environ. 200 (2021).
[20] D. Hui, Z. Bin, Association of the infection probability of COVID-19 with ventilation conditions in confined spaces, Build. Simul. 13 (6) (2020) 1321–1327.
[21] V.D. Neelee, B. Trenton, D.H. Morris, M.G. Holbrook, A. Game, B.N. Williamson, A. Tamin, J.L. Hackort, N.J. Thornburg, S.I. Gerber, J.O. Lloyd-Smith, W.E. De, V.J. Munster, Aerosol and surface stability of SARS-CoV-2 as compared with SARS-CoV-1, N. Engl. J. Med. 382 (16) (2020) 1564–1567.
[22] B. Zhao, Y. Zhang, X.T. Li, X.D. Yang, D.T. Huang, Comparison of indoor aerosol particle concentration and deposition in different ventilated rooms by numerical method, Build. Environ. 39 (1) (2004) 1–8.
[23] R. Zhang, G.B. Tu, J.H. Ling, Study on biological contaminant control strategies under different ventilation models in hospital operating room, Build. Environ. 43 (5) (2008) 793–803.

[24] P. Sadeqian, C. Wang, C. Duwig, S. Sadrizadeh, Impact of surgical lamp design on the risk of surgical site infections in operating rooms with mixing and unidirectional airflow ventilation: a numerical study, J. Build. Eng. 31 (2020).

[25] S. Sasan, P. Jovan, S. Max, C. Jordan, A. Omid, Airborne particle dispersion to an operating room environment during sliding and hinged door opening, J Infect Public Health 11 (5) (2018) 631–635.

[26] C.Y.H. Chao, M.P. Wan, G.N.S. To, Transport and removal of expiratory droplets in hospital ward environment, Aerosol Sci. Technol. 42 (5) (2008) 377–394.

[27] C. Mendez, J.P.S. Jose, J.M. Villafuerte, F. Castro, Optimization of a hospital room by means of CFD for more efficient ventilation, Energy Build. 40 (5) (2008) 849–854.

[28] J. Ren, Y. Wang, Q.B. Liu, Y. Liu, Numerical Study of Three ventilation strategies in a prefabricated COVID-19 inpatient ward, Build. Environ. 188 (2021).

[29] P.H. Kao, R.J. Yang, Virus diffusion in isolation rooms, J. Hosp. Infect. 62 (3) (2006) 338–345.

[30] S.Y. Cheng, C.C. Chi, W. Oscar, Dynamic airflow simulation within an isolation room, Build. Environ. 42 (9) (2007) 3194–3209.

[31] T.Y. Chan, S.Y. Cheng, H.S. Cheng, Numerical study on the dispersion of airborne contaminants from an isolation room in the case of door opening, Appl. Therm. Eng. 29 (8–9) (2009) 1544–1551.

[32] Z. Chang, K. Yi, W. Liu, A new ventilation mode of air conditioning in subway vehicles and its air distribution performance, Energy Built Environ. 2 (1) (2021) 94–104.

[33] T. Chen, S.J. Cao, Numerical study on the integrated effects of supplied air velocity and exhaust velocity on particles removal for industrial buildings, Energy Built Environ. 2 (4) (2021) 380–391.

[34] J. Ren, Y. Wang, Q. Liu, Y. Liu, Numerical study of three ventilation strategies in a prefabricated COVID-19 inpatient ward, Build. Environ. 188 (2021) 107467.

[35] Z. Liu, W. Zhuang, X. Hu, Z. Zhao, R. Rong, W. Ding, J. Li, N. Li, Effect of equipment layout on bioaerosol temporal-spatial distribution and deposition in one BSL-3 laboratory, Build. Environ. 181 (2020) 107149.

[36] Y. Li, X. Huang, L.T.S. Yu, T.W. Wong, H. Qian, Role of air distribution in SARS transmission during the largest nosocomial outbreak in Hong Kong, Indoor Air 15 (2) (2005) 83–95.

[37] B. Zhou, L. Ding, F. Li, K. Xue, P.V. Nielsen, Y. Xu, Influence of opening and closing process of sliding door on interface airflow characteristic in operating room, Build. Environ. 144 (2018) 459–473.

[38] B. Zhao, Y. Zhang, X. Li, X. Yang, D. Huang, Comparison of indoor aerosol particle concentration and deposition in different ventilated rooms by numerical method, Build. Environ. 39 (1) (2004) 1–8.

[39] Z. Liu, L. Wang, R. Rong, S. Fu, G. Cao, C. Hao, Full-scale experimental and numerical study of bioaerosol characteristics against cross-infection in a two-bed hospital ward, Build. Environ. 186 (2020) 107373.

[40] J.I. Choi, J.R. Edwards, Large-eddy simulation of human-induced contaminant transport in room compartments, Indoor Air 22 (1) (2012) 77–87.

[41] C. Wang, S. Holmberg, S. Sadrizadeh, Numerical study of temperature-controlled airflow in comparison with turbulent mixing and laminar airflow for operating room ventilation, Build. Environ. 144 (2018) 45–56.

[42] Q.Y. Chen, Comparison of different k-ε models for indoor airflow computations, numerical heat transfer, Part B Fundam. 28 (3) (1995) 353–369.

[43] K. Erdem, C. Bilal, Evaluating the influence of turbulence models used in computational fluid dynamics for the prediction of airflows inside poultry houses, Biosys. Eng. 183 (2019) 1–12.

[44] T.J. Chang, T.S. Hu, Transport mechanisms of airborne particulate matters in partitioned indoor environment, Build. Environ. 43 (5) (2008) 886–895.

[45] C.Q. Yang, X.D. Yang, T.F. Xu, L.C. Sun, W. Gong, Optimization of bathroom ventilation design for an ISO Class 5 clean ward, Build. Simul. 2 (2) (2009) 133–142.

[46] W. Lu, A. Howarth, N. Adam, S.B. Riffat, Modelling and measurement of airflow and aerosol particle distribution in a ventilated two-zone chamber, Build. Environ. 31 (5) (1996) 417–423.