An experimental investigation into the ventilation effectiveness of diffuse ceiling ventilation

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ABSTRACT

Diffuse ceiling ventilation is a novel air distribution concept, where the space above a suspended ceiling is used as a plenum and fresh air is supplied into the occupied zone through perforations in the suspended ceiling panels. Due to the low momentum supply, the airflow in the room is driven by buoyancy force generated by heat sources. The previous studies indicate that the diffuse ceiling ventilation system can effectively eliminate the draught risk in the occupied zone and provide a comfortable indoor environment even with low-temperature supply. However, the effectiveness of diffuse ceiling ventilation in term of air quality has not been studied systematically. It is essential to investigate whether the ventilation system could remove the air-borne contaminants in an efficient way. This study was based on experimental measurement in a full-scale test room simulated an office condition. Contaminant removal effectiveness were measured with N2O tracer gas by step-up method. Two different contaminant sources were analysed, one was occupants also served as heat sources, and the other was a point source located at floor level and 1.1 m height simulated the contaminant from floor finish and furniture. The measurements were conducted with different heat loads and air flow rates, which represented typical office operating scenario in the summer. When the contaminant released from occupants, mixing has been reached between contaminant and room air. In addition, the stronger the heat load, the higher mixing level was observed. When the passive contaminant source was located on the floor, due to lack of buoyancy it was trapped in the lower zone and high CRE was observed in the occupied zone (above 0.6 m height). However, the thermal plume around occupant created an upward movement and brought the containment to the breathing zone. This local disturbance of the concentration distribution may affect the personal exposure significantly. Finally, the contaminant concentration was measured in the plenum, and the results indicated that no reverse flow from occupied zone to the plenum occurred in all cases.

KEYWORDS
Diffuse ceiling ventilation, Ventilation effectiveness, Contaminant removal effectiveness, Experimental study

1. INTRODUCTION

Diffuse ceiling ventilation is a novel air distribution concept, where the space above a suspended ceiling is used as a plenum and fresh air is supplied into the occupied zone through perforations in the suspended ceiling panels. The inlet opening could occupy the entire ceiling area or part of the ceiling. Due to the large inlet area, the air is supplied into the occupied zone with very low momentum and the airflow in the room is mainly driven by buoyancy forces generated by heat sources. The previous studies indicate that the diffuse ceiling ventilation system can effectively eliminate the draught risk in the occupied zone and provide a comfortable indoor environment even with low-temperature supply (Chen Zhang et al. 2015)(Kristensen et al. 2017)(Hviid & Svendsen 2013).

Beside thermal comfort, air quality is another leading factor to evaluate the performance of a ventilation system. Although the measured temperature distribution indicated a good mixing level in the room with diffuse ceiling ventilation (Zhang et al. 2016)(Fan et al. 2013)(Nielsen et al. 2010), the effectiveness in term of contaminant distribution has not been studied systematically. Skistad. H et al. (Skistad et al. 2007) mentioned that the effectiveness of temperature distribution and effectiveness of concentration distribution are comparable only when the contaminant source is the significant heat source in the room. It is essential to investigate whether the ventilation system could provide good indoor air quality with different types of contaminant source. In this study, the experimental measurements are carried out in a full-scale test chamber simulated a two-person office room. Trace gas test is used to evaluate the ventilation effectiveness in the room and whether there is any reverse flow into the plenum. Two types of contaminant sources are analyzed, one is occupants also served as a heat source, and the other is point source simulated the contaminant from furniture and floor finish.

2. EXPERIMENTAL METHOD

2.1 Experiment facility

The tests were performed in a guarded hot box located in the laboratory of Aalborg University. The guarded hot box comprises a cold chamber simulated outdoor environment and a hot chamber simulated an office room, as shown in Figure 1. Cold chamber and hot chamber were separated by 1.4 cm thickness Plywood board with U-value of 3.6 W/m2.K.

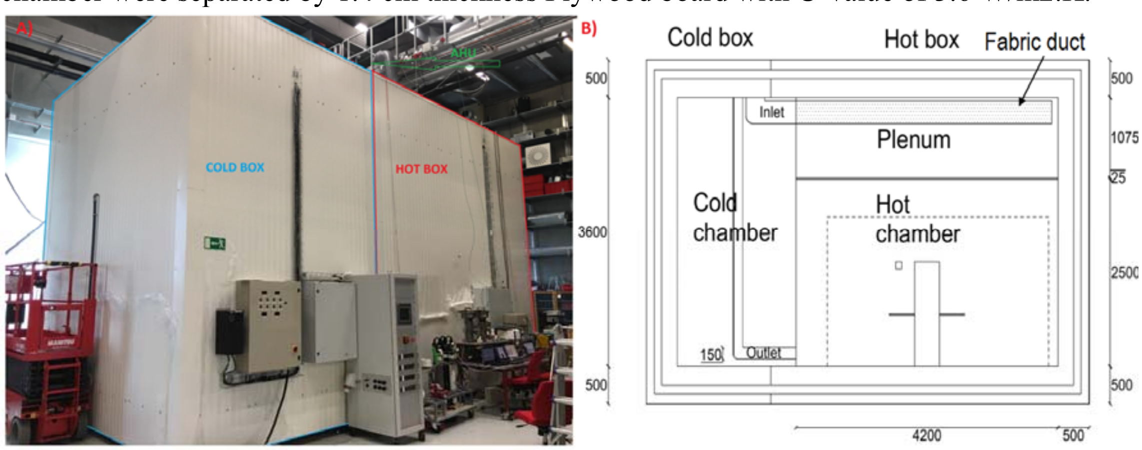


Figure 1. Guarded hot box (a) Photo (b) Cross-section

Diffuse ceiling separates the hot chamber into a plenum and an occupied zone. In this study, the diffuse ceiling was made by wood-cement panels with a thickness of 2.5 cm (Figure 2 (a)), the other physical properties of the wood-cement panel can be found in Table 1. Plenum is the space to distribute air before sending into the occupied zone. In the previous study (Chen Zhang et al. 2015), a slot opening located at one side of the plenum was used as an inlet, which caused uneven air distribution in the plenum. In this study, a fabric duct alone the length of the plenum was used as an inlet in order to obtain more uniform air distribution, as shown in Figure 2 (b).

(a) (b)

Figure 2. (a) Wood-cement panel (b) Fabric duct in the plenum

Table 1. Physical properties of the wood-cement panel

Density [kg/m3]	Conductivity [W/m.K]	Specific heat capacity [J/kg.K]	Porosity [%]
359	0.085	923	65

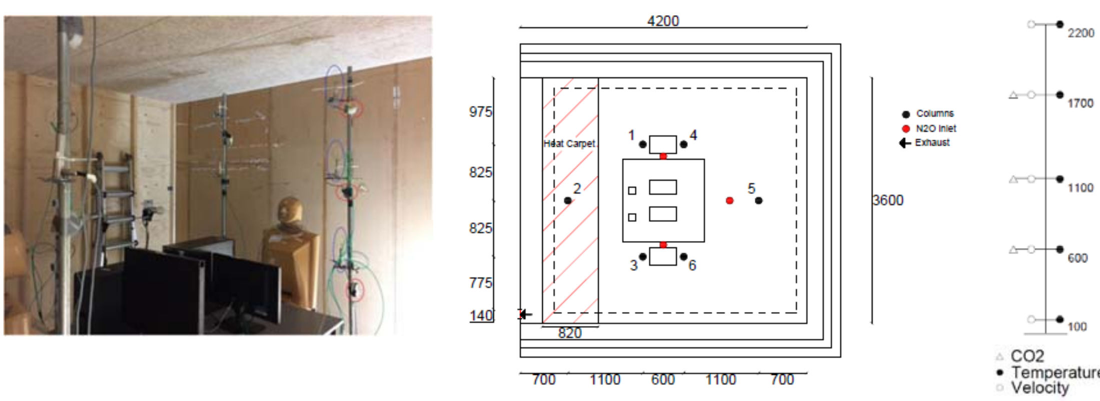
The test room represented a typical office room, with two manikins (100 W *2), two PC (75.5 W and 55 W) and two desk lamps (60 W*2). An electric carpet located on the floor simulated the solar heat gain (410 W).

2.2 Measurements

This study focused on the air quality in the occupied zone, therefore tracer gas tests were conducted by using N2O. Two type of contaminant sources were considered, one was pollutants from person's mouth and the other was a point source that was not heated source. The tracer gas concentrations were measured in fabric duct, exhaust duct, plenum and the occupied zone. The contaminant removal effectiveness (CRE) is used to evaluate how efficient the ventilation system removes the airborne contaminant from the room when the position of the contaminant source is known, which is calculated based on equation below:

$$CRE = \frac{C_e - C_s}{C_i - C_s} \quad [1]$$

where C_e is the concentration in the exhaust air; C_s is the concentration of the supplied air, and C_i is the concentration in the occupied zone. In well-mixing ventilation, the global CRE is 1.



(a) (b) (c)

Figure 3. Test room layout and measurement points (a) Office room layout (b) Placement of measurement columns (c) Sensors' positions in each column

Beside the air quality, thermal comfort was also evaluated in this study. Both air temperature and air velocity were measured in the occupied zone. The positions of the sensors are illustrated in Figure 3.

The investigations were carried out for 6 cases. The first two cases represent summer period with two persons inside the office who are contaminant sources. The first scenario includes solar gains and has 6ACH while the second scenario is without solar gains and has 3ACH. Furthermore, the third and fourth cases are identical to the first two cases with the only difference is that a point source located on the floor serves as contaminant source. The fifth and sixth case consist of only1 person operating scenario with different contaminant sources. The cases are described in detail in Table 2. Boundary conditions of test cases

Table 2. Boundary conditions of test cases

Case	Cold box temp	Room temp	Supply temp.	ACH	Internal heat load	Contaminant source
	oC	oC	oC	h-1	W	
1	21,6	22	14,19	3	451	2 persons
2	21,6	22	14,42	6	861	2 persons
3	21,6	22	14,42	6	861	point source on the floor
4	21,6	22	14,19	3	451	point source on the floor
5	21,6	22	17,34	3	275	point source at 1.1 m
6	21,6	22	17,34	3	275	1 person

3 RESULTS AND DISCUSSIONS

3.1 Ventilation effectiveness in the occupied zone

The average values of CRE in the occupied zone are summarized in Table 3. When the contaminant released from occupants (Case 1, 2 and 6), the ventilation effectiveness of diffuse ceiling ventilation was comparable with mixing ventilation. Case 2 with the largest heat load of 861 W provided the highest CRE of 0.97, while the Case 6 with only one person load of 275 W obtained the lowest CRE of 0.88. These results further prove that the air flow in the room with diffuse ceiling ventilation was driven by the thermal buoyancy from heat sources. The stronger the thermal plume the higher level of mixing can be reached. However, the CRE shows very different manners in the cases with passive contaminant sources (point source). Case 3 and Case 4 with the passive source located on the floor give the average CRE of 2.24 and 0.99, while, Case 5 with the passive source located at the breathing height obtains the average CRE of 1.21.

Table 3. Average contaminant removal effectiveness in different cases

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
CRE_{avg}	0,93	0,97	2,24	0,99	1,21	0,88

In order to understand the contaminant distribution in the occupied zone, the CRE profiles in different cases are illustrated in Figure 4. As expected, the cases with pollution from occupants (also as heat sources) have uniform contaminant distributions in both vertical and horizontal directions. In Case 6, the contaminant distribution has a slightly larger deviation in the horizontal direction with CRE from 0.75 to 1.02, this might due to the contaminant and heat only released from one occupant which created less mixing of air in this condition.

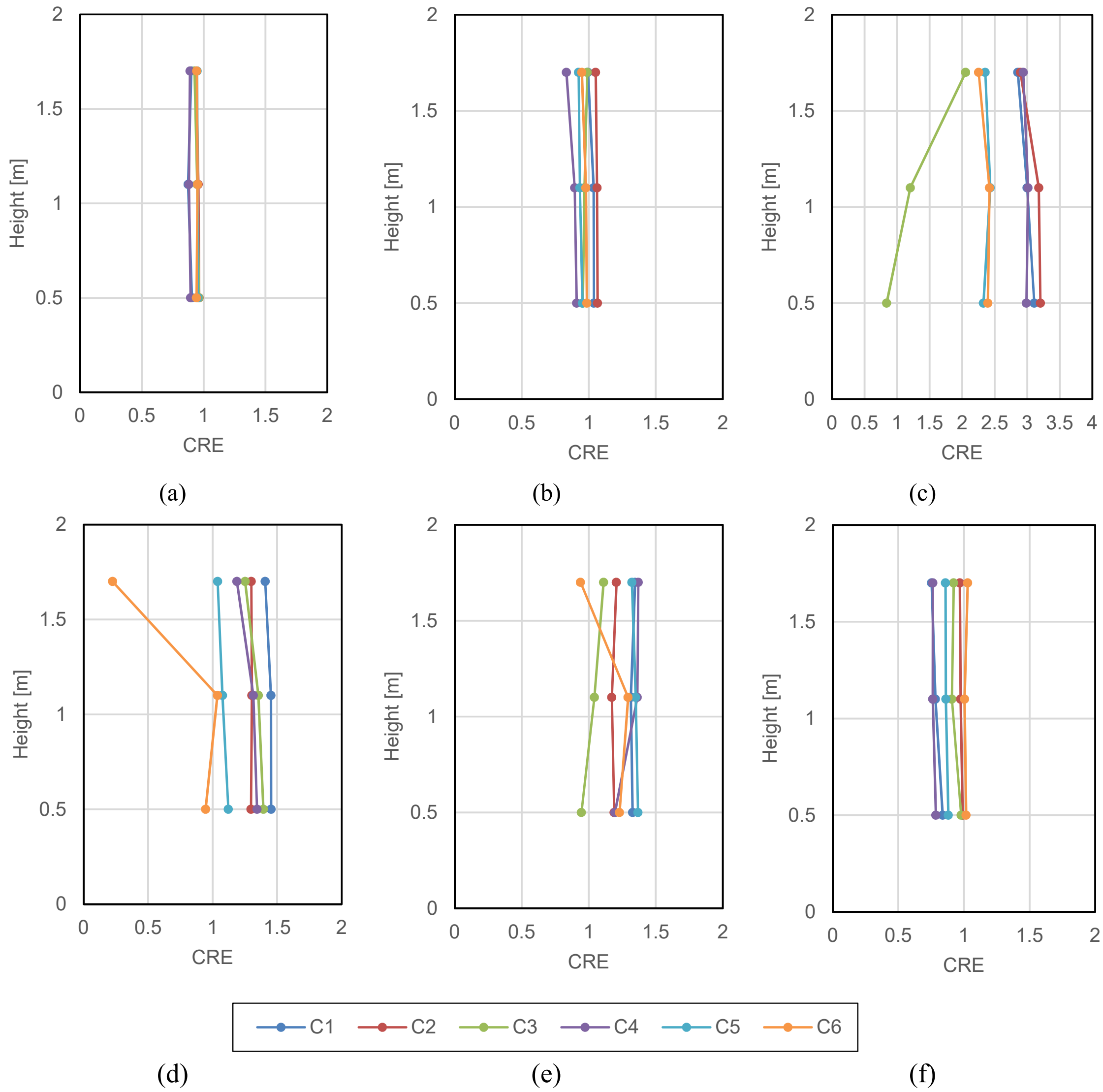


Figure 4. Contaminant removal effectiveness profiles (a) Case 1; (b) Case 2; (c) Case 3; (d) Case 4; (e) Case 5; (f) Case 6.

The contaminant distributions differ significantly in the cases with passive contaminant source. In Case 3, high CRE from 2 to 3.2 are observed in most of the occupied zone, which indicates good ventilation effectiveness has been obtained in these areas. However, high contaminant concentrations are observed in Column 3(close to the occupant 1) at 0.5m and 1.1 m height. This could be explained by the fact that contaminates source had a higher density than air and located on the floor, so the contaminant did not follow the airflow pattern and directly exhausted in the lower zone. However, the thermal plume around occupant created an upward movement to the flow field, and gave rise to a vertical flow of contaminant and brought the containment from lower zone to the breathing zone. This local disturbance of the concentration distribution may affect the personal exposure significantly (Mundt et al. 2004). The similar trend also shows in Case 4, the highest concentration exists in Column 6 (close to the occupant 1) at 1.7 m height with CRE of 0.22, and the CRE is between 1.1 to 1.5 in the rest of the occupied zone. The low average CRE in Case 4 than Case 3 may due to the low air change rate of 3 h-1 could not dispel contaminant as efficient as the one of 6 h-1, therefore, the contaminant stayed in the room for a longer period and had higher mixing with the room air. The CRE ranges from 0.94 to 1.37 in Case 5 with contaminant source located at 1.1 m height. The results indicate that the contaminant source seems involved by the warm convective flow and mix with the room air. However, the ventilation effectiveness is still better than mixing ventilation in this case.

3.2 Concentration in the plenum

Table 4. N2O concentration in the inlet and plenum

Concentration [ppm]	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Inlet	1,00	0,68	0,49	4,81	1,02	0,40
Plenum	0,59	0,52	0,49	3,03	0,57	0,38

The previous studies (Hviid & Svendsen 2013)(C. Zhang et al. 2015)(Elmroth & Fredlund 1996) mentioned that reverse flow from occupant zone to the plenum may occur due to the low pressure drop of the diffuse ceiling and the strong convective flow from heat sources. In order to investigate the reverse flow, the concentration in the plenum is also measured at two points. One locates just above heat sources and the other locates above the crack between two diffuse ceiling panels. Table 4 shows the average concentrations in the plenum and compare them with the concentrations in the inlet opening. The results indicate that the concentrations in the plenum have almost identical values as in the inlet. There is no evidence of reverse flow in all cases.

4 CONCLUSIONS

This study aims to investigate the ventilation effectiveness of diffuse ceiling ventilation with different types of contaminant source. If the contaminant from occupants which are significant heat source in the room, contaminant will be carried by the warm convective flow from the heat source and mix with the supply air. Therefore, the ventilation effectiveness is comparable with mixing ventilation with CRE of 1. In addition, the stronger the heat load, the higher mixing level will reach. If the contaminant source is cold and located on the floor, the contaminant will be trapped in the lower zone and high ventilation effectiveness occurs in the occupied zone. However, the thermal plume around occupant might create an upward movement and bring the containment from the lower zone to the breathing zone. This local disturbance of the concentration distribution may affect the personal exposure significantly. When the passive contaminant source located at the 1.1 m height, the contaminant seems involved into the convective flow. However, the contaminant concentration in the occupied zone is still lower than by mixing ventilation with average CRE of 1.2.

Besides the influence of contaminant source types and locations, there are still several impact parameters need to be explored in the future study. It is known that the exhaust has a small impact on the velocity and temperature distribution, but it may have a large influence on the ventilation effectiveness. Therefore, different locations of exhaust opening will be investigated in the further study. In addition, this study focused on the cooling conditions, where the ventilation system is used to remove the heat load. It will be interesting to see how is the ventilation effectiveness and whether there is any stagnant zone in the room when diffuse ceiling ventilation operates in the heating conditions.

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