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大学講義室内における置換換気性能に関する研究
Performance of Displacement Ventilation in a University Lecture Hall
(Part3) Effect of contaminant source position on transient spread of contaminant based on CFD analysis

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Displacement ventilation (DV) is considered an energy saving air conditioning system and is especially recommended for classrooms for providing cool clean air in the occupied zone. However, in the current pandemic situation, ventilation systems should be assessed in terms of infection-spread prevention as well. Hence, this paper aims at investigating the contaminant spread from a single source mimicking one infected individual scenario. Transient simulations were carried out to monitor the diffusion pattern of one pulse emission (exhale). The diffusion direction, speed and dispersion rate were observed and accordingly relatively safe and risky case-scenarios were highlighted among the case-study's ventilation system design.

Introduction

Displacement ventilation (DV) is a buoyancy dependent ventilation system which relay on heat sources inside the space to heat the cool air supplied at low velocity from inlets located near the floor. As air in the occupied zone gains heat it ascends washing along the contaminants upwards and entraining cool clean air from the supply. DV has been studied in multiple research work which investigated and proved its capability to reduce cross-contamination (1). One of the main space types in which DV is implement is educational spaces i.e. classrooms and lecture halls (2).

1. Analysis

The case-study chosen for this investigation is a mid-size university lecture hall (14m×10m×5m) of 120 student capacity, seated as shown in Fig.2a. The DV in the case-study differs from the typical system as inlet fans are placed on ceiling level supplying air to the wall-long flat diffusers through cavity walls. The diffusers are placed on the front and side walls as shown in Fig.1. The backside is an 8 m wide operable wall which allows expanding the room area to include the students lounge.

In order to study the effect of changing a single-contaminant-source location, 10 seats were selected based on the longitudinal symmetry of the hall, as highlighted in Fig.2a.. The standard k-ε model analysis was carried out using STREAM v.20 software using the conditions listed in Table.1. Fig.2b shows the simplified human model used in the simulations with the boundary conditions summarized in Table2.

The cases were simulated with CO_2 representing a passive infectious contaminant emitted from the mouth of source occupant. Although gases and particles possess different properties, research has proved gases to be representative of the diffusion pattern of small particles, < 3mm size, emitted at low velocity (3). Thus, CO_2 concentration was set to 1000 assuming the units to be quanta/m^3. For all cases, steady- state analysis with no emission were run until the temperature was stable, then, transient analysis was carried out for 50s, 2s to simulate one exhale then the emission was stopped to monitor contaminant diffusion.

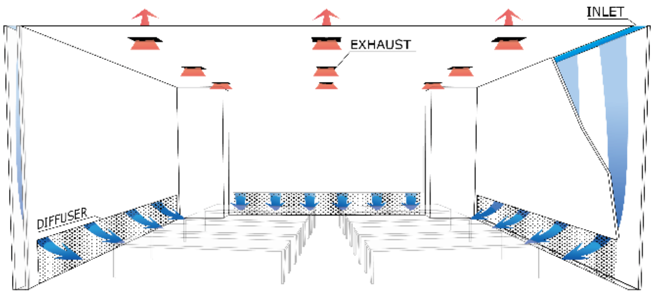


Fig.1 Displacement ventilation system in room

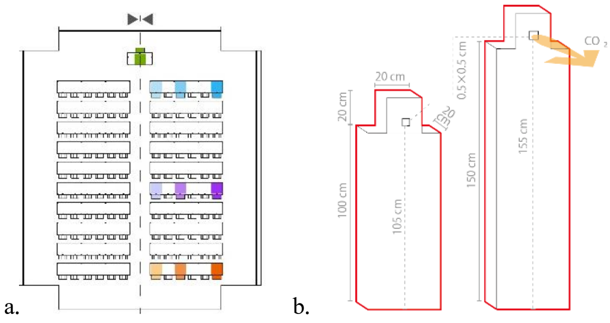


Fig.2 CFD model, a. Room plan with infected individuals highlighted, b. Occupants model

2. Results

In this section covers two main points: 1) Inspecting the temperature vertical distribution for DV stratification after reaching the steady state, and 2) Assessing the inhale air quality for the source, the uninfected occupants especially the source surrounding ones. For all uninfected occupants average inhaled air concentration is calculated. For contaminant source occupant, the inhale air quality is assessed in terms of stagnant time, i.e. how long high contaminant concentration is sustained. For source surrounding occupants, the number of affected occupants and effect severity by time are two factors chosen for evaluation.

To start with, the temperature vertical distribution shows typical stratification with interface height of above 1.7 m in most of the space volume. Fig.3 shows 2 graphs of the temperature vertical distribution; a. whole space average with variance bars,

Table.1 Analysis Conditions

Analysis Software	Stream v.20
Turbulence model	Standard k-ε model
Calculations	Heat, Radiation, Diffusion (CO_2)
Mesh count	~ 4M
Mesh size	0.04 m (1.1 growth rate)

Table.2 Boundary Conditions

Wall	Inner wall	Heat transfer coefficient, 3.06 W/m^2 K		
	Exterior	Adiabatic		
Inflow	Front	2850m^3/h	Sides	4530m^3/h
Outflow	Fixed flow velocity 0.98 m/s			
Heat	60 W/ person			
CO_2 emission	Emission velocity	1 m/s		
	Concentration:	1000 quanta/m^3		
	Mouth surface area	0.0025 m^2 (0.05×0.05 m)		
	Duration	2 s		

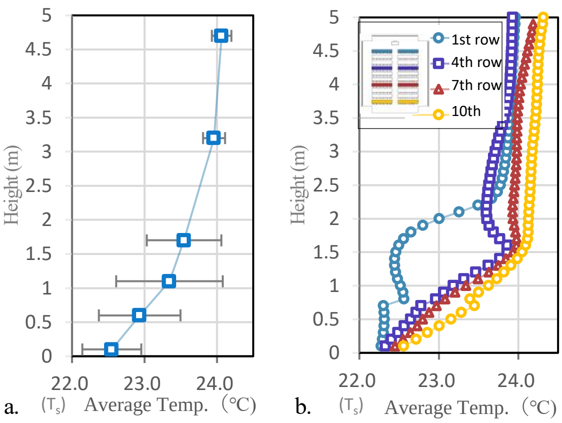


Fig.3 Temperature vertical distribution a. Whole space horizontal plane average with variance b. Breathing zone average of 4 different rows

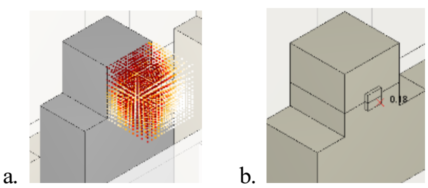
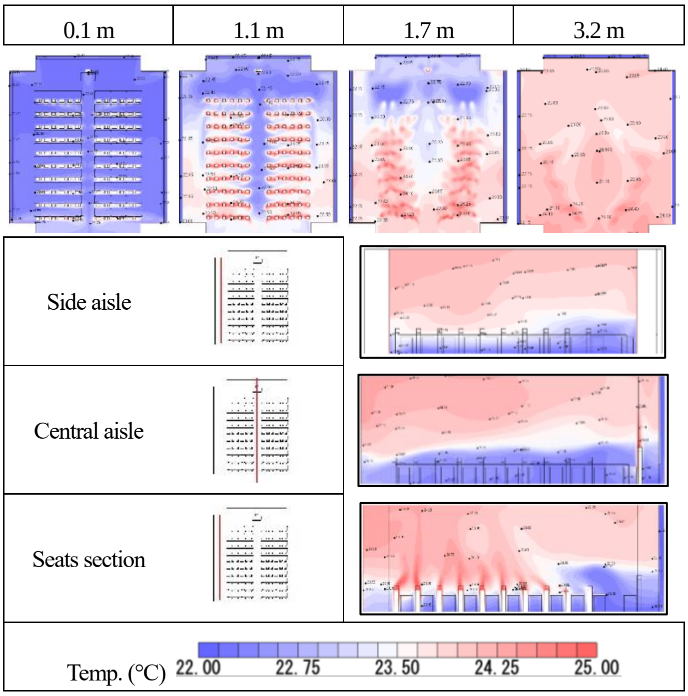


Fig.4 Contaminant measuring points, a. sample volume at source, b. measuring point at all other occupants

and graph b has the temperature at 4 sample rows plotted to represent the variation in the temperature distribution in the seating zone of the hall. Table.3 shows the temperature distribution at 4 horizontal sections, 3 sections within the occupied zone; at ankle level, seated and standing occupants head level, and one above the occupied zone at 3.2 m. Three vertical sections are presented as well in side and middle aisle, and through the seating zone. As can be observed from Fig.3b, the front row is affected by the front diffuser which can be the cause of the asymmetric air flow. This observation, as mentioned in (Part 2) can affect the contaminant distribution as well.

Regarding the contaminant diffusion assessment, the concentration in the source breathing zone was calculated using the average of 0.2 m cube in front of the occupant's face. For other occupants, a single measuring point in the center of the first mesh next to the mouth was used to derive the concentration as shown in Fig.4.

Table.3 Temperature horizontal and vertical contours



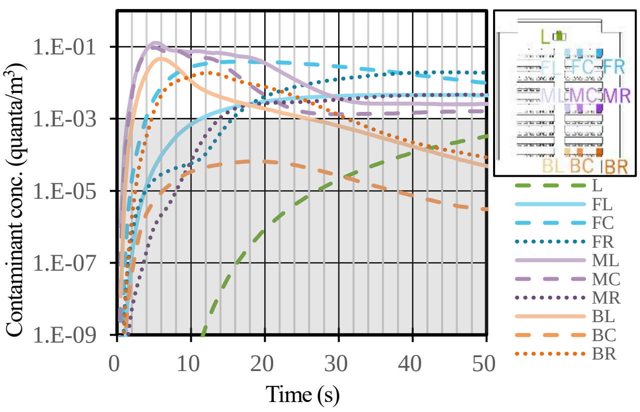


Fig.5 Contaminant concentration at source breathing zone vs time

Average contaminant concentration in inhaled air of all uninfected occupants for the ten cases are plotted in Fig.5. It can be observed that 4 cases reached relatively high concentrations: ML, MC, BL, and FC. Although, the middle cases had the highest concentrations (> 0.1 quanta/m^3), case-FC sustained 0.01 quanta/m^3 for 40 s. Other cases showed negligible concentrations. Case-L, however, showed a delayed increase in concentration that had not reached a peak until the end of the simulation time.

Table. 4 shows the inhaled contaminant concentration the source and surrounding occupants for all ten cases vs. time. First, regarding the stagnant time at the source, it can be noticed that cases L, FL, and FC had slow dispersion rate as it takes around 40 s for the concentration to reach 1 quanta/m^3 while its takes under 10 s in case-BC, for example. Another point worth noting is the trend of re-peaking after steep decrease shown in cases ML and MC which is not restricted to the source but also the surrounding occupants. Assessing the effect on surrounding occupants, front cases have almost all surrounding occupants above 0.1 quanta/m^3 in varying timing. ML and MC cases subjected their adjacent occupant to the right to the highest concentration of more than 10 quanta/m^3. Followed by case-BL, ML and MC are the fastest cases to affect the surrounding occupants as the adjacent occupant reached the maximum concentration within 5 s. BC had no concentration exceeding 0.01 quanta/m^3 which is unlike other back cases as both subjected an adjacent occupant to concentration higher than 1 quanta/m^3. Similar to Fig.5, the concentrations in case-L are increasing and had not reached its peak.

Finally, to visualize the diffusion direction, horizontal and vertical sections of sample cases are shown in Table.5 and Table.6 respectively. The difference in diffusion pattern can be seen in terms of speed, direction, and dispersion rate. Back cases show fast vertical diffusion with minimal dispersion. In contrast, in middle cases the contaminant diffused horizontally. Front cases, on the other hand, show slow horizontal diffusion with high dispersion rate, thus, affecting larger number of occupants.

Table.4 Contaminant concentration at the mouths of occupants surrounding the source vs. time

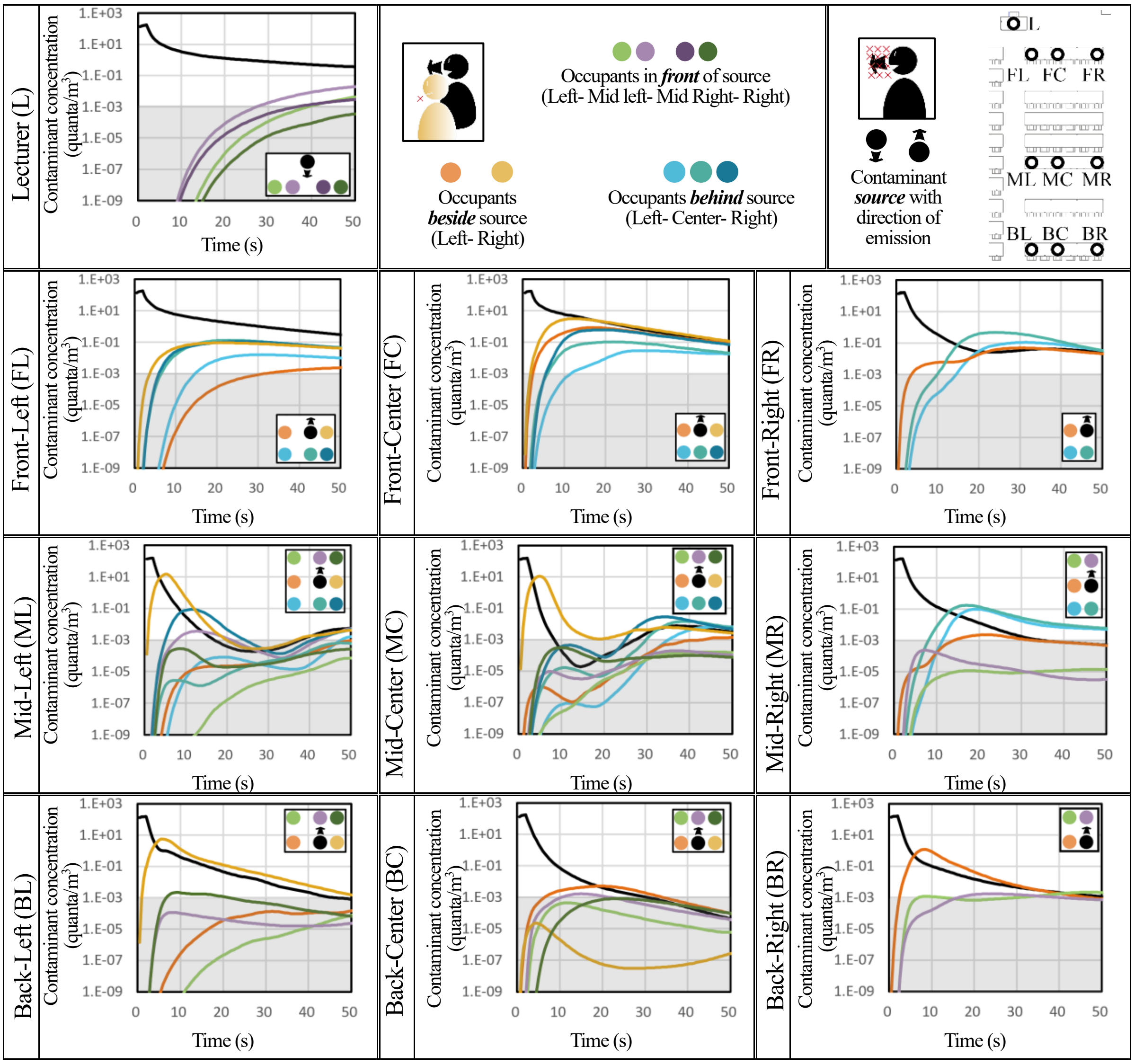


Table.5 Contaminant concentration at horizontal plane, 1.7 m for the standing source case-L and 1.1 m for the seated source cases

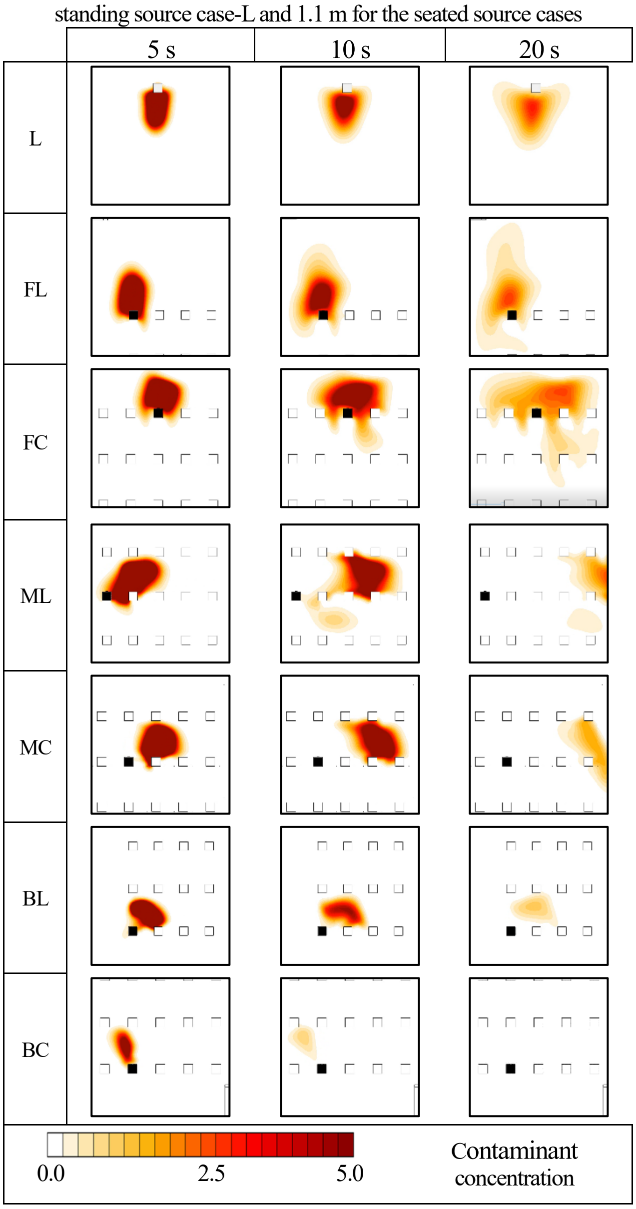
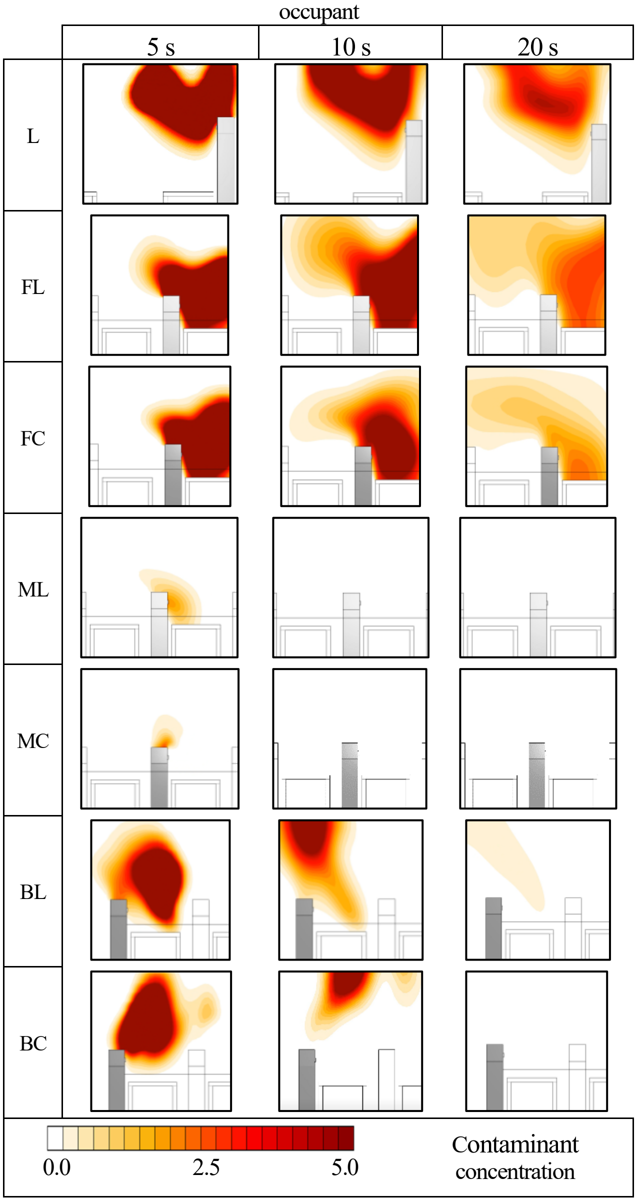


Table.6 Contaminant concentration on vertical plane through source occupant



3. Conclusion

It can be concluded the contaminant source occupant has varying effect severity according to his location in the room. Thus, it was observed that changing the source location has a significant effect on the adjacent occupants' air quality through the quantity of contaminants inhaled, the delay time until the contaminants reaches their breathing zone and the duration the contaminants stay within its range. In addition, the analysis results showed a clear relation between the source occupant location and his own inhaled air quality as well. This study supports the findings of the previous steady state simulation published in (Part 2), however, one significant addition of the transient results is that it highlighted the effect of buoyancy, despite the low speed horizontal air flows, in clearing the occupants' breathing zone by time.

Acknowledgement

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