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Research article

Evaluation of the distribution of COVID-19 particles in an Isolation room to reduce the possibility of transmission via CFD simulation

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ABSTRACT

The outbreak and prolonged COVID-19 pandemic has caused a population decline as well as a profound impact on the global economy, the COVID virus spreads highly in the air through the process of sneezing, contact leads to many dangers to the health and safety of people around the world. Many simulation studies have been carried out to predict the risk of spread, as well as to find solutions to limit the infection when spreading sneeze droplets in the air. In this study, the motion and distribution of droplets containing coronaviruses emitted by coughing or sneezing in the isolation room at Ho Chi Minh City, Vietnam National University were investigated using ANSYS Fluent software. The airflow in the isolation room was simulated by a 3D turbulence model and energy equation using the finite volume method (FVM) with a domain of isolation room solved for appropriate boundary conditions. The effect of ventilation airflow speed and the size of droplets on the distribution of particles in the air were investigated by the Lagrangian particle trajectory analysis method. The CFD analysis result showed that the velocity distribution, turbulent kinetic energy, and flow dynamics had strongly affected the reducing rate of average droplet concentration in the isolation room. Specifically, the study focused on the dispersion of liquid droplets containing the virus under fixed operating conditions of ventilation systems and exhaust fans, with a flow rate of 840 m^3/h. Under these conditions, the retention time of liquid droplets was determined to be 37.5 seconds, corresponding to droplet diameters ranging from 5 to 100 micrometres. The results indicate that the presence of particles in the room gradually becomes diluted over time due to the continuous circulation of air. The ability of air to diffuse within the vicinity of the occupant's position and the limited spread of small particles within the room demonstrate that the operating conditions are suitable.

Key words: COVID-19, CFD, isolation room, covid transmission, simulation

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INTRODUCTION

The outbreak of the COVID – 19 pandemic occurred at the end of 2019 and has continued to the present, caused leading to a decrease in the population as well as a profound impact on the global economy [1–3]. The Centers for Disease Control and Prevention (CDC) says that the novel severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) is highly airborne and is a potential pandemic hazard [4]. The occurrence of the COVID – 19 pandemic brings various challenges to scientists in medical research and other fields in many respects. The pandemic appears to have many variants, with acute respiratory syndrome occurring, leading to death if not treated properly. In many developing countries, such as Vietnam, the shortage of hospitals and medical centers is one of the leading causes of the global health crisis. Improper isolation and a lack of facilities to treat infections present a significant risk to the population's health. To improve this situation, many university student dormitories were requisitioned into an isolation area to support COVID – 19 patients. In addition, this utilization makes a significant contribution to the increase of the treatment area for the people as well as to the improvement of the overcrowding of the medical areas, the uniform distribution of human resources, and the reduction of the overload of the staff health care in the large city's central hospitals.

The World Health Organization (WHO) recommended factorial environmental control for isolation areas such as temperature and relative humidity due to the high infectious abilities of the virus. The viruses could be transmitted through direct or indirect interaction, such as human-to-human contact or by objects that an infected person has come into contact with. Many experimental studies have investigated the infection and behaviour of saliva droplets released during sneezing. The transmission of particles during a cough or sneeze is mainly determined by the size of the particles and the speed at which they propagate, and this process is rapidly increasing [5]. As a result, they were leading to difficulty in determining the in-

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fection process and the virus transmission rate by experimental methods. To facilitate the research, computational fluid dynamics (CFD) was used to aid in the rapid transmission survey, thereby predicting the behaviour of virus-containing liquid droplets in the isolation room and the office work environment public transport to help reduce the spread of infection[6]. Many ideas are presented in the simulation to support isolation, study, and work to protect human health. According to Hasan al et[7], improving the ventilation was performed based on CFD to reduce the spread of the virus and remove infectious particles. Mahshid Mirzaie et al.[8] simulated the airflow inside the classroom in the situation having a person who suddenly coughed. Besides, ventilation was investigated in the situation with partition and without partition. In particular, the mean concentration of the droplet was the highest in the without partition. In parallel, changing the exhaust fan speed showed that the retention time of the droplets in the classroom was reduced, predicting the behaviour of the particles accurately. Moreover, when coughing or sneezing, liquid droplets escape with an average velocity of about 1 –22 m/s[9]. Therefore, predicting the behaviour of liquid droplets containing the virus in the environment when sneezing or coughing is essential to predict the spread location to provide safe handling measures accurately. Social distancing is essential, but it's not the only determining factor in preventing airborne virus transmission. According to Hamid Motamedi et al.[10], an exposed person receiving only a tiny amount of virus per unit of time from a distantly infected person for a long enough time would reach a minimal infectious dose.

In this study, the Ho Chi Minh City National University Dormitory was used as an isolation area to investigate the transmission of particles inside the room. Based on the movement of the airflow and the exhaust fan, predict the most dangerous place when the isolated person in the ward suddenly sneezes. Thereby, surveying the retention time as well as the diameter of the liquid droplets containing the virus to know how long the particles are contained in the room, as well as know the position of the particles diffused to minimize the spread of the virus in the room, convenient for spraying disinfection after isolation. Furthermore, developing insights into infected surfaces under different real-world conditions has far-reaching applications in many other similar disease cases. The importance of ventilation in isolation rooms, homes or offices, and public places is of great concern after the COVID-19 pandemic. Because it will be a premise to form a factor determining the quality of health and mental health of all members of society, contributing to the design of a safe environment for sustainable development in the future.

MATERIAL AND METHODS

Geometry and mesh

In this study, the simulation investigates the fluid flow inside a dormitory working as an isolation room. Figure 1 presents the 3D (three-dimensional) model and the mesh in the room with 4 bunk beds and a closet. Table 1 shows the room's position and quantities of things and people. In particular, the dimensions of the geometry are defined as 8.0m (L) x 4.0m (W) x 4.0m (H) for full room, 2.0m (L) x 0.95m (W) x 2.1m (H) for each bed, 1.4m (L) x 1.2m (H) x 2.0m (H) for closet, 1.2m (W) x 1.2 (H) for the window and a 0.3m diameter of the exhaust fan. The grid generation is formed by the polyhedral method by ANSYS-Fluent with 1,583,310 cells and 7,141,545 nodes.

Mathematical models

This study performed three dimensions (3D) Eulerian – Lagrangian methods[11]. In order to simulate the airflow conditions, the Eulerian method is used, corresponding to the following governing equations for mass, momentum, and energy, respectively:

$$\frac{\partial\rho}{\partial t}+\nabla.\left(\rho\vec{V}\right)=0 \tag{1}$$

$$\rho\left(\frac{\partial\vec{V}}{\partial t}+\vec{V}\cdot\nabla\vec{V}\right)=-\nabla P+\mu\nabla^2\vec{V}+\vec{S} \tag{2}$$

$$\rho\frac{\partial T}{\partial t}+\rho.\vec{V}\left(T\vec{V}\right)=\nabla\left(\frac{K}{C_p}\nabla T\right)+S_T \tag{3}$$

The airflow inside the room is numerically modeled by the RNG k-ε model[12], where k and ε are the turbulent kinetic energy and dissipation rate. The model is presented by two transport equations concerning k and ε:

$$\begin{gathered}\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho k u_i)=\frac{\partial}{\partial x_j}\left(\alpha_k\mu_{eff}\frac{\partial k}{\partial x_i}\right)\\+G_k+G_b-\rho\varepsilon-Y_M+S_k\end{gathered} \tag{4}$$

$$\begin{gathered}\frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial x_i}(\rho\varepsilon u_i)=\frac{\partial}{\partial x_j}\left(\alpha_k\mu_{eff}\frac{\partial\varepsilon}{\partial x_j}\right)\\+C_{1\varepsilon}\frac{\varepsilon}{k}\left(G_k+C_{3\varepsilon}G_b\right)-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}-R_\varepsilon+S_\varepsilon\end{gathered} \tag{5}$$

Where:

- G_k: Turbulence kinetic energy due to mean velocity gradients
- G_b: Turbulence kinetic energy due to buoyancy
- Y_M: Fluctuating dilatation in compressible turbulence

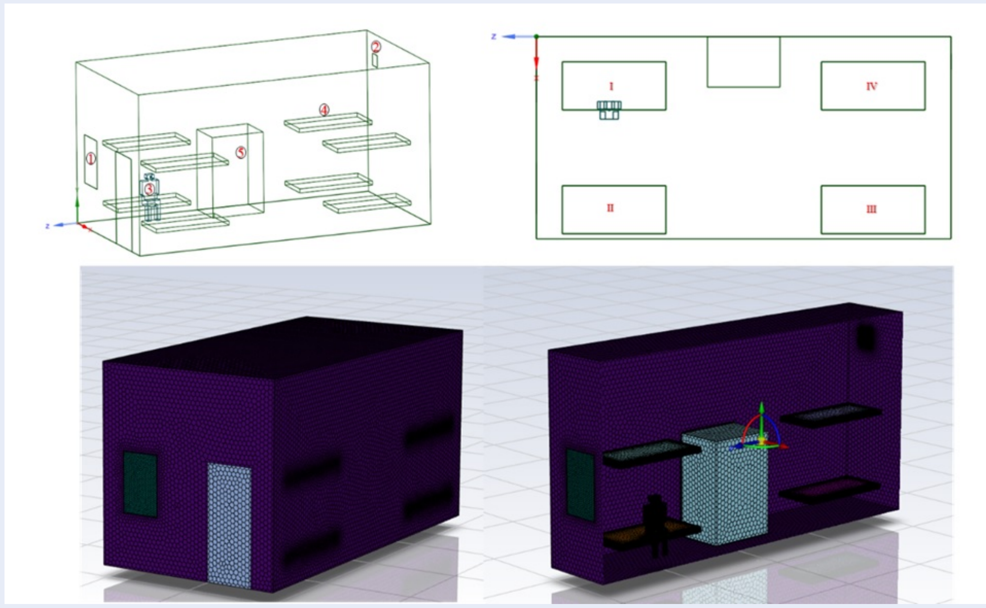

Figure 1: Geometry and mesh of the dormitory

Table 1: The detail of position and quantities of things and persons inside the dormitory room.

Name	Position	Quantity
Window	1	01
Exhaust fan	2	01
Person	3	01
Bunk bed	4 (I, II, III, IV)	04
Closet	5	01

- α_k, α_ε : Inverse effective Prandtl number
- S_k, S_ε : User-defined source terms

To track the movement of liquid droplets containing the COVID-19 virus through space when suppose a person in an isolation room suddenly coughs or through a cough stream field that converts to droplets. The 3D Lagrangian approach, which is used in combination with the discrete phase model (DMP) [13,14], is defined as follows:

$$\frac{dV_d}{dt} = F_D\left(\vec{V} - \vec{V}_d\right) + \frac{\vec{g}\,(\rho_d - \rho)}{\rho_d} + F_L + F_B \quad (6)$$

In this equation, F_L and F_B are Saffman lift force and Brownian force, respectively. While the drag force coefficient is defined by F_D, subject to the following equation:

$$F_D = \frac{18\mu}{p_d d_p^2}\frac{C_D Re}{24} \quad (7)$$

$$C_D = \alpha_1 + \frac{\alpha_2}{Re} + \frac{\alpha_3}{Re^2} \quad (8)$$

Where a_1, a_2, and a_3 are constants for smooth particles for the Reynold number in the range of 0 to 50000, given by Morsi and Alexander [15]. Re is the Reynold number, and μ is the viscosity. Also, the mass flow rate of the droplets with the evaporation in the air is presented by the following equation:

$$-\frac{dm}{dt} = k_c A_p\left(C_{v,s} - C_{v,bulk}\right) \quad (9)$$

Where:

- k_c: mass transfer coefficient
- A_p: droplet surface
- $C_{v,s}$: partial pressure vapour of droplet surface
- $C_{v,bulk}$: partial pressure vapour of the gas bulk

The mass transfer coefficient given in equation (9) is investigated from the following Sherwood number correlation [16]:

$$Sh_{AB} = \frac{k_c d_p}{D_{i,m}} = 2.0 + 0.6 Re_d^{1/2} Sc^{1/3} \qquad (10)$$

Where:

- $D_{i,m}$: diffusion coefficient of vapor in the bulk
- Sc: the Schmidt number
- d_p: particle (droplet) diameter

Case study

The passing of the covid epidemic has left many serious consequences, but thanks to the impact of the pandemic, improving physical and mental health has received more and more widespread attention. Focusing on improving the living environment and preparing in advance for situations such as a pandemic will be more careful. Promoting proactive approaches to protecting public health and promoting research and development of virus actions spread through computational simulation is necessary. Therefore, to contribute to the design of a safe environment for disease prevention and treatment, this study simulates the flow behaviour inside a dormitory room used as a field hospital or an isolation area. The goal is to understand the behaviour of the airflow inside the room, thereby predicting the behavior and retention time of the cough or sneeze droplets of the patient. In this study, a person's cough in this room is modeled by 10800 droplets of different sizes ejecting from a 4m^2 circular surface which describes a mouth. The sizes of droplets are distributed in six uniform groups: the minimum size is 0.15μm, and the maximum size is up to 150μm, as detailed in Table 2. The droplet temperature is assumed to be 37°C with 10 m/s velocities at the mouth. Because the droplet is too small (less than 1μm) the Brownian force is included in this study [17].

Computational settings

The ANSYS-Fluent program [18], which employs the FVM, was used to solve the governing equations. The error between the two successive iterations for all variables was set to 10^{-6} as the convergence criteria. The boundary and operating conditions as shown in Table 3 and Table 4. The airflow throughout the isolating room with natural velocity in the window and exited by the exhaust fan with its value is 840 m^3/h. A person sitting on the bed (I) suddenly coughed with a velocity value of 10 m/s, as shown in Table 2.

RESULTS AND DISCUSSIONS

Airflow distribution

The distribution of airflow velocity inside the dorm room is shown in Figure 2, figured out by vector, volumetric rendering, and YZ plane at the exhaust fan and window locations. To ensure ventilation of the isolation room, windows and exhaust fans are assumed to be open. Based on the results, the air from the environment sucked into the room by the exhaust fan has a relative velocity value of 0.49 m/s, corresponding to the maximum velocity at the output value of 3.028 m/s. In addition, the results indicate that the bed (I) near the door to the window is most affected by the airflow from the window. Based on this data, patients sitting in bed position (I) are more likely to disperse virus-containing droplets than in other positions when they suddenly cough or sneeze. Therefore, bed (I) is a dangerous location, and the isolation and distribution of people need to consider choosing the most appropriate location to limit the spread of the virus. The isolation area uses 04 lower beds in all bunk beds (the upper beds are for personal storage) and the room can only be used for one person.

Particle residence time

The residence time of the virus droplets is investigated, as shown in Figure 3. In particular, the time coughing or sneezing. The particle distribution at different times for the cases where the inlet velocities are natural convection and with the exhaust fan activated to mix the air in the room. In these figures, the distributions of particles emitted at different times from 1s to 37.5 s are presented. Ventilated air significantly affects particle dispersion and transport. At 1s after sneezing, the particles disperse near the sitting side, until after about 1s to 3s, the particles begin to fall and stick to the bed and floor surfaces. From the time from 5s to 10s, 20s, 30s, the particles adhere and gradually disappear due to the air circulation inside the room, as well as because the particle concentration becomes gradually diluted when the exhaust fan continuously sucks the air out. By 37.5 seconds, most of the sneeze droplets had been absorbed.

Particle diameter

Figure 4 shows the behaviour of particles of different sizes as shown in Table 2. In which the figures show the diameters of the sudden sneezing or coughing particles of a person at different time points of residence as 1s, 3s, 5s, 10s, 20s, 30s, and 37.5s, and is illustrated similarly to Figure 3. A cough or sneeze produces a

Table 2: The droplet information when the person sneezed [8]

Diameter (μm)	Particles velocity (m/s)	Numbers of particles	Injection time (s)	Mass flow rate of particles (kg/s)
0.150	10	1800	0.750	4.2413×10^{-15}
1	10	1800	0.750	1.2566×10^{-12}
10	10	1800	0.750	1.2566×10^{-09}
50	10	1800	0.750	1.5706×10^{-07}
100	10	1800	0.750	1.2566×10^{-06}
150	10	1800	0.750	4.2413×10^{-06}

Table 3: Boundary condition

Boundary	Material	Parameters	Value
Wall	Concrete	Thickness [m]	0.1
Window	Moist air	Temperature [K]	306.15
		Mass fraction	0.024
Exhaust fan	Moist air	Pressure [at]	1
		Flow rate [m3/h]	840
Mouth	Water liquid	Table 2	[10]

Table 4: Operating condition

Operating condition	Governing Equations
Solver	3D simulation Implicit formulation Absolute velocity formation Transient state analysis
Energy equation	Activated
Viscous model	Turbulence (k-epsilon)
Discrete phase model	Eulerian-Lagrangian

velocity of 10 m/s for a duration of 0.75 s. In addition, the liquid droplets varied in size from 4.3x10^{-5} to 0.00015 m according to the color scale, with the droplets with smaller diameter dispersed above (dark blue), and the droplets with larger diameter dispersed below at the time 1s. Retention time is from 5s to 30s, the concentration of particles becomes gradually diluted, and only most of the large diameter particles remain. After a period of 37.5s, almost only a very small number of liquid droplets are left on the surface of the bed and floor.

CONCLUSION

Based on simulation to predict the dispersion of virus-containing liquid droplets under fixed operating conditions of natural ventilation and exhaust fan with a flow rate of 840 m^3/h. Corresponding to this condition, the retention time of the liquid droplets is 37.5s, corresponding to the diameter from 5 to 100. The result is only that the existence of particles in the room will gradually dilute with the rotation process continuity of the air, the ability to diffuse in the range around the occupant position, and the spread of droplets in the room is not much, proving that the operating conditions are suitable.

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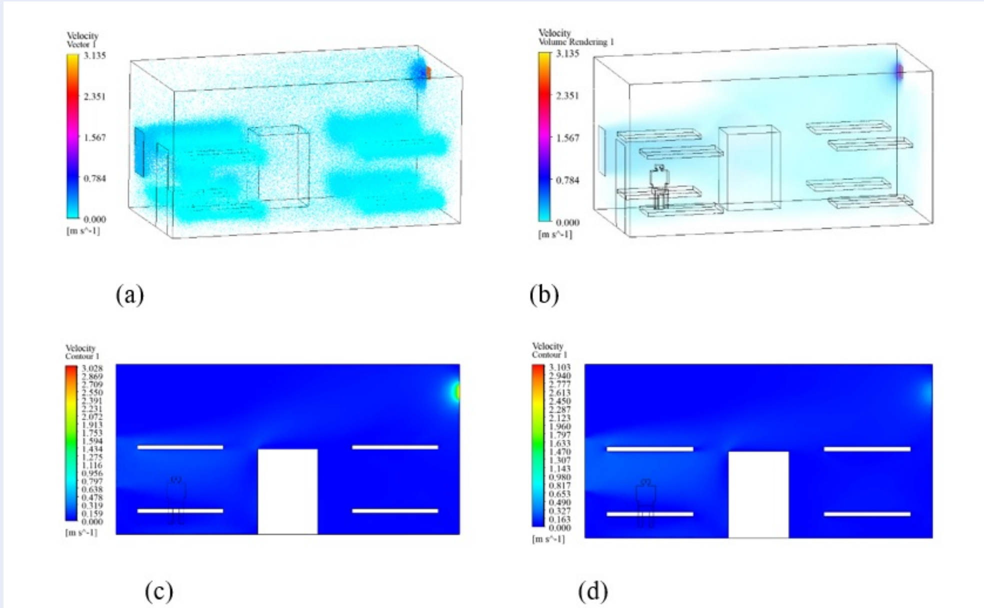

Figure 2: The velocity distribution inside the dormitory room: Velocity vector (a); Velocity volume rendering (b); Velocity distribution at the exhaust fan plane (c); Velocity distribution at the window plane (d).

COMPETING INTERESTS

The authors declare that they have no competing interests.

AUTHOR CONTRIBUTION

Viet Tan Tran and Yen Hoang Phi Duong Conceptualization; Datacuration; Roles/Writing - original draft; Writing - review & editing; Tan Minh Le Conceptualization; Datacuration; Roles/Writing-original, draft, review& editing. Duc Tan Le Formal analysis; Investigation; Visu-alization, review & editing. Viet Tan Tran Funding acquisition; Methodology; Project administration; Re-sources; Supervision. Both Viet Tan Tran and Yen Hoang Phi Duong contributed equally and have the right to list their name first in their CV. All authors contributed to the article and approved the submitted version.

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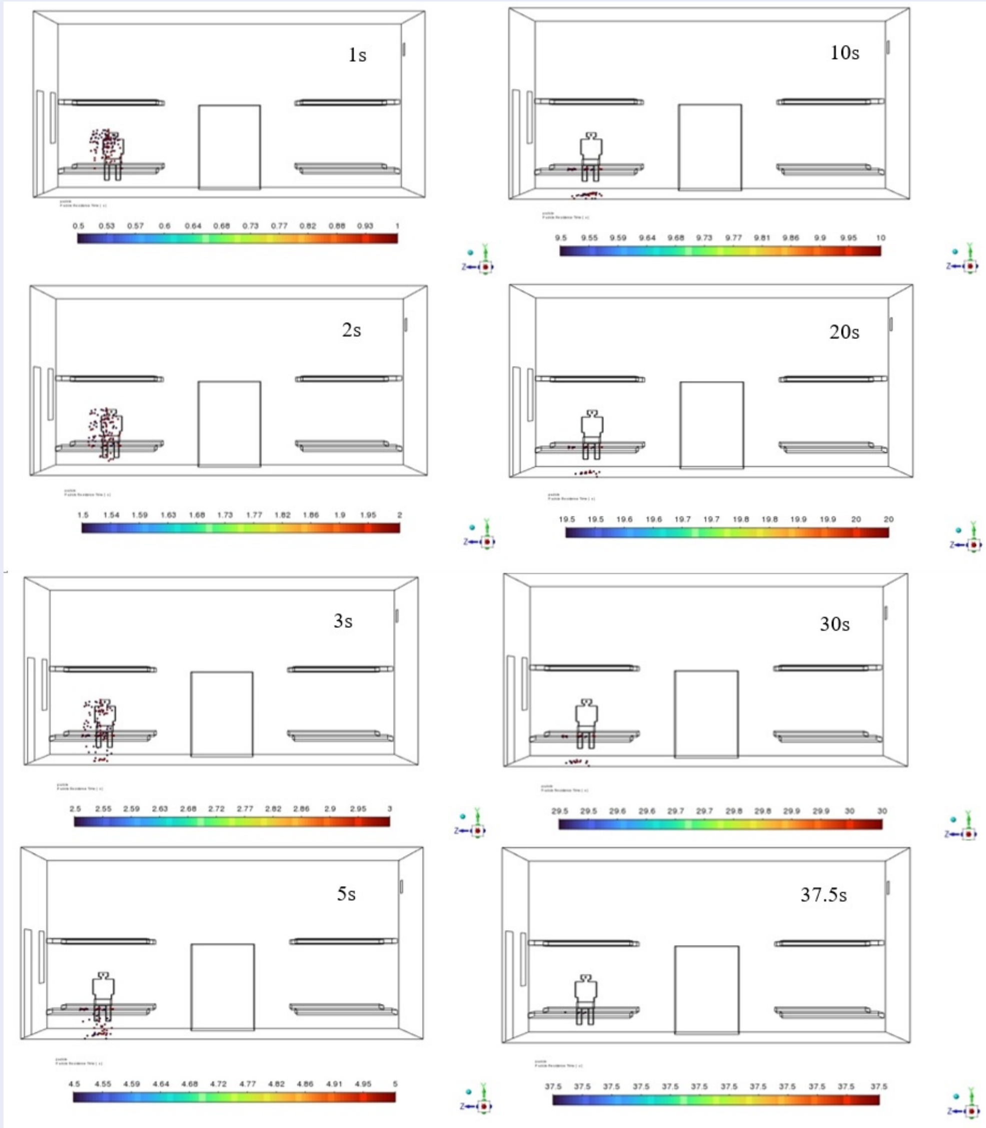

Figure 3: The particle residence time from 1s to 37.5s

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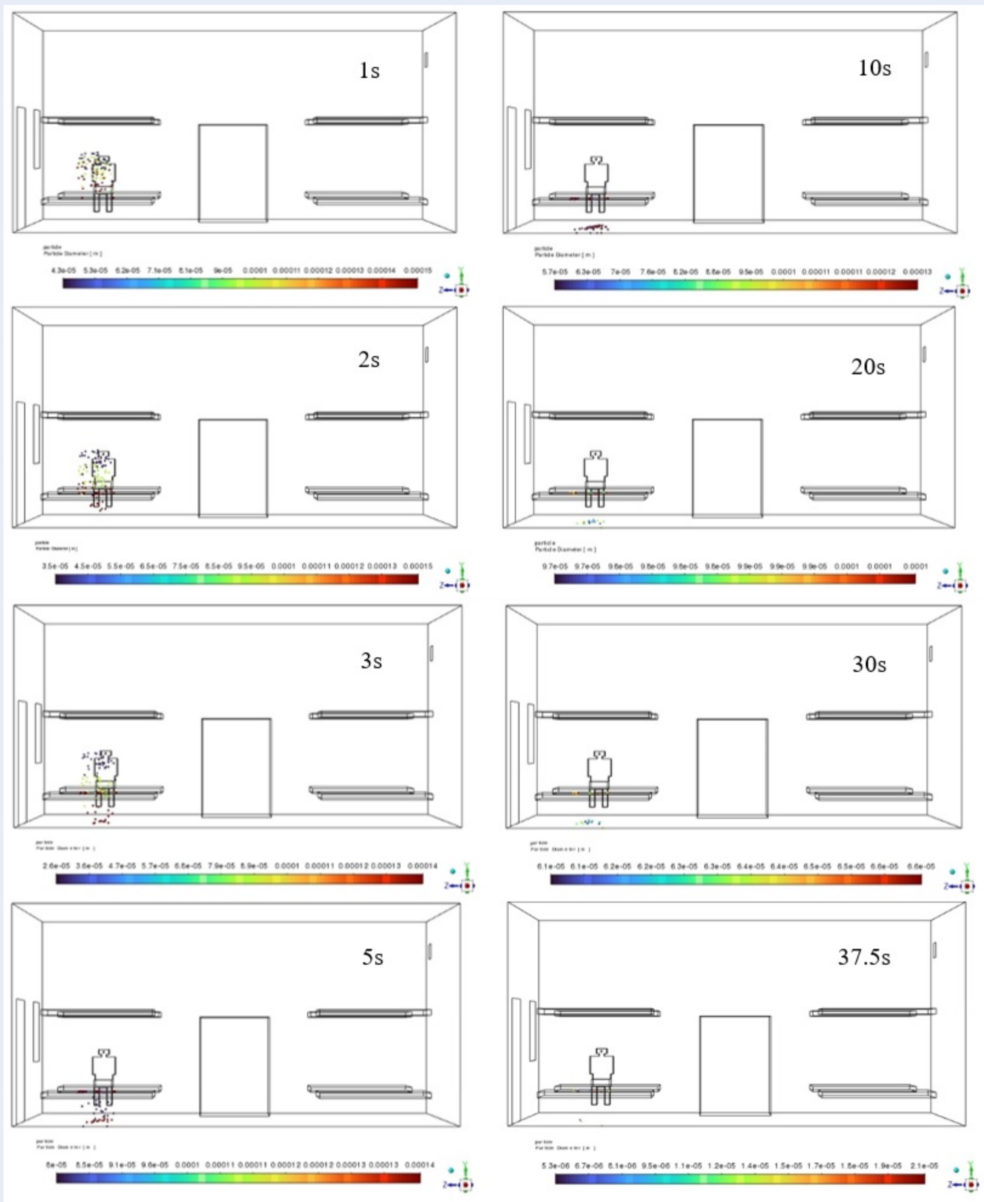

Figure 4: The diameter of particle droplets in isolating room

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Đánh giá sự phân bố của các hạt COVID-19 trong phòng cách ly để giảm thiểu khả năng lây nhiễm thông qua mô phỏng CFD

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TÓM TẮT

Đại dịch COVID-19 bùng phát và kéo dài đã gây suy giảm dân số cũng như ảnh hưởng sâu sắc đến nền kinh tế toàn cầu, virus COVID lây lan cao trong không khí thông qua quá trình hắt hơi, tiếp xúc và dẫn đến nhiều nguy hiểm cho sức khỏe cũng như sự an toàn của mọi người dân trên thế giới. Nhiều nghiên cứu mô phỏng đã được thực hiện nhằm dự đoán nguy cơ lây lan, cũng như tìm giải pháp hạn chế lây nhiễm khi phát tán các giọt hắt hơi chứa virus trong không khí. Trong nghiên cứu này, chuyển động và sự phân bố của các giọt chứa virus corona phát ra khi ho hoặc hắt hơi trong phòng cách ly tại Đại học Quốc gia Thành phố Hồ Chí Minh được khảo sát bằng phần mềm ANSYS Fluent. Luồng không khí trong phòng cách ly được mô phỏng bằng mô hình nhiễu loạn 3D và phương trình năng lượng bằng phương pháp thể tích hữu hạn (FVM) với miền của phòng cách ly được giải cho các điều kiện biên thích hợp. Ảnh hưởng của tốc độ luồng không khí thông gió và kích thước của các giọt lỏng đối với sự phân bố của các giọt trong không khí đã được nghiên cứu bằng phương pháp phân tích quỹ đạo hạt Lagrangian. Kết quả phân tích CFD cho thấy sự phân bố vận tốc, động năng rối và động lực dòng chảy đã ảnh hưởng mạnh đến tốc độ giảm nồng độ giọt trung bình trong phòng cách ly. Cụ thể, nghiên cứu tập trung vào sự phát tán của các giọt chất lỏng chứa virus trong điều kiện hoạt động cố định của hệ thống thông gió và quạt hút, với lưu lượng 840 m3/h. Trong các điều kiện này, thời gian lưu của giọt chất lỏng được xác định là 37,5 giây, tương ứng với đường kính giọt từ 5 đến 100 micromet. Kết quả chỉ ra rằng nồng độ của các hạt trong phòng dần dần bị loãng theo thời gian do không khí lưu thông liên tục. Khả năng khuếch tán không khí trong vùng lân cận vị trí của người ngồi và sự lan truyền hạn chế của các hạt nhỏ trong phòng chứng tỏ rằng các điều kiện vận hành là phù hợp.

Từ khoá: COVID-19, mô phỏng, phòng cách ly, CFD, động lực học dòng chảy

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