Environmental Science and Pollution Research (2024) 31:22308–22318
https://doi.org/10.1007/s11356-024-32239-8

REVIEW ARTICLE

Review of the research status on the transmission and diffusion characteristics of indoor viral aerosol particles

Yaxin Huang[1] · Jie Wan[2] · Sen Han[3] · Yu Li[4]

Received: 24 November 2023 / Accepted: 25 January 2024 / Published online: 2 March 2024

Abstract
This study reviews the generation and diffusion characteristics of indoor viral aerosol particles, numerical simulation methods for the diffusion process of viral aerosols, and related research on the impact mechanism of different ventilation methods on the diffusion process of viral aerosols. Research has shown that the selection of initial conditions such as exhalation mode, initial airflow velocity, particle size, turbulence model, and calculation method for the generation of aerosol particles by the human body is of great significance for the numerical simulation of the diffusion process of viral aerosol particles. At the same time, on the basis of selecting appropriate ventilation methods, the reasonable setting of ventilation parameters (temperature, speed, height, etc.) can effectively suppress the spread of viral aerosols. This study can provide a theoretical basis for the study of related respiratory diseases, as well as technical and theoretical support for the selection of indoor ventilation methods to reduce the risk of human exposure caused by viral aerosols in the construction field. It also provides guidance and reference for aerosol transport and environmental protection in indoor atmospheric environments.

Keywords Indoor · Aerosol diffusion · Ventilation · Numerical simulation

Introduction

Indoors are the main place for human work, study, and life. People spend 80 to 90% of their day indoors, and the quality of indoor environment directly affects human physical health (Klepeis et al. 2001). The concentration level of indoor microbial aerosols is one of the important indicators to measure indoor air quality, and there are significant differences in the concentration level of microorganisms in different places, which has varying degrees of impact on the health of indoor personnel (Fang et al. 2013). The main source of indoor microbial aerosols is the human body, which produces droplets through the mouth and nose, composed of aerosol particles. Regarding research on aerosol particles, public health scientist Wells (1934) proposed the droplet nucleus theory in 1934. The human body produces droplets carrying viruses and microorganisms through behaviors such as speaking, coughing, and sneezing, which can be suspended in the air for a long time and can lead to illness when inhaled by others. After exhalation, droplets undergo varying degrees of evaporation until they are completely dry or reach a balance between evaporation and condensation in the environment, becoming "droplet nucleus" aerosols, which have a strong ability to carry viruses (Ferry

Responsible Editor: Marcus Schulz

✉ Yaxin Huang
63686252@qq.com

Jie Wan
13373972343@163.com

Sen Han
hansen@xauat.edu.cn

Yu Li
liyuchd@chd.edu.cn

[1] School of Resource Engineering, Xi'an University of Architecture and Technology, Xi'an 710055, Shanxi, China

[2] School of Architecture, Xi'an University of Architecture and Technology, Xi'an 710055, Shanxi, China

[3] School of Environment and Municipal Engineering, Xi'an University of Architecture and Technology, Xi'an 710055, Shanxi, China

[4] School of Energy and Electrical Engineering, Chang'an University, Xi'an 710054, Shanxi, China

et al. 1958; Xie et al. 2007). If exposed to a closed environment containing viral aerosols for a long time, the risk of human infection with the virus will significantly increase. Taking hospitals as an example, hospital wards are a special environment with stricter requirements for air quality than general places. This is because there may be multiple pathogenic bacteria and viruses in the ward, and patients are usually weak and susceptible to the influence of bacteria, viruses, and other harmful gases. In order to ensure the health and recovery of patients, governments and medical institutions around the world have developed corresponding hospital ward air quality guidelines, which all mention requirements such as reducing ward microbial content, strengthening ventilation, and disinfection. Therefore, in order to maintain the safety of public life and health, prepare for the future respiratory transmission epidemic, and better respond to the future epidemic, this study intends to review the generation and diffusion characteristics of viral aerosol particles, the numerical simulation methods of viral aerosol diffusion process, and the impact mechanism of different ventilation methods on viral aerosol diffusion process. In the post COVID-19 era, provide technical and theoretical support for the selection of ventilation methods in indoor ventilation design of buildings, and provide reference for the safety protection of indoor air environment quality in buildings.

Production and diffusion characteristics of virus-containing aerosols

The human body undergoes different exhalation activities through the mouth and nose, resulting in aerosol particles of different sizes. The different source terms can affect the transport and diffusion of aerosol particles with air flow. Different exhalation methods such as breathing and coughing can produce different initial airflow velocities of particulate matter. Table 1 shows the source term parameters of viral particulate matter studied by scholars. From Table 1, it can be seen that the main exhalation modes studied by scholars are breathing, speaking, coughing, and sneezing. The airflow velocity generated by breathing and speaking is slightly lower, mainly within 0–5 m/s; The airflow generated by coughing and sneezing from the mouth and nose is relatively fast, concentrated at 10–50 m/s. Different initial velocities of particulate matter can also affect their propagation and diffusion in the air. Liu (2007) simulated the diffusion of particles at different initial velocities and found that the particle propagation distance caused by sneezing can reach up to 2 m, while coughing can only reach 0.6 m. He also proposed the concept of indoor microbial aerosol lifespan, pointing out that microbial particles have different transmission and elimination pathways due to their different particle sizes. The degree of harm to the human body also varies. Deng et al. (2005) pointed out that the particle size of aerosol particles produced by respiration is mainly distributed between 1 and 100 μm. As listed in Table 1, the particle size studied by scholars is mainly concentrated within 50 μm, especially for particles with a particle size of 1–10 μm.

Research has shown that (Wang et al. 2022a, b) droplets are usually larger in size and tend to settle over short distances, while aerosol particles are smaller in size and more susceptible to indoor flow fields. They are suspended in the air, carrying pathogenic viruses to further distances and causing widespread virus exposure, as shown in Fig. 1. Yin et al. (2021) conducted a study on the propagation characteristics of aerosol particles in indoor enclosed spaces and found that large diameter particles generated by exhalation methods such as coughing and sneezing move downwards, while small diameter particles are suspended in the air flow to the breathing area of the human body 2 m in front of the releaser.

At the same time, particle size also affects the effectiveness of airflow organization in removing particulate matter. Guo (2020) studied the effectiveness of liquid droplet removal under different airflow patterns by establishing a cough droplet evaporation and diffusion model. It was found that the grid side down supply and return air method (Fig. 2) has a stronger effect on the removal of small particle droplets, while the double-slit side up supply and return air method (Fig. 3) has a stronger effect on the removal of large particle droplets. Wu et al. (2021) studied the effectiveness of different ventilation forms, including single side

Table 1 Source term parameters of viral particles

References	Expiratory mode	Particle size (μm)	Initial airflow velocity (m/s)
Li et al. (2022)	Talk	1	2.2
Luan et al. (2022)	Cough	1	20
Mei et al. (2022)	Cough	1	22
Zhang (2019)	Breathe	1, 5, 10	2.14
Yu et al. (2014)	Sneeze	1	50
Pei et al. (2021)	Talk, breathe	1, 10	4 (talk), 1.5 (breathe)
Zhao et al. (2022)	Sneeze	50	50

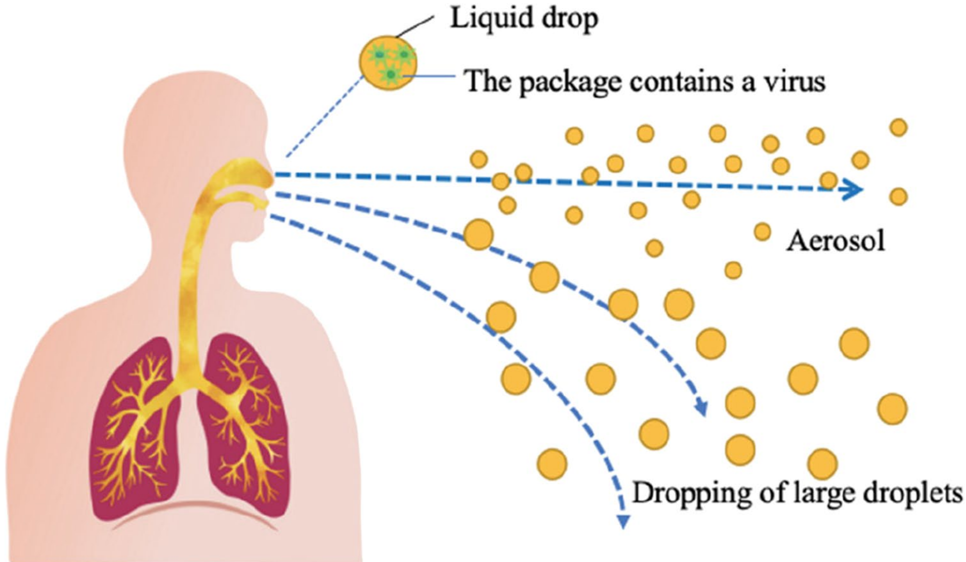

Fig. 1 Schematic diagram of the difference between aerosol propagation and droplet propagation

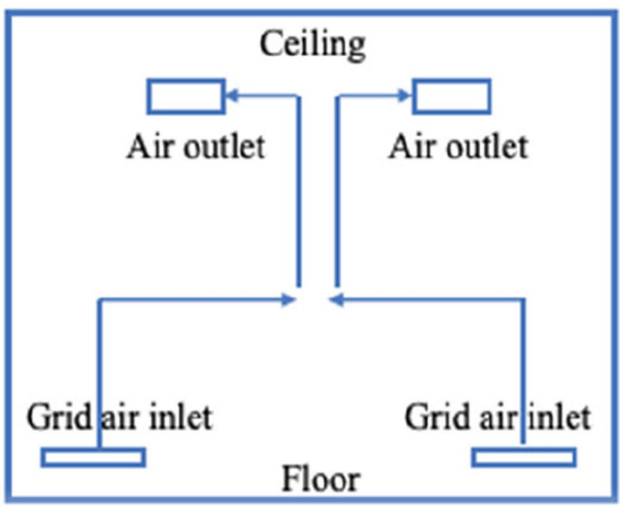

Fig. 2 Grid side down supply and return ventilation

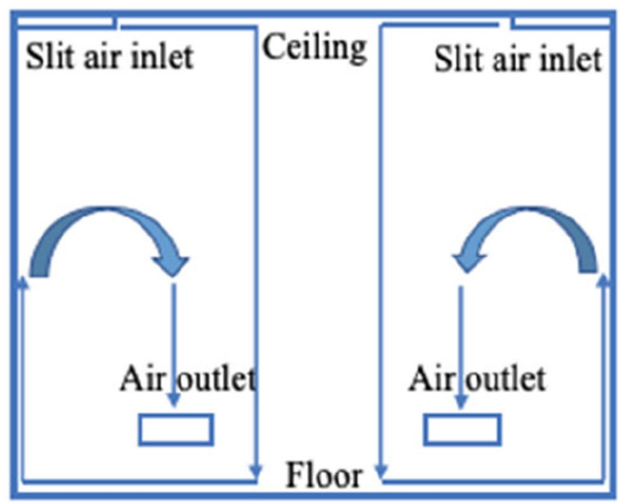

Fig. 3 Double-slit side up supply and return ventilation

seam–attached air supply (Fig. 4), the double-slit side up supply and return air method (Fig. 3), louvered air outlet air supply (Fig. 5), and displacement air supply (Fig. 6), on the removal of human cough droplets in the isolation ward. They found that displacement ventilation had an effect on small particle sizes (5–50 μm). The best effect is to eliminate cough droplets. Sun et al. (2007a, b) used the Euler Lagrangian model to study the propagation and diffusion of droplets generated by coughing in a ventilated room. The results showed that when the releaser sprayed upwards, the droplets only settled when the initial size was greater than 300 μm, while 80 μm and 100 μm remained suspended in the air during the simulation time. Wan et al. (2007) conducted a study on the propagation law of droplets generated by patients in hospital wards using mixed ventilation (Fig. 7) and found that the diffusion characteristics of droplets are mainly related to their particle size and the position of the air supply outlet. Therefore, when designing ventilation systems to protect the air quality of hospital wards, this needs to be considered. In addition, particle size also affects the evaporation time of particles. Wang et al. (2020) found through research on the evaporation process of individual droplets that the larger the particle size of virus carrying droplets, the longer their evaporation time.

In addition to the particle size factor of particulate matter itself, the influence of atmospheric environmental factors on the generation and diffusion of aerosol particles cannot be ignored. Ming (2013) studied the diffusion of aerosol particles exhaled by the human body in the room under the same ventilation frequency in winter and

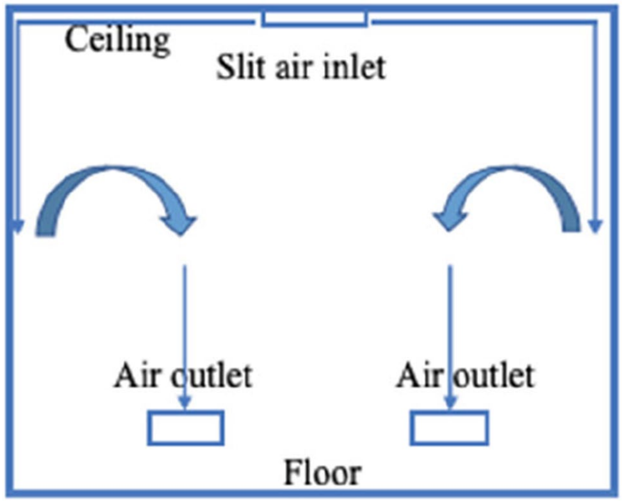

Fig. 4 single side seam–attached ventilation

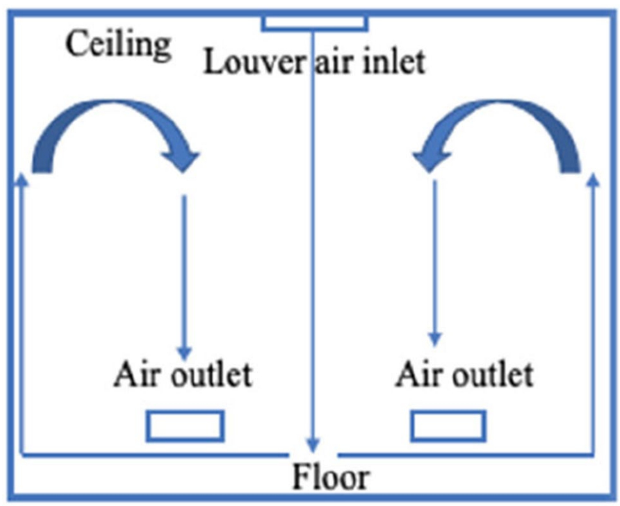

Fig. 5 Louver air outlet ventilation

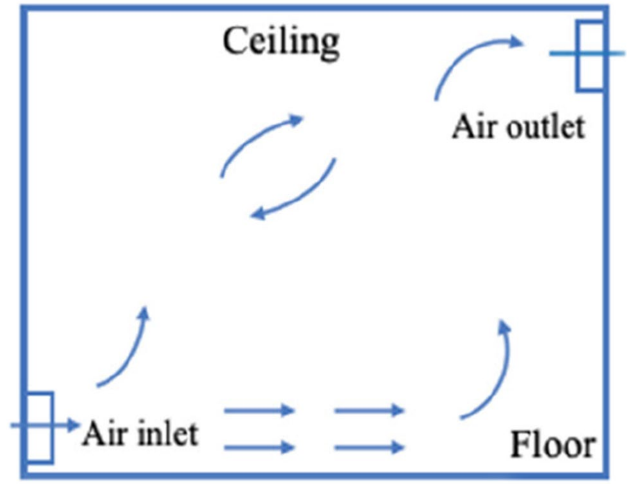

Fig. 6 Displacement ventilation

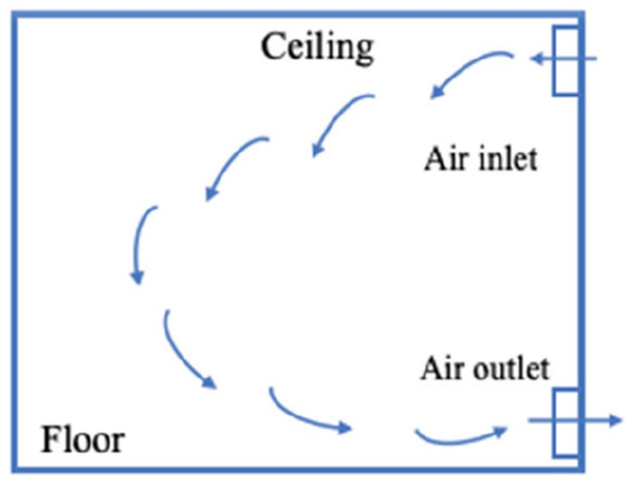

Fig. 7 Mixed ventilation

summer. The results showed that the concentration distribution varied due to different indoor temperature fields in winter and summer, but the difference in concentration distribution was not significant compared to the airflow field. The diffusion of aerosol particles was more affected by the indoor airflow field. Zhang et al. (2023) measured the concentration levels of aerosols in summer and autumn at the same site and found through comparative research that the concentration of aerosols containing bacteria and fungi in summer was higher than in autumn. During the epidemic period of COVID-19, relevant studies have found that bacteria and fungi in the environment can cause more serious harm to human respiratory tract infection in coordination with COVID-19 aerosol (Huttner et al. 2020; Chen et al. 2020; Zhang et al. 2020).

Numerical simulation of the diffusion process of virus containing aerosols

Computational fluid dynamics (CFD) is a type of modern simulation technology. Its basic principle is to numerically solve the differential equations that control fluid flow, obtain the discrete distribution of the flow field in a continuous region, and approximate the simulation of fluid flow. CFD technology has the characteristics of low-cost, high-efficiency, and complete functionality, and the ability to simulate various operating conditions, making it widely used in the study of indoor air flow, heat and mass transfer, and other issues. The commonly used CFD simulation software currently includes ANSYS Fluent, STAR CCM, and OpenFOAM, as listed in Table 2. Compared to other CFD simulation software, ANSYS Fluent software has the strongest

Table 2 Numerical simulation methods for scholars studying particulate matter

References	Software	Method of calculation	Turbulence model	Main algorithms
Liu (2007)	ANSYS Fluent	Euler–Lagrange	Standard k-ε	SIMPLEC, PISO
Zhang (2019)	ANSYS Fluent	Euler–Lagrange	Realizable k-ε	SIMPLE
Vuorinen et al. (2020)	OpenFOAM	Euler–Lagrange	LES	Second-order upwind
Zhao et al. (2022)	STAR CCM + 12.02	Euler–Lagrange	Realizable k-ε	SIMPLE, second-order upwind
Mirza et al. (2023)	OpenFOAM	Euler–Lagrange	SST k-ω	/
Dong	ANSYS Fluent	Euler–Lagrange	RNG k-ε	PISO
Li et al. (2023)	OpenFOAM	Euler-Euler	LES	/
Li et al. (2023)	ANSYS Fluent	Euler–Lagrange	RNG k-ε	SIMPLE, second-order upwind

applicability and powerful functional modules, usually consisting of three major program modules: pre-processor, solver, and post-processor. Its interactive preprocessing environment facilitates geometric modeling, high-quality mesh partitioning, setting boundary conditions, and physical modeling. In CFD software, ANSYS Fluent can provide a comprehensive numerical solution method that can meet different flow characteristics and computational needs. It also has a user-friendly graphical interface, making it easy to achieve post-processing visualization results. Therefore, the main computational software used by many mathematicians for the study of aerosol particle transport and diffusion is ANSYS Fluent. In addition, there have been studies using simulation software such as STAR CCM, Open FOAM, and PHOENICS. Cho et al. (2022) used STAR CCM + software to study the effect of ventilation control on eliminating cross infection and indoor virus clearance. Mirza et al. (2023) studied the propagation of aerosol particles under different ventilation conditions during coughing and speaking in humans using OpenFOAM. Li and Rao (2021) used PHOENICS to study the distribution of virus concentration field and air velocity field under different air flow organization forms in the COVID-19 isolation ward.

The main processes involved in the simulation research on the transport and diffusion of viral aerosols mentioned above include establishing mathematical and physical models, conducting numerical solutions, and achieving visualization of results. Establishing a mathematical and physical model is to mathematically describe the flow problem being studied. For the flow problem of indoor aerosol diffusion, the control equation for viscous fluid flow of incompressible fluid is usually used, and a complete description of the flow problem is combined with a turbulence model to facilitate numerical solution. There are three main CFD methods for indoor turbulent flow fields, namely direct numerical simulation (DNS), large eddy simulation (LES), and Reynolds average Navier Stocks (RANS). The main differences between the above three methods are listed in Table 3. DNS does not make any assumptions about irregular turbulent flow actions and can obtain the most accurate calculation results. However, the calculation is difficult and time-consuming. Currently, DNS is not commonly used in practical engineering calculation problems. LES can directly solve large-scale eddies through the N-S equation, while small-scale eddies can be simulated by establishing a relationship with large-scale eddies through subgrid scale models. LES can preserve the characteristics of large-scale eddies while reducing the complexity of simulation. RANS applies turbulence statistical theory to time average the N-S equation to obtain the Reynolds average equation, thereby calculating the time-averaged flow field and obtaining the average physical quantity of motion. The calculation efficiency is high and can meet the requirements of engineering calculations. Therefore, this method is currently a commonly used turbulence numerical simulation method in solving engineering problems. In the study of aerosol particles, Zhang et al. (2023) compared the advantages of the LES model over the RANS model and then used LES to study the propagation

Table 3 Main differences between DNS, LES, and RANS methods

CFD method	DNS	LES	RANS
Turbulence model	/	Subgrid model	All scale models
Turbulence model influence	/	Less impact	Greater impact
Grid dependency	Very detailed (significant impact)	Smaller grid (with greater impact)	Coarse grid (less impact)
Solution scope	Lower Reynolds number	Higher Reynolds number	High Reynolds number
Computation	Huge	High	Low
Calculation results	Instantaneous value	Instantaneous value	Average quantity

of aerosol droplets generated by coughing and nasal breathing with changes in indoor airflow. From Table 2, it can be seen that RANS is the most commonly used numerical simulation method in relevant research, and the commonly used Reynolds time-averaged turbulence models mainly include Standard k-ε, RNG k-ε, and Realizable k-ε. Luan et al. (2022) adopted the Standard k-ε model and studied the virus diffusion patterns in large indoor spaces using aerosols as carriers. Yu et al. (2014) used the Realizable k-ε model and analyzed the concentration distribution characteristics and transmission mechanism of pollutants generated by sneezing. Zhou et al. (2022) passed the RNG k-ε model and studied the coupling flow characteristics between droplets and air during sneezing. Bhattacharyya et al. (2020) used the SST k-ω model and numerically simulated the flow field in the isolation room and analyzed the effectiveness of mixing air conditioning equipment with aerosol disinfectants in suppressing viruses.

After establishing a mathematical model, it is necessary to solve the differential equation. Firstly, the computational domain of the actual problem needs to be discretized. For the low-speed, incompressible, and heat transfer problems that exist in the diffusion process of indoor virus-containing aerosols, the finite volume method is usually used for discretization. The discretized differential equations need to be solved through numerical algorithms to obtain the discrete distribution of the flow field. Based on Table 2, the main solving algorithms for aerosol particle–related problems studied by scholars are SIMPLE and PISO. The SIMPLE algorithm is mainly used to solve steady-state equations, while PISO is used to solve non-stationary equations. Li et al. (2022) used the SIMPLE algorithm to solve the discrete equation system and analyzed the aerosol distribution characteristics of open office spaces under five typical ventilation environments. Dong (2018) treated the diffusion process of aerosol particles released from human cough as a non-stationary process and solved it using the PISO algorithm. For practical problems with both steady-state and non-stationary processes, it is necessary to combine two algorithms. Zeng et al. (2022) simulated the diffusion process of cough droplets released by patients in the classroom. Firstly, the SIMPLEC algorithm was used to solve the steady-state indoor continuous phase flow field, and then, the PISO algorithm was used to perform non-stationary calculations on the discrete phase of droplets. Liao (2017) simulated the propagation process of droplet pollutants in the ward. Firstly, the SIMPLE algorithm was used to simulate the turbulent flow field in the ward, and then the PISO algorithm was used to calculate the distribution of droplet pollutants in patients, caregivers, and medical staff through coughing and breathing sprays.

In order to obtain the movement and distribution of particulate matter, it is necessary to combine the transport model of particulate matter for research. From Table 2, it can be seen that the multiphase flow models currently used by scholars to study the transport of aerosol particles mainly include the Euler Euler model and the Euler Lagrange model. The Euler Euler model considers both air and particles as continuous media and calculates the volume fraction of particles by solving the N-S equation. Compared with the Lagrangian model, this method can directly obtain particle concentration and has high computational efficiency and time saving in practical engineering calculations. It is widely used in predicting particle concentration distribution. For example, Pei et al. (2021) used the Euler Euler model to simulate the release of viral particles from patients' mouths and obtained aerosol concentrations in the respiratory area of the human body. The results indicate that a social distance of 1 to 2 m may not be sufficient to prevent the spread of aerosols smaller than 10 μm in the indoor environment. The Euler Lagrangian model treats air as a continuous phase and aerosol particles as discrete phases. First, the N-S equation is solved to calculate the air flow field, and then, the trajectory of each particle is tracked based on the flow field parameters. The particles can exchange momentum, mass, and energy with the flow field. Compared to the Euler Euler method, this model has a higher computational cost and time consumption, but the motion of each particle can be tracked to obtain more accurate calculation results. For example, Wang et al. (2022a, b) studied the motion trajectories of viral particles in nucleic acid sampling rooms at different times using the Euler Lagrange model and found that aerosol particles would stay in the room for a long time, enough to stay until the next tested person entered the sampling room.

When using numerical calculations, in order to verify the rationality and correctness of the method, some scholars will conduct reliability verification of the model before simulating the motion of particles. Zheng et al. (2016) compared the CFD simulation results with the measurement results of airflow distribution, air temperature, and tracer gas concentration in small offices by Yuan et al. (1999). The results confirmed that the calculation model used was in good agreement with the measurement results and then applied this method to simulate the diffusion process of droplets produced by coughing. Research has shown that this method can be used to predict airflow velocity, air temperature, and pollutant diffusion in enclosed spaces. Zhang et al. (2019) validated the effectiveness of the CFD model through a self-developed thermal model. The experimental and simulation results were compared using dimensionless concentrations, and a good agreement was observed between the simulated values and experimental data, indicating that the numerical model used can effectively predict the distribution of droplet aerosols.

Regarding the visualization of numerical simulation results, scholars usually use CFD post-processing software such as CFD-Post, ParaView, and Tecplot to visualize the discrete values on each grid node, obtaining intuitive images of particle velocity and concentration fields.

The effect of ventilation methods on the diffusion of viral aerosols

Ventilation is a method of controlling the spread and harm of air pollutants through ventilation dilution or ventilation elimination. Different ventilation methods have different air flow organizational forms, and the removal effect of aerosol particles in different air flow organizational forms is also different. Common ventilation methods include displacement ventilation (Fig. 6), mixed ventilation (Fig. 7), and floor ventilation (Fig. 8). Mixed ventilation is the process of diluting the concentration of indoor pollutants through air supply. A certain amount of clean air is sent into the air supply outlet, which is mixed with indoor air and discharged through the exhaust outlet, creating an indoor air environment that is similar to the exhaust state. Displacement ventilation is the process of sending fresh air with lower temperature into the room through the lower air supply outlet and expelling the indoor air containing heat out of the room. The indoor environment is similar to the air supply state. Floor ventilation is the process of sending clean air out at a higher wind speed through the air supply outlet, forming a strong air mixture. Li et al. (2022) compared the effectiveness of different ventilation methods on the removal of aerosol particles in open office spaces and found that the removal rate of mixed ventilation was higher than that of displacement ventilation, and the different side airflow organization in mixed ventilation was more conducive to the removal of viral aerosols. Zheng et al. (2016) found that increasing the ventilation rate and displacement ventilation mode under mixed ventilation can reduce the concentration of cough droplets and inhalation volume in the breathing area of healthy cabin personnel. However, compared to mixed ventilation, displacement ventilation has a better effect. Gao and Niu (2007) found through numerical simulation that floor ventilation can effectively reduce indoor particle concentration and improve ventilation efficiency.

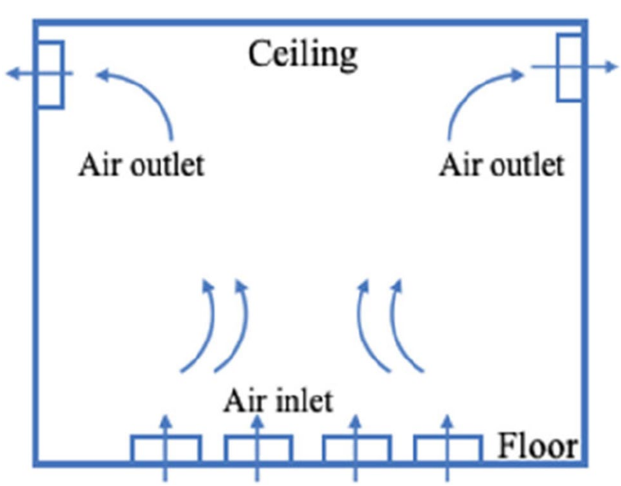

Fig. 8 Floor ventilation

Table 4 lists the different ventilation methods involved in scholars' research and their effects on aerosol particle diffusion. Liu (2016) conducted a study on the evaporation and diffusion laws of human droplet pollutants under three ventilation modes: top air supply, jet air supply, and recommended air supply. He found that under the recommended air supply mode in the ward, droplet pollutants are mainly concentrated and diffused near the hospital bed, and this air supply method has the best effect on removing droplet pollutants. Sun (2007a, b) found that down draft ventilation is the best ventilation method by comparing the efficiency of air conditioning airflow in expelling cough droplets and the number of droplets falling on medical personnel manikins under mixed ventilation, displacement ventilation, and down draft ventilation. Tan et al. (2022a, b) compared the effects of six ventilation methods on the diffusion efficiency of bacteria in negative pressure wards and found that the ventilation scheme with opposite side inlet and outlet is more conducive to the discharge of polluted gases and reduces the risk of infection for medical staff. Compared to traditional ventilation methods, personalized ventilation schemes have higher flexibility in practical applications and can more effectively suppress the diffusion of aerosol particles. Li et al. (2023) studied the effect of ceiling fan ventilation (as shown in Fig. 9) on the propagation of droplets and aerosols during coughing and found that ceiling fans can reduce the concentration of respiratory areas and protect the human body located below them from cough exposure. Li et al. (2023) studied the effect of ventilation methods on droplet propagation and found that compared to mixed ventilation and displacement ventilation, air curtain ventilation (as shown in Fig. 10) is more conducive to limiting the propagation of aerosol droplets and reducing exposure risk. Wang et al. (2022a, b) conducted a study on the diffusion of viral particles in a nucleic acid sampling room and found that setting up local inhalation equipment can quickly reduce the concentration of viral aerosol particles in the room and is not easy to cause diffusion.

Other factors cannot be ignored when studying the effect of ventilation methods on the effective removal of aerosol particles. Mei et al. (2022) compared the diffusion characteristics and concentration distribution of droplets produced by coughing in elevators under different ventilation methods. The study showed that in order to reduce the risk of infection among personnel, it is not only necessary to increase ventilation volume but also to consider ventilation location. Mao et al. (2016) conducted a study on the indoor emission

Table 4 Effect of ventilation methods on the diffusion of aerosol particles

References	Ventilation method	Air supply outlet speed (m/s)	Supply air temperature (℃)	Impact on aerosol particle diffusion
Pei et al. (2021)	Displacement ventilation (low speed floor air supply)	2.15	17	Compared to hybrid ventilation, displacement ventilation driven by buoyancy leads to longer transmission distances and higher risk of exposure to viral aerosols
	Mixed ventilation			
Wang et al. (2022a, b)	Mixed ventilation	0.556	22	Orifice plate ventilation makes the temperature and flow field distribution in the ward more uniform, accelerating the discharge of aerosol particles
	Orifice ventilation			
Li et al. (2023)	Mixed ventilation	1.5	22	Compared to mixed ventilation and displacement ventilation, air curtains are more conducive to limiting the spread of aerosol droplets and reducing exposure risks
	Displacement ventilation	0.5		
	Air curtain ventilation	0.75		
Wang et al. (2022a, b)	High wind speed mechanical ventilation	2.5	/	Strengthening mechanical ventilation can quickly improve the efficiency of virus particle displacement, but it is easy to cause spread. Setting up local suction equipment can quickly reduce the concentration of virus particles and is not easy to cause spread
	Set up local suction equipment			
Liu (2016)	Top air supply	3.28	16.5	Under recommended air supply, the return air outlet is close to the pollution source, and the diffusion range of droplet movement is small. It is the fastest to discharge outdoors, and the removal effect of droplet pollution source is the best
	Attached jet air supply	3.69		
	Recommended air supply	3.28		
Zhu (2022)	Mixed ventilation	2	20	The concentration of virus aerosols in the respiratory area of the floor ventilation conference room is the lowest, and the ventilation effect is floor ventilation > mixed ventilation > displacement ventilation
	Displacement ventilation	0.5		
	Floor ventilation	1		

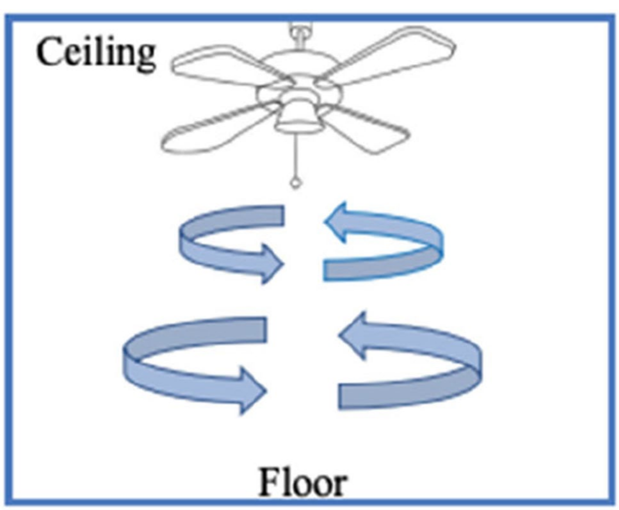

Fig. 9 Ceiling fan ventilation

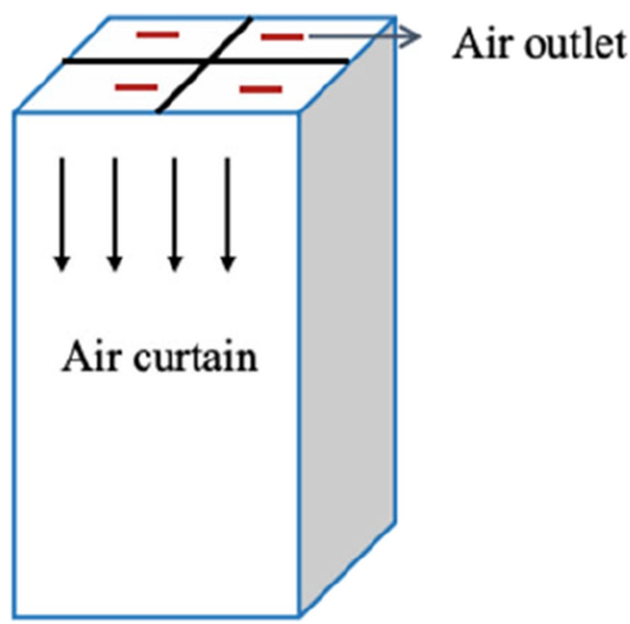

Fig. 10 Air curtain ventilation

of CO_2 under the same air supply form and different heights of return air vents. The results showed that a lower position of return air vents can not only save energy but also effectively discharge CO_2. Zeng et al. (2022) simulated the diffusion process of cough droplets released by patients in the classroom under two different wind speeds and found that high wind speeds can accelerate droplet removal speed, and the decrease in droplet concentration is related to the patient's cough location. Zhao et al. (2022) studied the effect of different ventilation directions on aerosol diffusion when passengers slowly move in airports. The study showed that human movement can disturb the surrounding air, forming a wake, and crosswind can significantly affect aerosol diffusion, leading to further aerosol diffusion. Tang (2021) simulated the effects of different air supply parameters on the spread of virus pollutants and human comfort in a bag air supply system. By changing the values of air supply height, air supply speed, and air supply temperature, he focused on the temperature and velocity distribution in the respiratory area of patients and medical staff and ultimately selected the optimal air supply parameters. Tan et al. (2022a, b) found that in addition to changing the air flow organization form and air supply speed, increasing the air supply humidity appropriately can slow down the evaporation rate of particles, thereby reducing the mass concentration of particles in the ward to a certain extent and reducing the risk of infection for medical staff.

Conclusion

This study reviews the generation and diffusion characteristics of viral aerosol particles, numerical simulation methods for viral aerosol diffusion processes, and the impact mechanism of different ventilation methods on viral aerosol diffusion processes. The following conclusions are drawn:

The different initial conditions such as the exhalation mode, initial airflow velocity, and particle size of aerosol particles can have an impact on the diffusion process of viral aerosol particles. Therefore, the study of the impact of different initial conditions on the diffusion process of viral aerosol particles is of great value.

Studying the diffusion process of virus-containing aerosols in enclosed spaces through numerical simulation has the advantages of low cost and being able to obtain both macro and micro results simultaneously. Therefore, it is of great significance to comprehensively consider the calculation accuracy and time and select appropriate turbulence models, calculation methods, and initial conditions for the numerical simulation of the diffusion process of viral aerosol particles.

In order to prevent viral aerosol particles from staying in the air for too long, it is of great practical significance to select the optimal ventilation form by simulating the elimination effect of viral aerosol particles through different ventilation methods. Compared to traditional ventilation forms, personalized ventilation schemes with higher efficiency can be considered to reduce the risk of aerosol propagation. In addition, on the basis of selecting appropriate ventilation methods, a reasonable setting of ventilation parameters (temperature, speed, height, etc.) can also effectively suppress the spread of viral aerosols. However, there is still a lack of more systematic research on the evaluation of ventilation effectiveness in existing studies. Usually, only a single or two or three types of ventilation forms and ventilation parameter settings are considered. In different types of indoor environments, the applicability of different ventilation methods and ventilation parameters needs further research. Therefore, further research on the removal of viral aerosol particles in indoor ventilation schemes needs to be further improved.

Author contribution Yaxin Huang: manuscript writing, data collation. Jie Wan: revise manuscript. Sen Han: manuscript writing, revise manuscript. Yu LI: manuscript writing, data collation.

Funding This work was supported by the National Natural Science Foundation of China [52006172], the Shaanxi Provincial Natural Science Basic Research Program [2024JC-YBMS-280], the National Funding Program for Postdoctoral Researchers [GZC20232228], and the Shaanxi Provincial Natural Science Basic Research Program-Youth Fund Project [2022JQ-506].

Data availability The data used during the study are available from the corresponding author by request.

Declarations

Ethical approval Not applicable.

Consent to participate All authors gave explicit consent to participate.

Consent for publication All authors gave explicit consent to submit.

Conflict of interest The authors declare no competing interests.

References

Bhattacharyya S, Dey K, Paul AR, Biswas R (2020) A novel CFD analysis to minimize the spread of COVID-19 virus in hospital isolation room. Chaos Solitons Fractals 139:110294

Chen X, Liao B, Cheng L, Peng X, Xu X, Li Y, Hu T, Li J, Zhou X, Ren B (2020) The microbial coinfection in COVID-19. Appl Microbiol Biotechnol 104(18):7777–7785

Cho J, Kim J, Kim Y (2022) Development of a non-contact mobile screening center for infectious diseases: effects of ventilation improvement on aerosol transmission prevention. Sustain Cities Soc 87:104232

Deng W, Shen J, Tang X, Shen D (2005) The study on the optimization of indoor air distribution for SARS isolation wards. Build Energy Environ 24(2):9–14

Dong J (2018) Study on indoor pollutant particles motion simulation and the optimizing control of air-conditioning system. Shenyang Jianzhu University (Thesis)
Fang Z, Sun P, Ouyang Z, Liu P, Sun L, Wang X (2013) Study on the particle size and distribution characteristics of indoor air microorganisms in Beijing. Environ Sci 34(7):2526–2532
Ferry RM, Brown WF, Damon EB (1958) Studies of the loss of viability of stored bacterial aerosols. II. Death rates of several non-pathogenic organisms in relation to biological and structural characteristics. Epidemiol 56(1):125–150
Gao N, Niu J (2007) Modeling particle dispersion and deposition in indoor environments. Atmospheric Environ 41(18):3862–3876
Guo X (2020) Study on the evaporation and diffusion patterns of cough droplets under the influence of airflow organization and infection risk assessment. Huazhong Univ Sci Technol (Thesis)
Huttner BD, Catho G, Pano-Pardo JR, Pulcini C, Schouten J (2020) COVID-19: don't neglect antimicrobial stewardship principles! Clin Microbiol Infect 26(7):808–810
Klepeis NE, Nelson WC, Ott WR, Robinson JP, Tsang AM, Switzer P, Behar JV, Hern SC, Engelmann WH (2001) The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants. J Expo Anal Environ Epidemiol 11(3):231–252
Li N, Rao D (2021) Simulation analysis of air distribution in a COVID-19 isolation ward in Kunming. Refrig Air Cond 35(4):542–546.551
Li X, Wang W, Kang N, Zhou L, Yu J (2022) Numerical study of aerosol propagation in open office spaces. Build Sci 38(02):209–216
Li WX, Hasama T, Chong A, Hang JG, Lasternas B, Lam KP, Tham KW (2023) Transient transmission of droplets and aerosols in a ventilation system with ceiling fans. Build Environ 230:109988
Liao Y (2017) Transmission and risk assessment of droplet pollutants in heating wards in high-altitude areas. Chongqing Univ (Thesis)
Liu S (2007) Study on the indoor transmission and movement patterns of microbial aerosols emitted from the oral cavity. Tianjin Univ (Thesis)
Liu P (2016) Characteristics of concentration changes and pollution control of airborne pollutants in wards. Chongqing Univ (Thesis)
Luan Y, Zhang L, Yin Y, Yan L, Wu X, Sun T (2022) Optimization of ventilation structure and virus spread patterns in large indoor places. Environ Eng 40(12):180–186
Mao N, Song M, Chan M, Pan D, Deng S (2016) Computational fluid dynamics (CFD) modelling of air flow field, mean age of air and CO_2 distributions inside a bedroom with different heights of conditioned air supply outlet. Appl Energy 162:906–915
Mei D, Wang C, Li J, Xing F (2022) The impact and risk analysis of ventilation methods in box elevators on the spread of cough droplets. Chin J Infect Control 21(01):8–14
Ming Y (2013) Study of aerosol particulate pollutant of human body movement rule in air conditioning room. Shenyang Jianzhu Univ (Thesis)
Mirza S, Niwalkar A, Gupta A, Gautam S, Anshul A, Bherwani H, Biniwale R, Kumar R (2023) Is safe distance enough to prevent COVID-19? Dispersion and tracking of aerosols in various artificial ventilation conditions using OpenFOAM. Gondwana Res 114:40–54
Pei G, Taylor M, Rim D (2021) Human exposure to respiratory aerosols in a ventilated room: effects of ventilation condition, emission mode, and social distancing. Sustain Cities Soc 73(4):103090
Sun W (2007a) Transport of droplets expelled by coughing in ventilated rooms. Indoor Built Environ 16(6):493–504
Sun W (2007b) Research on the diffusion of polluted droplets in air conditioning rooms and the indoor thermal environment. Univ Sci Technol China (Thesis)
Tan B, Peng L, Long M, Feng Y, Zhu J, Pan Y (2022a) Numerical simulation and analysis and optimization of airflow in negative pressure wards based on CFD technology. Sci, Technol Eng 22(3):1117–1121
Tan F, Lin H, Li Z, Xie FJ, Yu RX, Liao Y (2022b) Simulation study on airflow organization and particle diffusion behavior in negative pressure isolation wards. Sci Technol Innov Appl 12(28):79–83
Tang S (2021) Simulation of air flow organization and energy consumption of air supply system in shelter hospitals in severe cold regions. Heilongjiang: Harbin Inst Technol (Thesis)
Vuorinen V, Aarnio M, Alava M, Alopaeus V, Atanasova N, Auvinen M, Balasubramanian N, Bordbar H, Erästö P, Grande R, Hayward N, Hellsten A, Hostikka S, Hokkanen J, Kaario O, Karvinen A, Kivistö I, Korhonen M, Kosonen R, Kuusela J, Lestinen S, Laurila E, Nieminen HJ, Peltonen P, Pokki J, Puisto A, Råback P, Salmenjoki H, Sironen T, Österberg M (2020) Modelling aerosol transport and virus exposure with numerical simulations in relation to SARS-CoV-2 transmission by inhalation indoors. Saf Sci 130:104866
Wan MP, Chao CYH, Ng YD, To GNS, Yu WC (2007) Dispersion of expiratory droplets in a general hospital ward with ceiling mixing type mechanical ventilation system. Aerosol Sci Technol 41(3):244–258
Wang X, Ren A, Wu Y, Wang B, Shi L (2020) Numerical simulation of viral droplet diffusion process based on Euler Lagrange method. Nat Mag 42(3):239–248
Wang F, Gao W, Li Q, Li J, Kong LY (2022a) Simulation and ventilation scheme optimization of viral particle diffusion in nucleic acid sampling rooms. Comput Aided Eng 31(1):5
Wang F, Niu G, Yang H, Xu X (2022b) Characteristics of aerosol diffusion in isolation wards under mixed and perforated ventilation. J Huazhong Univ Sci Technol (Nat Sci Ed) 50(10):18–25
Wells WF (1934) On air-borne infection. Study II. Droplets and droplet Nuclei. Am J Epidemiol 20(3):611–618
Wu X, Guo X, Xie J, Hou J, Duan M (2021) Numerical simulation of the effect of air supply on the propagation of cough droplets in isolation wards. Refrig Air Cond 35(03):305–311
Xie X, Li Y, Chwang ATY, Ho PL, Seto WH (2007) How far droplets can move in indoor environments revisiting the Wells evaporation-falling curve. Indoor Air, Copenhagen: Danish Tech Press 17(3):211–225
Yin Y, Li Y, Fu H, Luan Y (2021) Aerosol diffusion characteristics in indoor enclosed and ventilated spaces. Environ Eng 39(04):79–85
Yu Y, Gu Z, Liu SC, Zhao W (2014) Numerical study on the propagation and control of suspended biological particles in passenger cars. Sci Technol Eng 14(12):277–283
Yuan X, Chen Q, Glicksman LR, Hu Y, Yang X (1999) Measurements and computations of room airflow with displacement ventilation. ASHRAE Trans 105(1):340–352
Zeng K, Chen Y, Tan Y, Zhu Q (2022) The effect of wind speed on the diffusion of cough droplets in naturally ventilated classrooms. Build Therm Vent Air Cond 41(06):7–11
Zhang Y, Feng G, Bi Y, Cai Y, Zhang Z, Cao G (2019) Distribution of droplet aerosols generated by mouth coughing and nose breathing in an air-conditioned room. Sustain Cities Soc 51:101721
Zhang G, Hu C, Luo L, Fang F, Chen Y, Li J, Peng Z, Pan H (2020) Clinical features and short-term outcomes of 221 patients with COVID-19 in Wuhan. China J Clin Virol 127:104364
Zhang J, Feng D, Zuo Y (2023) Indoor microbial aerosol pollution and exposure assessment in public places in summer and autumn. Build Sci 39(02):251–260

Zhang Y (2019) A study on the mechanism of the effect of temperature stratification in displacement ventilation on the spread of droplets between people. Xi'an Univ Archit Technol (Thesis)

Zhao Y, Feng Y, Ma LD (2022) Impacts of human movement and ventilation mode on the indoor environment, droplet evaporation, and aerosol transmission risk at airport terminals. Build Environ 224:109527

Zheng L, Xu J, Wu F, Xu W, Long Z (2016) The effect of ventilation mode on the diffusion process of cough droplets among cabin personnel. China Shipbuild Res 11(02):12–20

Zhou Y, Ji S, Zhang D, Shi B, Tao W (2022) Numerical study on the risk of human infection caused by airborne particle transmission in consulting rooms. Archit Sci 38(02):217–222

Zhu Q (2022) Numerical simulation study on indoor aerosol propagation under different air supply methods. Donghua Univ (Thesis)