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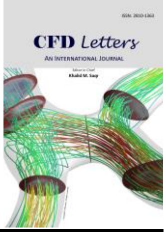

An Analysis of Air Conditioning System Operation Patterns on Droplet Particle Distribution in a Classroom-A CFD Approach

Luthfi Hakim[1,2], Wawan Aries Widodo[1,*], Sutardi[1], Anton Nugroho[1], Zain Lillahulhaq[1]

[1] Department of Mechanical Engineering, Sepuluh Nopember Institute of Technology (ITS), Surabaya, Indonesia
[2] Department of Mechanical Engineering, Universitas Islam Majapahit , Mojokerto, Indonesia

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ABSTRACT

In the classroom context, the transmission of pathogens among students is a significant concern. Therefore, it is important to determine appropriate airflow patterns, the placement of supply and exhaust ventilation, and the optimization of classroom design to reduce the risk of pathogen transmission. This research aims to determine the performance of two air conditioning (AC) operating patterns—low speed and high speed—in six scenarios involving window and door configurations and identify the most effective strategies for minimizing virus exposure to occupants in classrooms. The method used in this research is numerical simulation with the 3D unsteady k-ε RNG model to simulate air flow and the Eulerian-Lagrange approach to capture the movement of SARS-CoV-2 aerosol droplets. The results of this research show that of the six scenarios determined by the researchers, the low-speed AC operating pattern with an incoming air speed of 3.5 m/s occurs in scenario 5, that is, all windows open and doors closed. This is based on the lowest number of students exposed to the virus, which is 22.22%. Meanwhile, the high-speed AC operating pattern with an incoming air speed of 6 m/s occurs in scenario 2, that is, all windows closed and doors open. This is based on the lowest number of students exposed to the virus, which is 22.22%, so it can be concluded that increasing the air flow speed originating from the AC will speed up the droplets to leave the room through the outlet. Meanwhile, increasing the outlet capacity will shorten the particle path, thereby shortening the time when the droplets are in the classroom.

1. Introduction

The influenza (H1N1) pandemic in March 2009, the Severe Acute Respiratory Syndrome (SARS) outbreak in November 2002-2003, and the COVID-19 pandemic caused by the coronavirus (SARS-CoV-2) have served as stark reminders that airborne transmission of infectious diseases remains a serious and potentially life-threatening concern for human health. The transmission patterns of these diseases involve the dispersal of infectious agents through respiratory droplets or small airborne particles. These droplets can be inhaled by individuals at distances of approximately 1 to 2 meters [1, 2]. There is substantial evidence that the spread and transmission of airborne diseases are

* *Corresponding author.*
E-mail address: wawanarie@its.ac.id (Wawan Aries Widodo)

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significantly influenced by the indoor air ventilation systems [2–10]. For example, with SARS-CoV-2, transmission can occur through contact with infected individuals, respiratory secretions, as well as through droplets released by infected individuals [11–17]. Corona virus transmission can take place both directly through contact or proximity to infected individuals and indirectly through contact with surfaces previously touched by infected individuals, and even via droplets expelled by infected individuals [7, 18–23]. Airborne transmission can be depicted as the dissemination of virus-carrying agents through the processes of exhalation and inhalation. The evaporation of droplets generates microscopic aerosols, while breathing and speaking produce exhaled aerosols. As a result, individuals vulnerable to such aerosols may inhale them and become at risk of virus infection.

Indoor ventilation is closely linked to the risk of respiratory infections [24–32] and plays a crucial role in reducing pathogen transmission during human respiratory processes. Therefore, it is essential to identify the correct airflow direction, placement of supply/exhaust vents, and optimize room design to minimize the risk of pathogen transmission. Classrooms, as environments prone to COVID-19 infection among students, have garnered significant research attention. Various factors, such as particle size, aerosol source location, glass barriers, and windows, have been explored [33]. It has been observed that a significant proportion of particles smaller than 15 µm (ranging from 34% to 50%) exit the system through the air conditioning within a 15-minute period, while particles larger than 20µm tend to settle on the floor, desks, and adjacent surfaces in the room. Other studies have investigated the impact of ventilation airflow rates (3 m/s, 5 m/s, 7 m/s) on the dispersion of droplets of different sizes [34]. It was found that the highest average droplet concentration was 3.8×10^{-8} kgm^{-3} at an airflow rate of 3 m/s. Notably, the highest concentrations were not only near the infection source but also increased significantly in the vicinity of the outlet. Consequently, the presence of students in these areas elevated the risk of disease transmission [27].

Room conditions can be carefully designed to ensure the safety and comfort of its occupants. Various factors have been considered to achieve these conditions. Indoor air humidity (relative humidity) [35–37], the number of individuals, and the room size significantly impact the transmission of pathogens through the air. Furthermore, this can be achieved through airflow adjustments and the configuration of existing air ventilation systems in classrooms [26 ,27, 34, 38, 39], hospitals [8, 29, 40], and public transportation [41, 42]. Predictions of the number of students infected by the virus have been made based on the concentration of particles that settle on surfaces such as faces or student desks [43]. Residential time is also a parameter that can be used as a basis for evaluating the risk of infection within a room [38]. The concentration of particles can be reduced by up to 95% when the airflow and air ventilation system in the room is correctly adjusted. In other words, the available ventilation becomes a parameter to control the concentration of viruses in the air. Therefore, ventilation and air circulation systems play a crucial role in controlling virus-contaminated air.

Classrooms are recognized as high-risk environments for airborne disease transmission due to their crowded nature and the level of activity among their occupants [44, 45]. Therefore, it is crucial to conduct research that provides recommendations to reduce the spread of airborne diseases within classrooms. In this study, the performance of air ventilation systems (both mechanical and natural) is examined because they can significantly impact the airborne transmission of diseases from infected individuals. Taking into account various pathogen transmission mechanisms and the results of a literature review conducted by the researchers, the study attempts to mitigate airborne transmission within classrooms by enhancing air circulation systems. Simulations are conducted to analyze the unsteady airflow distribution within the classroom under various ventilation scenarios, with the aim of creating classroom conditions that are relatively safe from the spread of SAR-CoV-2 aerosols.

Based on the background explained above, the aim of this research is to determine the performance of two air conditioning (AC) operating patterns that is low speed and high speed in six scenarios involving window and door configurations and identify the most effective strategies for minimizing virus exposure to occupants in classrooms. This is done to reduce the spread of SAR-CoV-2 aerosols by adjusting the operating speed pattern of the AC (low speed and high speed) and adjusting the opening/closing pattern of classroom windows and doors. The lowest transmission occurs when SAR-CoV-2 particles take the shortest path and require a relatively short time to leave the room [38]. In addition, the average particle concentration decreased over time and was inversely proportional to the ventilation rate of air in the classroom. Higher air ventilation velocities result in lower average droplet concentrations within the classroom [34].

Adjustment of air flow ventilation speed patterns (low speed, high speed) along with window and door scenarios as outlets that can control the spread of droplets in the classroom. Increasing the air ventilation speed can speed up the removal of particles from the classroom. However, the path the particles travel becomes wider and can cause significant transmission. Conversely, reducing the air ventilation speed can result in an increase in the average concentration of settled particles in the classroom. In addition, this research was carried out by varying the ventilation speed of the air flow in an open/closed window and door scenario, allowing the incoming air to interact with the droplet particles emitted by the source and facilitating the rapid exit of these particles from the classroom via the shortest path. As a result, the particle concentration decreases over time.

2. Methodology

2.1 Physical Model

The research method employed in this study is numerical simulation. This method was chosen to assess the impact of AC operation patterns on the distribution and transmission of SARS-CoV-2 contaminated aerosol droplets. The performance of two air conditioning (AC) operation patterns, low speed and high speed, was tested under six scenarios involving window and door configurations. In general, the droplets were tracked in each of the six different ventilation conditions, as shown in Table 1. The six scenarios were chosen to see the distribution of SARS-CoV-2 particles originating from the teacher in front of the class by opening or closing the window, causing the outlet capacity in the room to increase and the number of particles to spread more quickly and leave the room. Thus, this scenario can estimate the number of students exposed to the classroom. One of the best scenarios was selected based on the minimization of infections. The tracking was based on the concentration of particles adhering to the 36 students present in the classroom.

Table 1
Introducing scenario

Scenario	Definition
Scenario 1	All windows and door closed
Scenario 2	All windows closed and door open
Scenario 3	Windows number 1 open and door closed
Scenario 4	Windows number 1 and 2 open and door closed
Scenario 5	All windows open and door closed
Scenario 6	Windows number 1 and door open

Table 1 shows 6 scenarios for ventilation arrangements in classrooms. The six scenarios were selected based on outlet capacity and outlet location in the classroom. By increasing the outlet capacity and arranging the right outlet location, particles can be accelerated to leave the room and can take the shortest path so as to reduce the concentration of particles that settle in the room. The greater the outlet capacity, the more opportunities for particles to leave the room through the outlet [9]. These conditions can minimize exposure to room occupants, thereby minimizing transmission of the SARS-CoV-2 between occupants. In this study, a numerical model for the dispersion and transmission of SARS-CoV-2 was conducted in two stages. The first stage involved the simulation of steady-state classroom turbulence using the RNG-k-epsilon model. This model is very suitable for describing various types of turbulent flows. With a total of 36 students in the classroom, it is estimated that there are many areas full of vortices, so this model is very effective in modeling this case [27]. The RNG k-ε turbulence model has been widely utilized to simulate airflow in indoor spaces [46] and the RNG model includes the effect of swirl on turbulence, enhancing accuracy for swirling flows [47]. In the second stage, droplet particles emitted by infected individuals were tracked using the Eulerian-Lagrange method. Particle tracking was performed over a 30-second period following their release from the infection source, taking into consideration the short evaporation time of droplet particles, which is influenced by relative humidity [1, 35, 48]. This research aimed to comprehensively investigate the spread of SARS-CoV-2 within a classroom environment, considering the dynamics of both airflow and infectious particle transport.

Figure 1(a) represents the simulation domain of the classroom, which measures 10m × 7m × 3m, accommodating 36 students (with a seated student height of 1.3 m) and one teacher as the source of virus-carrying particles (with a height of 1.7 m) located at the front of the classroom. The classroom is equipped with two electric ventilations (AC), each measuring 1.1m × 0.3m × 0.3m, and three natural ventilations (windows) measuring 1m × 1.1 m, along with one door measuring 1.4m × 2m. The classroom's interior includes desks and chairs. The teacher's desk measures 1.4m × 0.05m × 0.75m, and the student desks measure 0.7m × 0.05m × 0.75m (Figure 1(b)). There are two electric ventilations (AC) installed at the back of the classroom, three windows, and one door serving as outlets. The AC produces cool air at 20°C, with speeds of 3.5 m/s and 6 m/s for the low-speed AC operation and high-speed AC operation respectively. The numbering of students is done with the aim of facilitating the determination of the quantity and positions of students affected by droplets released by the teacher standing at the front of the classroom.

Referring to various sources from previous research, the modeling for AC is modeled using one boundary condition that is the inlet speed. This is because the speed of air flow entering the room is the main factor that influences air circulation and temperature distribution in the room.

To ensure that simulation results are no longer dependent on the mesh count, a grid independence test was conducted without the presence of droplets. The mesh count was chosen by considering five levels of refinement, ranging from very coarse to very fine (Table 2). ANSYS Meshing generated a polyhedral mesh type, as illustrated in Figure 2. The accuracy of polyhedral meshes closely approximates hexahedral meshes and surpasses tetrahedral meshes. However, the number of cells in polyhedral meshes is roughly half that of hexahedral meshes and only about a quarter of the tetrahedral mesh count [49]. This approach ensures that simulation results are not excessively influenced by the mesh refinement level used in the analysis.

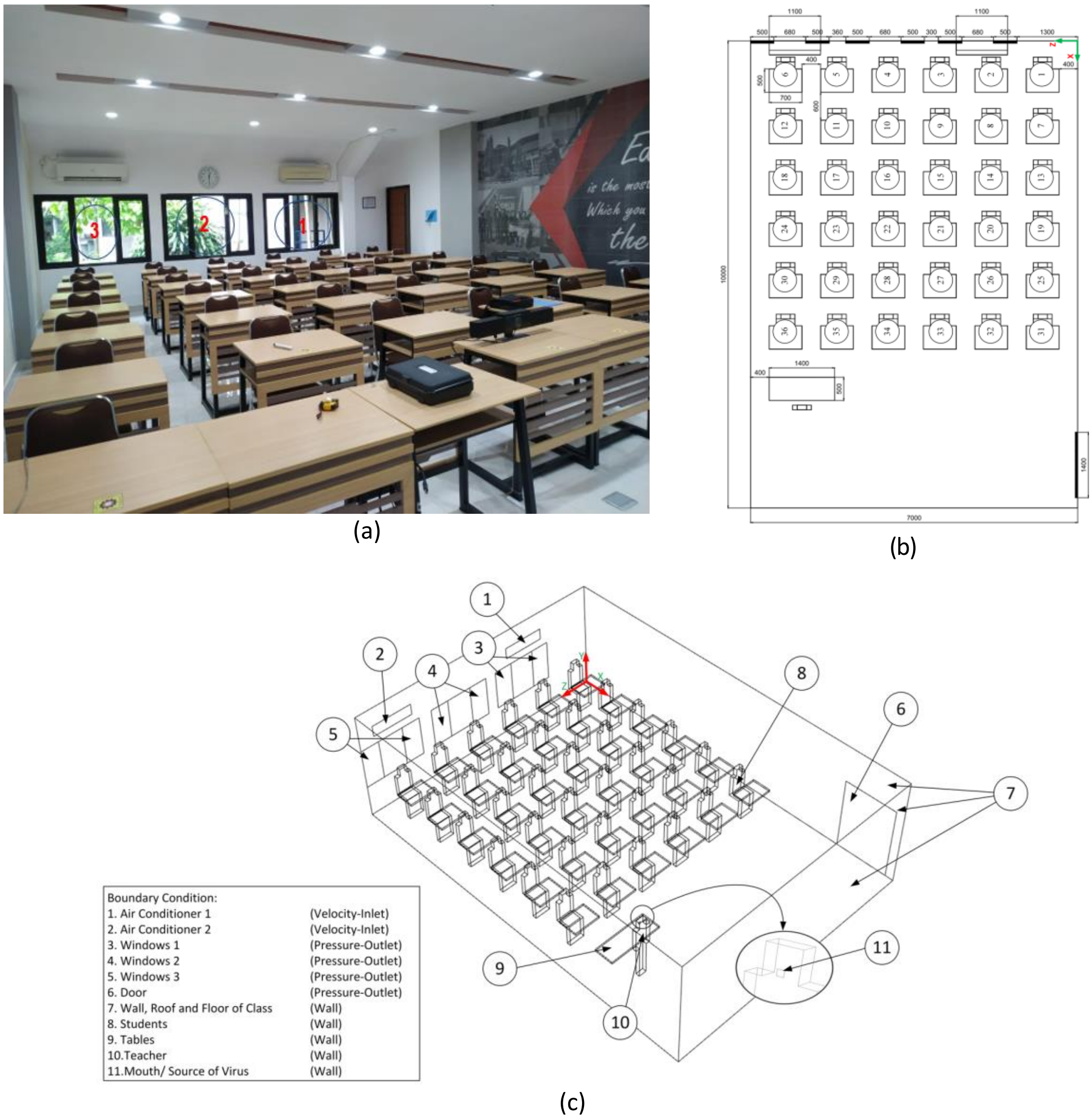

Fig. 1. Classroom geometry and schematics (a) Classroom in Surabaya, Indonesia (b) Geometric model of classroom from top view (c) The 3D model isometric view

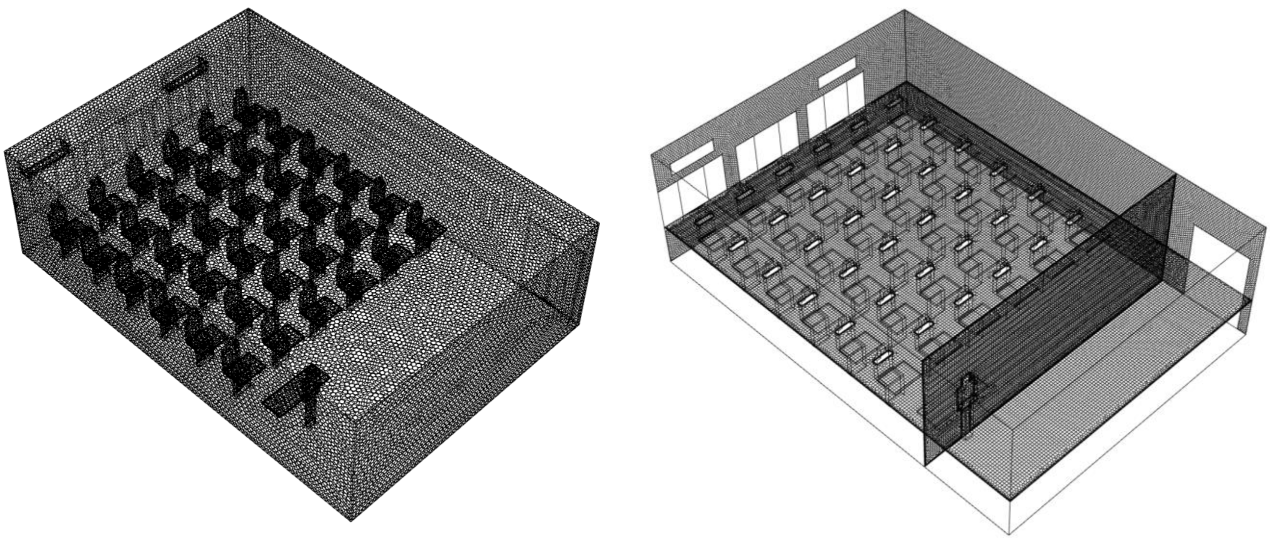

Fig. 2. Classroom mesh of the computational model

The comparison of simulation results with direct measurements was performed at the point X=1.95; Y=2.2; Z=6.25. This was conducted under the condition where all windows were closed, the door was open, and the AC was operating in high-speed mode. Air velocity measurements from the AC outlet were obtained using an anemometer. The grid independence test results indicated that the medium mesh type, with a cell count of 1372046, was selected and subsequently used as the parameter for meshing. In addition to having the smallest error, the medium mesh exhibited a Velocity magnitude (m/s) value that did not significantly differ from the fine mesh (1524327), despite the substantial difference in cell count (Figure 3). This choice ensures that the simulation results are robust and not highly sensitive to variations in mesh granularity.

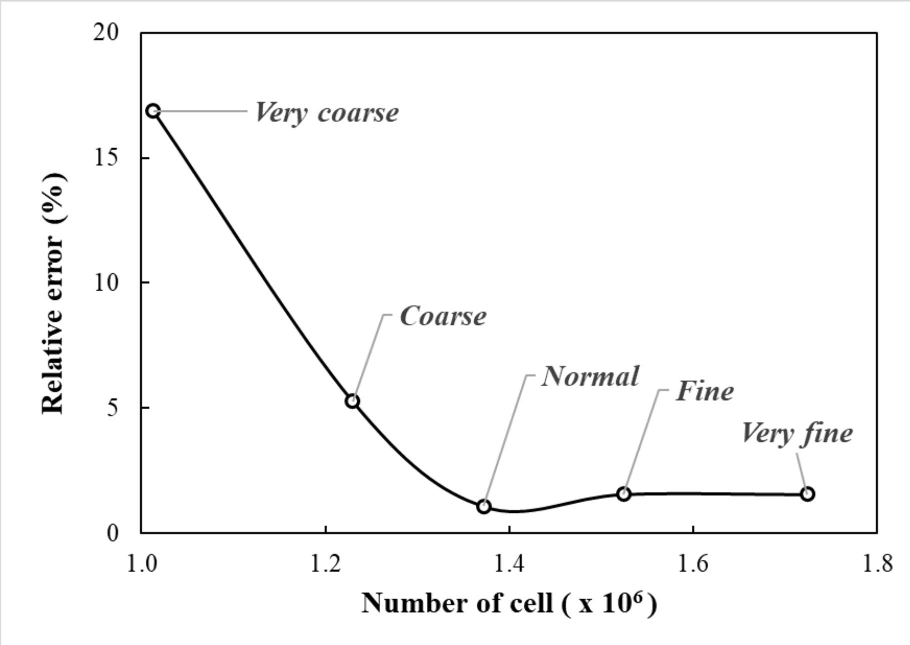

Fig. 3. Relative error

Table 2
Grid independence test

Mesh refinement	Cell number	Velocity magnitude (m/s) from numerical measurement	Velocity magnitude (m/s) from actual measurement	Relative difference (%)
Very coarse	1012796	3.05	2.61	16.88
Coarse	1229646	2.47	2.61	5.27
Normal	1372046	2.58	2.61	1.07
Fine	1524327	2.65	2.61	1.55
Very fine	1724159	2.65	2.61	1.55

2.2 Numerical Method

In this research, 10 µm diameter droplets are emitted from a person's mouth in front of a classroom when coughing. The droplet particles are injected from the mouth of the individual with a source surface area of 0.001 m × 0.002 m, which is positioned in front of the classroom. These particles are very small with low inertia, allowing them to evaporate rapidly after leaving the source. The estimated total number of particles released from the source is 36000 (all particles contaminated with the SARS-CoV-2) [50]. However, for the purposes of this study, the assumed number of particles is 10800 [34]. Table 3 provides detailed information about the particles when injected from the source.

Table 3
Details of DPM for water liquid

Particle component	Water liquid
Density	$998.2\frac{kg}{m^3}$
Specific heat capacity	$4.182\frac{kJ}{kg}K$
Drag low	spherical
Turbulent dispersion	Stokes Tracking: Particle Random Walk Model (DRWM)
Injection	Particle size: 10 μm Injection velocity: 10 ms^{-1} Injection type: surface

Computational Fluid Dynamics (CFD) is employed to model the dispersion and transmission of SARS-CoV-2 aerosol droplets when a lecturer (as the source) coughs within a classroom environment. In this scenario, particle behavior is investigated under steady-state conditions. To understand the interaction between the dispersed and continuous phases, the simulation is conducted in two steps, beginning with the steady-state classroom's turbulent airflow and subsequently transitioning to the unsteady state. The ANSYS-Fluent program, utilizing the finite volume method, is utilized to solve the governing equations. The convergence criteria are set at a value of 10^{-6}.

This validation involved the evaporation of a 10 µm droplet expelled through coughing at a mass flow rate of $5.24 \times 10^{-11}\text{kgs}^{-1}$ under 10% humidity conditions. It was assumed that the droplets are released from the mouth at a temperature of 37°C, while the room temperature is also 37°C. Notably, the disparities between our work and Li *et al.,* results are less than 1%. The second validation depicts the airflow patterns in a classroom. The simulation domain matched the classroom dimensions, which are 10 m × 7 m × 3 m. This validation was carried out by extracting velocity values at predefined coordinates and comparing them to the simulated velocity data obtained through measurements. The validation results are shown in Figure 4.

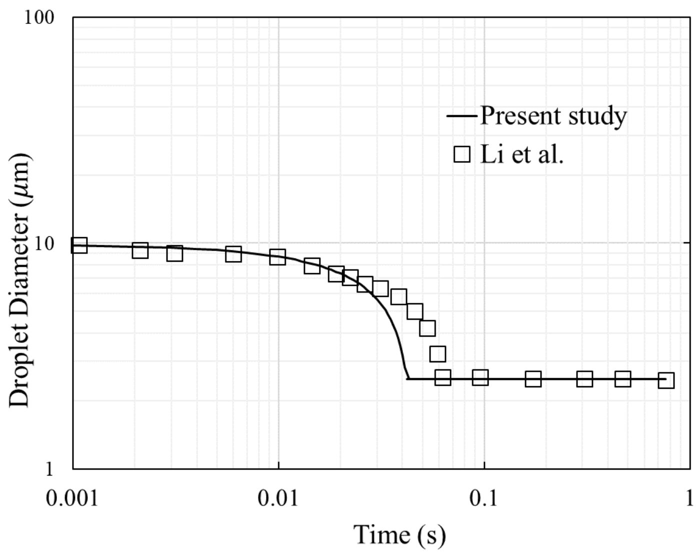

Fig. 4. Comparison the outcomes of current research regarding the evaporation of a 10 μm droplet with those obtained by Li *et al.,* [48]

2.3 Mathematical Model

For the incompressible steady flow, the general equation of conservation of mass, momentum, and energy applies as follows:

$$\frac{\partial \rho}{dt} + \nabla \cdot (\rho \vec{v}) = 0 \tag{1}$$

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

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

The RNG k-ε turbulence model has been utilized to simulate airflow in indoor settings and has proven to be an appropriate model for this investigation. Below is the equivalent transport equation for dissipation rate ε and turbulent kinetic energy k:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma k}\right)\right] + G_k + G_b\ - \rho\varepsilon - Y_M + S_k \tag{4}$$

$$\frac{\partial}{\partial t}(\rho\varepsilon) + \frac{\partial}{\partial x_i}(\rho\varepsilon ui) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma\varepsilon}\right)\frac{\partial\varepsilon}{\partial xj}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}(C_k + C_{3\varepsilon}G_b) - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} + S_\varepsilon \tag{5}$$

Where, $C_{1\varepsilon}$, $C_{2\varepsilon}$, $C_{3\varepsilon}$, σ_k, and σ_ε constants.

The droplet movement is tracked using a Lagrange approach. For very small droplets (micron-sized) with a droplet density that is much greater than the carrier fluid (air), the interfacial forces that depend on density are ignored. The Lagrange equation used is as follows:

$$m_d\frac{d\overline{U_d}}{dt} = \vec{F}_{Buoy} + \vec{F}_D \tag{6}$$

$$\vec{F}_{Buoy} = \frac{\pi d^3}{6}(\rho_f - \rho_d)\vec{g} \tag{7}$$

$$\vec{F}_D = \frac{C_D}{2}\frac{\pi d^4}{4}\rho_m\left|\vec{U}_d - \vec{U}_m\right|\left(\vec{U}_d - \vec{U}_m\right) \tag{8}$$

Mass flow rate of particles is presented as:

$$\dot{m} = \frac{\frac{4}{3}\pi r^3 \times \rho_d \times n}{t} \tag{9}$$

Where n and ρ_d are the number and density of particles, respectively.

In this research, there are several assumptions used, including the following: (1) temperature variations are ignored; (2) Coughs only consist of particles/droplets; (3) Students do not wear masks when in the classroom; (4) particle size of droplets is 10 μm and (5) evaporation is ignored.

3. Results

In this section, the dispersion patterns of particles generated from a source are analyzed under various airflow patterns, including the configurations of air conditioning (AC) input and the ventilation patterns of air exiting through windows and doors. The airflow distribution within the indoor environment (continuous phase) is presented in the form of flow visualization. Furthermore, we present the impacts of the existing airflow distribution within the room on the transmission of SARS-CoV-2 droplets from the source (instructor) to a group of 36 students (dispersed phase). In this case, the airflow in the classroom is evaluated using the transient k-ε RNG turbulence model. The incoming air for cooling originates from the AC inlet installed in the classroom, and there are two types of outlets, one door, and three windows, located on the backside of the classroom. Particle tracking is conducted over a duration of 30 seconds, commencing after the particles are released from the source.

3.1 Results of Continuous Phase

The airflow speed entering through the inlets is a critical factor that significantly influences the formation of recirculation zones and directly impacts the range of air movement within the studied domain. In research aimed at understanding and optimizing indoor air quality and thermal comfort, airflow speed serves as a fundamental parameter. The rate at which air is introduced into a space not only affects the distribution of contaminants, heat, or conditioned air but also plays a pivotal role in maintaining a healthy and comfortable environment. Proper management of inlet airflow speed can help minimize stagnant regions, reduce the potential for pollutant accumulation, and promote efficient heat distribution, making it a key focus in studies that aim to enhance indoor air quality and thermal performance.

Ventilation within a classroom is closely related to respiratory infections and plays a vital role in reducing pathogens generated during the respiratory process. The patterns and directions of airflow inside the classroom are critical factors that can influence the trajectory of droplets produced from the infection source [32–34, 43, 49]. In general, air sourced from the HVAC system flows out at relatively high speeds and then disperses throughout the room in various directions. Figure 5 illustrates the velocity field distribution of indoor airflow during low-speed operation of the air conditioning system. These vortices are formed due to the placement of individuals, objects, and the classroom's geometry. These zones can potentially trap pathogens for a considerable amount of time, making them areas prone to exposure to viruses.

The airflow within the classroom is highly dependent on the locations of the inlets and outlets available in the room. As shown in Figure 5, the airflow sourced from the inlets follows a straight path until it encounters the opposite wall, then it is distributed in various directions throughout the classroom. However, some of it returns towards the inlets or does not flow effectively throughout the entire classroom.

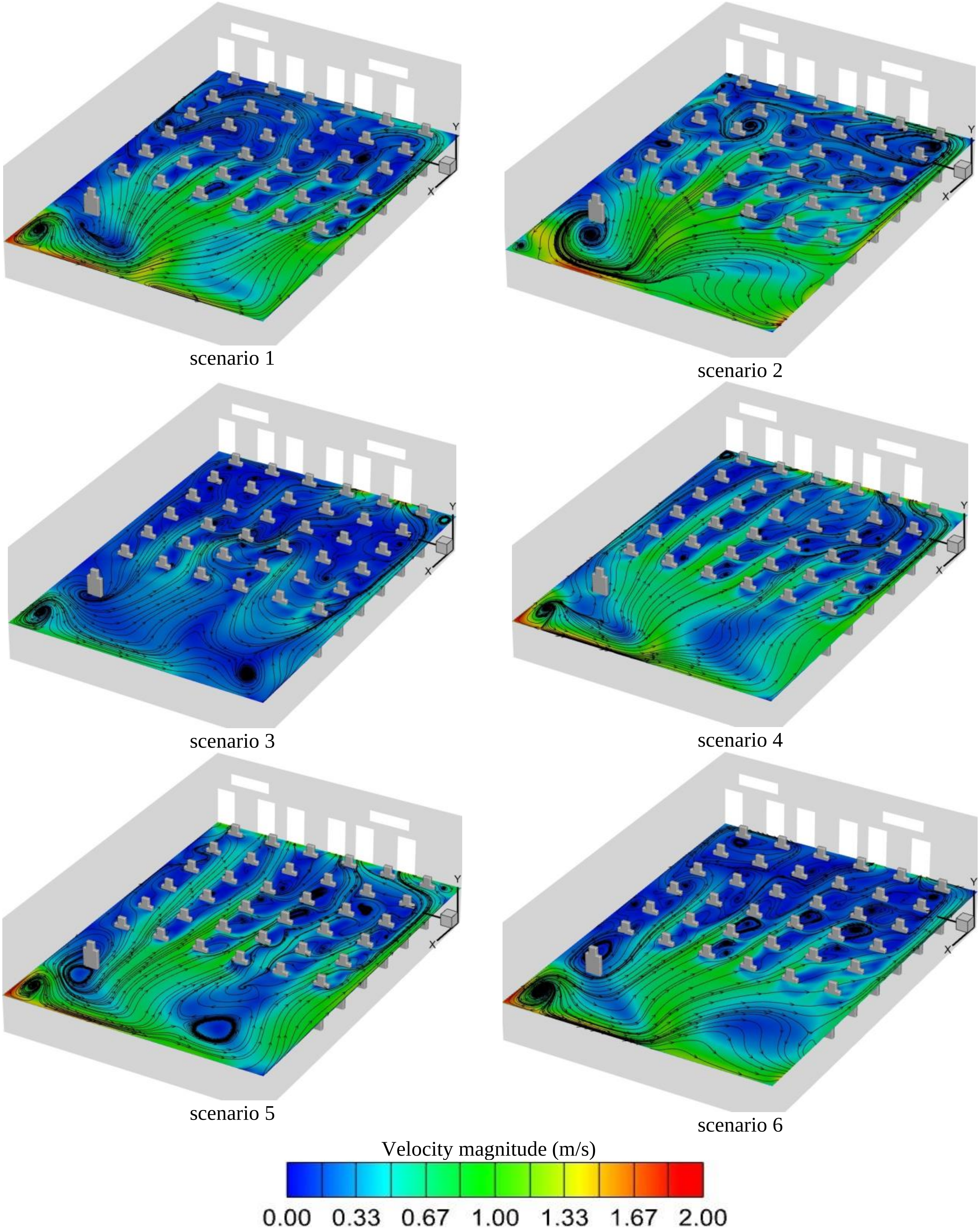

Fig. 5. Velocity magnitude of indoor air flow at low speed operation pattern on the isometric view for all scenario

Figure 5 shows that the speed of the air flow entering through the inlet also plays a role in forming the recirculation zone and influences the range of air movement across the domain. Velocity magnitude contours are taken at a distance of one meter from the floor surface. The picture in scenario 1 shows that the direction of air flow originating from the AC cannot leave the room. This is because all ventilation is closed so that a recirculation zone is formed evenly in the room. This is different from the pictures in scenarios 2, 3, 4, 5, and 6 which show that the direction of air flow originating from the AC can exit through open ventilation, either through doors or windows so that the recirculation zone formed is uneven or more dominant at several points. For example, in scenarios 3 and 5 there is a recirculation zone formed in front of the class.

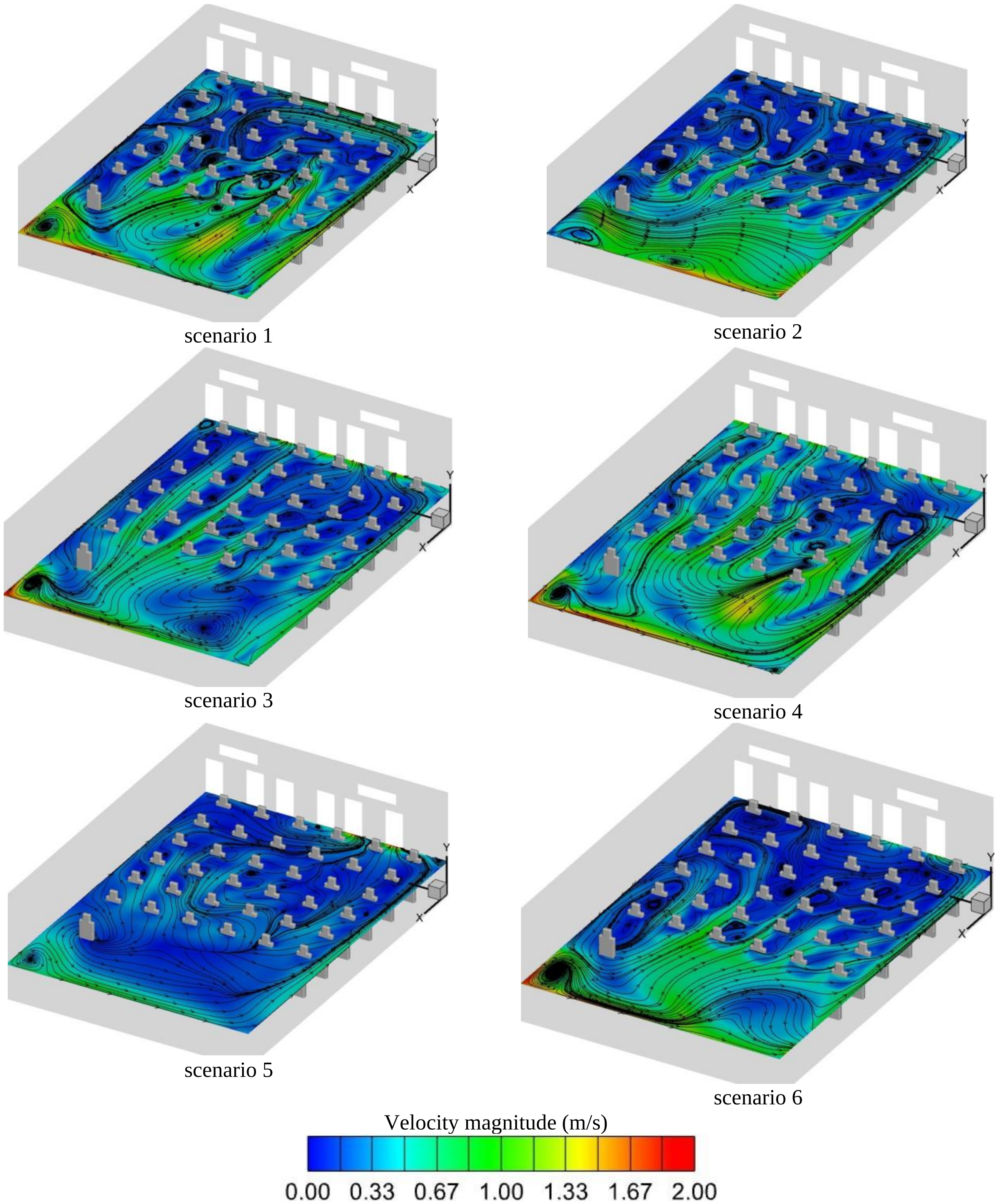

Fig. 6. Velocity magnitude of indoor air flow at high speed operation pattern on the isometric view for all scenario

Figure 6 shows that the speed of air flow entering through the inlet with a high speed AC operation pattern causes many recirculation zones to form at several points. This is because when air at high speed enters the classroom it tends to have inertia which makes it difficult to change direction suddenly, causing the air to bounce off the walls or interior (objects) in the room and creating a recirculation zone behind the object. In addition, the high speed of the air flow will cause an imbalance in the distribution of air in the room. This means some areas may receive too much airflow while others receive little airflow. Areas that receive too much air flow can become recirculation zones because air becomes trapped. From the six scenarios, it can be seen that scenario 5 has the fewest recirculation zones compared to the other scenarios. The indoor air flow in scenario 5 has been directed out towards the outlet after hitting the wall in front of the classroom.

3.2 Result of Dispersed Phase

Dispersed Phase in this study describes two parameters that is particle residence time and droplet concentration. Particle residence time refers to the average time required by particles in the air stream before leaving the classroom through the outlet. These parameters depend on the air flow velocity, particle size distribution, and the geometry and boundary conditions of the classroom. Meanwhile, particle droplet concentration is the number of particles dispersed in the air flow at a location and at a certain time.

Dispersed Phase refers to the particles from the droplets produced by the source during a single cough. It has been assumed that all droplets produced from the source are virus particles. This is considered to be a representation of virus particles carried by air currents and some of which settle in the occupant's body. When the source coughs, the droplets produced are very small and become Dispersed Phase and then spread throughout the classroom.

In this research, particle concentration refers to how many SAR-Cov-2 droplets are floating in the air and settling on the body surface of occupants in the classroom. through particle residence time and the amount of concentration that settles on the surface of the student's body, it will provide information about how long the particles are in the air and how many particles stick to the surface of the occupant's body. The higher the concentration of particles floating in the air, the greater the possibility that people in the room will be exposed to the virus. The concentration of particles that settle on the occupant's body is measured in the mass of particles per volume of air (kilograms per cubic meter) [29, 34].

3.2.1 Particle residence time

Particularly in the context of SARS-CoV-2 droplets, is a crucial parameter to consider in understanding disease transmission dynamics. The residence time refers to the duration that virus-laden respiratory droplets remain suspended in the air. This parameter is highly relevant for assessing the risk of exposure in various indoor and outdoor settings. Research has shown that smaller respiratory droplets can remain airborne for longer periods, potentially increasing the likelihood of inhalation by individuals nearby. Understanding particle residence time is vital for designing effective ventilation systems, public health guidelines, and protective measures to reduce the spread of SARS-CoV-2, contributing to the overall management of the pandemic.

Figure 7 shows that the particle residence time in all scenarios is towards the outlet. This is because the very small droplet size has a lower gravitational force and the air flow tends to move from the high pressure area to the low pressure area so that the particles will be easily carried by the air flow towards the outlet.

Figure 8 illustrates the distribution of particle droplets within the classroom over a 30 second period for all scenarios. The distribution of particles that occurs in all scenarios adjusts the direction of the air flow out towards the outlet. Over time, these particles move and spread to various classroom areas and are influenced by the air flow towards the outlet. For example, in scenario 1 the particles spread throughout the room evenly because the ventilation is closed. In contrast to scenarios 2, 3, 4, 5, and 6, the particle distribution leads to the outlet. In scenario 2, the distribution of particles is more concentrated at the front of the class because the outlet is at the front of the class so no particles are found at the back of the class. In scenarios 3, 4, and 5, the outlet is at the back and causes particles to concentrate at the back of the classroom, thereby allowing students sitting at the back to be exposed to the virus. Meanwhile, in scenario 6 there are two outlets (front and back) so that the particles are distributed in all directions and allow more students to be exposed.

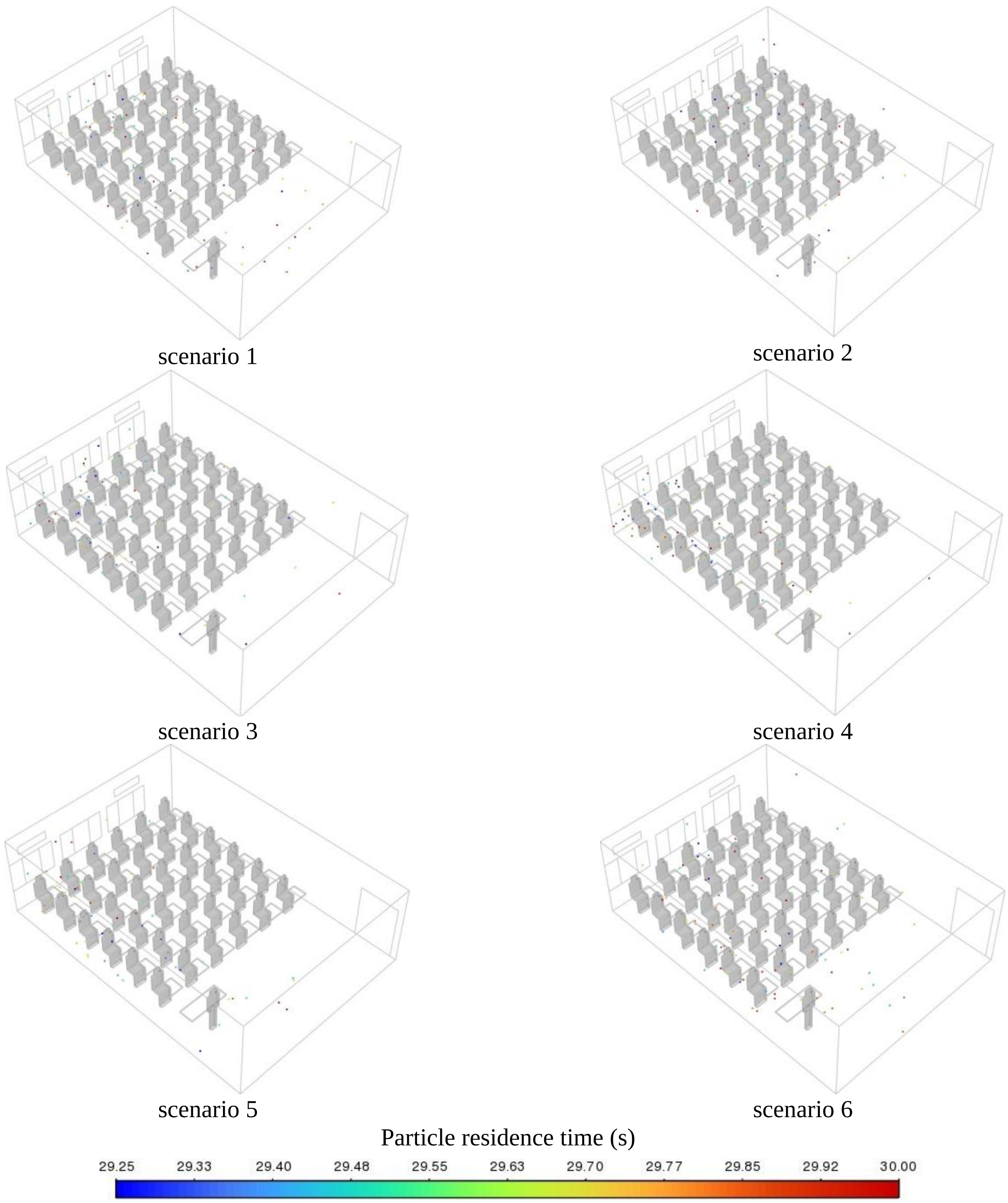

Fig. 7. Illustrates the droplet distribution 30 seconds after exiting the infection source for all scenario in the low-speed AC operation pattern

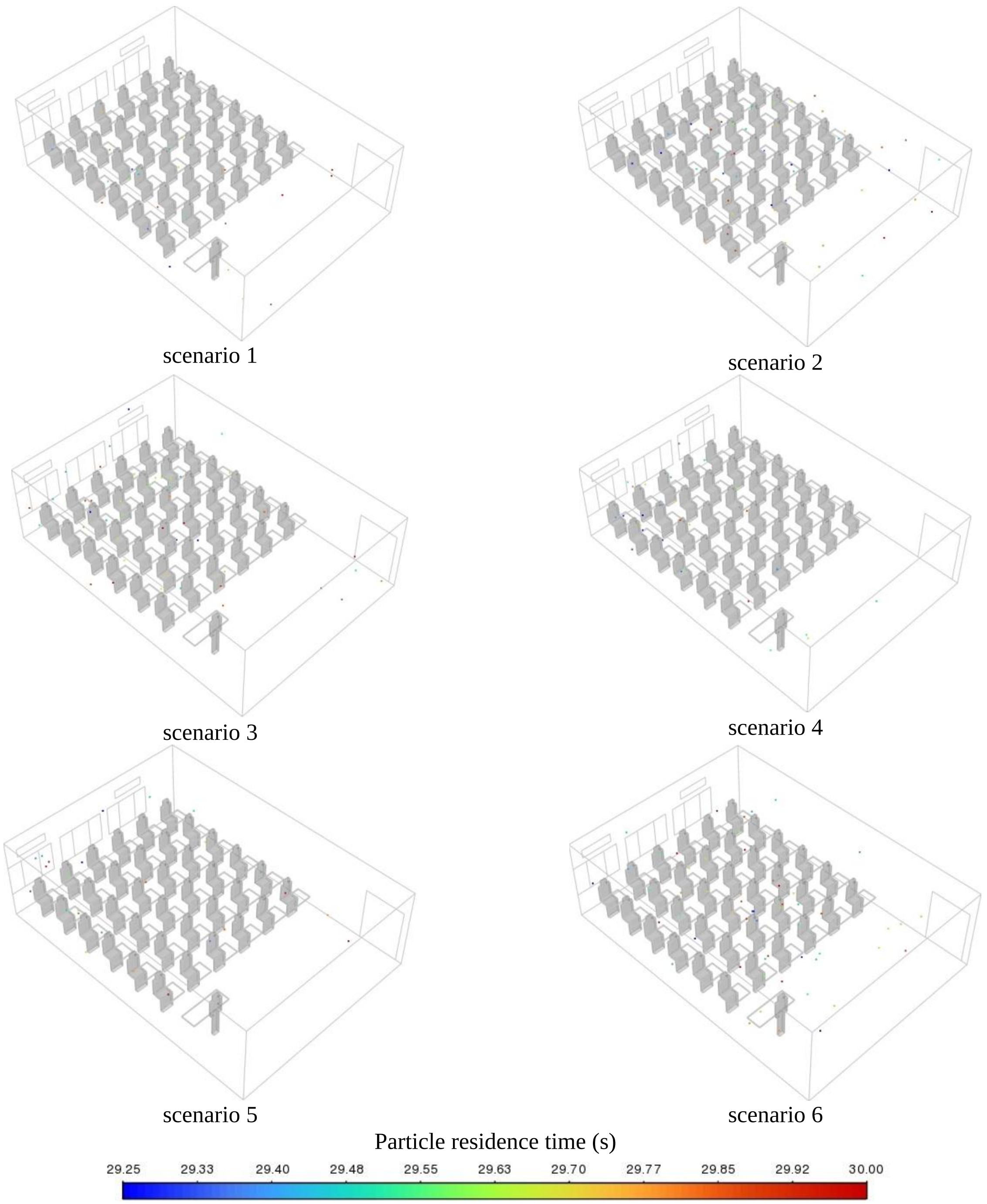

Fig. 8. Depicts the droplet distribution 30 seconds after exiting the infection source for all scenario in the high-speed AC operation pattern

3.2.2 Droplet concentration

Droplet concentration refers to the amount of concentration that sticks to the surface of the student's body. To find out the average concentration of droplet particles attached to students' bodies, it can be identified by location or seating position that is at high risk of transmitting SARS-CoV-2.

Figure 9 describes the average concentration of droplets trapped in the student's body in the low speed AC operation pattern. In general, the highest number of students exposed to droplets was seen in Scenario 4. Of the 36 students, 15 (41.67%) students were exposed. Students exposed included numbers 11, 12, 17, 18, 23, 24, 27, 28, 29, 30, 32, 33, 34, 35, and 36. Among these scenarios, exposure to the highest droplet concentration occurred in student number 36 amounting to 7.24×10^{-8} kgm^{-3}. While the lowest concentration of 3.25×10^{-16} kgm^{-3} trapped to student number 35. When compared to the study conducted by Mirzaie *et al.,* [34], these concentrations are higher. The highest average particle concentration is 7.24×10^{-8} kgm^{-3}.

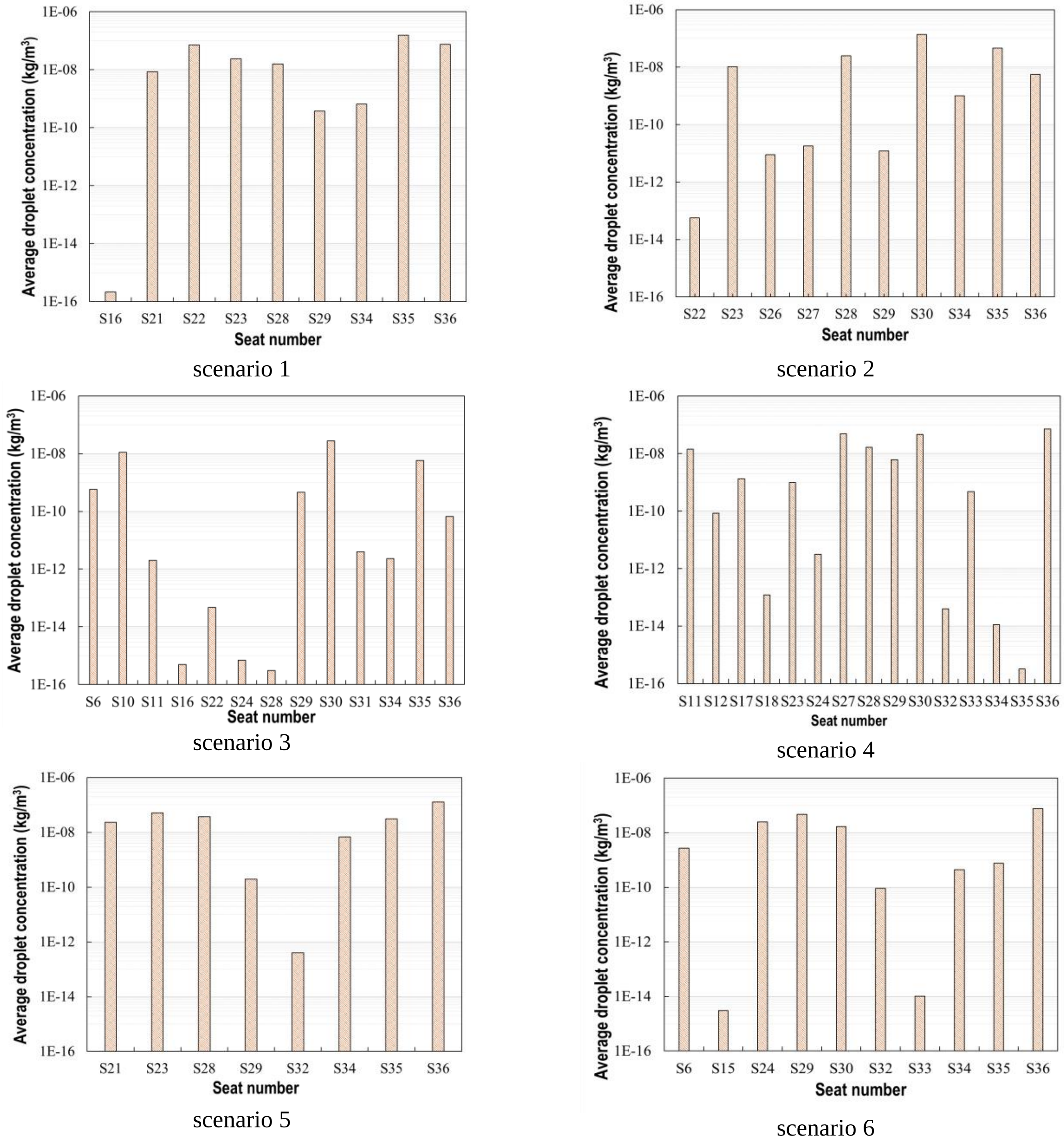

Fig. 9. Average droplet concentration trapped on the student body at low speed AC operation pattern for all scenario

Furthermore, from Figure 9, it can be explained that the scenario with the fewest students exposed is Scenario 5. In scenario 5, 8 out of 36 students are infected (22.22%). These include students 21, 23, 28, 29, 32, 34, 35, and 36. The student with the highest particle concentration is student number 36, with 1.29×10^{-7} kgm^{-3}, while the student with the lowest concentration is student number 32, with a concentration of 3.94×10^{-13} kgm^{-3} adhering to their body.

Students seated to the left of the source tend to have a higher risk of infection compared to those on the right side of the source. This is because particles emitted by the source have lower inertia, causing droplet particles to follow the direction of fluid flow. The trajectories of particles that travel further and against the flow direction from the inlet result in droplet particles spreading throughout the room (when the door is closed).

Figure 10 presents a graph of the average concentration of droplet particles adhering to students' bodies for each scenario with the high-speed AC operation pattern. Among the six scenarios, the highest potential for student infection occurs in scenario 3. Out of the 36 students in the classroom, 14 (38.89%) students were exposed. The highest concentration of droplets adheres to student number 18, with a quantity of 3.4×10^{-8} kgm^{-3}. While the lowest concentration adheres to student number 29, with 2.2×10^{-16} kgm^{-3}. The highest particle concentration in the study conducted by Mirzaie *et al.,* [34] was 3.8×10^{-8} kg/m³, which is higher than the concentrations obtained in this study. This strengthens the idea that scenario 2 is the most effective. Furthermore, Figure 6 indicates that scenario 2 is the most effective in reducing infections. A total of 8 out of 36 students (22.22%) are exposed to COVID-19, as evidenced by the concentration of particle particles adhering to the students' bodies. These students include numbers 5, 14, 26, 27, 31, 33, 34, and 35. The highest concentration of particles adheres to student number 5, with 1.89×10^{-8} kgm^{3}, while the lowest concentration adheres to student number 32, with 1.08×10^{-11} kgm^{-3}.

The high-speed AC operation pattern, opening the door can shorten the particle path for exiting the room, reducing the number of infected students. The higher AC inlet speed can propel particles out of the room more quickly, thus reducing the time particles spend in the room. This can decrease the risk of infection. This effect can also be attributed to the proximity of the source locations to the outlet (door) compared to the source to outlet (window), causing the flow pattern to guide particles out before spreading to other areas, thus shortening their path.

Based on the research results on the number of particles attached to students' bodies, it shows that the best scenarios are scenario 5 and scenario 2 for low speed and high speed AC air flow patterns respectively. However, scenario 5 becomes the worst scenario when the AC operating pattern is increased. Among all scenarios, the three priority students who contracted the virus were students number 34, 35, and 36. Based on this figure, the average number of droplet particles attached to students 34, 35, and 36 occurred in all scenarios of low-speed AC operation. This suggests that students in front of teachers (the source of the virus) generally have a higher risk, and their risk percentage depends greatly on the airflow pattern in each scenario.

The research findings presented in this paper provide valuable insights into the dispersion of particles within a classroom setting, specifically focusing on the Dispersed Phase. The data analysis reveals important patterns and factors influencing the spatial distribution of particles, such as the influence of ventilation systems, human movement, and the size of the particles. Understanding these dispersion dynamics is crucial for assessing the risk of airborne diseases, including the transmission of respiratory infections like SARS-CoV-2, within educational spaces. These results contribute to our knowledge of indoor air quality and can guide the design and implementation of effective ventilation and hygiene strategies to create safer and healthier learning environments.

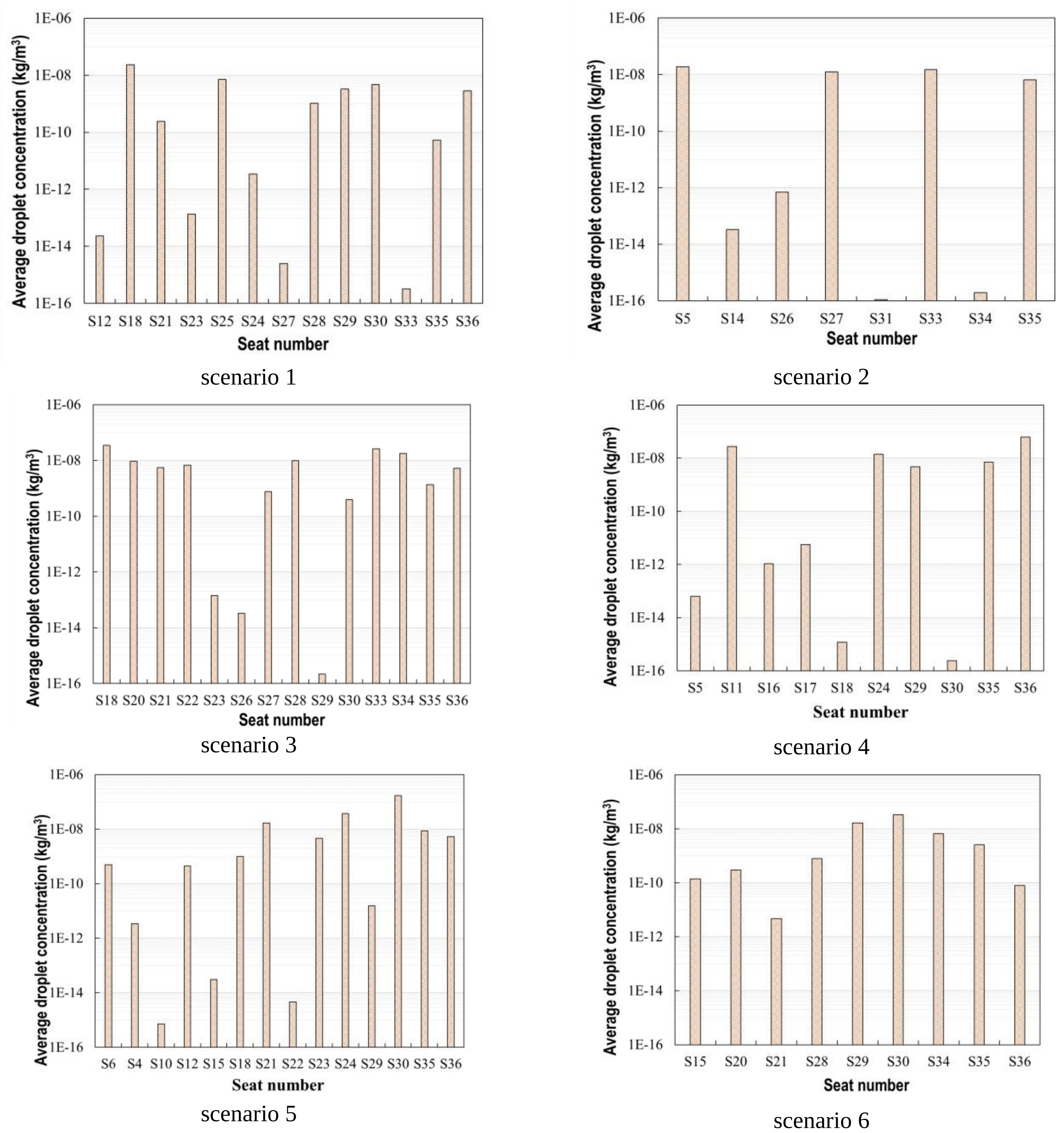

Fig. 10. Average droplet concentration trap on the student body at high speed AC operation pattern for all scenario

4. Conclusions

The operating pattern of AC air flow, both low speed and high speed, in each window/door scenario as an outlet, can control the spread of SARS-CoV-2 particles in the classroom. Based on these results, several conclusions can be drawn:

In the low-speed AC operating pattern, scenario 4 with windows 1 and 2 open and the door closed is the worst scenario, resulting in the level of exposure to the virus in students reaching 41.67%. Meanwhile, in the high speed AC operating pattern, the worst scenario 3 reached 38.89%. These two AC operating patterns have produced a best scenario with a virus exposure rate of 22.22%. The best scenario for a low speed AC operating pattern is scenario 5 with all windows open and doors closed, while scenario 2 with all windows closed and the door open is the best scenario for a high speed AC operating pattern. The average concentration of droplet particles is highest in the low-speed AC operation pattern, higher than the average highest concentration in the high-speed AC operation pattern, which are 7.24×10^{-8} kgm^{-3} and 3.4×10^{-8} kgm^{-3}, respectively. In the low-speed AC operation pattern, droplet particles are concentrated in front of the infection source (mainly adhering to students seated at 34, 35, and 36), resulting in consistently high droplet particle concentrations for these students in each scenario. However, in the high-speed AC operation pattern, droplet particles spread randomly among several students (students seated at 5, 18, 25, 30, and 36).

This is because the airspeed coming from the AC can push droplet particles to disperse across the classroom. Increasing the AC operation pattern can accelerate particles toward the outlet, allowing them to exit the classroom more quickly. However, to exit the room, SARS-CoV-2 particles must pass through students in front of the infection source, leading to higher particle concentrations among those close to the infection source and faster spread throughout the room. In all scenarios, when most windows are closed, indicating low outlet capacity, particles can disperse throughout the classroom and increase the risk of infection.

This study emphasizes the impact and importance of having an appropriate ventilation system in classrooms. To reduce the likelihood of infection indoors, careful attention to the ventilation system's settings is necessary, as indoor air is not entirely free from pathogenic particles.

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