Impact of design parameters of diffuse ceiling ventilation systems on indoor air quality in school classrooms: a numerical assessment

Parastoo Sadeghian[*], Sasan Sadrizadeh
KTH Royal Institute of Technology, Stockholm, Sweden

* Corresponding author: parsad@kth.se

Abstract

Indoor air quality directly impacts an individual's productivity and health condition in office buildings, hospitals, schools, and residential buildings. Diffuse ceiling systems have been used widely in classrooms at schools that have high heat loads. In this regard, this study investigated the role of diffuse ceiling design parameters, including active diffuse panels' configuration and contamination locations, on indoor air quality in a classroom. The spread of airborne infectious diseases was simulated using computational fluid dynamics techniques. The results revealed that the central configuration of diffuse ceiling panels had the minimum spread of contaminations in the classroom compared to the dispersed configuration.

Keywords: Diffuse ceiling ventilation system, Computational fluid dynamics, Airborne infectious diseases, Indoor air quality

Introduction

Indoor air quality can impact the activity and performance of the students, employees, and occupants in the buildings (Fisk, 1999; Mendell et al., 2002). Since the students spend a considerable part of their daytime at school rather than at home, indoor air quality has been considered an essential environmental factor in their health conditions. Several studies have shown that indoor air pollution can cause serious damage to kids since they need a larger volume of air than their body weight during the inhalation process (Goldizen et al., 2016; USEPA & US EPA, 2006).

Heating and cooling ventilation systems improve indoor air quality and ensure a thermally comfortable condition for the occupants. Various air distribution strategies have been applied to supply clean air to the indoor environment, including diffuse ceiling systems. Diffuse ceiling ventilation systems are common systems in schools and office buildings. These systems deliver cold air using a large diffuse ceiling perforated area between the plenum and the room. Diffuse ceiling ventilation systems supply cold air with a considerably low velocity through diffuse panels, resulting in a low draft risk in the occupant's zone (Fan et al., 2013; Jacobs & Knoll, 2009; P. V Nielsen & Jakubowska, 2009).

The performance of diffuse ceiling is affected by various design parameters, including heat load distribution, active diffuse panel configuration, plenum and room geometry. Zhang et al. (2016(a)) reported the role of plenum size and inlet duct location on the cooling capacity of the diffuse ceiling ventilation systems. Moreover, Nielsen et al. (2015) accomplished an experimental study on the influence of heat load distributions in the occupied zone. Their results showed that the diffuse ceiling system had the highest cooling performance with an even distribution of the heat loads. Further, Zhang et al. (2016(b)) investigated the cooling capacity of the diffuse ceiling system in a classroom with various configurations of heat loads. The experimental results revealed that evenly distributed heat sources resulted in a lower draft risk for the occupants than the centred, front and back locations of heat loads.

Besides heat load distribution, the impact of diffuse ceiling active panels' configuration has been evaluated by various studies (Nocente et al., 2020; Rahnama et al., 2019, 2020). Nocente et al. (2020) considered a chessboard and complete cover of the active diffuse panel on the ceiling. The numerical results indicated that these two configurations had no significant difference regarding the pressure drop. All the literature mentioned above has considered the role of an individual design parameter for a few configurations; consequently, reaching a general conclusion is not possible. However, Rahnama et al. (2020) performed an experimental and numerical investigation on the role of relative locations of heat loads and diffuse ceiling configurations for ten various scenarios. They reported that the central configuration of the active diffuse panels with even distribution of the heat loads had the highest cooling capacity.

Due to a considerable increase in indoor air pollution and airborne infectious diseases, such as COVID-19 and influenza, it is required to assess the performance of diffuse ceiling ventilation systems in indoor environments, especially classrooms. In this regard, the

current study numerically evaluated the role of diffuse ceiling design parameters, i.e., different diffuse ceiling configurations with the various contamination locations on indoor air quality in a classroom. The computational fluid dynamics (CFD) technique was used to model the airflow field and contamination distribution. The applied numerical models were validated with the experimental data.

Methods

Case study

The current study simulated airflow behaviour and contamination distribution in a classroom with a dimension of 4.2 m × 6.0 m × 3.3 m, as shown in Figure 1. Two different configuration of active diffuse panels were considered, including central (Fig.1 (a)) and dispersed (Fig.1 (b)) configurations.
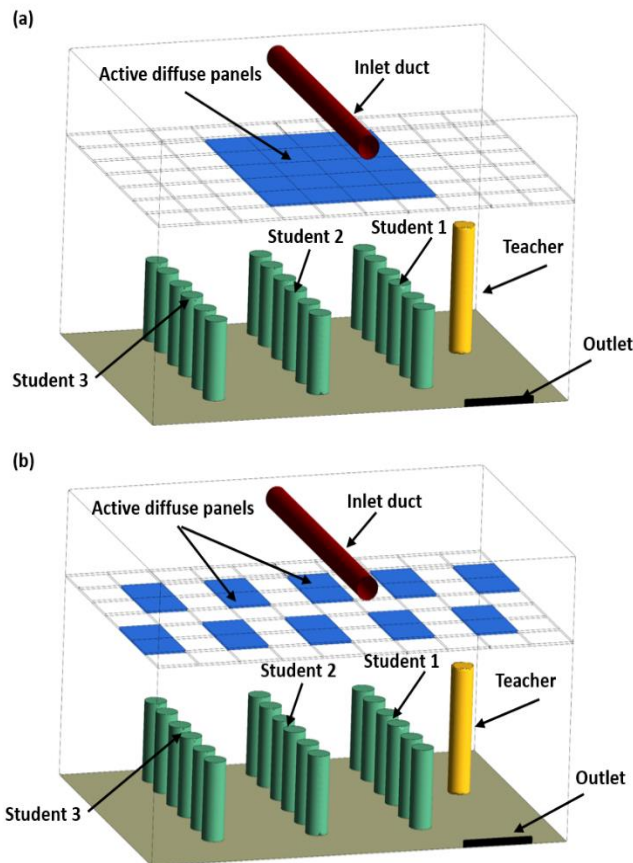

Figure 1: Isometric view of the classroom with a) central active diffuse panels and b) dispersed active diffuse panels

The investigated classroom was subdivided into the plenum and the occupied zone (Fig.1). The cold air was supplied to the plenum through an inlet duct with a flowrate of 0.15 m³/s and a temperature of 10.6 ˚C. The diffuse ceiling panels were located 0.8 m below the classroom ceiling. The suspended ceiling had 20 active

diffuse panels with a size of 0.6m × 0.6m and a density of 360 kg/m³ in both central and dispersed configurations. The active diffuse panels were wood cement with a porosity of 65% and thermal conductivity of 0.085 W/m K. The diffuse panels' characteristic was selected based on the authors' previous experimental and numerical study (Rahnama et al., 2020).

The classroom contains 19 cylinders as a representative of students and a teacher with a surface area of 1.14 m² and 1.63 m², respectively. The emitted heat by each student was 89 W, while the teacher had a total heat emission of 100 W, defined based on the ASHRAE standard (Mora et al., 2021). An exhaust grill with a dimension of 0.5 m × 0.05 m was located at one of the side walls in the classroom.

The release of SF_6 gas was adopted to simulate the dispersion of airborne infectious diseases from an infected student in the classroom. The $SF6$ gas was released from nose of the patients. In this regard, six different scenarios were simulated to assess the impact of active diffuse panel configuration and location of the contamination source in the classroom, as shown in Table 1.

Table 1: Simulated scenarios in the classroom

Case studies	Active diffuse panel configuration	The release point of contamination
Case 1	Central	Student 1
Case 2		Student 2
Case 3		Student 3
Case 4	Dispersed	Student 1
Case 5		Student 2
Case 6		Student 3

Numerical models

The steady-state airflow field in the classroom was simulated by adopting ANSYS Fluent 19.2. In this regard, the governing equations of mass, momentum and energy were adopted in steady state condition as following:

$$\nabla.\left(\rho\phi\vec{V}\right) = \nabla.\left(\Gamma_\phi\nabla\phi\right) + S_\phi \qquad (1)$$

In the above equation, ϕ is the transport quantity, $\vec{V}$ is the air velocity vector, ρ is defined as the air density that in the current work was an incompressible ideal gas, $\Gamma\phi$ and $S\phi$ are effective diffusivity and source terms, respectively.

The Realizable k-ε turbulence model was considered to simulate the turbulent behaviour of the airflow in the classroom. The adiabatic and no-slip boundary conditions were used for all the solid walls. The occupants' heat transfer was modelled using a constant heat flux boundary condition. The release of airborne infectious agents from infected students was simulated by adopting Fluent software's Species Transport model. All the numerical models were validated with our previous experimental study, and details are available in the authors' previous work (Rahnama et al., 2019).

The airflow field in active diffuse panels was modelled by adopting the porous media equations in ANSYS Fluent. This model considered the viscous and inertial resistance for the passing flow through porous media. In this regard, the momentum source term is defined as below:

$$S_M = -\left(\frac{\mu}{\alpha} + C_2 \frac{1}{2}\rho|v|v\right) \qquad (2)$$

Based on the previous experimental results, the inertial resistance of $C_2 = 50635$ m^{-1} and viscous resistance coefficient of $1/\alpha = 7.6 \times 107$ m^{-2} were adopted in simulations.

The physical domain of the classroom was subdivided into 5 million cells by using the ICEM CFD software. Moreover, the grid independency study was performed to assure the grid resolution had no impact on the simulation results.

Results and Discussion

The velocity distribution at a cut plan passing the centre of the classroom with two different configurations of the active diffuse panels is shown in Figure 2.
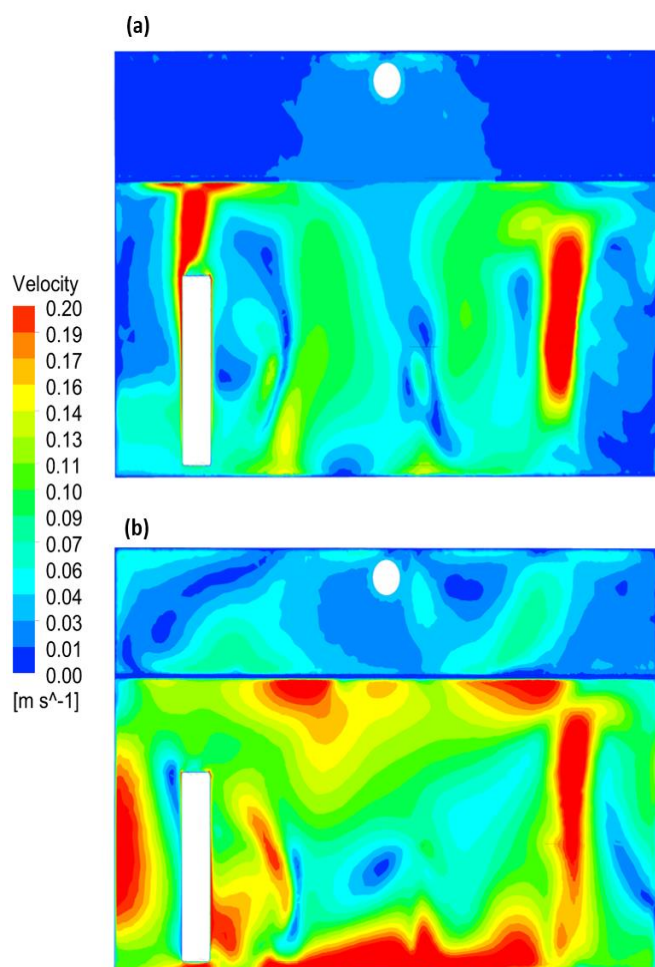

Figure 2: Velocity distribution at a cut plan passing centre of the classroom with a) central and b) dispersed active diffuse panel configurations

The highest velocity of 0.2 m/s was obtained close to the floor and side walls in the classroom with the dispersed configuration of diffuse panels. According to the ASHRAE standard (Mora et al., 2021), velocity values above 0.15 m/s can cause dissatisfaction for the occupants. In contrast, the average velocity of 0.11 m/s was reported in the classroom with a central configuration and a more even velocity distribution in the occupied zone.

The distribution of temperature at the centre of the classroom with both diffuse ceiling configurations is displayed in Figure 3.
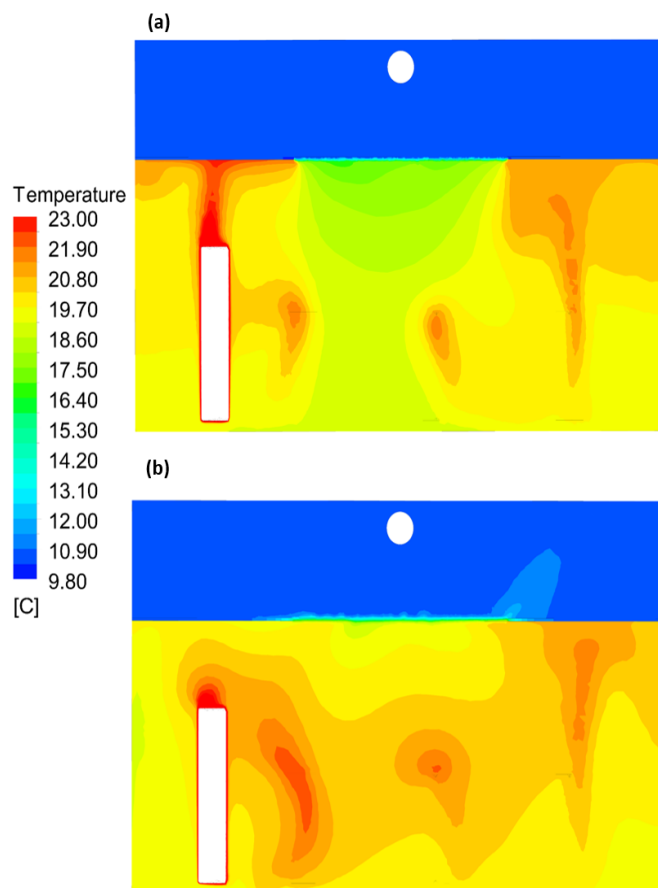

Figure 3: Temperature distribution at a cut plan passing centre of the classroom with a) central and b) dispersed active diffuse panel configurations

The vertical temperature difference is less than 3˚C in both classrooms with central and dispersed configurations. The average air temperature was 19.79 ˚C in the classroom with a central diffuse ceiling configuration and 20.05 ˚C for the dispersed one.

Figure 4 shows the temperature distribution at a horizontal cut plan located 0.6 m above the floor for both configurations of diffuse panels in the classroom. In the central configuration, the average temperature of the air was about 19 ˚C at the centre of the classroom, as shown in Figure 4 (a). However, the average air temperature was

about 21 ˚C in the middle of the classroom with a dispersed configuration. Consequently, the dispersed configuration had a lower cooling efficiency than the central configuration of active diffuse panels. Thus, the central configuration of the diffuse panels can be recommended for the classrooms and offices with a high number of occupants.
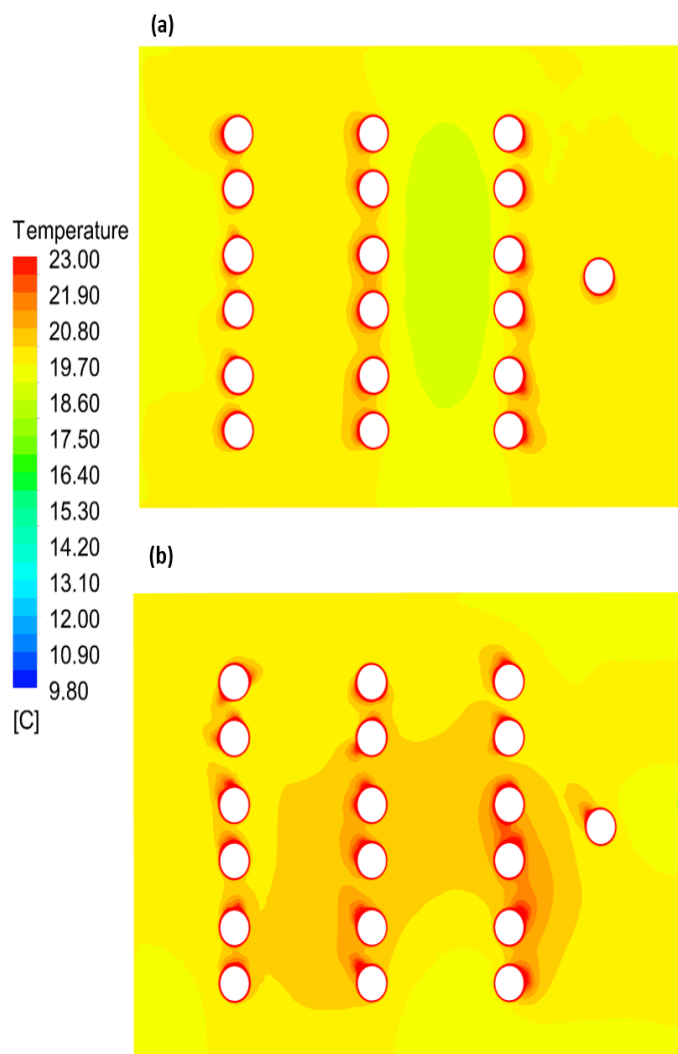

Figure 4: Temperature distribution at a horizontal cut plan above the floor of the classroom with a) central and b) dispersed active diffuse panel configurations

The indoor air quality was investigated in the classroom with both configurations by considering the dispersion of airborne infectious agents from various students, as shown in Figure 5. In this regard, SF_6 gas was used as an airborne infectious agent in our numerical study. The SF6 gas was released from student 1 in Cases 1 and 4 (Fig. 5 (a, b)), while the contamination source was student 2 in Cases 2 and 5 (Fig. 5 (c, d)). Finally, the contamination was released from student 3, located at the end of the classroom in Cases 3 and 6 (Fig. 5 (e, f)).

Overall the dispersion of contamination from the infected student in the classroom using the central diffuse ceiling configuration (Fig. 5 (a, c, e)) was less than the dispersed configuration (Fig. 5 (b, d, f)). In Cases 1 and 4, in which the infected student was located in front of the classroom, the contamination penetrated less to the back of the classroom than in other cases. Since student 1 was located adjacent to the classroom outlet, the infectious agents were mainly extracted from the occupied zone. Consequently, locating the contamination source close to the room extract can reduce the distribution of the infectious agents.

In Cases 2 and 5, where the infected student was in the middle of the classroom, the contamination was distributed evenly in the occupied zone for both configurations of the diffuse ceiling. However, the airborne infectious agent was distributed to further distances in Case 5 using the dispersed configuration compared to Case 2. This result might be due to location of the student 2, which was below the central active diffuse panel configuration. Thus, the relative location of the contamination source with the active diffuse panels had an impact on the distribution of the airborne contaminated agents in the classroom.

Student 3 was positioned at the back of the classroom, the furthest distance to the outlet and active diffuse ceilings with both configurations. Overall, the distribution of the airborne infectious agents was higher in Cases 3 and 6 since the contamination source is at the furthest distance from the outlet and active diffuse panels. Figure 5 (f) shows that the contamination had a high concentration in the half of the classroom with the dispersed configuration. However, the dispersion of the contamination from student 3 was minimum with the central configuration in the classroom. Consequently, the relative distance of the contaminated student with the diffuse ceiling active panels and classroom outlets can be considered an essential factor in controlling the spread of airborne infectious diseases.

Overall, the location of student 3 as a contamination source created the highest risk of contaminating all the students and the teacher in the classroom. However, the position of student 1 had the minimum contamination risks for the rest of the occupants in the classroom with both configurations of the diffuse ceiling panels. Moreover, the central opening of diffuse ceiling panels provided better indoor air quality and less dispersion of the infected airborne agents in the classroom compared to the dispersed one.
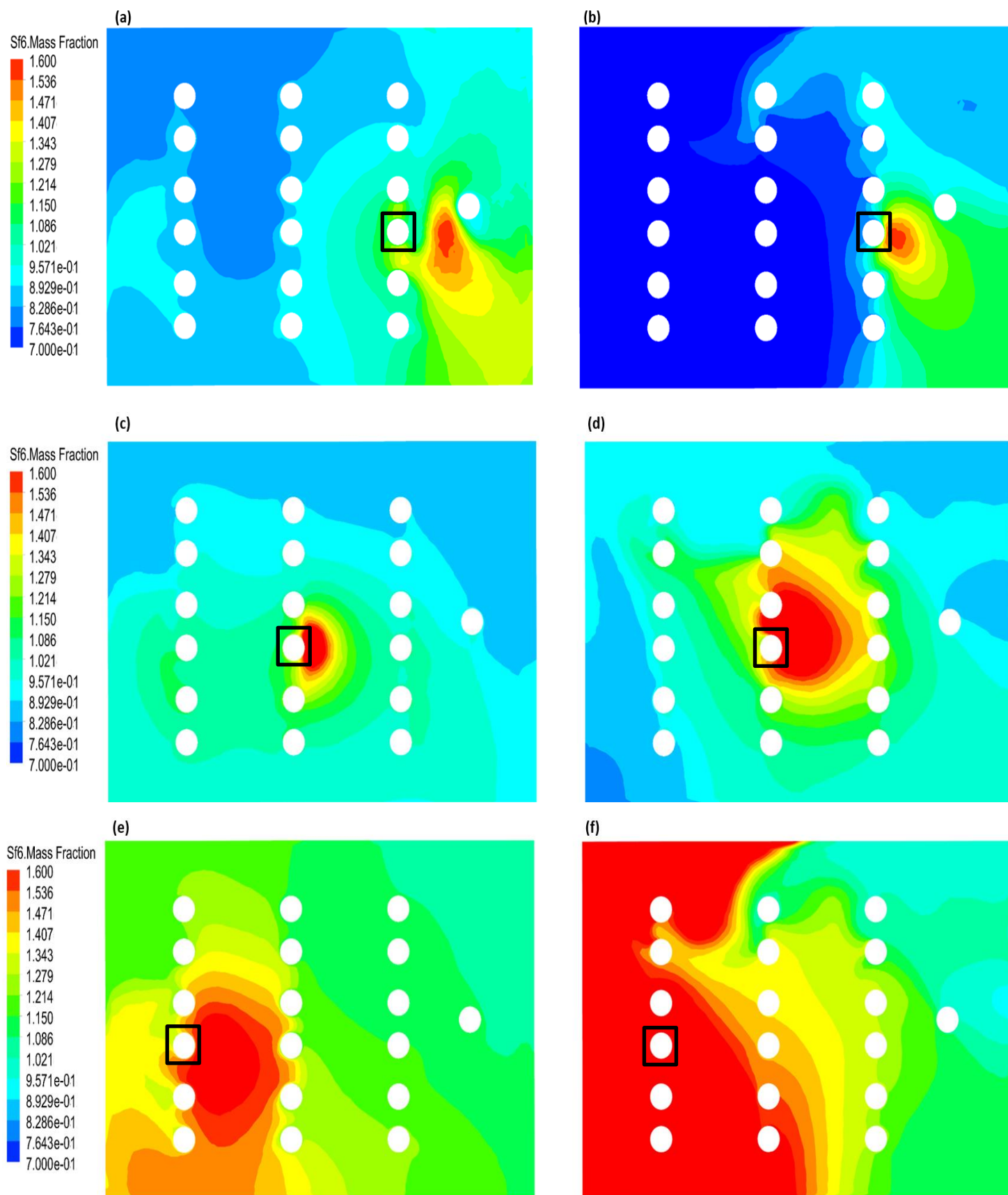
Figure 5: SF$_6$ distribution at a horizontal cut plan above the floor of the classroom for a) Case 1, b) Case 4, c) Case 2, d) Case 5, e) Case 3 and f) Case6

Conclusion

This study numerically investigated the impact of diffuse ceiling design parameters, i.e. diffuse ceiling configuration and location of the contamination sources on indoor air quality in a school classroom. In this regard, two different configurations, including central and dispersed active diffuse panels were considered. Moreover, the release of airborne infectious agents like SARS-CoV-2 from three students at three different locations in the classroom was simulated. The applied numerical models were validated with previous experimental results.

The airflow field showed that the average air temperature with a dispersed configuration is about 2 ˚C higher in the middle of the classroom compared with the central configuration. Thus, the central configuration of diffuse panels had a higher capacity for cooling the classroom. Moreover, the simulation results revealed that the spread of contamination in the classroom with the central configuration of diffuse panels was less than in the dispersed configuration. The obtained result indicated that the relative distance of the contamination sources to the active diffuse panels and classroom outlet had a considerable impact on dispersion patterns of the airborne infectious agents in the air.

Acknowledgement

References

Fan, J., Hviid, C. A., & Yang, H. (2013). Performance analysis of a new design of office diffuse ceiling ventilation system. *Energy and Buildings*, *59*, 73–81.

Fisk, W. J. (1999). *Benefits from better indoor environments: an update*. 1–38.

Goldizen, F. C., Sly, P. D., & Knibbs, L. D. (2016). Respiratory effects of air pollution on children. *Pediatric Pulmonology*, *51*(1), 94–108.

Jacobs, P., & Knoll, B. (2009). Diffuse ceiling ventilation for fresh classrooms. *4 Th Intern. Symposium on Building and Ductwork Air Tightness*, 1–7.

Mendell, M. J., Fisk, W. J., Kreiss, K., Levin, H., Alexander, D., Cain, W. S., John, R., Hines, C. J., Jensen, P. A., Milton, D. K., Larry, P., & Wallingford, K. M. (2002). *Improving the Health of Workers in Indoor Environments : Priority Research Needs for a National Occupational Research Agenda*. *92*(9), 1430–1440.

Mora, R., Rose, D. M., Eddy, J., Alspach, P. F., Smith, A. R., Williams, J. G., Barnaby, C. S., Burkhead, R. B., & Hanson, S. S. (2021). ASHRAE Standard 55-2020,Thermal Environmental Conditions for Human Occupancy. *ASHRAE*. www.ashrae.org

Nielsen, P. V., Vilsbøll, R. W., Liu, L., & Jensen, R. L. (2015). Diffuse Ceiling Ventilation and the Influence of Room Height and Heat Load Distribution. *Proceedings of Healthy Buildings 2015*.

Nielsen, P. V, & Jakubowska, E. (2009). The Performance of Diffuse Ceiling Inlet and other Room Air Distribution Systems. *Cold Climate HVAC*, 7.

Nocente, A., Arslan, T., Grynning, S., & Goia, F. (2020). CFD study of diffuse ceiling ventilation through perforated ceiling panels. *Energies*, *13*(8), 1–14.

Rahnama, S., Nielsen, P. V., Afshari, A., Bergsøe, N. C., Johra, H., & Jensen, R. L. (2019). Evaluating the cooling capacity of diffuse ceiling ventilation system - Full-scale experimental study. *E3S Web of Conferences*, *111*(201 9), 4–9.

Rahnama, S., Sadeghian, P., Vilhelm, P., Zhang, C., Sadrizadeh, S., & Afshari, A. (2020). Cooling capacity of diffuse ceiling ventilation system and the impact of heat load and diffuse panel distribution. *Building and Environment*, *185*(August), 107290.

USEPA, & US EPA. (2006). Risk Assessment Guidance for Superfund Volume I: Human Health Evaluation Manual (Part F, Supplemental Guidance for Inhalation Risk Assessment). *Office of Superfund Remediation and Technology Innovation Environmental Protection Agency*, *I*(January), 1–68.

Zhang, C., Kristensen, M. H., Jensen, J. S., Heiselberg, P. K., Jensen, R. L., & Pomianowski, M. (2016). Parametrical analysis on the diffuse ceiling ventilation by experimental and numerical studies. *Energy and Buildings*, *111*, 87–97.

Zhang, C., Yu, T., Heiselberg, P., Pominaowski, M., & Nielsen, P. (2016). Diffuse Ceiling Ventilation – Design Guide. *DCE Techincal Report*, *27*.