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Risk Study Of Virus Transmission Through Aerosols In Negative Pressure Wards

Chengzhen Cui, Huadong Yang*

Department of Mechanical Engineering, North China Electric Power University, Baoding 071003,China;

Abstract:
During the COVID-19 pandemic, negative pressure isolation rooms have been widely utilized as a crucial measure for infection control, effectively mitigating the crisis. Numerous studies have demonstrated that aerosol transmission plays a significant role in the spread of viruses. This study aims to predict the dissemination, distribution patterns, and infection risks associated with viruses carried by particles in aerosols within negative pressure isolation rooms. The study develops a model of aerosol transmission in these rooms using Fluent software and validates it through experiments and data analysis. The findings reveal that high concentrations of particles ranging from 0.3μm to 1μm can still be detected at distant locations from the infection source, indicating a substantial risk of infection for healthcare workers in the current conditions of negative pressure isolation rooms. The results of this study offer theoretical and technical support for the reduction of nosocomial infections.

Keywords: *negative pressure isolation rooms; aerosol transmission; virus spread*

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I. Introduction

In recent years, there have been increasing cases of virus transmission through aerosols in hospital environments. Respiratory infectious diseases, including COVID-19, can be transmitted through aerosols released by patients when they speak, breathe, or cough. Wang et al. conducted experiments to confirm the aerosol transmission of viruses generated by three respiratory behaviors in negative pressure isolation rooms and the potential risk to healthcare workers [1]. Similarly, Vuorinen et al. found that coughing in enclosed spaces like supermarkets can lead to rapid virus transmission [2]. The average speed of coughing ranges from 1 to 10 meters per second [3]. A recent study reported that 49.8% of COVID-19 patients experience persistent coughing [4]. Therefore, this study focuses on the transmission of aerosol-carrying viruses generated by patients coughing in negative pressure isolation rooms.

While Wang et al. studied three respiratory behaviors, they did not consider the different positions of patients on the bed. Yi et al. conducted experiments that demonstrated patients in a supine position have higher pollutant concentrations in rooms with displacement ventilation compared to patients in a sitting position. They also confirmed the significant role of ventilation systems in pollutant distribution in hospital wards [5]. Additionally, Jurelionis et al. found that mixing ventilation can reduce the age of indoor air and improve the removal efficiency of harmful substances [6]. Numerous studies have shown that the average particle concentration during displacement ventilation is higher than that during mixing ventilation, and the pollutant concentration during displacement ventilation is higher than that during mixing ventilation [7][8][9]. Therefore, this study focuses on

mixing ventilation.

The key to ventilation in negative pressure isolation rooms lies in the minimum ventilation rate, air distribution, and directional airflow [10]. The ventilation system determines the minimum ventilation rate and the efficient transport of air to each room to effectively remove pollutants. The ventilation configuration within the room determines the directional airflow. Therefore, by modifying the configuration, it is possible to improve indoor air quality and reduce the risk of infection for healthcare workers. This study uses a typical negative pressure isolation room in a hospital as an example to investigate the spatial dispersion characteristics of aerosols generated by patients coughing in a supine position on the bed. Measurements were conducted in the negative pressure isolation room to determine the farthest distance of aerosol transmission. A numerical simulation was then performed based on the actual size of the room to further analyze aerosol dispersion. The findings of this study provide valuable references and recommendations for reducing the occurrence of healthcare-associated infections.

II. Materials and Methods

The negative pressure isolation room used in this study is a standard double-bed ward. It has a buffer room at the entrance and a toilet on the opposite side of the beds. The airflow in the room follows a specific pressure difference distribution. The pressure difference between the negative pressure isolation room and the clean area is -20Pa. The pressure difference between the corridor of the negative pressure isolation room and the clean area is -10Pa. The pressure difference between the buffer room and the corridor of the negative pressure isolation room is -5Pa. And the pressure difference between the negative pressure isolation room and the buffer room is -5Pa. These pressure differences comply with the requirements set by the Isolation Room Environmental Control Specification (GB/T 35428–2017). The room has two windows on the other side, but any airflow escaping through the window gaps is minimal and is not considered in the simulation.

The negative pressure isolation room consists of two beds and a cabinet. There is an air supply port at the top of the room and two air supply vents on each side of the beds. These vents are located more than 10cm above the ground, providing mixed ventilation. The air velocity at the air supply port, measured by a velocimeter, is 0.25m/s. This measurement aligns with the calculated value of 0.265m/s based on the ventilation rate and the size of the air supply vents. The pressure difference between the air supply vents and the outside environment is -2.5Pa, and the air velocity is 0.22m/s, meeting the requirements for negative pressure isolation rooms. The experiment and simulation settings are provided in Table 1, Figure 1, and Figure 2.

Table 1 Indoor parameters

Name	Quantity	Size (m)	Temperature（k）	Boundary Conditions
Isolation Room	1	5.0×5.0×3.6	-	-
Human Model	2	0.3×0.4×1.75	307.1	Trap
Air Supply Port	1	0.3×.0.3	299.1	Reflect
Exhaust Port	2	0.27×0.27	-	Escape
Beds	2	2.2×1.0×0.5	-	Trap
Cabinet	1	0.5×0.5×0.6	-	Trap
Walls	-	-	-	Trap
Simulated human oral cavity	2	-	-	Trap

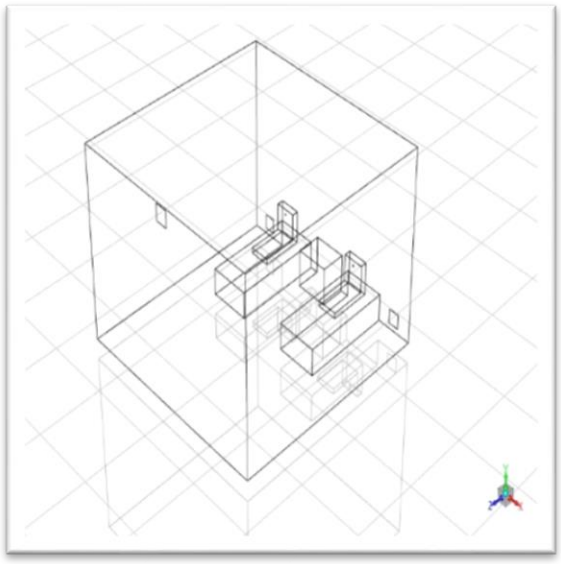


Figure 1 Simulation settings

Figure 2 Measurement settings

In this study, the researchers used the RNG k-ε turbulence model to simulate the flow field environment in the negative pressure isolation room. They verified the stability and accuracy of this model in previous studies conducted by Zhang et al. [11][12]. The researchers utilized the computational fluid dynamics (CFD) tool in the ANSYS 2021R1 software package to simulate the airflow and particle dynamics in the negative pressure isolation room. They generated a computational mesh using a fluid mesh generation tool, resulting in 600,000 polyhedra. The solution was obtained using a pressure-based solver and a coupled algorithm with a second-order pressure scheme. To simulate the motion of discrete aerosol particles, the researchers employed the Euler-Lagrange method, considering the effects of drag, gravity, and Saffman forces on particle motion. The mixing ventilation in the negative pressure isolation room had a ventilation rate of 12 air changes per hour (ACH), while the mixing ventilation in the buffer area had a ventilation rate of 10 ACH. These rates align with the standard supply flow rate for hospital wards. The supply air temperature for both systems was 299.1K.

III. Experimental Measurement Content

The experimental measurement content of this study focused on investigating the dispersion pattern of pollutants exhaled by patients in a supine position on the bed when coughing. In the case of mixing ventilation, the exhaust port in the negative pressure isolation room is located at the bottom of the side wall. Although there may be air leakage from the door and window gaps in reality, this leakage was not considered in the subsequent simulation. The researchers placed several sets of particle monitors (ranging from 0.3-10μm) in the negative pressure isolation room during the experiment. They also placed the same instruments in an empty room with the same conditions as a control. The air sampling flow rate was maintained at 190 L/min for continuous measurement. The relative humidity in the room during the experiment was 299%.

CFD Simulation Content Settings

The researchers considered the size of droplets exhaled by individuals in their CFD simulation. They noted that larger droplets tend to deposit quickly on walls or floors, while the main size range of droplets transmitted in the air is between 0.8μm and 3μm[13][14]. This information is supported by studies conducted by Fabian et al., who used an optical particle counter and qPCR technology to study the particle size distribution of pollutants exhaled by flu patients. According to their findings, approximately 70% of particles have diameters

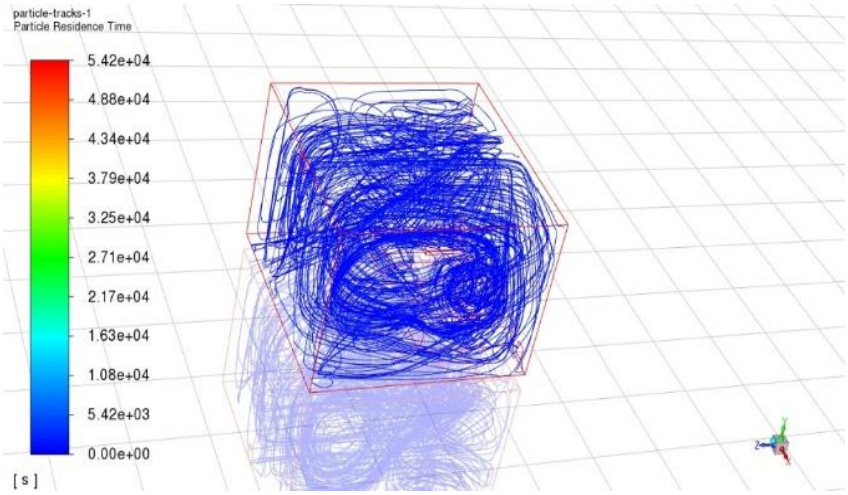
ranging from 0.3μm to 0.5μm, while 20% have diameters ranging from 0.5μm to 1μm[15]. Taking into account the effect of evaporation, this study sets the diameter of particles at 1μm.

In hospitals, patients generate pollutants through various respiratory activities such as coughing, breathing, speaking, and sneezing. The velocities of these activities differ, with speaking and breathing having lower velocities compared to coughing. The transport mechanisms of pollutants generated by these activities also vary. Breathing, with its lower and more uniform velocity, can be considered as a fixed source. On the other hand, coughing has a variable duration of approximately 1 second, making it challenging to determine the instantaneous transport of viruses generated by a single cough. To address this, the researchers referred to a study by Gupta et al[16]. and set the outlet diameter at 0.035m in a horizontal direction. They simulated a single cough by a human model with a velocity of 11.7 m/s and a quantity of 1500. The measurements were conducted under steady-state conditions to establish highly accurate and stable measurement conditions.

IV. Result discussion

The model of aerosol particle dispersion in the ward when there are people coughing on two beds was obtained through CFD simulation, as shown in Figure 3.

Figure 3 Aerosol Particle Diffusion Model



By conducting CFD simulations, we obtained the trajectory map on the ZY plane passing through the ventilation outlet. It can be observed that the airflow pattern on one side of the negative pressure ward is consistent with the particle emission path during coughing. Similar phenomena can be observed at the exhaust outlet on the other side, indicating the existence of simultaneous airflow circulation paths on both sides of the negative pressure ward. Additionally, the velocity cloud map shows that the velocity at the exhaust outlet is greater than the overall airflow velocity within the room, as shown in Figure 4and Figure 5.

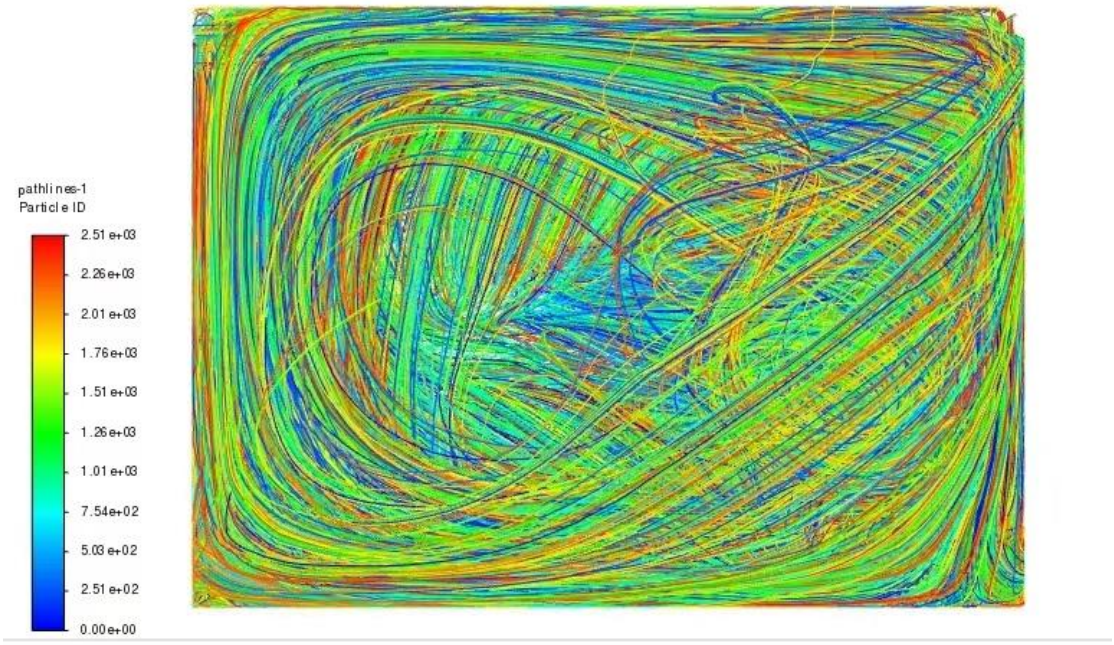


Figure 4 Aerosol Particle Diffusion Model

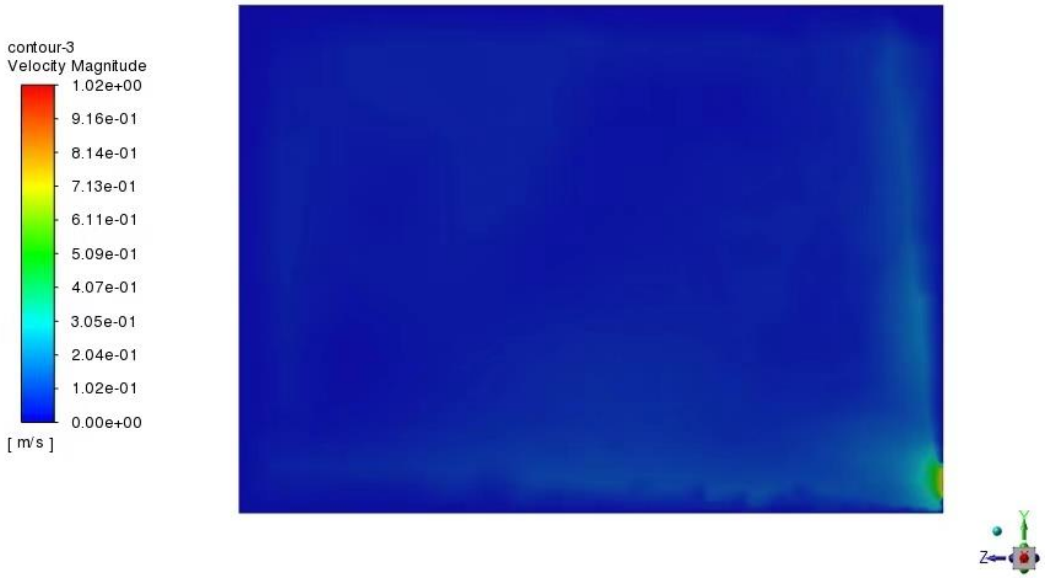


Figure 5 Cloud Chart of Air Outlet Plane Velocity

High-concentration areas and areas with lower concentrations of virus transmission were identified through CFD simulations. Experimental measurements of the concentration of 0.3~1μm aerosol particles at different locations in the negative pressure ward were performed, along with measurements of aerosol particle content in the control ward. The experimental data was combined with the control data and optimized to reduce the impact of indoor particles. The measurement results are presented in Table 2.

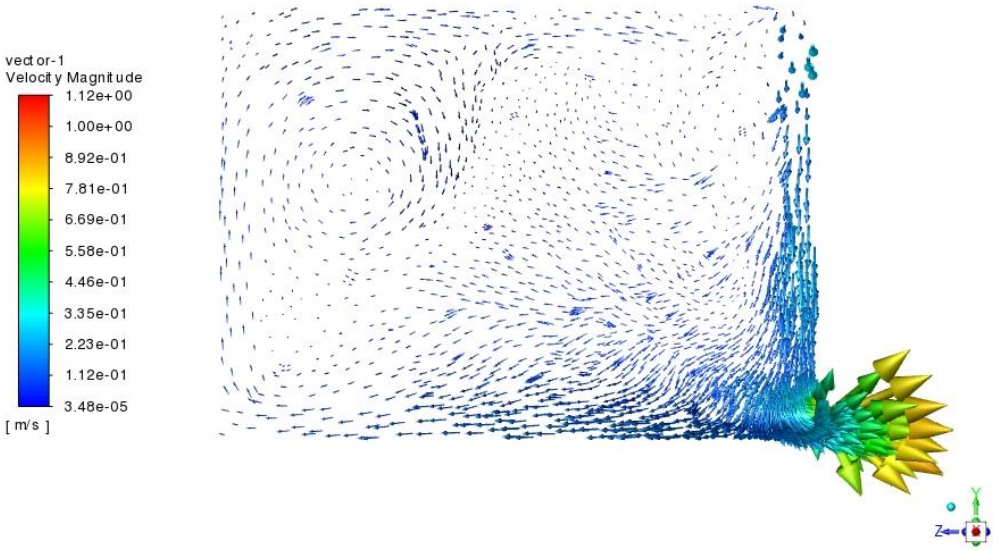
Table 2 Measurement values of aerosol particles in ward

position	0.3~0.5um (#/0.1L)	0.5~1um (#/0.1L)
0.5m high on the side of the exhaust outlet	5374	1524
1.5m high on the side of the exhaust outle	5302	1686
0.5m high on the side of the air inlet	3660	1145
1.5m high on the side of the air inlet	3320	1017

V. conclusion

In negative pressure isolation rooms, viruses are continuously exhaled by patients through coughing and other means. These viruses gradually spread and deposit throughout the room via aerosols. Simulation results indicate that it only takes a few minutes for the room to reach a dynamic equilibrium state of aerosol particles. Negative pressure rooms are in a cycle of continuous virus release and deposition. In the case of a double-bed room, the virus dispersion model differs from that of a single-bed room. In previous simulations of aerosol dispersion in single-bed rooms, the results mostly showed a single circulation pattern, where aerosols exhaled from the patient's mouth move in the initial direction and then rise within the room under the influence of diverted airflow, forming high-concentration areas between the ceiling and the exhaust outlet [17]. In the case of a double-bed room, the same characteristics of aerosol transmission are observed, with two circulation patterns formed on each side of the room and two high-concentration areas between the ceiling and the exhaust outlet. Most aerosols are carried to the exhaust outlet after rising for a period of time due to diverted airflow. The remaining aerosols continue to rise near the ceiling and are carried to other areas by the horizontal flow generated by the diversion of the ceiling airflow. Some airflow, when passing through the intake port, is influenced by the vertical airflow and flows towards the floor. Due to the effect of the floor, it is diverted and spreads to the corners of the room as shown in Figure6.

Figure 6 Single side airflow circulation diagram



Measurement results show that at a height of 0.5m, the concentration of aerosol particles in the high-concentration area is 46% higher than that in the low-concentration area. At a height of 1.5m, the concentration of aerosol particles in the high-concentration area is 60% higher than that in the low-concentration area. This is consistent with the predictions from the simulation results. It indicates that the exhaust outlet side of the negative pressure room has a higher concentration of aerosol particles. Referring to the study by Fabian et al. [15], the concentration reaches 4219 particles/0.1L, which is the position frequently accessed by healthcare workers. When healthcare workers are in these positions, they are exposed to a high concentration of viruses, posing a greater risk of infection.

The experimental and CFD simulation presented in this study were conducted under ideal conditions without the presence of personnel. However, in real-world situations, the presence of medical equipment, movement of personnel, and room size may have a significant impact on aerosol dispersion. When considering ventilation strategies to remove aerosol particles from the air, it is important to carefully consider various factors, including other factors that may affect the behavior of aerosol pollutants in the ventilation space.

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