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Exposure Assessment of Infectious Virus Particles in a Classroom Setting Using Computational Fluid Dynamics Model

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ABSTRACT

Indoor air quality in classrooms directly affects comfort, focus, and academic performance. This research leveraged Computational Fluid Dynamics (CFD) to analyze the dispersion of infectious virus particles in classrooms. While Negative Pressure Systems (NPS) are often used at medical centers to inhibit virus particles' dispersion, those are seldom applied in educational settings. The study aimed to pinpoint optimal ventilation and heating/AC flow rates to prevent virus particle spread. Results showed that prioritizing a higher flow rate at the ventilation unit over the heating/AC unit creates a negative pressure differential, decreasing virus dispersion by up to 93%. To establish negative pressure, the minimum flow rate ratio of ventilation to heating/AC should be 1.0. But for maximal virus particle reduction, a ratio of 2.8 is optimal. This research underscores CFD's value in understanding NPS dynamics and simulating virus behavior in classrooms. The findings suggest that NPS implementation in schools could significantly curb virus particle spread.

Introduction

Virus particles have become an increasing issue recently, especially due to the rise in plastic production and the poor waste management practices over the last couple of decades. Many school classrooms still lack the means to guarantee secure and healthy environments according to "Ventilation strategies to reduce airborne transmission of viruses in classrooms: A systematic review of scientific literature." The study points out that indoor environments are considered to be at high risk of contagion, and ventilation should be the first preventive measure.

In recent years, several noteworthy studies have shed light on critical aspects of our environment and its impact on human health. In 2021, Ferrari et al. found that school classrooms in winter are centres for the spread of diseases such as influenza, the most common virus responsible for acute respiratory illness among school-age children. Influenza viruses share the same route of transmission as Coronaviruses, so ventilation is an appropriate way to reduce infectious spread. In 2023, Firatoglu et al. conducted studies that demonstrated the transmission of the virus through two main routes in a classroom: direct transmission via inhalation of respiratory droplets and indirect transmission through hand-to-mouth, hand-to-nose, or hand-to-eye movements resulting from close contact. However, recent studies have determined that the primary factor contributing to the virus's contagiousness is the movement of droplets through the air. Moreover, Sadrizadeh et al. (2022) conducted research on the delicate vulnerability of children to environmental exposures during their developmental stages. Their study highlighted the potential long-term negative consequences, such as respiratory diseases and impaired cognitive function, emphasizing the importance of safeguarding children from harmful environmental influences. Addressing another concerning aspect, Na et al. (2023) evaluated the adverse effects of fine dust, categorizing it as a Group 1 carcinogen. Prolonged exposure to fine dust was found to be associated with respiratory, cardiovascular, and cerebrovascular diseases, calling for urgent measures to mitigate its impact on public health. The amalgamation of these studies reveals the interconnectedness between environmental factors and human well-being, underscoring the need for continued research and targeted interventions to create a safer and healthier world for future generations.

A solution to address these harmful particles in the environment is using a negative pressure system (Kim, 2021). A negative pressure system is created when the pressure inside of an enclosed space is less than the pressure outside. This can be achieved by manipulating the volumetric flow rate at inlet (VFR_{in}) such as air condition/heating unit and the rate at outlet (VFR_{out}) such as ventilation. There have been several studies that emphasize the significance of using a negative pressure system to improve indoor air quality. Haun et al. (2019) conducted research emphasizing the significance of negative pressure rooms in preventing hospital-acquired infections (HAIs). The study highlights how NPS, particularly in intensive care units and isolation units, plays a critical role in protecting vulnerable patients from virus particle dispersion and reducing infection rates in healthcare facilities. Allen and Ibrahim (2020) discussed the role of ventilation strategies, including negative pressure systems, in mitigating the transmission of SARS-CoV-2 (the virus responsible for COVID-19) in indoor environments. The review article provides evidence supporting the use of NPS in enclosed spaces like hospitals to control virus particles' concentration and prevent their spread among patients and staff. Aliabadi et al. (2011) conducted a systematic review evaluating various ventilation strategies to control airborne infectious disease transmission in hospital waiting areas. The study underlines the importance of negative pressure systems as an effective measure to contain virus particles and minimize their dispersion in healthcare settings, contributing to patient safety. Faridi et al. (2021) discussed the management of indoor air quality in healthcare environments during the COVID-19 pandemic. The paper emphasizes the role of negative pressure systems, particularly in intensive care units treating COVID-19 patients, in preventing virus transmission and protecting healthcare workers from exposure.

In the context of improving indoor air quality, it becomes meaningful to investigate the behavior of infectious virus particles in different settings, including classrooms, and identify optimal HVAC operating conditions to prevent their dissemination. This study employs computational fluid dynamics to evaluate behavior, dynamics, and concentration of virus particles within a classroom. By mathematically simulating deposition, dispersion, and diffusion, the research aims to enhance our understanding of indoor virus particle pollution and its potential impact on human health. The findings will contribute to effective mitigation strategies and environmental awareness.

Methods

Computational Fluid Dynamics (CFD) is a specialized branch of fluid mechanics that employs numerical methods and algorithms to simulate and analyze the behavior of fluids, such as gases and liquids, in various engineering and scientific applications. CFD enables researchers and engineers to study complex fluid flow phenomena and understand how fluids interact with solid boundaries and other forces. To run a CFD simulation, several inputs are required. These include the geometric model of the system, defining the shape and boundaries of the domain where fluid flow occurs. Additionally, the user needs to specify the initial conditions of the fluid, such as velocity, pressure, and temperature distribution, to initiate the simulation. Boundary conditions are also vital as they define how the fluid interacts with the domain boundaries and may include information on inflow, outflow, and wall conditions. Inside CFD, the fundamental governing equations that describe fluid flow and behavior are the Navier-Stokes equations.

Equation 1: Navier-Stokes Equation:

$$\rho\frac{\partial\vec{v}}{\partial t}+\rho(\vec{v}\cdot\nabla)\vec{v}=-\nabla P+\vec{\gamma}\rho+\mu\nabla^2\vec{v}$$

where:

- $\rho\frac{\partial\vec{v}}{\partial t}$: Local acceleration where ρ = density, $\vec{v}$ = velocity, and t = time.
- $\rho(\vec{v}\cdot\nabla)\vec{v}$: Convective acceleration where ∇ = gradient.
- $-\nabla P$: Pressure gradient where P = pressure.
- $\vec{\gamma}\rho$: Gravitational force where $\vec{\gamma}$ = gravity.
- $\mu\nabla^2\vec{v}$: Viscous force where μ = viscosity, ∇^2 = Laplacian operator representing the divergence of the gradient

These equations represent the conservation of mass (continuity equation) and conservation of momentum (momentum equations) for the fluid. They take into account various factors, such as fluid density, velocity, viscosity, and pressure, and help to predict the flow field within the specified domain. CFD simulations provide a wide range of outputs that aid in understanding and analyzing fluid behavior. The primary outputs include velocity profiles, pressure distributions, temperature fields, and shear stresses, which offer insights into the flow patterns and forces acting on the system. Additionally, CFD can provide visual representations, like flow animations and contour plots, which make it easier to interpret and communicate the results effectively. In conclusion, CFD is a powerful and indispensable tool for engineers and researchers to numerically study fluid behavior and its interaction with solid surfaces. By solving the Navier-Stokes equations with appropriate inputs, CFD simulations yield valuable outputs that help optimize designs, troubleshoot problems, and enhance the understanding of fluid flow phenomena in various practical applications.

Preprocessing:

In order to conduct simulations, it was imperative to establish a base model capable of simulating a classroom environment. Utilizing Autodesk Inventor®, as shown in Fig. 1, we meticulously designed a virtual classroom with dimensions that closely mirrored those of a standard educational setting, measuring 9 by 8.5 meters. Within this virtual classroom there were a total of 10 desks each around 2-2.5meters apart. This consistent base model serves as the foundation for running simulations. It allows us to isolate specific variables, such as HVAC system inflow (VFR_{in}) and outflow (VFR_{out}) as well as virus particle size, in order to identify optimal solutions. Through these simulations, we aim to gain insights into achieving the best balance between safety and comfort within the classroom environment.

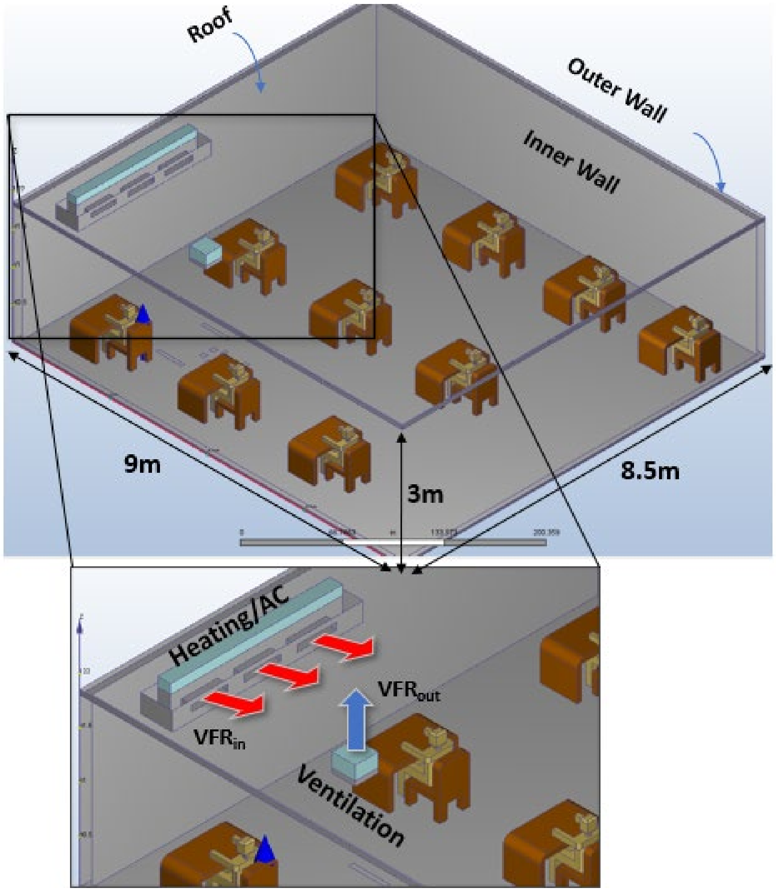

Figure 1. Classroom and HVAC design

Simulation:

In this Computational Fluid Dynamics (CFD) modeling procedure, a comprehensive simulation was conducted to assess the indoor air quality in a controlled environment. There are four distinct simulations, each aimed at evaluating a unique variable to pinpoint the key factors contributing to an optimal solution. As described in Table 1, Scenario 1 investigated the influence of VFR_{in} on the concentration of particles within the room. All other parameters remain constant, while VFR_{in} vary across three settings: 1.5, 3, and 4.5. In scenario 2 the affect VFR_{out} is observed. While everything else remains constant the VFR_{out} is adjusted across three different settings: 0, 3, and 4.25 cubic feet per minute (CFM). Scenario 3 examines the size of particles to see how this affects the concentration, and to do this the simulations are run with 2 different particles sizes: one being respirable (9μm; Fernstrom, 2013) and the inhalable (50μm; Fernstrom, 2013). Lastly scenario 4 investigates the effectiveness of our proposed solution, negative pressure system, to mitigate the concentration of virus particles in a room. To do this the VFR_{in} and VFR_{out} need to be changed while everything else remains constant. Initially, the VFR_{in} to 1.5 CFM and VFR_{out} to 4.25 CFM, creating a negative pressure environment. To form and evaluate a positive pressure system, VFR_{in} is set to 4.25 CFM while the VFR_{out} is 0 CFM. This parallel helps compare the two results to assess the effectiveness of a negative pressure system. Each simulation considered a mean residence time of 100 minutes, and the computing time for each run was set at one hour, comprising 100 iterations.

Table 1. Characteristics of the four scenarios in terms of exit temperature, volumetric flow rate (VFR_{in}) at air conditioning (AC), volumetric flow rate (VFR_{out}) at ventilation, and virus particle size.

Scenarios		**Exit Temp.(°C)**	**VFR_{in}(m^3/min)**	**VFR_{out}(m^3/min)**	**Size(μm)**
Control		N/A	0	0	<10
Scenario 1 (VFR @ H/AC)	Low	67	1.5	4.25	<10
	Average		3		
	High		4.25		
Scenario 2 (VFR @Ventilation)	Low	67	4.25	0 (off)	<10
	Average			3	
	High			4.25	
Scenario 3	Low	67	4.25	4.25	Respirable
	Average				Non-respirable
	High				
Scenario 4	Low	67	1.5	4.25	<10
	Average				
	High		4.25	0	

Post-processing:

In the post-processing phase of this Computational Fluid Dynamics (CFD) modeling, various crucial steps were undertaken to analyze and visualize the simulation results. The visualization in the AutoDesk CFD® (AutoDesk User Guide, 2023) included infectious virus particle distribution using Global, Planes, Traces, Iso-Surface, and Iso-Volumes techniques, providing comprehensive insights into particle dispersion. Specifically, the Traces module calculated the motion of size-specific infectious particles, enabling trajectory tracking and behavior analysis. Moreover, raw output data was extracted in .csv format for further statistical analysis, facilitating the quantification and comparison of key parameters related to indoor air quality and particle behavior. These post-processing methods offered valuable insights into infectious particle dynamics within the simulated indoor environment, identifying potential hotspots and guiding strategies for ventilation and contamination control, ultimately contributing to enhanced public health outcomes.

Results

Scenario 1: Sensitivity of Virus Particle Exposure to Heating/AC Conditions

Scenario 1, where the three volumetric flow rates at heating/AC unit (VFR_{in}) were simulated with a constant volumetric flow rate at ventilation (VFR_{out}) of 4.25 CFM revealed a notable trend in infectious virus particle concentrations. As displayed in Fig. (a), (b) and (c), the densities represented as concentration of virus particle trajectories increased as VFR_{in} increased, denoting a strong linear positive correlation (Fig. 1(d)) between the VFR_{in} and the concentration of infectious particles. These results imply that simply manipulating only the VFR_{in} without other engineering controls is not sufficient in minimizing particle dispersion.

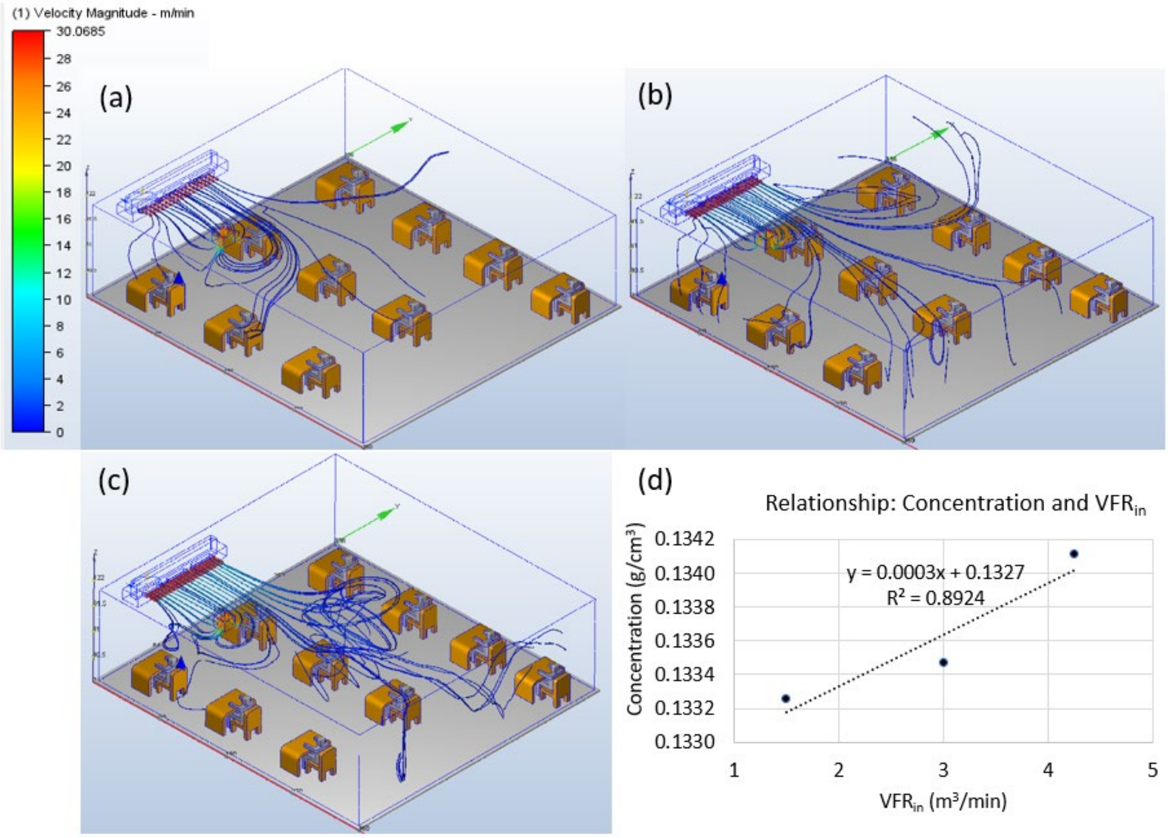

Figure 2. Visualized virus particle trajectories and dispersion from AC unit at VFR_{in} of 1.5 CFM (a), 3.0 CFM (b), and 4.25 CFM (c) with constant ventilation VFR_{out} of 4.25 CFM in the classroom. Regression analysis is displayed in (d) to present relationship between virus particles concentration and $VFR_{in.}$ The color scale denotes velocity magnitude, indicating dispersion speed of virus particles, while trajectory density indicates the concentration of virus particles during the given time.

Scenario 2: Sensitivity of Virus Particle Exposure to Ventilation Conditions

In Scenario 2, the focus shifted to investigating the impact of varying the volumetric flow rate at the ventilation (VFR_{out}) while keeping the VFR_{in} at HVAC /AC constant. The results shown in Fig. 3 (c) presented a significant and noteworthy pattern, revealing a strong linear negative correlation between VFR_{out} and particle concentration. As the VFR_{out} increased, there was a clear decrease in the concentration of particles within the indoor environment as exhibited in Figures (a) to (c). This finding aligns with expected outcomes, as higher VFR_{out} facilitates better air exchange and improved ventilation, leading to a reduced accumulation of infectious virus particles. The negative correlation demonstrated that increasing the VFR_{out} is an effective engineering control measure for minimizing particle dispersion and enhancing indoor air quality.

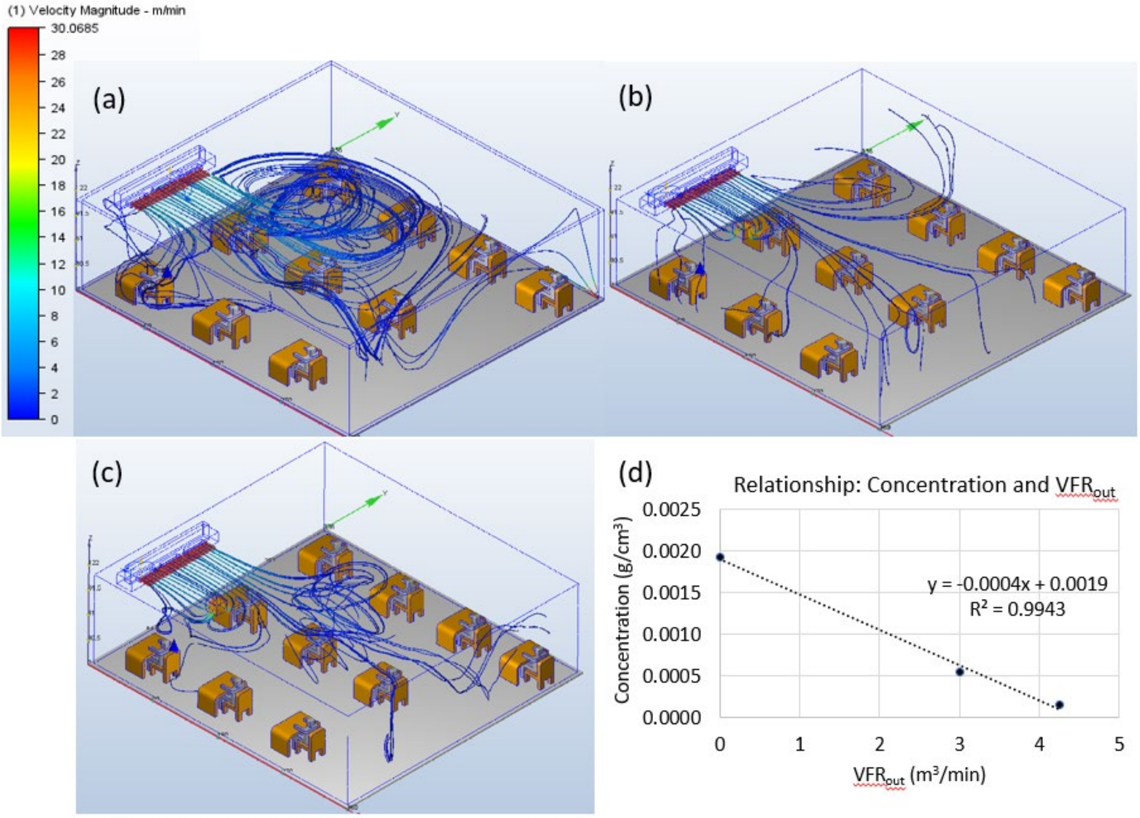

Figure 3. Regression Analysis between virus particles concentration and VFR$_{in}$ for Scenario 2. The graph shows a positive correlation between the increase in the VFR$_{out}$ in and the increase in concentration of particles. The color scale denotes velocity magnitude, indicating dispersion speed of virus particles, while trajectory density indicates the concentration of virus particles during the given time.

Additional factors, such as the efficiency of filtration systems, air circulation patterns, and the type of ventilation unit, may play a crucial role in determining the overall effectiveness of infection control measures. Further investigation into these contributing factors is essential for developing comprehensive strategies to combat the spread of infectious virus particles and enhance indoor air quality in various environments.

These findings emphasize the critical role of ventilation systems in infection control strategies, particularly in enclosed spaces, and underscore the importance of optimizing ventilation parameters to create safer and healthier indoor environments. By understanding the implications of VFR$_{out}$ adjustments, this research provides valuable insights for architects, engineers, and policymakers in designing and implementing effective ventilation strategies to mitigate the spread of infectious particles and improve overall occupant well-being.

Scenario 3: Sensitivity to Inhalable and Respirable Particle Sizes

In Scenario 3, the focus was on exploring the influence of particle size as the changing variable. Two different particle sizes, 9µm and 50µm, were examined, and the results depicted that Fig. 4 (a) and (b) demonstrated intriguing trends. The color scale denotes velocity magnitude, indicating dispersion speed of virus particles, while trajectory density indicates the concentration of virus particles during the given time. It was observed that the 9µm particles exhibited lower concentration levels (3.8 µg/cm^3) compared to the 50µm particles (10.1 µg/cm^3). Notably, despite the higher concentration of 50µm particles in Fig. 4 (b), the visualization revealed that a considerable portion of the larger particles remained suspended in the air due to their greater gravitational force. On the other hand, the smaller 9µm particles exhibited a higher rate of extraction by the ventilation system, suggesting that their lower gravitational force enabled better removal from the indoor environment.

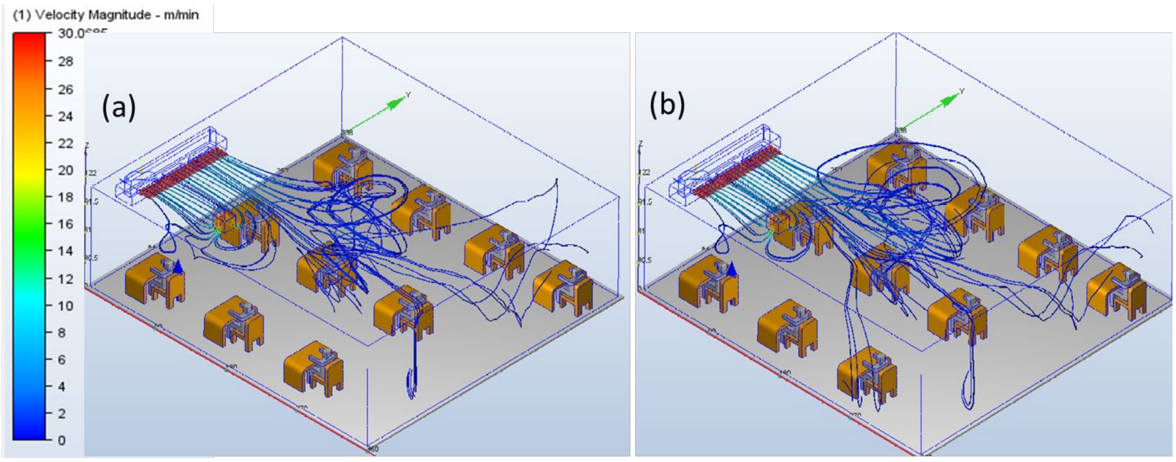

Figure 4. Visualized virus particle trajectories and dispersion from AC unit at a particle size of 9µm (a), and particles sizes of 50µm (b) with constant AC/HVAC VFR_{in} of 4.25 CFM in the classroom. The color scale denotes velocity magnitude, indicating dispersion speed of virus particles, while trajectory density indicates the concentration of virus particles during the given time.

The result of scenario 3 indicated that particle size is of critical importance in evaluating exposure of virus particles in a classroom. Optimizing ventilation systems to effectively capture and remove different size particles can play a critical role in reducing the concentration of infectious agents in ventilated classrooms.

Scenario 4: Sensitivity of Respirable Virus Particle Exposure to Pressure Systems

In Scenario 4, the focus was on the atmospheric pressure of air that departs from the room, while keeping the airflow from the Heating, Ventilation, and Air Conditioning (HVAC) system into the room constant. By adjusting the ratio of VFR_{out} to VFR_{in} in a classroom, a negative pressure environment was achieved. The results, as depicted in Fig. 5, displayed that there was a noticeable decrease in particle concentration and ambient air pressure within the indoor environment as the rate of ventilation and air leaving the room increased. This finding reinforces the effectiveness of engineering controls in minimizing particle dispersion in terms of atmospheric pressure. Fig. 5 depicts two scenarios: (a) a room with VFR_{out} less than VFR_{in} and (b) a room with VFR_{out} greater than VFR_{in}. The simulation result in Fig. 5 (a) shows a positive pressure and elevated concentration of virus particles within the room, while the simulation in Fig. 5 (b) shows a negative pressure and a decrease of concentration. Creating a negative pressure environment enhances the elimination of infectious particles and stops them from spreading from the classroom to the hallway. This significantly lowers the risk of airborne transmission, ensuring greater safety and well-being for occupants.

Table 2 explains how estimated ambient pressure values in the classroom changed as the ratio of VFR_{out} to VFR_{in} were adjusted. Both Case 1 and Case 2 result in positive pressure, since both cases have a VFR_{out} to VFR_{in} ratio of less than 1. Cases 3, 4 and 5 have VFR_{out}/VFR_{in} ratios greater than 1, resulting in a negative pressure drop within the room. The difference in particle concentration between Case 1, which has no VFR_{out} input and represent the most positive pressure, and Case 5, which represents the highest VFR_{out}/VFR_{in} ratio for a negative pressure system, results in a 93% decrease in ambient air pressure.

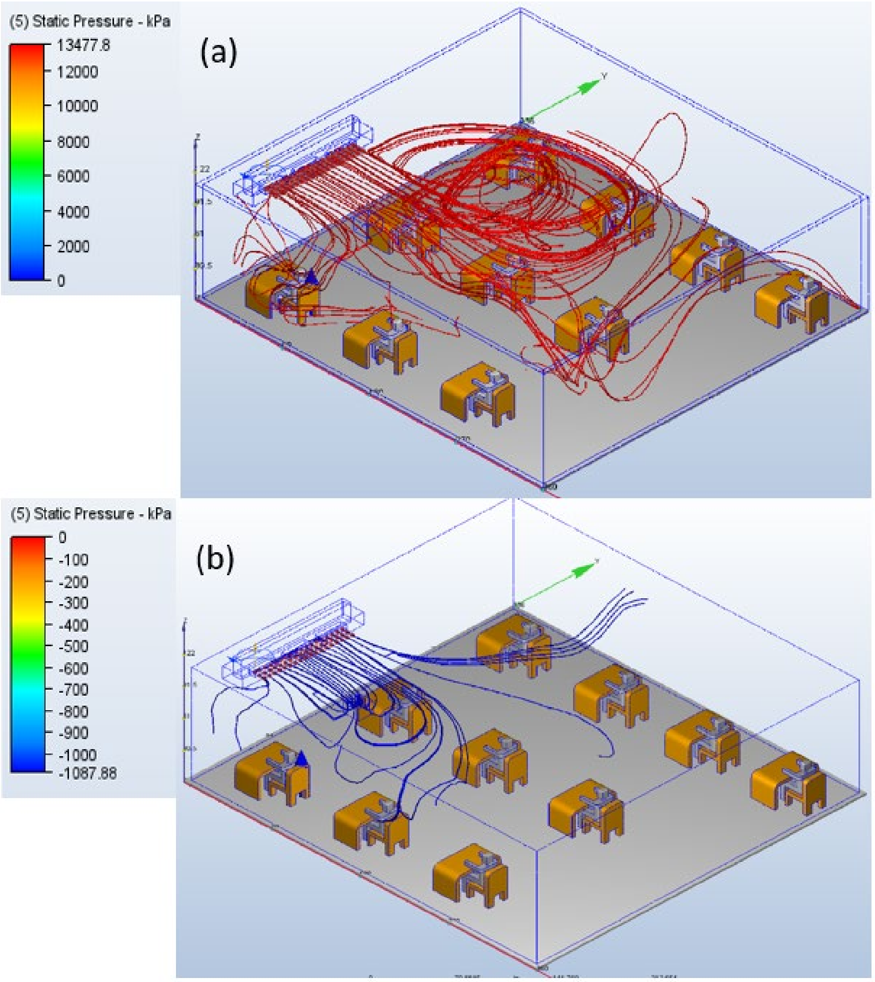

Figure 5. Trace visualization of virus particles in positive pressure room (a) and negative pressure room (b) in Scenario 4. The color scale denotes velocity magnitude, indicating dispersion speed of virus particles, while trajectory density indicates the concentration of virus particles during the given time.

Table 2. Native pressure system vs. positive pressure system compared with ratio of VFR_{out} to VFR_{in}

Case	**VFR_{out} @ Vent. (m^3/min)**		**VFR_{in} @ H/AC (m^3/min)**	**VFR_{out}/VFR_{in}**	**Pressure (kPa)**
#1	0(off)	<	4.25	NA	1.34E+05
#2	3	<	4.25	0.71	2.21E+00
#3	4.25	=	4.25	1.00	**-1.09E-02**
#4	4.25	>	3	1.42	**-5.37E+01**
#5	4.25	>	1.5	2.83	**-1.10E+03**

These results emphasize the critical role of ventilation strategies in infection control and highlight the importance of optimizing ventilation rates to achieve the desired negative pressure differentials in indoor spaces. The findings from this scenario offer valuable insights for designing and implementing ventilation systems in various settings, ultimately helping to create healthier and safer indoor environments for occupants.

Conclusion

The escalating problem of virus particles poses significant human health challenges. The impact of virus particles is not limited to outdoor environments but has also permeated indoor spaces, making it a pressing concern for human health. Though medical centers commonly use Negative Pressure Systems (NPS) to prevent the spread of virus particles, such systems are rarely found in educational environments.

By conducting sensitivity analysis with the Computational Fluid Dynamics (CFD) model, researchers explored the impact of various engineering control strategies on virus dispersion. The findings revealed that maintaining a higher volumetric flow rate (VFR) in the ventilation unit than in the heating/AC unit results in a negative pressure differential. The effective ratio of VFR_{out}/VFR_{in} to create the negative pressure spanned from 1.0 to 2.8. With a ratio of 1.0 being the minimum requirement for a negative pressure system and a ratio of 2.8 being the most suitable in this study, the atmospheric pressure of the room decreased drastically by 93%. This demonstrates the effectiveness of such engineering controls in mitigating the risk of airborne transmission in enclosed spaces.

Implementing this engineering control measure offers the potential to mitigate the concentration of microplastic particles, thereby enhancing indoor air quality and safeguarding the well-being of occupants. As we tackle this critical issue, incorporating the negative pressure system demonstrated in our simulations could play a crucial role in creating safer and healthier indoor environments for present and future generations.

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