Study on contaminant distribution in a mobile BSL-4 laboratory based on multi-region directional airflow

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Abstract

The outbreak of COVID-19 has caused increasing public attention to laboratory-acquired infections (LAIs), especially for a mobile Bio-Safety Level 4 Lab (BSL-4) with high potential of exposure. In this paper, the distribution and removal mechanism of bioaerosols in the biosafety laboratory were studied. A simulation model of airflow distribution in the opening and closing state of air-tight door was established and verified. The results showed that the airflow entrainment velocity during the opening of the door was approximately 0.12 m/s. It increased the probability of vortex generation in the laboratory. The deposition rate of particles was doubled when the air-tight door opening is compared with air-tight door closing. Besides, nearly 80% of the particles deposited on the surface of the wall and ceiling, increasing the possibility of LAIs. The findings of this paper could provide new scientific methods for high-level biosafety laboratories to avoid cross-infection. Moreover, future work regarding air-tight door rotation speed regulation and control should be emphasized.

Keywords Laboratory-acquired infections · Mobile Bio-Safety Level 4 Lab · Removal mechanism · Airflow distribution · Bioaerosols · Entrainment velocity

Introduction

With the outbreak of severe infectious diseases caused by pathogenic microorganisms all over the world, MERS, Ebola virus, Hendra nipah virus (including Hendra virus and Nipah virus) (Shurtleff et al. 2012) and other viruses with high transmission speed and high mortality have attracted worldwide attention. Furthermore, since December 2019, the

outbreak of pneumonia infections has spread worldwide caused by novel coronavirus, infecting more than one hundred million people and killing millions of people.

The mobile BSL-4 laboratory can go to the epidemic areas to detect the pathogenic bioaerosol when a major outbreak of severe infectious disease occurs, avoiding the transfer of dangerous infection samples midway and reducing the diffusion risk of virus, while ensuring highly infectious pollutants (such as novel coronavirus) were discharged safely (Huang et al. 2020). Bioaerosols produced by experimental operations are the main possible sources of laboratory-acquired infections, viruses and bacteria in aerosols can live for hours or even years (Wang et al. 2012; Perazzo et al. 2017), the exposure risk of pollutants is the most common (Lai and Nazaroff 2000; Li et al. 2019) and the reasonable diffusion mode and appropriate deposition rate of bioaerosol particles are conducive to reducing the possibility of potential exposure risk of bioaerosols (King et al. 2013; Cheng et al. 2021).

In recent years, a lot of research on the diffusion of aerosol particles in biosafety laboratories have been done. Liu et al. (2020a, b) compared and evaluated the influence of experimental equipment layout on bioaerosol diffusion deposition by establishing different computational fluid dynamics (CFD) numerical simulations; the results showed that the bioaerosol

Highlights

- This study was conducted based on a mobile BSL-4 laboratory.
- The mechanism of bioaerosol diffusion between multi-region was analyzed.
- Entrainment velocity altered the locations of high concentration zones of bioaerosols.
- Opening or closing of airtight doors raises the possibility of cross-infection.
- The mode of interaction between airflow and bioaerosols was explored.

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particles always stay in a lower space under the effect of vortex current, and the most of bioaerosol particles adsorbed on the surface of experimental equipment and floor. However, reasonable equipment layout can reduce the ground pollution. Honda et al. (2004) used ultrasonic anemometer to analyze the dynamic characteristics of airflow caused by the opening and closing of clean room and found that no matter there is an in-opening door or out-opening door, it will both cause local strong countercurrent, which improves the possibility of cross contact of suspended particles between indoor and outdoor. Barbosa et al. (2017) found that the bioaerosol produced by laboratory operation is the source of LAIs. The CFD simulation results showed that the movement characteristics of pollutant particles in BSC are related to the airflow pattern, inflow velocity and indoor turbulence degree in the biological laboratory, and the enhancement of turbulence level increases the possibility of workers being exposed to pollutants. Xin et al. (2019) described the research progress of airflow bioaerosol protection from the perspective of mechanical engineering and pointed out that a good airflow distribution strategy can reduce the residence time of bioaerosols in the room and reduce the exposure risk of workers. Zhang and Chen (2006) analyzed three kinds of ventilation systems by combining CFD simulation and Lagrange particle tracking method, and the research results showed that a good ventilation system was the main way to remove pollutant particles, and the floor air supply system had better particle removal performance. Wang et al. (2021) conducted numerical simulation and field measurement on the ventilation performance of a typical blast furnace casthouse. The results showed that the unreasonable opening and closing of doors and windows was the main reason affecting the removal of pollutant particles. Zhao et al. (2003) conducted a comparative study on the airflow distribution and bioaerosol particle deposition rate between the displacement ventilation chamber and the mixed ventilation chamber, and found that the mixed ventilation chamber had a higher bioaerosol particle removal rate than the displacement ventilation chamber. Liu et al. (2020a, b) studied the removal rates of two kinds of bioaerosols by combining experiments with numerical simulation. The research results showed that the vortex area was strongly associated with the high concentration area of bioaerosol particles, and nearly 70% of the bioaerosol particles would deposit on the wall and the surface of the equipment. Lu et al. (1996) used computational fluid dynamics (CFD) method to study the airflow movement and the deposition characteristics of bioaerosol particles in ventilated two-zone chambers. The results showed that the movement of large particles is mainly affected by the deposition process, while the movement of small particles is mainly influenced by the airflow pattern, which has a significant influence on the pollutant concentration and indoor air quality.

Most of the above studies focused on the effect of airflow movement in the biological laboratory on bacteria carriers, such as bioaerosols, while few have assessed the potential risk of infection from airflow caused by opening and closing doors when operators leave or enter the laboratory. Meanwhile, airflow exchange will occur among buffer, transfer window and pass-through box-laboratory. It significantly increases the possibility of cross-infection and the escape of pathogenic microorganisms. Therefore, the purpose of this paper is to explore the diffusion and deposition characteristics of pollutant particles in the mobile BSL-4 laboratory under different airflow conditions. It also provides a new idea for experimental disinfection protection from the perspective of removing mechanism of contaminant deposition. In addition, a reasonable space layout of experimental equipment is also conducive to experimental protection. Moreover, the study can be a scientific operational guideline for experimenters from the perspective of multi-region airflow motion characteristics. The mobile biosafety laboratory developed by a company in Jiangsu Province is taken as the research model. Firstly, the mechanical coupling analysis of bioaerosol particles in the laboratory was carried out when the air-tight door was opened and established the theoretical basis of particle deposition; secondly, because of the pressure difference between indoor and outdoor, the airflow caused by the door opening was kinematically coupled to facilitate the subsequent theoretical verification; finally, based on computational fluid dynamics (CFD), the airflow simulation was carried out to analyze the trajectory of the airflow in the laboratory and the formation mechanism of vortex zone, and to study the effects of door opening and closing on the movement, deposition and removal characteristics of bioaerosols.

Establishment of mobile BSL-4 laboratory model

Physical model

Fig. 1a shows a three-dimensional CFD simulation model with the same shape as the mobile laboratory square cabin (the first buffer has been neglected). As shown in Fig. 1c, the internal dimensions of the model are 6.2m(X)×2.2m(Y)×2.3m(Z), “+” and “-” correspond to the left and right walls, front and rear walls respectively. The types, quantity and location of the equipment in the laboratory all meet the requirements of the international standard “Manual of Laboratory Biological Safety (Third Edition)” for high-level biological laboratories. The main equipment in the laboratory includes a biological safety cabinet (BSC), a common equipment table and a laboratory table. Considering the cost of calculation, these devices are reasonably simplified to rectangular boxes (Liu et al. 2017, 2020a, b), as shown in Fig. 1b. The overall layout of the

Fig. 1 (a) Three-dimensional structure of mobile BSL-4 laboratory, (b) top view of equipment layout of mobile BSL-4 laboratory, (c) schematic diagram of two-dimensional simulation model of mobile BSL-4 laboratory square cabin, and (d) location of sampling points and laboratory dimension

biological laboratory is shown in Fig. 1a. The up-supply and down-return ventilation mode was taken in this laboratory, the size of air inlet and exhaust outlets is 0.61 m (a) × 0.305 m (b) and the biological laboratory is equipped with three air supply outlets which are evenly distributed and one exhaust outlet. Airflow flows into the room through the air supply outlet and then flows out of the laboratory through exhaust outlet 0.15 m away from the bottom of the laboratory, which meets the basic ventilation requirements of radial flow clean rooms (Xu 2014). In order to ensure the negative pressure in the laboratory and buffer zone, the air volume difference between the air supply outlet and the exhaust inlet should be controlled, and reasonable air exchange rates help to reduce the spread of viruses (El-Salamony et al. 2021), so the air change rate is set to 15 times in this paper.

Data acquisition is the most important step in the research process. In order to collect enough available data and conform to the actual operating environment, 8 data sampling points (C1–C8) were selected at the height of 1.6 m in the Z direction of biological laboratory and marked with a yellow star. As shown in Fig. 1c, the sampling points are distributed in each key position, to collect the data at the positions including the air supply outlet better, the air exhaust outlet and the edge joint of the equipment. It is also helpful for the subsequent establishment and verification of the laboratory airflow model. Furthermore, three pollutant emission sources are set under the air supply outlet to simulate the residual pollutants in the laboratory, which can improve the credibility of this study. The spatial distribution of contaminant sources and sampling points is listed in Table 1.

Kinematic coupling model of bioaerosol particles

When the air-tight door is opening, according to the basic theory of bioaerosol mechanics (Zhao, 2003), bioaerosol particles are subjected to various types of forces in different directions, including Saffman force (Morsi and Alexander 1972), drag force, gravity and pressure gradient force. The

force analysis of a bioaerosol particle directly below the air inlet is shown in Fig. 2.

According to Newton's Second Law of Motion:

$$m_b \frac{d\vec{U}_b}{dt} = \vec{F}_s + \vec{F}_G + \vec{F}_D + \vec{F}_P \quad (1)$$

where, U_b is the velocity of particle motion, F_s is the Saffman force, F_G is the gravity of particle, F_D is the drag force of particle motion and F_P is the negative pressure gradient force. Saffman force is defined by Eq. (2):

$$F_s = 1.62 \mu d_b^2 \frac{du/dy}{\sqrt{\nu |du/dy|}} (u - u_{bx}) \quad (2)$$

where, u_{bx} is the velocity of particles in the X direction, du/dy is the velocity gradient perpendicular of airflow to the laboratory wall.

Because of the different size of biological bioaerosol particles, gravity deposition is also a factor to be considered. The gravity of particles is defined by Eq. (3) (Zhao et al., 2003):

$$F_G = \frac{\pi}{6} d_b^3 \rho_b g \quad (3)$$

where, d_b is the diameter of the particle, ρ_b is the density of the particle.

Drag force is defined as Eq. (4):

$$F_D = \frac{18\mu}{\rho_b d_b^2} \cdot \frac{C_d Re}{24} (u_i - u_{bi}) \quad (4)$$

$$C_d = \alpha_1 + \frac{\alpha_2}{Re} + \frac{\alpha_3}{Re^2} \quad (5)$$

$$Re_b = \frac{\rho_b d_b (u_i - u_{bi})}{\mu} \quad (6)$$

where μ is the viscosity coefficient of air, C_d is the fluid drag coefficient, Re is the relative Reynolds number, u_i is the velocity of airflow, u_{bi} is the velocity of bioaerosol particles. α_1 , α_2 and α_3 are constants, which can be obtained according to the results of the smooth spherical particle experiment (Haider and Levenspiel 1989).

When the research object is the bioaerosol particles in the laboratory, the pressure change is very small due to the extremely high air tightness in the laboratory of BSL-4, and the negative pressure gradient force can be described as Eq. (7)

Table 1 Distribution of sampling points and pollution sources

	Source 1	Source 2	Source 3	C1	C2	C3	C4	C5	C6	C7	C8
x(mm)	1887.5	2892.5	3897.5	5200	4700	4700	4700	3600	2500	1400	300
y(mm)	1947.5	1947.5	1947.5	2050	2050	1550	1100	1100	1100	1100	1100
z(mm)	2000	2000	2000	1600	1600	1600	1600	1600	1600	1600	1600

Fig. 2 Force schematic diagram of bioaerosol particle

(Zhao et al. 2003; Wang 1989):

$$F_P = \frac{\rho}{\rho_b} \cdot u_{bi} \cdot \frac{\partial u}{\partial x_i} \quad (7)$$

where ρ is the density of air, which is very small compared to the density of bioaerosol particles, so the negative pressure gradient force can be neglected; negative pressure gradient force is defined as

$$F_P = \Delta P \cdot s \quad (8)$$

where, ΔP is the negative pressure gradient, s is the projection area of spherical bioaerosol particles.

The acceleration of airflow can well reflect the trajectory characteristics of airflow, and the diffusion mode of airflow is the key factor affecting the residence time of bioaerosols (Feng et al. 2019). Therefore, understanding the airflow trajectory can further analyze the diffusion law of bioaerosol particles. The volume of airflow introduced by opening the air-tight door will disturb the original airflow balance in the biological laboratory. On the one hand, it will change the removal rate of bioaerosol particles. On the other hand, it will increase the vortex distribution density of the airflow in the biological laboratory, and the vortex area can increase bioaerosol suspended time (Liu et al. 2020a, b) and raise the risk of infection, so high concentration areas of bioaerosols always tend to occur the phenomenon called pollutant lockup in the vortex area (Li et al. 2015). Therefore, the influence of the opening and closing state of the door on the airflow movement in the biological laboratory should not be neglected.

Numerical simulation

Grid independence test

Grid density and structure have a great influence on the results of CFD numerical simulation (Srebric et al. 2008; Li et al. 2005; Roache 1997; Romano et al. 2015; Nielsen 2009), so it is necessary to test the grid independence of the model. The

vertical velocity changes of typical section $y = 1250$ mm and C8 sampling points in the biological laboratory with 209,303, 502,475 and 1,646,390 grid cells are compared respectively. The results of grid independence test are shown in Fig. 3a,b.

It can be found from Fig. 3 that when the number of grid cells increases from 502,475 to 1,646,390, the velocity field of the selected section almost does not change, and the difference of the velocity changes of sampling points is less than 6%. Therefore, this study recognizes that it is reasonable to select the second kind of grid for subsequent simulation.

Model of airflow movement

The airflow in mobile BSL-4 biosafety laboratory is considered to be continuous, the internal airflow is low-speed flow and the basic equations of airflow are Navier-Stokes equation and continuity equation. In the experimental cabin, due to the influence of the layout of indoor experimental equipment, the airflow in the laboratory will produce whirling motion when it hits the wall. According to Eqs. (9) and (10), the Reynolds number of the airflow can be obtained to judge the airflow motion mode. The basic equations of indoor turbulent motion can be obtained by using the basic equations combined with continuity equations. RNG $k-\varepsilon$ model for CFD simulation was used in this paper (Romano et al. 2015); the $k-\varepsilon$ two-equation model and Reynolds equation form a closed system of equations.

$$Re = \frac{\rho v L}{\mu} \quad (9)$$

$$L = \frac{4A}{C} \quad (10)$$

where ρ is the air density, L is the characteristic length, μ is the dynamic viscosity coefficient, v is the air velocity of the air supply outlet, A is the area of the air supply outlet and C is the perimeter of the air supply outlet. Re is obtained as 7525, which indicates that the airflow in the biological laboratory is turbulent.

The viscous, incompressible, homogeneous and isotropic steady flow state can be described by the tensor form of Navier-Stokes equation (Gresho and Sani 1998):

$$\rho \left[\frac{\partial u_i}{\partial \tau} + \frac{\partial u_i u_j}{\partial x_j} \right] = F_i - \frac{\partial P}{\partial x_i} - \frac{2}{3} \mu \frac{\partial}{\partial x_i} \left(\frac{\partial u_j}{\partial x_j} \right) + \mu \frac{\partial}{\partial x_j} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \quad (11)$$

where, F_i is the unit mass force in i direction, P is the hydrostatic pressure and ρ is the air density. The continuity equation can be described as

$$\frac{\partial u_j}{\partial x_j} = 0. \quad (12)$$

Fig. 3 Grid independence verification. (a) Velocity field of $y = 1250$ mm section, (b) vertical position velocity independent verification of sampling point C8

If the atmospheric pressure at the same altitude is taken as the reference, the isotherm and isobaric air density are taken as the reference density ρ_0 . Then, Eq. (12) is substituted into Eq. (11), and the simplified Eq. (13) is obtained finally:

$$\rho \left[\frac{\partial \vec{u}}{\partial t} \right] = -\frac{\partial P}{\partial x_j} + \mu \nabla \left(\nabla \vec{u} + \left(\nabla \vec{u} \right)^T \right) - \vec{F} \quad (13)$$

where F is the volume force on the airflow micro-element.

In this paper, the Euler method is used to simulate the convection field. The diffusion of bioaerosol particles adopts one-way coupling Lagrangian method. Additionally, the effect of turbulence on particle diffusion can be determined by using the discrete random walk (DRW) model (Zhao et al. 2003). In other words, because the volume fraction of particles is small enough, the influence of bioaerosol particles on the fluid can be neglected. Then, the interaction between fluid and bioaerosol particles is unidirectional.

Boundary conditions

The airflow environment in the Cabin laboratory was considered to be low speed and incompressible (Nielsen 2004). When the biological laboratory is taken as the research object, the air supply outlet in the ventilation system is defined as the “velocity inlet”, in which the air velocity is specified at the inlet and the pressure is specified at the outlet. When the area between the biological laboratory and the buffer room is taken as the research object, the air supply outlet is defined as the “velocity inlet”, and the air-tight door area is set as the pressure or velocity boundary due to the airflow coupling. When the air-tight door is opened or closed, the standard wall functions are used to simulate the low Reynolds number regions near the wall (Lauder and Spalding 1974), and the non-slip

boundary condition is applied. Moreover, this study was based on the following assumptions:

- The temperature in each area of the laboratory was kept the same and remained stable, so the effects of heat and mass transfer between air and particles, the thermophoretic force of particles and heat source on the deposition and airflow of bioaerosols were neglected (Chen et al. 2006).
- There was no collision between particles, that is, there was no condensation between particles (Liu et al. 2020a, b).
- When the particles contact with the inner wall of the laboratory and the wall of the experimental equipment, they were bonded to the surface. In other words, the collision condition between the particles and the wall was set to “freeze” in the simulation process.

Verification and discussion

The internal airflow field of mobile BSL-4 laboratory was simulated and analyzed in three stages, and then comparisons were validated with the experimental data provided (the civil-military integration project involves confidentiality clauses, data provided by a company in Jiangsu).

Simulation of airflow distribution in mobile BSL-4 biological laboratory

Firstly, the three-dimensional simulation of the biological laboratory area was used to analyze the movement characteristics of the airflow, the movement trajectory of the bioaerosol particles and the deposition and removal characteristics.

Secondly, the airflow near the air-tight door was analyzed by two-dimensional numerical simulation, and the characteristics of airflow near the air-tight door were analyzed when operator enters or leaves the biological laboratory. Finally, combined with the two-dimensional simulation, the entrainment velocity caused by the door opening was obtained, and a new “velocity entrance” boundary was set in the three-dimensional model to complete the final coupling simulation of the airflow inside and outside the mobile BSL-4 laboratory.

Simulation of airflow distribution in mobile BSL-4 laboratory

In the mobile BSL-4 laboratory, airflow is the main factor to determine the trajectory of bioaerosols. Fig. 4 shows the directional airflow diffusion characteristics of a typical section in the laboratory with velocity field vector diagram and streamline diagram.

It can be seen from Fig. 4 that the airflow enters the biological laboratory vertically at a constant speed from the three air supply outlets. After 3.75 s, a part of the airflow reaches the laboratory cleaning table and the experimental table. Under the effect of reaction force, the airflow diffuses to the X + direction, and the air-tight door direction of the laboratory; another part of the airflow flows into the ground, after hitting the ground, towards the bottom of the experimental table and

other experimental equipment surface diffusion. According to the arrow on the velocity streamline diagram, it can be found that the airflow generally flows into the exhaust outlet. The high velocity area is always on the upper side of the laboratory, and the maximum velocity is about 0.35 m/s. After 35 s, the airflow impinges on the wall, and a number of vortex areas gradually appear in the biological laboratory. The whole process takes about 50 s, as shown in Fig. 4a–f. The streamline arrow represents the airflow direction.

The swirling vortex areas are the main reason for the formation of high concentration areas of bioaerosols. The vortex will weaken the carrying capacity of particles in the airflow, resulting in the shedding of bioaerosol particles and the long-term retention in the laboratory, finally forming high concentration residual areas. Therefore, further analysis of the vortex formation mechanism in the laboratory is needed.

Fig. 5 is a typical cross-section distribution diagram. Figs. 6 and 7 are velocity streamline diagrams of sampling points C7 and $x = 4200$ vertical sections, revealing the formation mechanism of the vortex region. The results show that most of the vortex regions are near the ground, which is closely related to the spatial layout of the experimental equipment. The airflow mainly flows towards the exhaust outlet, which is consistent with the previous observation results. It can also be found that there are many divergent airflow regions in the space, most of

Fig. 4 Nephograms and streamline diagrams of velocity distribution at different moments

Fig. 5 Diagram of section distribution

which occur near the wall surface. It is formed by the back-flow phenomenon caused by the sudden change of airflow velocity near the wall surface, which makes the airflow diffuse to both sides. Therefore, a reasonable location of air inlets and exhaust outlets is very important for the distribution of pollutant particles.

Fig. 6 Velocity distribution and streamline of section 1 ($x = 1400$ mm)

Fig. 7 Velocity distribution and streamline diagram of section 2 ($x = 4200$ mm)

Simulation of airflow during opening the air-tight door

Because of the high air tightness of mobile square cabin, the sensitivity of the airflow in the cabin to the external disturbance is improved. Therefore, the influence of the opening and closing of the air-tight door on the directional airflow in the laboratory cannot be neglected. The analysis shows that in the process of opening the air-tight door, the airflow crisscross between the laboratory and the buffer zone, forming the backstep flow phenomenon. In order to analyze the airflow field distribution intuitively, this paper uses the velocity contour map to analyze the airflow movement characteristics of the door at different opening angles, as shown in Fig. 8a–f.

Considering that the air-tight door should not have too large opening angular velocity, the whole opening action is set to last for 6 s. The simulation results show that at the beginning of the door opening, a large flow rate of vortex airflow will be generated in the outer ring of the door frame. It is because of a certain pressure difference between the biological laboratory and the buffer room. At the initial stage of

Fig. 8 Velocity distribution nephogram near the air-tight door at different times

the air-tight door opening, the airflow on the side of the air-tight door is mainly in the form of vortex shedding behind the door (Saarinen et al. 2018); with the opening of the air-tight door, the pressure difference between the two chambers decreases, and the air supply and exhaust become the predominant driving force. In the meantime, the vortex airflow gradually dissipates and finally transfers to the inside of the door frame and the back of the door. In addition, it can be seen from Fig. 8 that the right side of the door frame and the upper surface of the door are the main areas where airflow exchange occurs.

Simulation of airflow coupling inside and outside mobile BSL-4 laboratory

Through the above research on the airflow field in the opening process of the door, it can be concluded that the entrainment velocity caused by the opening of the air-tight door is about 0.12 m/s, which is similar to the results of previous researches (Feng et al. 2019; Chang et al. 2017). Finally, the stable state of the directional airflow in the laboratory is destroyed during the opening of the door. To ensure the availability and accuracy of the simulation, the comprehensive simulation of the airflow movement in the laboratory square cabin is carried out.

Fig. 9b–h shows the comparison of the vertical velocity of each sampling point during the opening and closing of the air-tight door in the mobile BSL-4 biological laboratory,

reflecting the impact of the opening of the air-tight door on the air flow in the laboratory. The results show that the overall airflow trend is almost the same before and after the air-tight door is opened, and set $t = 13$ s as the data acquisition time node. When the air-tight door is closed, the airflow velocity of the seven sampling points in the biological laboratory is relatively stable, which indicates that the vortex intensity and turbulence degree of the airflow are small when the airflow encounters obstacles. During the opening process of the air-tight door, the airflow coupled with each other. When the same airflow encounters obstacles again, the boundary layer separation occurs near the wall, forming a relatively concentrated turbulent zone. Meanwhile, the strong relative movement of the airflow occurs, which leads to a large fluctuation of the velocity at the sampling point, especially at the uneven height of the obstacles, such as the velocity change at the sampling points C2 and C5. Finally, it can be found that after the air-tight door is opened, the airflow velocity is greater than that when the air-tight door is closed, increasing by about 30%, which proves that the opening of the air-tight door will destroy the original stable airflow state of the laboratory.

The final experimental data show that the actual airflow velocity in the area above 1 m is less than the theoretical velocity and the flow rate in the area below 1 m is higher than the theoretical speed. This may be due to the interference of the experimental equipment with the flow movement. The difference between the test and simulation data values is within 10%, which verifies the accuracy of the simulation results.

Fig. 9 Velocity comparison at sampling points C2–C8

Mechanism of bioaerosol removal

In order to reveal the removal mechanism of bioaerosol particles, particle tracking technology is used in this paper to conduct tracking analysis of bioaerosol particles. According to previous results (King et al. 2013; Roache 1997), when the number of particles is greater than 50,000, the movement independence of particles is strengthened. Therefore, the particle number adopted in this paper is 50,000, the particle diameter is $1\ \mu\text{m}$, and the density is $1000\ \text{kg/m}^3$.

Fig. 10 shows the bioaerosol removal characteristics in two different cases based on numerical simulation. It can be found that particle removal is accomplished in the biological laboratory at approximately $t = 500\ \text{s}$ by keeping the air-tight door closed. The complete removal of particles is achieved at

approximately $t = 250\ \text{s}$ when the air-tight door is opened to full opening, resulting from the coupling of internal and external airflow to increase the removal rate. In addition, the removal rate of bioaerosols during the opening of the air-tight door is 69.28%, which is little changed compared with the closing of the airtight gate. This is because the airflow driven by the door rotation changes the eddy current distribution in the closed state of the airtight door, whereas the probability of generating vortex has not changed.

Analysis of deposition characteristics of bioaerosol particles

Combined with the above studies on the mechanism of bioaerosol particle removal, it can be found that the removal

Fig. 10 Bioaerosol removal characteristics in two cases

rate of bioaerosol particles is at a low level. A part of particles are suspended in the laboratory under the action of the internal flow field, and the other part are bonded on the surface of the experimental equipment, which raises the contact risk of contaminant particles. However, the spatiotemporal characteristics of particle deposition on different surfaces are also different, and further analysis of the deposition of bioaerosol particles on each surface is necessary.

Fig. 11 shows the deposition ratio and quantity of bioaerosols on different surfaces when the air-tight door is opened and closed. The bioaerosol deposition ratio is defined as the percentage of total particles deposited on each statistical surface to the original number of pollutants released, and the local deposition ratio of different surfaces is defined as the percentage of particles deposited on the surface of different

units (equipment or walls) to the total particles deposited on each statistical surface. The mathematical models are shown in Eqs. (14) and (15), where K is the deposition ratio, m is the surface on which particle deposition may occur and N_i is the total particle number deposited on the surface of unit i , A is the total amount of particles released and k is the local deposition ratio.

$$K = \frac{\sum_{i=1}^m N_i}{A} \quad (14)$$

$$k = \frac{N_i}{\sum_{i=1}^m N_i} \quad (15)$$

Combined with Fig. 11, the distribution of pollutants in the laboratory can be reflected. There is a significant difference in the deposition characteristics of bioaerosol particles when the air-tight door is opened and closed. The number of particles deposited on the surface of the former is higher than that on the surface of the latter except for the laboratory floor, which indicates that the amount of bioaerosols deposited indoors is increased after the air-tight door is opened. The results show that, when the outlet is close to the ground, taking the air-tight door closed state as an example, the deposition ratio of particles on the surface of the surrounding walls is the largest, accounting for 15.36% and 72.1% of the total deposition particles; the deposition ratio of particles on the surface of the laboratory ceiling is 3.6%, 16.9% of the total deposition particles; the deposition ratio of particles on the surface of the experimental equipment is 1.18%, 5.5% of the total deposition

Fig. 11 Statistics of bioaerosol deposition on different surfaces in two cases

Fig. 12 Local deposition characteristics of bioaerosols on the surface of laboratory equipment in two cases

(a) Air-tight door closed

(b) Air-tight door opening process

particles; and the deposition ratio of particles on the surface of the laboratory cleaning table is 0.56%, 17% of the total sediment particles. In addition, it is pointed out that the surface of the Biological Safety Cabinet is also the main surface of particle deposition, and more attention should be paid to it when cleaning the laboratory.

Figs. 12a,b and 13a,b show the local deposition ratio of bioaerosols on the experimental equipment and the wall surface when the air-tight door is opened and closed, respectively, reflecting the deposition of bioaerosols on each surface. Obviously, the particle deposition rate is faster when the air-tight door is opened than when it is closed, and the deposition ratio and local deposition ratio are also higher, especially for the experimental equipment 2 and the right wall of the laboratory; the former local deposition is increased to 2.4 times of the original, and the latter is increased to 25 times of the original, which proves that the door opening leads to a great change of indoor and outdoor airflow. Moreover, the amount of particle deposition on the wall surface is much larger than that on the experimental equipment surface, which is due to the larger surface area providing a wider adsorption area.

Conclusions

In this paper, CFD simulation technology was used to analyze the airflow distribution, bioaerosol removal and deposition characteristics in the opening process and the closed state of the air tight-door of mobile BSL-4 laboratory. The results showed that the directional airflow movement in the adjacent areas has a significant effect on the above characteristics. From our studies, the following conclusions have been drawn:

- (1) During the opening of the air-tight door, the directional airflow in the laboratory produced vortex in many places, and airflow rewinding always occurred at the junction of the equipment, which increased the stagnation time of the bioaerosol particles in the laboratory. The opening of air-tight door increased the probability of vortex generation. Compared with the closed state of the air-tight door, the indoor airflow velocity increased by about 30% on average. Hence, more attention should be paid to the influence of airflow disturbance on bioaerosol particles in high-level biosafety laboratories to avoid particle suspension infection.

Fig. 13 Local deposition characteristics of bioaerosols on laboratory walls under two conditions

(a) Air-tight door closed

(b) Air-tight door opening process.

- (2) The opening of the air-tight door has no effect on the removal rate of bioaerosol particles, but the particle deposition rate was increased by 50%. When the air-tight door was closed, the bioaerosol removal rate is 67.85%. After the airtight-door was opened, the bioaerosol removal rate was 69.28%, which has important guiding significance for the protection of potential acquired infection in high-level biosafety laboratories.
- (3) Nearly 80% of the bioaerosol particles deposited on the surface of the wall and ceiling during the opening and closing of the air-tight door, among which the local deposition ratio of experimental equipment 1 and the Biological Safety Cabinet was the largest. The number of bioaerosol deposition on each surface of the former is about 1.6 times that of the latter. Therefore, when entering or leaving the laboratory, the door should be opened and closed as gently as possible, and the surface disinfection of the wall and the above equipment should be focused.

In summary, the optimizations of the rotational speed regulation of air-tight door and the laboratory space layout would be focused on in our future research. Avoiding vortex dead angles to effectively reduce the possibility of LAIs is also a point. However, the subject of this paper is a specific type of biosafety laboratory. Therefore, the influence of the change of the location and size of airflow inlet or outlet on the diffusion of bioaerosol was not considered; it can be explored in-depth in further work.

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Author contribution YW: conceptualization, methodology, supervision, writing—review & editing; JM: formal analysis, visualization, writing—original draft; JBC: investigation, software; HYC: resources, data curation; CYZ: visualization, software; HAT: software, data curation; YG: investigation, software.

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Declarations

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