SEMARAK ILMU PUBLISHING

CFD Letters

Journal homepage:
https://semarakilmu.com.my/journals/index.php/CFD_Letters/index
ISSN: 2180-1363

Air Quality Improvement in COVID-19 Pandemic: Numerical Study of ventilation system in a classroom

Elang Pramudya Wijaya[1], Ardiyansyah Saad Yatim[1,*]

[1] Department of Mechanical Engineering, Faculty of Engineering, Universitas Indonesia, Depok, Indonesia

ARTICLE INFO

Article history:
Received 11 August 2022
Received in revised form 17 September 2022
Accepted 9 December 2022
Available online 11 Jan 2023

Keywords:
Air Quality, HVAC, COVID-19, Computational Fluid Dynamics, IAQ

ABSTRACT

Air quality plays a significant role during the coronavirus pandemic. Air acts as a spreading media as well as a control measure for infection in polluted spaces. Insufficient ventilation around the building may lead to a rise of pollutants carrying the virus. One way to improve ventilation is by increasing the air change rate. This study investigates the air change rate effectiveness in reducing droplets spreading in a classroom. Cases with various layouts of inlet and outlet vents are considered, and the spread of droplets is studied. The airflow analysis shows the impact of the different ventilation layout configurations. The results show that the CFD model simulation indicates an optimum ventilation configuration to decrease the droplet spread. The discrete phase model results also determine the trajectory of droplets spread along the classroom. CFD results show that in the selected configuration, a significant number of droplets are expelled to the outside and reduce their concentration inside the classroom.

1. Introduction

The COVID-19 pandemic has spread in various countries including Indonesia. The SARS-CoV-2 virus that causes the disease can spread through droplets contained in the air exhaled by people exposed to the virus. Insufficient ventilation in highly crowded environments such as schools, restaurants, underground stations, and gyms does not allow proper dilution of virus particles emitted by the infected people, leading to a high probability of virus transmission to other people in the area [1]–[4]. To prevent this, the government worldwide has regulated some policies about the temporary shutdown of most indoor environments that are likely to be affected by COVID-19 transmission and being in the difficult role of deciding whether to prioritize education or health. After the first pandemic wave in early 2020, guidelines for reopening schools and universities were prepared, but they mainly relied on promoting personal and basic non-pharmaceutical mitigations such as social distancing, hand washing, wearing masks, and occupancy reduction to half of the normal level [5]–[7]. These prevention methods still lead to close contact transmission, which is a transmission route in indoor environments [8], [9]. Clean air is beneficial for human health as it impacts the regular

* *Corresponding author.*
E-mail address: ardiyansyah@eng.ui.ac.id

https://doi.org/10.37934/cfdl.15.1.2638

metabolism of our body. Indoor air quality can be improved by using different techniques such as implementing engineering controls with purified air circulation, better ventilation, portable air purifiers, etc. Engineering controls like providing ventilation or air filtration have been endorsed as a capable method to improve air quality [10]. Ventilation can dilute the air contaminants in confined spaces by indoor-outdoor air exchange. Different ventilation can be achieved through windows, louvres, vents, or mechanically through the HVAC system. Although a high ventilation rate does not give assurance of eliminating the virus, it can reduce the number of viruses in the ventilated space [11]. To lower the concentration of the COVID-19 virus in the spaces further research is of great importance.

Therefore, much research has been carried out regarding the size, number, and dispersion of air particles exhaled by a person in indoor space [12]–[14]. Characteristics of different respiratory processes such as breathing, sneezing, and coughing have also been studied [15]–[17], as well as the dispersion of exhaled particles and the ventilation systems [18], [19]. Other factors such as the relative position between the source and the receiver also have been experimentally studied to analyse the risk of transmission and the distribution of airborne particle viruses.

The SARS-CoV-2 virus can spread through droplets and aerosols, expelled through exhalation when coughing, sneezing, and talking [20]–[23]. The aerosols and tiny droplets could travel longer distances and stay in the air for a longer time [24]. With a high infection and mortality rate, it is feared that this virus can endanger human health, and researchers are also evaluating the characteristics and behaviour of the spread of this virus. The droplet spread in the air mostly evaporates instantaneously to half of their initial size and becomes droplet nuclei [25]. Several factors that can affect the spread of the droplets are controlled by their physical properties i.e. density, viscosity, surface tension, and temperature, and the ambient properties such as surface temperature, roughness, surrounding gas temperature, and relative humidity, as well as the air movement [26]–[29].

In the classroom, ventilation is an essential factor in the comfort of students and teachers. On the other hand, ventilation can also be a medium for spreading the virus in the classroom. Furthermore, the negative impact of low ventilation and air change rate per hour (ACH) on occupants has increased the possibility of aerosol transmission containing the virus. The standard protocols for the prevention of airborne infections suggest a 4 – 6 ACH and even 12 ACH during the COVID-19 pandemic conditions. The classroom is predicted to increase virus infection through droplets/particles/aerosols if there are no changes to the design or the addition of ventilation layouts. This study uses CFD simulation to determine the opportunities for spreading the COVID-19 virus in the classroom in different ventilation configurations.

2. Methodology

Many factors affect indoor air quality, from flow rate, temperature, CO_2, humidity, etc. In the case of the COVID-19 pandemic, there are several cases in a room setting that are vulnerable to virus transmission due to mask opening [30]. High contamination load also plays a vital role in obtaining an infection, especially for healthcare workers. In addition, the literature review-based analysis determined some techniques for decreasing the risk, such as using an air purifier equipped with HEPA filters or UV light, which will reduce contamination load and sterilize the indoor room.

To analyze complex problems, this kind of research can use either mathematical, numerical, or statistical methods, and this study will use the numerical method using Computational Fluid Dynamics (CFD). Literature review, and analysis with CFD simulation to analyze the indoor airflow pattern, air change rate and the location of inlet and outlet are conducted. Different ventilation configuration was simulated to analyze their effect on the droplets' dispersion and airflow inside the classroom. Here is the flowchart of this study, which can be seen in Figure 1.

The main factors in the HVAC systems have been investigated, and the boundary conditions and setup of this study according to the previous case studies have been determined. The average values based on several previous case studies make the research outcomes more reliable and not limited to other cases. The geometry model is already defined by using the Mirzaie et al. classroom geometry [3]. The dimension and specifications of the classroom and the seats are presented in Figure 2. The classroom floor is 6 m wide by 8 m long and 5 m in height according to the design recommendation of educational buildings and classrooms. The student seating in the classroom is arranged to have an appropriate distance.

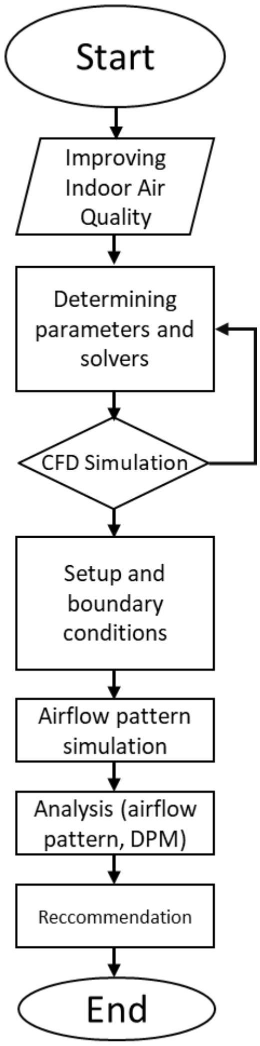


Fig. 1. Analysis flowchart

2.1 Classroom Geometry

The geometry of the typical classroom uses the model with various inlet, outlet, and ACH variations [3]. Details of the geometry dimensions are listed in Table 1 and shown in Fig. 2.

Table 1
Classroom design parameters

Description	Dimension
Width	6 m
Length	8 m
Window	2 x 2 m^2
Door	2.1 x 1 m^2
Chair	0.6 x 0.6 m^2
Number of seats	30
Number of windows	2
Exit doors	1
Table	1 x 0.6 m^2
Platform	1.5 x 4.5 m^2

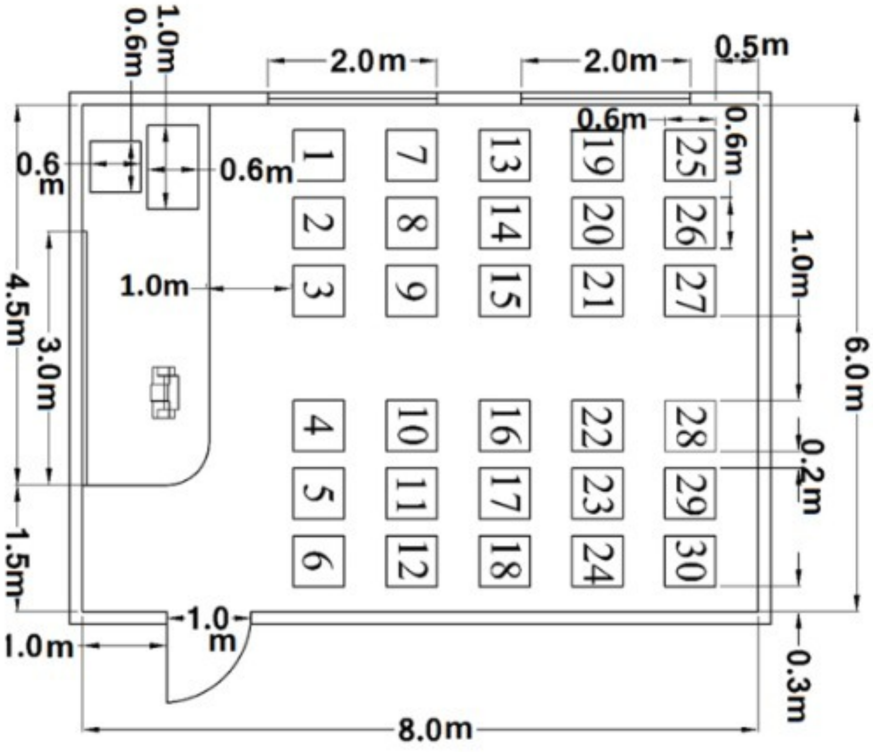


Fig. 2. Classroom geometry [3]

The classroom has no partitions between seats In this study, a COVID-19 infected person of 1.8 height and mouth area of 4 cm^2 standing in front of the class suddenly coughed and released the droplets containing the virus into the environment. The ventilation air is supplied with an intake on the wall and exits through the door and another outlet duct. The dimension of the intake and outlet duct is the same. The ventilation inlet dimension is 0.7 x 0.4 m^2.

2.2 Boundary Conditions

This simulation is run using ANSYS- fluent 19.2. The boundary conditions are based on the airflow rate supplied through the split-type air conditioner. In addition, there is a supply and return air with various placements in the classroom. The simulation has been done in the steady-state condition, with an air temperature of 25 ^oC . The case in this study is listed in Table 2 below. Furthermore, the boundary conditions show in Table 3 and figure 3.

Table 2
Inlet and outlet configuration

Case Study	Inlet Location	Outlet Location
Cross ventilation	1	2
Single sided ventilation	2	3
Diagonal ventilation	1	3

Based on the previous study [31] the average dimension of the aerosols in one cough or sneeze is 5 µm with a speed of 10 m/s and a duration of 0.5 s has been selected for the boundary conditions.

Table 3
Case Study

Case Study	Airflow Speed [m/s]
Cross ventilation	1.5
Single sided ventilation	1.5
Diagonal ventilation	1.5
Air Conditioning Inlet	1.2
Air Conditioning Outlet	1.2

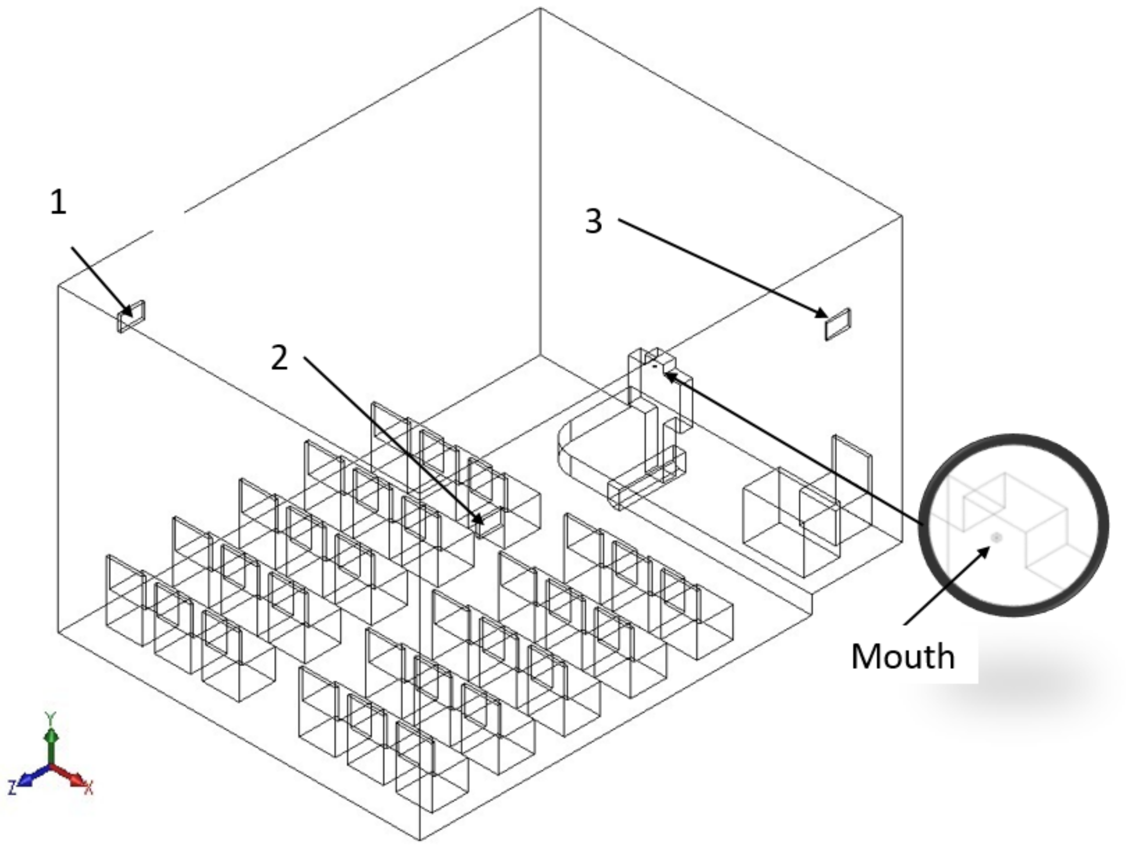


Fig. 3. Computational setup of a typical classroom

After the steady-state simulation was completed, a steady simulation was done to analyze the distribution of droplets of aerosol released by the manikin model. The simulation was performed using the RNG k-ε turbulence model. RNG k-ε turbulence model was chosen since the performance was verified for airflow pattern simulation [32]–[34]. Furthermore, the droplet was tracked using the Eulerian-Lagrangian method.

2.3 Governing Equations

The general equation of conservation of mass, momentum, and energy for the incompressible steady airflow is given as:

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

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

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

For turbulence modelling, the RNG k-ε turbulence model has been used for airflow simulation in indoor environments and has shown to be a suitable model for this study. The corresponding transport equation for turbulent kinetic energy k and dissipation rate ε are given below:

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

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

Where, G_k is the generation of turbulence kinetic energy generated by mean velocity gradients while G_b is the generation of turbulence kinetic energy based on buoyancy. μ_t is the turbulent kinetic viscosity coefficient, $\mu_t = C_\mu \rho k^2 / \varepsilon$, $C_\mu = 0.09$ is a constant, Y_M represents the contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate. S_k and S_ε are the user-defined source parameters; $C_{1\varepsilon}$, $C_{2\varepsilon}$ and $C_{3\varepsilon}$ are transmission dissipation constants, $C_{1\varepsilon} = 1.44$, $C_{2\varepsilon} = 1.92$, $C_{3\varepsilon} = 1.00$, in the other hand, σ_k and σ_ε are the turbulent Prandtl numbers for k and ε, $\sigma_k = 1.00$, $\sigma_\varepsilon = 1.3$.

Assumptions used in this simulation are: (1) temperature variations are negligible; (2) cough emits only droplets; (3) droplet particle size is 5 µm; (4) student bodies and their thermal plume are neglected; (5) thermal radiation from the outside are negligible; (6) no infiltration from door and window.

2.4 CFD Model Set Up

Geometry and mesh details in selected case studies are shown in Fig. 4 and Table 4, with the location of inlets, outlets, and droplet injection sources location. To simplify the simulation, the details of the models are simplified, particularly for the human bodies. k-ε RNG turbulence model has been selected for the simulation since the performance was recommended by the previous studies. Discrete phase modelling to analyze droplet transmission has been considered. Mesh independency to improve the quality of this simulation has been done. The mesh independence tests were conducted using steady-state, single-phase methods [35]. The skewness and the quality determine the final meshes which are suitable for this simulation. The mesh is presented in Fig. 5. The setup of the CFD model in ANSYS software is presented in Table 5. In this simulation, we used 48 core, 3.8 GHz computer at an estimated simulation time of six hours per simulation.

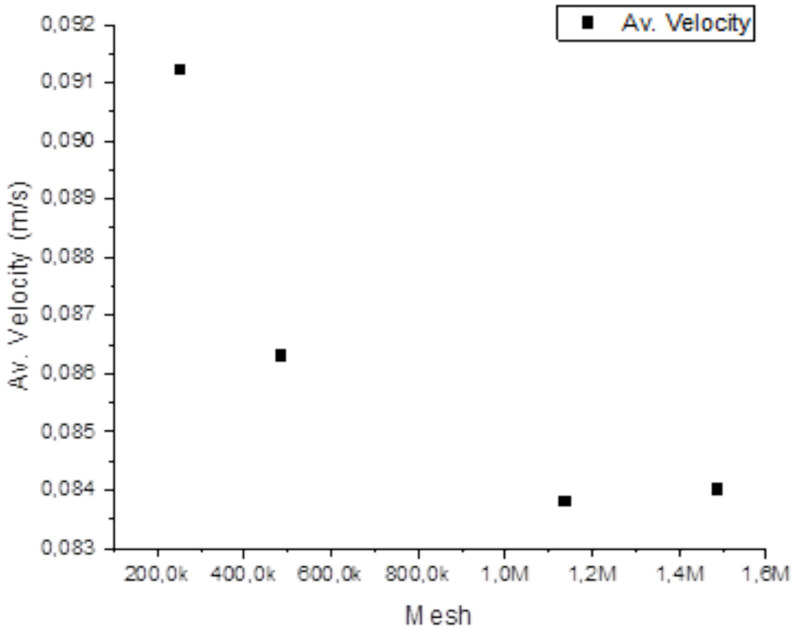


Fig. 4. Mesh independency

Table 4
Mesh Independence

Mesh	Fluid Cells	Av. Velocity (m/s)	Difference
Mesh 1	252946	0.0912	0.086
Mesh 2	485615	0.0863	0.027
Mesh 3	1139406	0.0838	0.002
Mesh 4	1488112	0.084	-

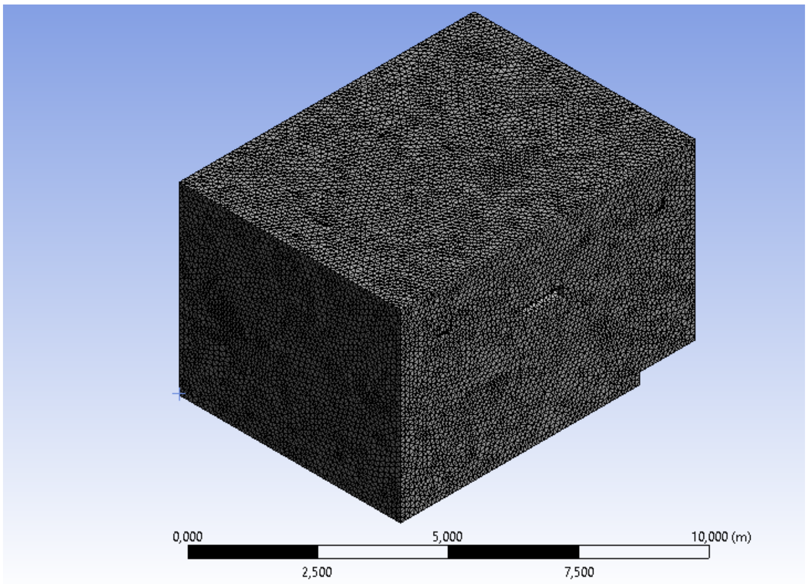


Fig. 5. Mesh of the typical classroom model

Table 5
CFD Model Setup

Item	Setup			
Solver		Type		Pressure Based
		Velocity formulation		Absolute
		Gravity		-9.81
Time	Airflow Analysis	Steady	Iteration	1000
	Discrete Analysis [36]	Unsteady	Time step (s) / No of time step / Max Iteration	1 / 1800 / 20

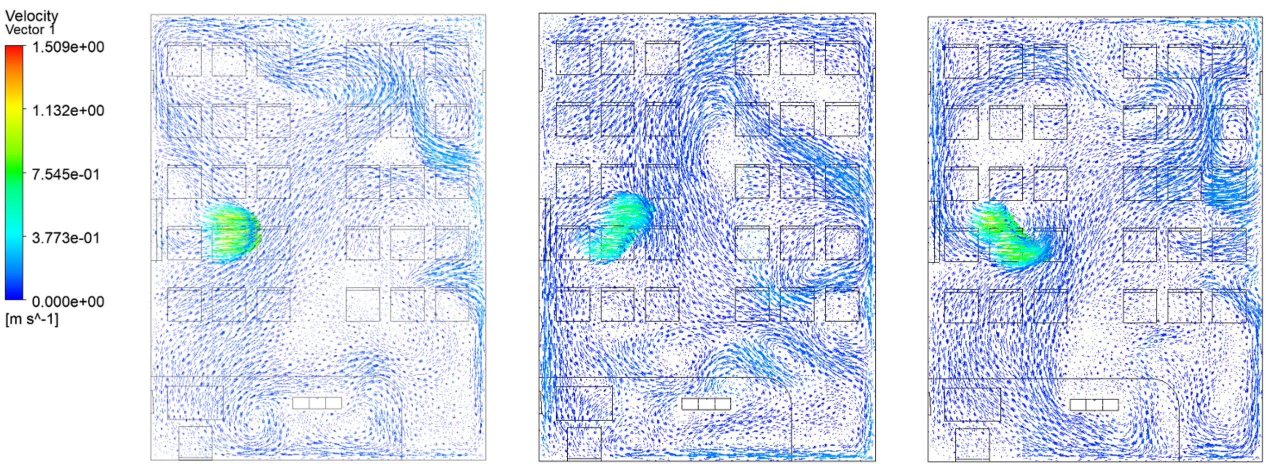
3. Results and Discussion

In the present study, the internal airflow characteristic is analysed with a numerical simulation by variating the inlet and outlet vent locations that are generally used in all kinds of indoor rooms, especially classrooms. In this simulation, the distribution of streamlines and the dead zones inside the classroom are compared with respect to two other inlet and outlet vent configurations, and the trajectory of the aerosols has been investigated.

3.1 Indoor airflow patterns, and the inlet/outlet configuration impact

Indoor airflow patterns and direction are essential factors that could influence the trajectory of aerosols. In the case of contamination, airflow patterns might negatively affect the safe distance between occupants inside the classroom. Figure 5 shows the distribution of the velocity vector for all three cases.

As we see in Fig. 6, the steady airflow in the classroom is evaluated using the RNG turbulence model for the inlet from both the vent and the split-type air conditioning unit. Three different layouts of inlet and outlet vents were studied for this study. Fig 6. Illustrates the velocity vector field under the steady flow condition for different ventilation layouts. Circulating flow could be observed in the three cases, which can cause the distribution of the droplet from its source. We analyse the airflow in case 1 and case 2 circulating from the front region to the back region of the classroom. This phenomenon will cause the droplet to disperse along the classroom and take a long time to be taken out through the outlet vent. This figure also shows that the diagonal ventilation (case 2) layout has directed airflow from the droplet source to the outlet ventilation.

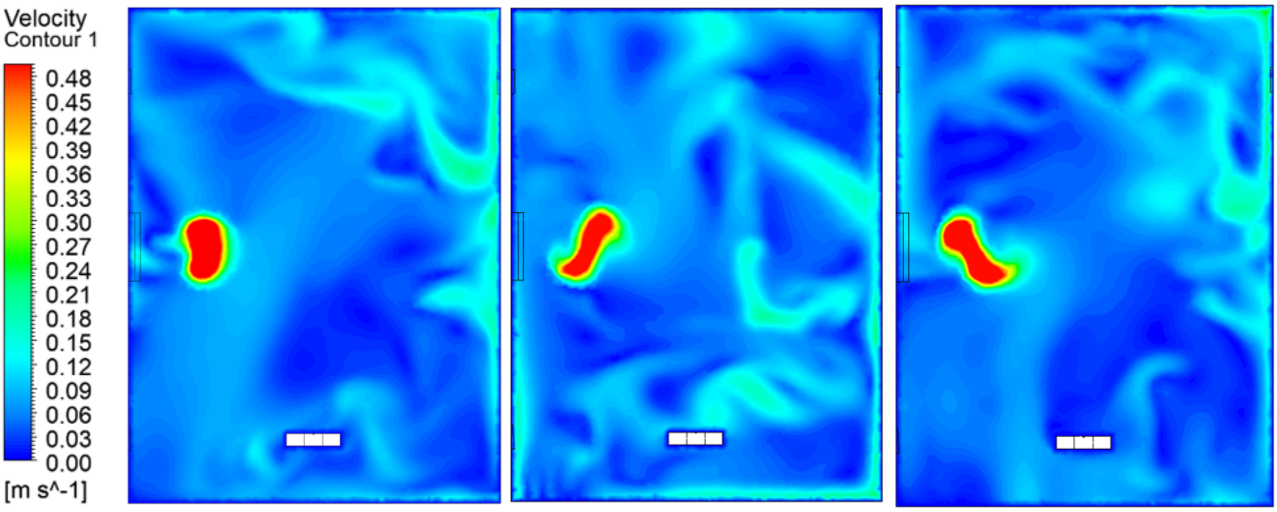


(a) (b) (c)

Fig. 6. Velocity vector in each case (a) case 1, (b) case 2, (c) case 3

The diagonal ventilation layout shows the best layout in this simulation due to the airflow pattern. The next step in this study is simulating the diagonal ventilation layout to see the droplet spread, which can be seen in the next section.

CFD results also could determine the dead zone (areas with low airspeed). The higher dead zone area will result in a higher contamination load. The dead zone can be seen in Fig.7. with dark blue colour with an airflow velocity of nearly zero. The dead zone can be minimized by changing the inlet and outlet layout of the classroom.



(a) (b) (c)

Fig. 7. Dead zones with very low air speed in each case (a) case 1, (b) case 2, (c) case 3

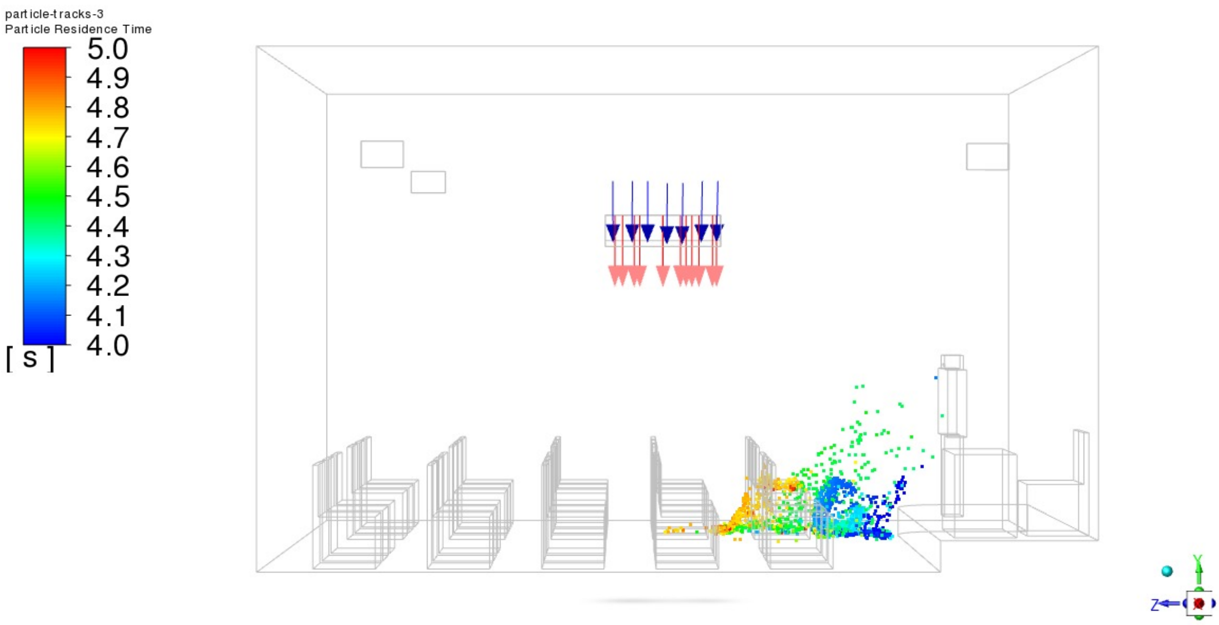
3.2 Impact of different ventilation layouts on the trajectory of droplets

The Air Change Hour (ACH) regulation for classrooms is about 4-6 ACH. Conversely, the standard protocol for COVID-19 prevention is more than 12 ACH. To deal with safe air quality and lower energy use, this CFD modelling was then studied. The theoretical ACH in this study with a volume area of 240 m^3 (8m x 6m x 5 m), and the total airflow rate was 1512 m^3/h or 6.3 ACH. This is a proper setup and complies with the standard. The results in Fig. 8. show that the ventilation layouts have a significant impact in addition to the contaminant source location. The contaminant (droplet) source was in front of the classroom. The droplets flow directly to the outlet ventilation by locating the outlet ventilation near the contaminant source location. On the other hand, compared to the classroom without ventilation, the droplets directly disperse and distribute, then fell due to their density. The split air conditioner also worsens droplet spread. Fig.8 (b) shows that some amount of droplet particles already disperse at 5s, leaving only a few droplets that fell to the ground.

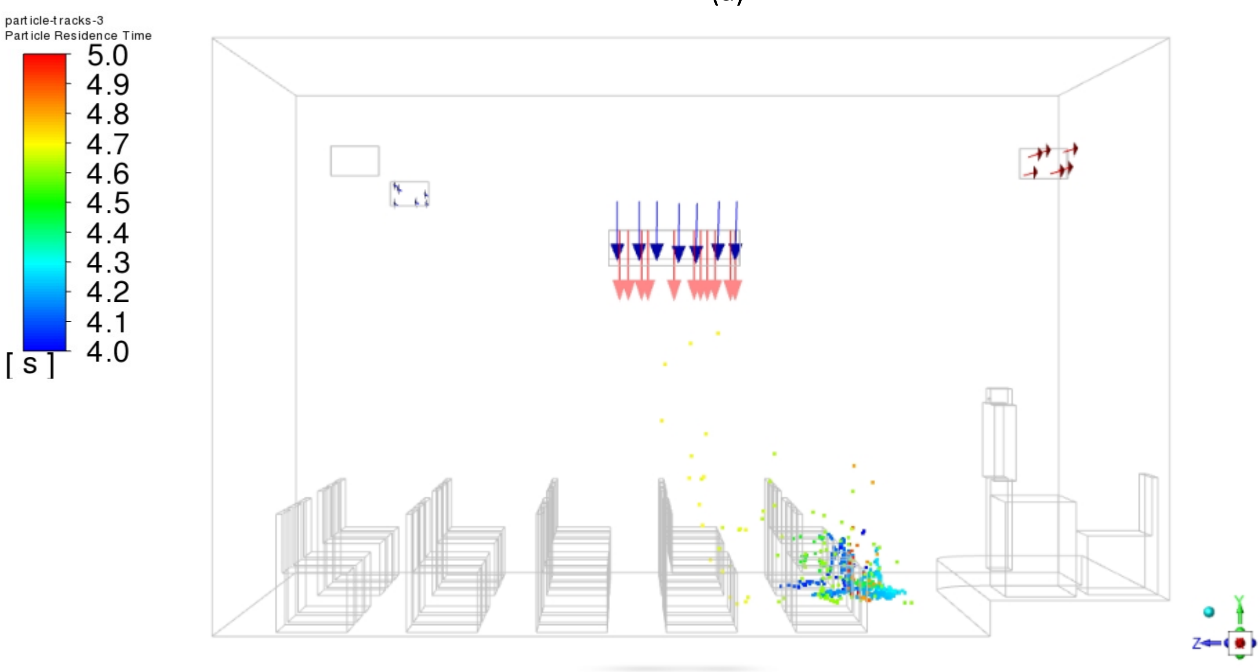
The tested configurations have different performances in dispersing the droplets. It is clear that different ventilation layouts, also have different possibilities for students to expose to the COVID-19 virus carried by the droplet. The concentration of the three cases in 0 minutes to 30 minutes showed in Fig.9. We found that the diagonal ventilation shows the most efficient layout for absorbing the droplets outdoors.

4. Conclusions

The airflow analysis results showed the impact of the ventilation layout of HVAC systems. From the virus transmission by droplets, the airflow pattern plays a significant role and the air change rate



(a)



(b)

Fig. 8. Discrete phase modelling of the classroom (case 2) (a) without ventilation, (b) with additional ventilation

inside the room. CFD simulation is able to provide insight into aerosol transmission inside the classroom and exhibit optimum ventilation configuration of inlet and outlet placement to decrease the health risk. The discrete phase model results also determine the trajectory of droplets spread along the classroom. It can be seen that the dead zone with poor ventilation and improper ventilation layout has a higher risk. In this study, the diagonal ventilation layout shows the best performance in expelling the aerosols directly to the outlet vent. CFD results show that significant amounts of droplets were expelled to the outside and reduced their concentration inside the classroom.

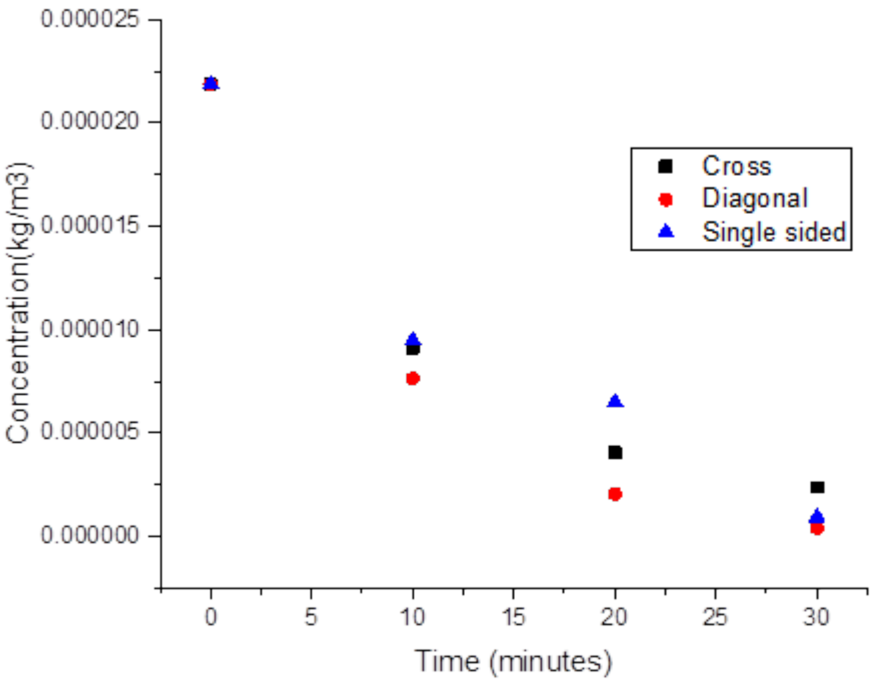


Fig. 9. Concentration of particles each time

Acknowledgement

This research was funded by a grant from the Ministry of Research, Technology and Higher Education Indonesia No. NKB-665/UN2.RST/HKP.05.00/2021.

References

[1] Schibuola, Luigi, and Chiara Tambani. "High energy efficiency ventilation to limit COVID-19 contagion in school environments." *Energy and Buildings* 240 (2021): 110882. https://doi.org/10.1016/j.enbuild.2021.110882

[2] Gil-Baez, M., J. Lizana, JA Becerra Villanueva, M. Molina-Huelva, A. Serrano-Jimenez, and R. Chacartegui. "Natural ventilation in classrooms for healthy schools in the COVID era in Mediterranean climate." *Building and Environment* 206 (2021): 108345. https://doi.org/10.1016/j.buildenv.2021.108345

[3] Mirzaie, Mahshid, Esmail Lakzian, Afrasyab Khan, Majid Ebrahimi Warkiani, Omid Mahian, and Goodarz Ahmadi. "COVID-19 spread in a classroom equipped with partition–A CFD approach." *Journal of Hazardous Materials* 420 (2021): 126587. https://doi.org/10.1016/j.jhazmat.2021.126587

[4] Sanguinetti, Angela, Sarah Outcault, Theresa Pistochini, and Madison Hoffacker. "Understanding teachers' experiences of ventilation in California K-12 classrooms and implications for supporting safe operation of schools in the wake of the COVID-19 pandemic." *Indoor air* 32, no. 2 (2022): e12998. https://doi.org/10.1111/ina.12998

[5] Neuwirth, Lorenz S., Svetlana Jović, and B. Runi Mukherji. "Reimagining higher education during and post-COVID-19: Challenges and opportunities." *Journal of Adult and Continuing Education* 27, no. 2 (2021): 141-156. https://doi.org/10.1177/1477971420947738

[6] Triyason, Tuul, Anuchart Tassanaviboon, and Prasert Kanthamanon. "Hybrid classroom: Designing for the new normal after COVID-19 pandemic." In *Proceedings of the 11th International Conference on Advances in Information Technology*, pp. 1-8. 2020. https://doi.org/10.1145/3406601.3406635

[7] Bazant, Martin Z., and John WM Bush. "A guideline to limit indoor airborne transmission of COVID-19." *Proceedings of the National Academy of Sciences* 118, no. 17 (2021): e2018995118. https://doi.org/10.1073/pnas.2018995118

[8] Yang, Fan, Amir A. Pahlavan, Simon Mendez, Manouk Abkarian, and Howard A. Stone. "Towards improved social distancing guidelines: Space and time dependence of virus transmission from speech-driven aerosol transport between two individuals." *Physical Review Fluids* 5, no. 12 (2020): 122501. https://doi.org/10.1103/PhysRevFluids.5.122501

[9] Catching, Adam, Sara Capponi, Ming Te Yeh, Simone Bianco, and Raul Andino. "Examining the interplay between face mask usage, asymptomatic transmission, and social distancing on the spread of COVID-19." *Scientific reports* 11, no. 1 (2021): 1-11. https://doi.org/10.1038/s41598-021-94960-5

[10] Xia, Yaowen, Wenxian Lin, Wenfeng Gao, Tao Liu, Qiong Li, and Anran Li. "Experimental and numerical studies on indoor thermal comfort in fluid flow: A case study on primary school classrooms." *Case Studies in Thermal Engineering* 19 (2020): 100619. https://doi.org/10.1016/j.csite.2020.100619
[11] El-Haroun, Ahmed Fahmy, Sayed Ahmed Kaseb, Mahmoud Ahmed Fouad, and Hatem Omar Kayed. "Numerical Investigation of Covid-19 Infection Spread Expelled from Cough in an Isolation Ward Under Different Air Distribution Strategies." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 95, no. 1 (2022): 17-35. https://doi.org/10.37934/arfmts.95.1.1735
[12] Pogačnik Krajnc, Anja, Luka Pirker, Urška Gradišar Centa, Anton Gradišek, Igor B. Mekjavic, Matej Godnič, Metod Čebašek, Tina Bregant, and Maja Remškar. "Size-and time-dependent particle removal efficiency of face masks and improvised respiratory protection equipment used during the COVID-19 pandemic." *Sensors* 21, no. 5 (2021): 1567. https://doi.org/10.3390/s21051567
[13] Simpson, J. P., D. N. Wong, L. Verco, R. Carter, M. Dzidowski, and P. Y. Chan. "Measurement of airborne particle exposure during simulated tracheal intubation using various proposed aerosol containment devices during the COVID-19 pandemic." *Anaesthesia* 75, no. 12 (2020): 1587-1595. https://doi.org/10.1111/anae.15188
[14] Tang, Julian W., Linsey C. Marr, Yuguo Li, and Stephanie J. Dancer. "Covid-19 has redefined airborne transmission." *bmj*373 (2021). https://doi.org/10.1136/bmj.n913
[15] El Hassan, Mouhammad, Hassan Assoum, Nikolay Bukharin, Huda Al Otaibi, Md Mofijur, and Anas Sakout. "A review on the transmission of COVID-19 based on cough/sneeze/breath flows." *The European Physical Journal Plus* 137, no. 1 (2022): 1. https://doi.org/10.1140/epjp/s13360-021-02162-9
[16] Pahar, Madhurananda, Marisa Klopper, Robin Warren, and Thomas Niesler. "COVID-19 detection in cough, breath and speech using deep transfer learning and bottleneck features." *Computers in Biology and Medicine* 141 (2022): 105153. https://doi.org/10.1016/j.compbiomed.2021.105153
[17] Issakhov, Alibek, Yeldos Zhandaulet, Perizat Omarova, Aidana Alimbek, Aliya Borsikbayeva, and Ardak Mustafayeva. "A numerical assessment of social distancing of preventing airborne transmission of COVID-19 during different breathing and coughing processes." *Scientific Reports* 11, no. 1 (2021): 1-39. https://doi.org/10.1038/s41598-021-88645-2
[18] Abbas, Günsu Merin, and Ipek Gursel Dino. "The impact of natural ventilation on airborne biocontaminants: a study on COVID-19 dispersion in an open office." *Engineering, Construction and Architectural Management* 29, no. 4 (2021): 1609-1641. https://doi.org/10.1108/ECAM-12-2020-1047
[19] Zhai, Zhiqiang, He Li, Robert Bahl, and Keith Trace. "Application of portable Air purifiers for mitigating COVID-19 in large public spaces." *Buildings* 11, no. 8 (2021): 329. https://doi.org/10.3390/buildings11080329
[20] Jamal, Mohamed, Maanas Shah, Sameeha Husain Almarzooqi, Hend Aber, Summayah Khawaja, Rashid El Abed, Zuhair Alkhatib, and Lakshman Perera Samaranayake. "Overview of transnational recommendations for COVID-19 transmission control in dental care settings." *Oral diseases* 27 (2021): 655-664. https://doi.org/10.1111/odi.13431
[21] Hwang, Seo Eun, Je Hwan Chang, Bumjo Oh, and Jongho Heo. "Possible aerosol transmission of COVID-19 associated with an outbreak in an apartment in Seoul, South Korea, 2020." *International Journal of Infectious Diseases* 104 (2021): 73-76. https://doi.org/10.1016/j.ijid.2020.12.035
[22] Liu, Jiaye, Xuejiao Liao, Shen Qian, Jing Yuan, Fuxiang Wang, Yingxia Liu, Zhaoqin Wang, Fu-Sheng Wang, Lei Liu, and Zheng Zhang. "Community transmission of severe acute respiratory syndrome coronavirus 2, Shenzhen, China, 2020." *Emerging infectious diseases* 26, no. 6 (2020): 1320. https://doi.org/10.3201/eid2606.200239
[23] Li, Qun, Xuhua Guan, Peng Wu, Xiaoye Wang, Lei Zhou, Yeqing Tong, Ruiqi Ren et al. "Early transmission dynamics in Wuhan, China, of novel coronavirus–infected pneumonia." *New England journal of medicine* (2020).
[24] Ai, Zhengtao, Cheuk Ming Mak, Naiping Gao, and Jianlei Niu. "Tracer gas is a suitable surrogate of exhaled droplet nuclei for studying airborne transmission in the built environment." In *Building Simulation*, vol. 13, no. 3, pp. 489-496. Tsinghua University Press, 2020. https://doi.org/10.1007/s12273-020-0614-5
[25] Nicas, Mark, William W. Nazaroff, and Alan Hubbard. "Toward understanding the risk of secondary airborne infection: emission of respirable pathogens." *Journal of occupational and environmental hygiene* 2, no. 3 (2005): 143-154. https://doi.org/10.1080/15459620590918466
[26] Herbert, Stefan, Tatiana Gambaryan-Roisman, and Peter Stephan. "Influence of the governing dimensionless parameters on heat transfer during single drop impingement onto a hot wall." *Colloids and Surfaces A: Physicochemical and Engineering Aspects* 432 (2013): 57-63. https://doi.org/10.1016/j.colsurfa.2013.05.014
[27] Yarin, Alexander L. "Drop impact dynamics: splashing, spreading, receding, bouncing." *Annual review of fluid mechanics* 38, no. 1 (2006): 159-192. https://doi.org/10.1146/annurev.fluid.38.050304.092144
[28] Rein, Martin. "Phenomena of liquid drop impact on solid and liquid surfaces." *Fluid dynamics research* 12, no. 2 (1993): 61-93. https://doi.org/10.1016/0169-5983(93)90106-K
[29] Josserand, Christophe, and Sigurdur T. Thoroddsen. "Drop impact on a solid surface." *Annual review of fluid*

*mechanics*48, no. 1 (2016): 365-391. https://doi.org/10.1146/annurev-fluid-122414-034401

[30] Lu, Jianyun, Jieni Gu, Kuibiao Li, Conghui Xu, Wenzhe Su, Zhisheng Lai, Deqian Zhou, Chao Yu, Bin Xu, and Zhicong Yang. "COVID-19 outbreak associated with air conditioning in restaurant, Guangzhou, China, 2020." *Emerging infectious diseases* 26, no. 7 (2020): 1628. https://doi.org/10.3201/eid2607.200764

[31] Pirouz, Behrouz, Stefania Anna Palermo, Seyed Navid Naghib, Domenico Mazzeo, Michele Turco, and Patrizia Piro. "The role of HVAC design and windows on the indoor airflow pattern and ACH." *Sustainability* 13, no. 14 (2021): 7931. https://doi.org/10.3390/su13147931

[32] Chen, Qingyan. "Comparison of different k-ε models for indoor air flow computations." *Numerical Heat Transfer, Part B Fundamentals* 28, no. 3 (1995): 353-369. https://doi.org/10.1080/10407799508928838

[33] Wijaya, Elang Pramudya, and Ardiyansyah Saad Yatim. "Numerical Investigation of Air Movement on Laboratory Scale Psychrometric Chamber." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 84, no. 2 (2021): 82-91. https://doi.org/10.37934/arfmts.84.2.8291

[34] Bahar, Ananda Reno Andi, Ardiyansyah Saad Yatim, and Elang Pramudya Wijaya. "CFD Analysis of Universitas Indonesia Psychrometric Chamber Air Loop System." (2022): 465-469. https://doi.org/10.5109/4794173

[35] Al-Rawi, Mohammad. "The thermal comfort sweet-spot: A case study in a residential house in Waikato, New Zealand." *Case Studies in Thermal Engineering* 28 (2021): 101530. https://doi.org/10.1016/j.csite.2021.101530

[36] Al-Rawi, Mohammad, Ahmed M. Al-Jumaily, and Annette Lazonby. "Did You Just Cough? Visualization of Vapor Diffusion in an Office Using Computational Fluid Dynamics Analysis." *International Journal of Environmental Research and Public Health* 19, no. 16 (2022): 9928. https://doi.org/10.3390/ijerph19169928