Ejaz, Muhammad Farhan; Kilpeläinen, Simo; Mustakallio, Panu; Kosonen, Risto

A CFD study to explore the impact of classroom dimensions and infector location on indoor air quality

Published in:
E3S Web of Conferences

DOI:
10.1051/e3sconf/202456209005

Published: 07/08/2024

Document Version
Publisher's PDF, also known as Version of record

A CFD study to explore the impact of classroom dimensions and infector location on indoor air quality

Muhammad Farhan Ejaz[1] , Simo Kilpeläinen[1], Panu Mustakallio[1], Risto Kosonen[1,2]

[1] Department of Mechanical Engineering, Aalto University, Espoo,02150, Finland
[2] College of Urban Construction, Nanjing Tech University, China

Abstract. This study investigates the influence of infector location and classroom size on indoor air quality, utilizing CO_2 as a tracer gas. We employ Computational Fluid Dynamics (CFD) simulations, focusing on the local air quality index as a crucial evaluation parameter. Our research underscores the intricate relationship between infector location, classroom size, and ventilation effectiveness. In a learning environment comprising 16 students and one teacher, larger classrooms, approximately 2.3 times in size, demonstrated the potential to reduce the number of vulnerable students. However, the occupants in the proximity to the infector may still face an increased risk of exposure. The CFD results exhibit that the increasing size (dimensions) of the teaching space significantly reduced the number of vulnerable occupants in all simulated test cases. Moreover, our study also reveals that, when the infector is located near return openings, it not only enhances air quality in its immediate vicinity but also positively influences the overall classroom space.

1 Introduction

The COVID-19 pandemic, caused by the novel SARS-CoV-2 virus, has drawn attention to indoor environments as primary locations for virus transmission. [1-3]. Inadequate ventilation in densely populated spaces such as schools hinders the effective dilution of respiratory particles containing the virus, contributing to a high rate of secondary infections. [4-6]. Consequently, governments globally faced the challenging decision of temporarily closing various indoor settings, including schools, grasping with the dilemma of balancing the right to education against public health concerns [7-9].

Therefore, the indoor air quality (IAQ) of educational environments, particularly classrooms, has become a growing concern due to its profound impact on the health and well-being of students, educators, and staff. The confined nature of classrooms, often coupled with factors such as high occupancy rates, inadequate ventilation, and diverse pollutant sources, contributes to the potential spread of airborne contaminants. Understanding the dynamics of these contaminants and implementing effective mitigation approaches is crucial for fostering a healthy and conducive learning environment [10, 11]. Studies conducted by [12-14] emphasize the significance of IAQ in schools, highlighting the need for strategies to improve environmental conditions. These studies identify various pollutants, including biological agents, particulate matter, and volatile organic compounds (VOCs), originating from sources such as building materials, occupant activities, and outdoor air.

Ventilation stands out as a pivotal factor in mitigating the spread of airborne contaminants within classrooms. Previous studies [15, 16] extensively explore the relationship between ventilation rates and occupant health. Their findings underscore the importance of optimizing ventilation systems and design to enhance IAQ, thereby reducing the concentration of pollutants in indoor environments.

The present study endeavours to explore and substantiate the impact of teaching space dimensions on the airborne spread of contaminants while maintaining a consistent number of occupants. Larger teaching spaces inherently feature increased distances between students, and our research aims to investigate this phenomenon in the context of airborne contaminants spread.

This investigation was conducted within the scope of the ILMIRA project, an interdisciplinary initiative. The project addresses the resilience of ventilation systems in indoor environments concerning both overheating issues and the potential transmission of infectious diseases. This conference article specifically focuses on the outcomes of the classroom study conducted within the broader project. The goal was to scrutinize the correlation between teaching space size and the potential spread of airborne contaminants and to contribute valuable insights to the existing body of knowledge.

2 Methodology

2.1 Studied Classroom Space

In this investigation, the airborne spread of infectious contaminants was examined in two classrooms, each distinguished by variations in size. The larger classroom is an extension of the smaller classroom as shown in Fig. 1. The smaller classroom, spanning 56.5 m², accommodated 17 occupants with a supply air flow rate of 230 l/s, facilitated by two supply air diffusers and a single return opening. Conversely, the larger classroom, covering 129.5 m², maintained an identical occupancy of 17 individuals but operated with a higher supply air flow rate of 520 l/s. This larger space featured five supply air diffusers and three exhaust openings. The 17 individuals within each classroom were positioned at average distances of

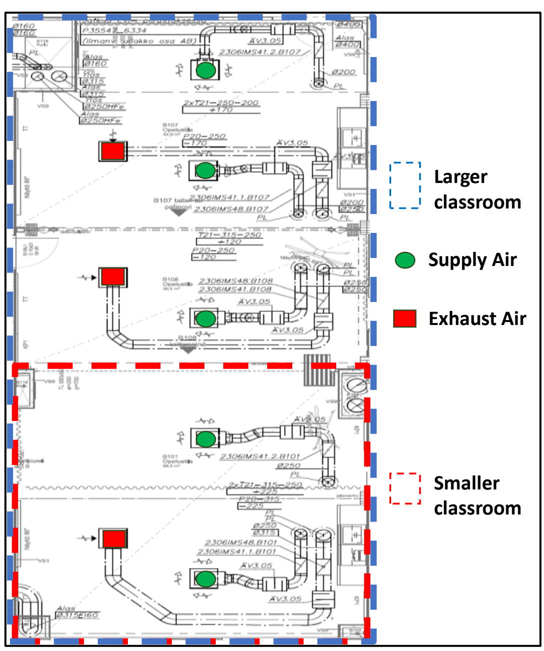

Fig. 1. Layout of classroom space

 https://doi.org/10.1051/e3sconf/202456209005

1.5 meters in the smaller setting and 2.5 meters in the larger one. Both classrooms adhered to a consistent specific supply air flow rate of 4 l/s/m², maintaining indoor operating temperatures at 21°C with a supply air temperature of 19°C.

2.2 CFD Simulations

The studied classroom space (Fig. 2.) was modeled in SolidWorks and later it was imported into the design modeler of commercial ANSYS FLUENT 2022 R2. Time-independent RANS (Reynolds-Averaged Navier-Stokes simulation), where the flow field is time-averaged, was used as the simulation method.

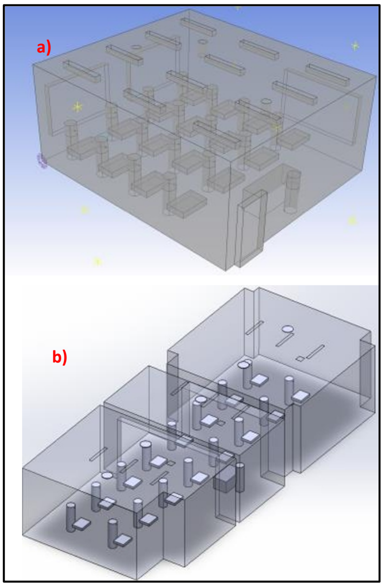

Fig. 2. CFD domain of classroom space a) Smaller classroom b) Larger classroom

Cylindrical heated dummies (75W/m^2) as shown in Fig. 3. were used as human models and the exhalation was realized with a 3 cm diameter "mouth hole" made onto the cylinders. CO_2 was used as a tracer gas for infectious particles, the volume flow rate of exhalation was 6 l/min, and a person breathing while seated. Since the calculations were time-independent, continuous exhalation was used. The real average diameter of a human mouth/nose is around 1 cm when exhaling but due to the large size of the studied space, such a small opening caused convergence problems in the simulation.

The infected person's breathing was modeled with a dimensionless contaminant concentration added to their exhalation. This concentration was normalized to be exactly one in the exhaled breath, making the concentrations elsewhere directly give the relation to the contaminant source.

 https://doi.org/10.1051/e3sconf/202456209005

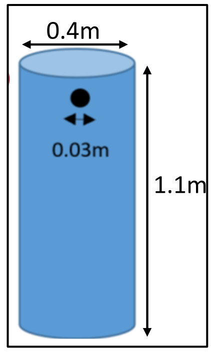

Fig. 3. Dummy (occupant) model

In CFD analysis, the discretization of governing equations is done by dividing the entire spatial domain into numerous small finite control volumes by using the meshing process. Integration of governing equations over each control volume is performed by discretely conserving quantities like energy, mass, momentum, etc. over each control volume. The computational domain for this study was discretized into a fine polyhedral volumetric mesh using ANSYS fluent meshing. In this investigation, a polyhedral volumetric mesh was crafted, encompassing approximately 3 million elements. The mesh exhibited a range of resolutions, with a minimum element size specified at 0.001m and a maximum size of 0.2m. To ensure numerical stability, a minimum orthogonal quality criterion of 0.1 was imposed, emphasizing the importance of maintaining mesh integrity.

Additionally, a skewness value of 0.3 was targeted, reflecting a balanced consideration for well-shaped mesh elements. These mesh characteristics collectively aim to strike a pragmatic equilibrium between resolution, stability, and element geometry, aligning with the essential requirements for an effective computational fluid dynamics study. Moreover, all the walls have 4 transition layers. This specific design choice was made to effectively capture the near-wall effects, particularly focusing on the boundary layers. Transition layers are integral in refining the mesh near the walls to ensure a more accurate representation of the flow physics, especially in regions where significant gradients occur. The inclusion of these transition layers enhances the CFD simulation's ability to capture intricate details in the boundary layer and provides a more reliable representation of the near-wall effects within the studied space. In the end, the post-processing of results was conducted using ANSYS CFD-Post.

 https://doi.org/10.1051/e3sconf/202456209005

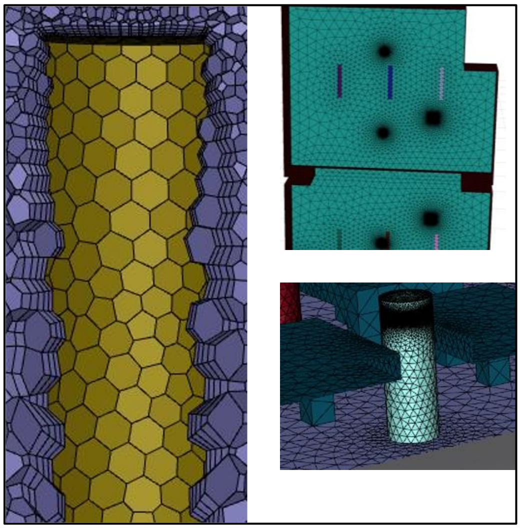

Fig. 4. Grid (focused on walls, inlets, and outlets)

2.3 Test cases and evaluation index

In the classroom of 17 occupants, there was one infector. For both classrooms, the educational settings were one teacher and 16 students. The study investigated three different infector locations (A, B and C) for both classroom spaces (small and large). A description of total 6 tested scenarios can be found in Table 1. Moreover, Fig. 5 shows the examined locations of the infector.

Table 1: Description of test cases

Classroom	Infector	Case #
Small classroom	A	S1
	B	S2
	C	S3
Larger classroom	A	L1
	B	L2
	C	L3

 https://doi.org/10.1051/e3sconf/202456209005

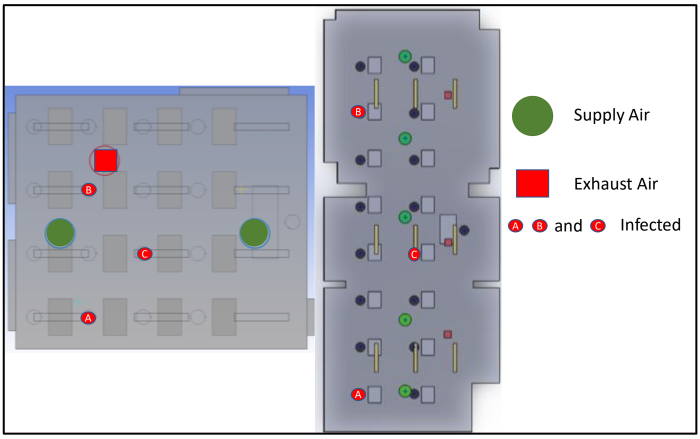

Fig. 5. Locations of the infector for test cases

The local air quality index (ε_p) is used to evaluate the ventilation efficiency of ventilation systems in mitigating the spread of pathogens within a gym environment when there is a single or few individuals releasing contaminants.

It is defined as follows:

$$\varepsilon_p = \frac{C_e - C_0}{C_p - C_0}, \quad (1)$$

where c_e is the (average) contaminant concentration in the exhaust air duct(s), c_0 is the concentration in the supply air, and c_p is the local concentration. The location where $\varepsilon_p < 1$ was considered vulnerable.

3 Result and discussion

The results for both classroom spaces are shown in Fig. 6. The measurement results for the local air quality index εp reflect that the size of the classroom highly affects the number of susceptible occupants. In the case of a smaller classroom, the infectious exhale of infector A made at least 2 occupants vulnerable ($\varepsilon_p < 1$), however in case of larger classroom with larger distance between the occupants, the vulnerable individual was 1.

 https://doi.org/10.1051/e3sconf/202456209005

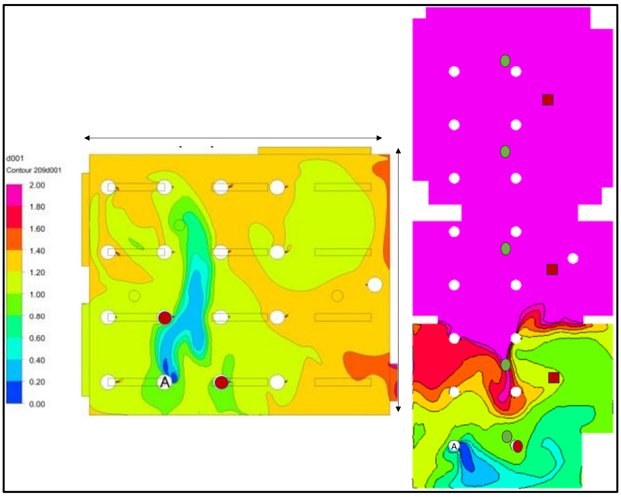

Fig. 6. Local air quality in case of infector A Left: Small classroom Right: Larger Classroom

The simulation results from the infector B are summarized in Fig. 7. In this case, there are at least 6 vulnerable occupants in the smaller classroom, while the for the larger teaching space, the number of susceptible occupants is reduced to 2. Thus, about 2.3 times increase in classroom space, reduce the susceptible occupants to 3 times.

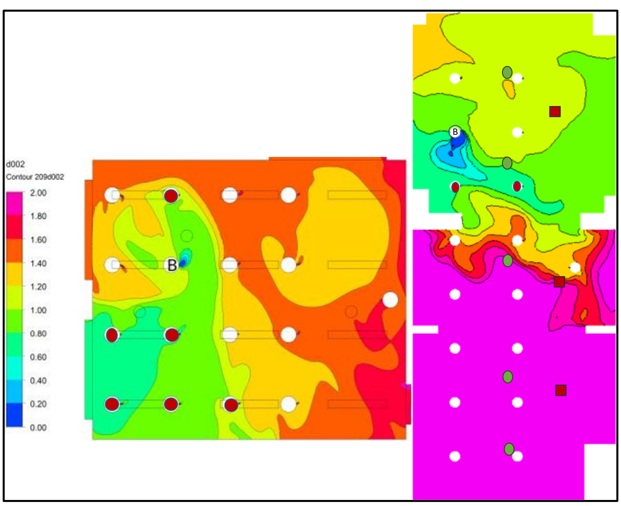

Fig. 7. Local air quality in case of infector B Left: Small classroom Right: Larger Classroom

The ε_p results from infectious contaminants from infector C are summarized in Fig. 8. In this case, the smaller classroom exhibits 7 susceptible occupants, while the results from the larger classroom were exceptional as no susceptible occupant in this case.

 https://doi.org/10.1051/e3sconf/202456209005

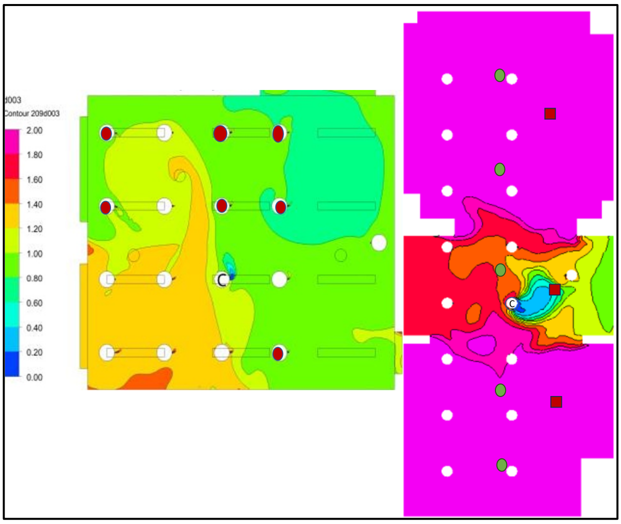

Fig. 8. Local air quality in case of infector C Left: Small classroom Right: Larger Classroom

Another interesting observation surfaced during the study: when the infector is positioned near the return opening, as demonstrated by infector C in the larger classroom (refer to Fig. 8), the spread of contaminants is considerably limited. A similar phenomenon was observed when the infector was situated close to a wall, exemplified by infector A in the smaller classroom (refer to Fig. 6). In this scenario, infectious contaminants predominantly dispersed on one side of the wall, away from the breathing zone (1.1 meters). They interacted with the wall, redirecting their movement away from the occupied area towards the side adjacent to the wall.

4 Conclusion

This classroom-based study, incorporating Computational Fluid Dynamics (CFD) simulations, focused on evaluating the impact of the dimension of the teaching space on airborne pathogen dispersion. The study investigated the indoor air quality of a teaching space with the relationship between classroom size and the local air quality index. We use CO_2 as a tracer gas in this study. The CFD simulations-based results depict that larger classroom, approximately 2.3 times the size, exhibited potential advantages in reducing the number of individuals susceptible to compromised air quality. Nevertheless, interesting insights emerged during our investigation. Specifically, when the simulated source was placed near certain points, such as the return opening or close to a wall, the dispersion of contaminants was significantly restricted.

Acknowledgments

The authors wish to acknowledge the Finnish Prime Minister’s Office (VN TEAS 457/2023) for financial support of the ILMIRA project. The authors would also like to thank Halton Oy for providing product data to help with the modelling of the air supply diffusers.

References

1. L. Morawska *et al.*, "How can airborne transmission of COVID-19 indoors be minimised?," *Environment international,* vol. 142, p. 105832, 2020. [Online]. Available: https://doi.org/10.1016/j.envint.2020.105832.
2. S. Chang *et al.*, "Mobility network models of COVID-19 explain inequities and inform reopening," *Nature,* vol. 589, no. 7840, pp. 82-87, 2021. [Online]. Available: https://doi.org/10.1038/s41586-020-2923-3.
3. J. Wei and Y. Li, "Airborne spread of infectious agents in the indoor environment," *American journal of infection control,* vol. 44, no. 9, pp. S102-S108, 2016. [Online]. Available: https://doi.org/10.1016/j.ajic.2016.06.003.
4. G. Buonanno, L. Morawska, and L. Stabile, "Quantitative assessment of the risk of airborne transmission of SARS-CoV-2 infection: prospective and retrospective applications," *Environment international,* vol. 145, p. 106112, 2020. [Online]. Available: https://doi.org/10.1016/j.envint.2020.106112.
5. G. Buonanno, L. Stabile, and L. Morawska, "Estimation of airborne viral emission: Quanta emission rate of SARS-CoV-2 for infection risk assessment," *Environment international,* vol. 141, p. 105794, 2020. [Online]. Available: https://doi.org/10.1016/j.envint.2020.105794.
6. T. P. Baggett, H. Keyes, N. Sporn, and J. M. Gaeta, "Prevalence of SARS-CoV-2 infection in residents of a large homeless shelter in Boston," *Jama,* vol. 323, no. 21, pp. 2191-2192, 2020, doi: doi:10.1001/jama.2020.6887.
7. R. M. Viner *et al.*, "School closure and management practices during coronavirus outbreaks including COVID-19: a rapid systematic review," *The Lancet Child & Adolescent Health,* vol. 4, no. 5, pp. 397-404, 2020. [Online]. Available: https://doi.org/10.1016/S2352-4642(20)30095-X.
8. M. Klimek-Tulwin and T. Tulwin, "Early school closures can reduce the first-wave of the COVID-19 pandemic development," *Journal of Public Health,* pp. 1-7, 2020, doi: 10.1007/s10389-020-01391-z.
9. J. Bayham and E. P. Fenichel, "Impact of school closures for COVID-19 on the US health-care workforce and net mortality: a modelling study," *The Lancet Public Health,* vol. 5, no. 5, pp. e271-e278, 2020. [Online]. Available: https://doi.org/10.1101/2020.03.09.20033415.
10. L. Stabile, A. Pacitto, A. Mikszewski, L. Morawska, and G. Buonanno, "Ventilation procedures to minimize the airborne transmission of viruses in classrooms," *Building and Environment,* vol. 202, p. 108042, 2021/09/01/ 2021. [Online]. Available: https://doi.org/10.1016/j.buildenv.2021.108042.

11. S. Ferrari, T. Blázquez, R. Cardelli, G. Puglisi, R. Suárez, and L. Mazzarella, "Ventilation strategies to reduce airborne transmission of viruses in classrooms: A systematic review of scientific literature," *Building and Environment,* p. 109366, 2022. [Online]. Available: https://doi.org/10.1016/j.buildenv.2022.109366.
12. G. de Gennaro *et al.*, "Indoor air quality in schools," *Environmental chemistry letters,* vol. 12, pp. 467-482, 2014.
13. S. Sadrizadeh *et al.*, "Indoor air quality and health in schools: A critical review for developing the roadmap for the future school environment," *Journal of Building Engineering,* p. 104908, 2022. [Online]. Available: https://doi.org/10.1016/j.jobe.2022.104908.
14. L. Chatzidiakou, D. Mumovic, and A. J. Summerfield, "What do we know about indoor air quality in school classrooms? A critical review of the literature," *Intelligent Buildings International,* vol. 4, no. 4, pp. 228-259, 2012. [Online]. Available: https://doi.org/10.1080/17508975.2012.725530.
15. J. Sundell *et al.*, "Ventilation rates and health: multidisciplinary review of the scientific literature," *Indoor air,* vol. 21, no. 3, pp. 191-204, 2011. [Online]. Available: https://doi.org/10.1111/j.1600-0668.2010.00703.x.
16. P. Wargocki *et al.*, "Ventilation and health in non-industrial indoor environments: report from a European multidisciplinary scientific consensus meeting (EUROVEN)," *Indoor air,* vol. 12, no. 2, pp. 113-128, 2002. [Online]. Available: https://doi.org/10.1034/j.1600-0668.2002.01145.x.