Evaluation of the spatial aspect of building resilience in classrooms equipped with displacement ventilation

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Abstract

Throughout their lifetime, buildings might face unpredictable shocks leading to fast deterioration of comfort levels. The ability of buildings and systems to absorb the shock and bring back the indoor conditions to their designed state is termed as “resilience”. Ventilation and thermal resilience have been studied under homogeneous conditions. However, the established airflow indoors and hence resilience is non-homogeneous. In this work, the spatial aspect of ventilation and thermal resilience will be assessed in a classroom equipped with displacement ventilation using 3D CFD modeling. Two sources of pollution were considered in the space: CO_2 and VOCs. To study resilience, the numerical model was simulated until steady state. Subsequently, a power outage shock of 60 min was induced. The temporal and spatial mappings of temperature, and pollutants’ concentration were recorded in the occupied zone at the breathing height of 1.2 m and compared to that at the exhaust. Building resilience was assessed through *ppm.hours* and *degree.hours* and compared at both locations. Results showed that resilience is rather a non-homogeneous field that depends on the location of heat sources and pollution sources in the space. However, results showed that any over or under estimations ($\sim 20-28\%$) in assessing the thermal or ventilation resilience are negligible when evaluated at either the breathing plane or the exhaust.

Introduction

Throughout their childhood and adult lives, people spend a considerable amount of time in educational buildings and more specifically in classrooms (Schweizer et al. 2006). These spaces are characterized by high heat loads due to high occupancy and large glazing surface areas. Moreover, they are characterized by multiple pollutants of either gaseous nature (CO_2 (Du et al. 2020), volatile organic compounds or VOCs (Mølhave 1991), bio-effluents (Zhang, Wargocki, and Lian 2015)) or particulate matter (Braniš, Řezáčová, and Domasová 2005). These pollutants can infiltrate indoors through the ventilation system or are generated indoors to due occupants and their activities or other exogenous sources.

The indoor temperatures among other factors affect the thermal comfort of students while contaminants’ concentration fields at the breathing level determine the exposure level of occupants. Thermal comfort and indoor air quality (IAQ) are mainly dictated by indoor environmental quality (IEQ) management strategies such as the heating ventilation and air conditioning systems (HVAC) and the air distribution system design (i.e., positioning of inlet and outlet, types of diffusers).

In the case of inefficient IEQ management strategies in classrooms, thermal discomfort and short- or long-term acute exposure trends can occur, causing adverse effects from a decrease in cognitive performance and learning capacity of students to lower life quality due to illnesses, and diseases (e.g., infections) (Stafford 2015; Wargocki and Wyon 2017). Therefore, it is necessary to implement smart, energy-friendly HVAC strategies (e.g., demand-controlled ventilation) via well-designed air distribution systems. A conventional system is the mixing ventilation (MV) system, where the conditioned clean or recirculated air is supplied overhead from occupants at higher velocities. The supplied air mixes with the room air diluting the concentration of contaminants. However, in most cases, fully mixed conditions are not achieved, resulting in a non-homogeneous IAQ (Shan et al. 2016). A superior system to the MV is the displacement ventilation (DV) system. In rooms with DV, low momentum conditioned clean air is supplied near the floor and rises upwards due to buoyancy effects, forming a stratified flow. The space is thus divided into a lower clean zone and an upper fully mixed polluted zone. Therefore, DV systems ensure better IAQ than the MV system, making them a good choice of air distribution system in classrooms (Shan et al. 2016). (Merema et al. 2018) monitored the performance of a demand-controlled ventilation system in an educational building equipped with a DV system. Their results showed that the ventilation system was able to maintain good IAQ levels at reduced airflow rates and energy use.

Often, smart ventilation strategies are designed under well-known indoor and outdoor conditions (i.e., occupancy, weather, outdoor air quality). However, throughout a building’s lifetime, there is a probability that these conditions might suddenly shift from their expected values (e.g., sudden increase in outdoor air pollution, heat waves, additional occupants in the space beyond the expected peak, power outages) (Stasiulaitiene et al. 2019; Shivakumar et al. 2017). These unexpected events are defined as “shocks”. During shocks, the temperature and IAQ can shift quickly from their design conditions to uncomfortable levels causing thermal discomfort ranging from mild to extreme heat stress, and acute exposure events to extremely high concentrations of harmful pollutants. With the possible increase in shock occurrence (Lopes et al. 2020; Añel et al. 2017a; Adélaïde, Chanel, and Pascal 2021), existing HVAC systems and air distribution systems, should be able to maintain good IAQ

https://doi.org/10.1051/e3sconf/202236214006

levels, not only under anticipated conditions but also in the case of shock occurrence. This characteristic is defined as "thermal and ventilation resilience". Some recent research (Annex 80 IEA EBC, Sengupta A. 2022; Al Assaad D. 2021; Ko et al. 2018) studied both thermal and ventilation resilience in office spaces and in the residential sector by simulating indoor environments under different types of shocks and shock intensities. The studies were conducted using building energy simulation (BES) tools that assume lumped conditions of temperature and IAQ. However, temperature and contaminants' concentration fields depend on the air distribution system. Hence, they are non-homogeneous, especially in a room with DV. This might lead to over or under estimation of the thermal and ventilation resilience of the rooms.

The aim of this project is to test out this theory by conducting computational fluid dynamics (CFD) simulations of an occupied classroom space equipped with a DV system and undergoing a power outage shock of 60 minutes. Both thermal and ventilation resilience will be assessed using $degree.hours$ and $ppm.hours$, both at the breathing plane and occupied zone of the occupants and at the exhaust located in the upper polluted zone where mixed conditions are established. The results will give insight on the reliability and accuracy of fully mixed space assumption, usually adopted in BES tools; in accurately evaluating the resilience of buildings to shocks.

Methodology

Classroom and system description

In this work, a typical classroom space having a surface area of 49 m^2 (7 m × 7 m), a volume of 122.5 m^3 (height of 2.5 m) and that can be occupied by a maximum of 9 students was considered (Tanner 2000). The classroom was in Ghent, Belgium. It was conditioned by a DV system, served by its own air handling unit (AHU). It supplied conditioned clear outdoor air from rectangular grill outlets on either side of the walls (6 m × 0.12 m). The air was exhausted from a rectangular diffuser (0.5 m × 0.3 m) situated on the back wall of the classroom behind the students, 2 m from the floor. **Figure 1a** illustrates the considered classroom with the students represented by simplified heated cylindrical dummies having a surface area of 1.8 m^2 equivalent to that of a human body. The students were performing sedentary activities (126 W). Contributing to the internal load was also the lighting installed at ceiling level (163 W equivalent to 300 lux). For simplification, the classroom was considered to be an internal space to represent zone within a large floor plan with other floors above and below. Thus, the walls were assumed as adiabatic. The occupants generated through respiratory activities CO_2 and VOCs at rates of 2.6×10^7 μg/h.person and 6.25×10^3 μg/h.person respectively (Persily and de Jonge 2017; Fenske and Paulson 2011; Won, Shaw, and Won n.d.). According to experimental studies (Tang et al. 2016), the envelope (walls, floor, ceiling) always generated 2 to 4 times more VOCs than occupants. Thus, in this study, the envelope (walls, floor, ceiling) having a surface area of 168 m^2 was assumed to generate 2.5×10^4 μg/h (2 times higher than the generation rate per occupant).

In this work, summer conditions were assumed (cooling season from May to September). At maximum occupancy, a flow rate of 0.3 m^3/s at 18°C was delivered through the DV inlet diffusers, such as the supply velocity was 0.2 m/s. This was to avoid thermal draft discomfort at the student's feet level.

The outdoor air was assumed to have a concentration of 450 ppm of CO_2 and 6.8 ppb in VOCs (Do et al. 2013). According to a royal degree on indoor working conditions ("Codex welzijn op het werk 2019), a threshold of 900 ppm should be maintained for CO_2. Violations are allowed for 5% of the time over a maximum of 8 hours (24 minutes of violation). As for VOCs, the Flemish guidelines recommend a threshold of 50 ppb ("Hoge Gezondheidsraad. Indoor Air Quality in Belgium" 2017). For temperature, a threshold of 24°C (thermoneutral conditions) was assumed during summer conditions (ANSI and ASHRAE 55:2004).

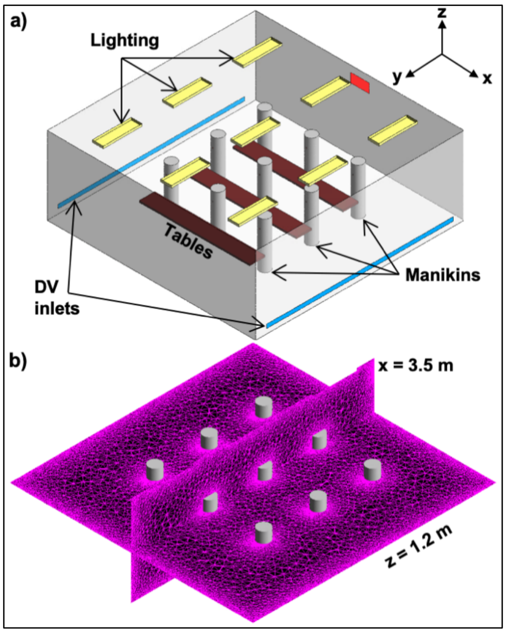

Figure 1: (a) computational domain as seen in Fluent, (b) corresponding mesh

Shocks and disturbances

Shocks and disturbances are unpredictable events that occur outside or inside the building envelope and that can shift IEQ from its design conditions. During such events, if the ventilation or source control strategies can maintain IEQ within the recommended levels of violation, then the building and associated systems can be characterized as resilient. Note that to be characterized as shocks, the events must occur suddenly; in a way that the occupants or building owner have no time to take preventive measures. In this work, a power outage shock was considered due to an interruption of electricity supply from the grid. Interruption can be due to extreme weather conditions (i.e., heat waves, severe storms)(Añel et al. 2017b) or equipment damage (Vinogradov, Vinogradova, and Bolshev 2020). Information on current and future trends of sudden power outages (in Belgium) are scarce. Hence, there is at this moment no typical duration to consider for power outage shocks. Thus, in this work, a power outage shock of 1 hour was considered. The shock was considered to occur during peak occupancy when there are 9 students in the classroom.

Resilience assessment

To assess ventilation resilience, and its effect on IAQ, the $ppm.hours$ index will be used as seen in equation (1) below for both CO_2 and VOCs.

$$ppm.hours = \int C_s(t)dt \qquad (1)$$

Where C_s is the temporal variation of the concentration of either CO_2 or VOCs calculated at the exhaust or average at the breathing level (z = 1.2 m). The $ppm.hours$ will be calculated for concentrations above 900 ppm for CO_2 and above 50 ppb for VOCs.

To assess thermal resilience, the $degree.hours$ [Kh] index will be used as seen in equation (2) below:

$$degree.hours\ [Kh] = \int T_r(t)dt \qquad (2)$$

Where T_r is the temporal variation of the room temperature calculated at the exhaust or averaged at the occupied level (0 < z <1.5 m). The $degree.hours$ will be calculated for temperature violations above 24°C.

CFD model

In this work, there are complex airflow field behaviours taking place due to the presence of the DV establishing stratification, multiple pollution sources from the building envelope and occupants and the build-up of contaminants during the 60 min power outage shock. Moreover, there are heat sources (occupants and lighting) in the space giving rise to thermal plumes. This affects the airflow field variables such velocity, temperature, and species' concentrations. Consequently, a 3D CFD model was needed to resolve for these different variables. The commercial software ANSYS Fluent v.19.2 ("Ansys Fluent | Fluid Simulation Software") was used to solve for the momentum, energy equations, pressure velocity coupling as well as the turbulence and its dissipation rate equations.

For exact predictions of flow behaviour, the space should be appropriately meshed (Figure 1b). The space was meshed into tetrahedral elements with face sizing applied at the boundaries (thermal manikin: 1.5 cm, walls: 2 cm). This was a typical and well-documented mesh treatment for CFD modelling of indoor spaces (al Assaad et al. 2021a). This mesh ensured a grid independent solution with maximum relative error of less than 5% on velocity predictions in the x-midplane. The final mesh had 3,561,473 finite volume elements and a maximum skewness of 0.79. The mesh of the computational domain (Figure 1a) can be seen in Figure 1b at the x = 3.5 m (midplane) and the z = 1.2 m (breathing plane).

The discretization schemes for the different variables were shown in Table 1. Numerical convergence was reached if the scaled residuals were less than 10^{-5} for all quantities except energy where it should be less than 10^{-6} and when the total heat flux in the domain is lower than 1% of the net heat gain (al Assaad et al. 2021b).

Accurate prediction of the airflow is essential for robust tracking of species transport in the space. As a compromise between computational cost and accuracy, the Reynolds Average Navier Stokes (RANS) models were chosen and particularly the RNG k-ε model with enhanced wall treatment and full buoyancy effects (Liu, Li, and Feng 2016).

Table 1: Flow field variables and discretization schemes

FLOW FIELD VARIABLES	SCHEME
Momentum, energy, k, ε and turbulence equations, species transport	Second order upwind scheme
Pressure equation	"PRESTO!" scheme
Transient term	Second order implicit time stepping scheme
Pressure velocity coupling	PISO algorithm

To obtain a physical solution for the airflow field in the space, the boundary conditions for the different flow field variables should be accurately selected. The DV inlet diffusers were chosen as velocity inlets with a constant velocity of 0.2 m/s, and an inlet temperature of 18°C, a turbulence intensity of 5%, a hydraulic diameter of 0.24 m and constant species' concentration of 450 ppm and 68 ppb for CO_2 and VOCs respectively. The exhaust was assigned as a pressure outlet with zero-gauge pressure. The manikins and lighting were assigned a constant heat flux and diffusive fluxes of CO_2 and VOCs. The CO_2 was emitted from a circular opening having a diameter of 3 cm mimicking occupants' mouths (Katramiz et al. 2021). The rest of the surfaces were considered as walls.

The model was first simulated with these inputs until steady state conditions were established. Hence, before inflicting the power outage shock, the solver was steady. When steady state was reached, the solver was switched to transient and at *t = 0 s*, the power outage shock was inflicted by changing the DV inlet, outlets from velocity inlet and pressure outlet to 'wall' boundary conditions. The model was simulated under these conditions for 60 minutes with a time step of 5 s. After that, the DV system was switched back on and the CFD model was simulated for additional 40 minutes to recover the original steady state conditions.

Note that the manikins' breathing pattern was neglected for the sake of computational cost as the CFD model was simulated for 100 minutes during a shock event.

Breathing patterns are normally periodic with a period of 6 s. Thus, simulating breathing accurately requires a time step of 0.05 s (Katramiz et al. 2021) which can increase computational costs considerably. Moreover, this assumption could be made as the velocity of exhaled flow from occupants quickly decreases to negligible values at 2-3 cm away from the occupants' mouths (Katramiz et al. 2021).

Results

Figure 2 illustrates the temporal evolution of room temperature averaged in the occupied zone ($0 < z < 1.5$ m) and at the exhaust ($z = 2$ m) as well as the temporal evolution of the CO_2 and VOCs' concentrations averaged over the breathing plane ($z = 1.2$ m) and at the exhaust. The results were illustrated from $t = 0$ min (steady state conditions) to $t = 100$ min. The power outage shock spanned from $t = 0$ min to $t = 60$ min. Figures 3, 4 and 5 illustrate the contours of temperature, CO_2 and VOCs before the shock (steady state, $t = 0$ s) and right towards the end of the 60 min power outage in the x-midplane. Table 2 shows the calculated $ppm.hours$ and $degree.hours$ at the exhaust and occupied zone from $t = 0$ s (steady state) to $t = 100$ min.

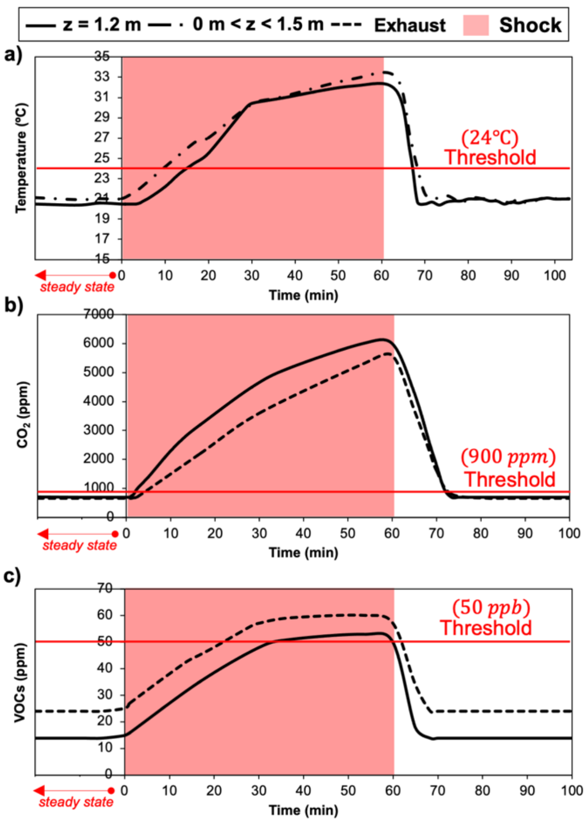

Figure 2: Evolution of (a) temperature, (b) CO_2 and (c) VOC concentrations before, during and after a 60 min power outage

Thermal resilience

According to Figure 2a, at steady state, the average temperature in the occupied zone was equal to 21°C. This can also be seen in Figure 3 along with the temperature stratification created by the DV system with a lower conditioned zone and an upper warmer zone. Once the shock occurs, the temperatures in the space increase due to a lack of cool air supply, with the temperatures measured at the exhaust higher than the ones in the occupied zone by an average of 0.7°C. Moreover, the temperature computed at the exhaust exceeds the 24°C threshold after only 8 minutes of shock while that in the occupied zone, after 15 minutes. At the end of the shock, at 60 minutes, the peak temperature reached was 31.7°C in the occupied zone and 33°C at the exhaust. Occupants were exposed to these extremely high temperatures for almost 30 minutes (Figure 2a) resulting in heat stress and discomfort (Ren, Wang, and Chen 2014; Adélaïde, Chanel, and Pascal 2021).

The effect of the shock can also be seen in Figure 3. The stratification due to the DV system was destabilized. A stagnant air volume with temperatures between 33-35°C can be seen at the ceiling level due to the presence of lights as a heat source. This also explains why the temperatures measured at the exhaust were higher than the ones in the occupied zone. Looking at the $degree.hours$ in Table 2, calculating them at the exhaust and thus implicitly assuming fully mixed conditions would over-estimate temperature violations by 21% as opposed to evaluating the $degree.hours$ in the occupied zone.

After the shock, the DV system was able to decrease the temperatures back to their initial steady state quite fast. The recovery time was 8 minutes in the occupied zone and 10 minutes if evaluated at the exhaust. This was expected as the positioning of the exhaust was very close to the lights (Figure 1a).

Therefore, when assessing the thermal resilience of an indoor space equipped with DV, there is a chance of a small overestimation in both the resilience impact on comfort and the absorption time of the building to the shock if the exhaust is located close to a heat source. This overestimation is negligible. In this case, resilience (i.e., degree of impact, recovery) can be evaluated in either the occupied zone or at the exhaust.

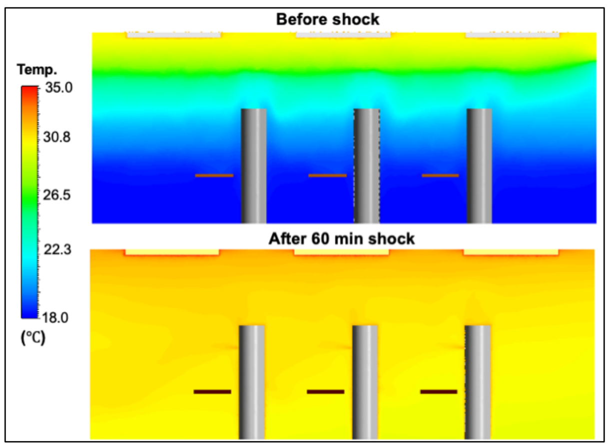

Figure 3: Temperature contours before shock and after a 60 min shock in the x-midplane

Ventilation resilience

According to Figure 2b, at steady state, the average CO_2 concentrations at the breathing level was equal to 650 ppm and 750 ppm at the exhaust. The gradient in CO_2 concentrations established by the DV system before the shock occurred can be seen in Figure 4. Once the shock occurs, it only takes a few minutes for concentrations to quickly build-up due to a lack of ventilation and exceed the 900-ppm threshold. The concentrations at both locations follow a similar trend with the ones computed at the breathing plane exceeding those at the exhaust by an average of 800 ppm. This can be explained that the breathing plane is simultaneously the CO_2 generation plane. At the end of the shock, at 60 minutes, the peak concentrations were 6000 ppm at the breathing level and 5300 ppm at the exhaust. These concentrations (1000-5000 ppm) are extremely high and despite the short-term exposure can affect cognitive performances including decision making and compromise psychomotor performance (Azuma et al. 2018).

The effect of the shock can also be seen in Figure 4. The space was completely saturated with CO_2 except near the exhaust. Figure 4 also helps in further explaining why the concentrations at the exhaust were lower than those at the breathing level. In fact, the exhaust grills were located behind the occupants at the back of the classroom. Moreover, the occupants were generating CO_2 towards the front of the classroom in the opposite direction. Thus, the back of the classroom was the last location towards where the CO_2 diffused. Had the shock been any longer, it is expected that the concentrations would eventually be uniform in the entire space due to saturation in CO_2.

Looking at the $ppm.hours$ in Table 2, calculating them at the exhaust for a 60 min shock would under-estimate CO_2 violations by 28% as opposed to evaluating the $ppm.hours$ at the breathing level. After the shock, the DV system was able to decrease the concentrations back to their initial steady state quite fast. The recovery time was 10 minutes in both locations.

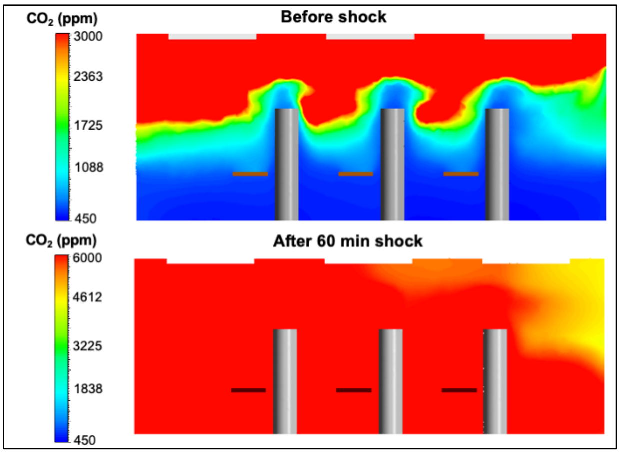

Figure 4: Contours of CO_2 concentrations (ppm) before shock and after a 60 min shock in the x-midplane

As for VOCs, according to Figure 2c, at steady state, the average VOCs concentrations at the breathing level was equal to 15 ppb and 30 ppb at the exhaust. The contours VOCs concentration before the shock can be seen Figure 5. The contribution to VOC emissions from the building envelope was more significant than that from occupants as there was no clear vertical gradient of VOCs as was the case with CO_2. Once the shock occurs, concentrations slowly build-up and follow a similar trend at both locations. The build-up was slower than that of CO_2 due to the smaller generation rates of VOCs. It took 20 and 30 minutes to exceed the 50-ppb threshold at the exhaust and at the breathing level respectively. The concentrations at the exhaust were higher than those at the breathing plane by an average of 10 ppb. This was since the exhaust was at proximity to the walls – the source having the highest VOC contribution. At the end of the shock, at 60 minutes, the peak concentrations were 60 ppb at the exhaust and 52 ppb at the breathing plane. These concentrations did not violate the 50-ppb threshold considerably to cause a short acute exposure event, especially if evaluated at the breathing level (Figure 2c).

The effect of the shock can also be seen in Figure 5. The upper space was more saturated with VOCs due to generation from the building envelope. The VOCs then diffused inwards towards the occupied zone. Had the shock been any longer, it is expected that the concentrations would eventually be uniform in the entire space due to saturation in VOCs. In fact, the upper space was already saturating with VOCs at $t = 30$ min (Figure 2c).

Looking at the $ppb.hours$ in Table 2, calculating them at the exhaust for a 60 min shock would result in no VOCs violations at the breathing plane and some violations at the exhaust. After the shock, the DV system was able to decrease the concentrations back to their initial steady state quite fast. The recovery time was also 10 minutes in both locations.

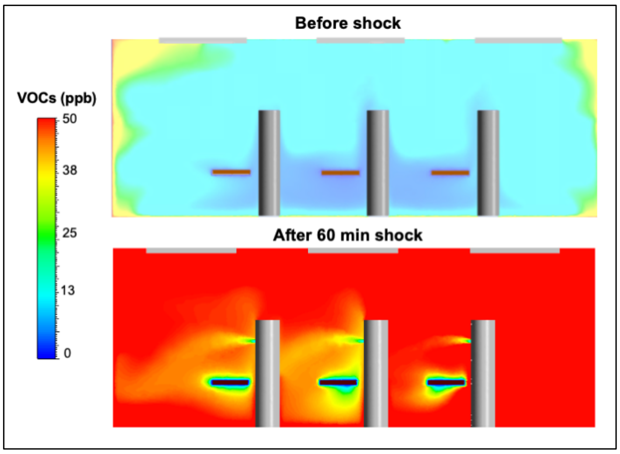

Figure 5: Contours of VOCs concentrations (ppb) before shock and after a 60 min shock in the x-midplane

Therefore, when assessing the ventilation resilience of an indoor space equipped with DV for power outage shocks < 60 min, the evaluation depends on the pollutant emission sources, strengths and the location of the exhaust with respect to those sources. For CO_2 – a pollutant generated indoors only by occupants, evaluating the impact of ventilation resilience on IAQ (i.e., violations of thresholds), by exhaust measurements would lead to under-estimations compared to the breathing plane, if the exhaust was positioned against the generation direction. However, the under-estimation was negligible. This was the case in this classroom, where the exhaust was located at the back of the classroom away from the students. For VOCs – a pollutant generated indoors pre-dominantly by the building envelope, evaluating the impact of ventilation resilience on IAQ, by exhaust measurements would lead to slight over-estimations compared to the breathing plane since exhaust diffusers are always positioned at either a wall or a ceiling in any design. However, these overestimations are also small and negligible (Figure 2c).

Table 2: Degree hours and ppm hours at the occupied zone (temperature), breathing height (IAQ) and exhaust

	$\boldsymbol{Kh}$	$\boldsymbol{ppmh\ CO_2}$	$\boldsymbol{ppbh}$ **VOC**
Breathing plane	4.5	3760.0	1.0
Exhaust	5.7	2700.0	4.9

Conclusion

In this work, a 3D CFD model of an occupied classroom equipped with a DV system, was developed to evaluate the spatial aspects of thermal and ventilation resilience against a power outage shock of 60 minutes. The $degree.hours$ and the $ppm.hours_{CO_2\,\&\,VOCs}$ and the temporal evolution of temperature and concentrations were evaluated in the occupied zone and breathing plane respectively and compared to those at the exhaust, where supposedly fully mixed conditions are assumed. Results showed that both thermal and ventilation resilience are not spatially uniform. Resilience is rather a non-homogeneous field that depends on the location of heat sources and pollution sources in the space. However, results showed that any over or under estimations in estimating the thermal or ventilation resilience are negligible when evaluated at either the breathing plane or the exhaust.

The main takeaway from this work is that using BES tools (e.g., Modelica, EnergyPlus, Contam) is reliable in assessing the thermal and ventilation resilience of indoor spaces. However, building designers should be aware of the presence of slight over and underestimations when using lumped conditions. In this case, they should add this remark to their conclusions depending on the space layout (positioning of inlet/outlets with respect to heat and pollution sources). While it would be always beneficial to evaluate resilience at the breathing level or in the occupied zone through CFD methods, due to their high computational costs, BES tools would be preferred. Note that a possible compromise between BES and detailed CFD models are fast CFD methods (e.g., Fast fluid dynamics, Lattice Boltzmann methods). The ability of these methods in accurately modelling indoor spaces shows promise and is still a topic of current research.

Future work includes a more detailed CFD study of a real-use classroom space where an experimentally validated CFD model will be used to consolidate the results of this study, as the latter considers a simple internal classroom with adiabatic walls and cylindrical dummies. In addition, several air distribution systems will also be simulated and compared (MV, DV, personalized ventilation…). The positioning of the inlet and outlet opening of these air distribution systems will be also investigated as the results of this study showed that their relative position with respect to heat/pollution sources can have an influence on the evaluation of resilience. The CFD methods will also be compared with fast CFD methods.

Acknowledgement

The authors would like to acknowledge the Agency Innovation & Entrepreneurship (VLAIO), Flanders, Belgium, for funding the strategic basic research (SBO) Flux50 project "Towards Smart Ventilation in mid-sized buildings" to which this current work contributes.

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