Distribution of contaminants in the occupied zone of a room served by a novel enhanced displacement ventilation system

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ABSTRACT

The aim of this study is to examine contaminant distribution in the occupied zone of a room served by a novel enhanced displacement ventilation system which brings cooler air near the floor upward around human body via 4 fans mounted at each corner of a chair. An office with two workstations was simulated in a full-scale test room. The discharge angle of the flow from the fans was varied to be 0°, 30°, and 60° from the horizontal plane. Two breathing thermal manikins were used to simulate the occupants with one served as a polluting manikin and the other one as an exposed manikin. The exhaled air of the polluting manikin was marked by a tracer gas Freon, and it was sampled at the mouth of the exposed manikin to study the cross effect and the impact of the flow generated by the fans on the exposure. Freon was also sampled at 6 different heights in the occupied zone at 2 locations in the chamber as well as in the supply and exhaust units. The results show an insignificant impact of the fan angle on the inhaled air quality. It is also found that the exposure to the exhaled air of the polluting manikin was increased when either the polluting manikin or the exposed manikin used the fans. And the exposed manikin is prone to more polluted air transported from the polluting manikin when the exposed manikin uses the fans. The use of the fans increased the contaminant concentration in the occupied zone.

1. INTRODUCTION

Displacement Ventilation (DV) has been widely adopted in Scandinavian countries since 1980s in large spaces such as theatres and assembly halls. Gradually, DV system is also used for ventilation of office spaces. However, research has found that in an office environment with low heat load and low ceiling height, the temperature stratification is less obvious as compared to this in spaces with high heat load and ceiling height (Akimoto et al, 1995; Lin et al, 2006). In such spaces thermal comfort level is usually less satisfactory than in rooms with high ceiling levels. The thermal plume around the occupants is too weak to bring fresh cool air from the floor up to the occupants.

In order to overcome the above-mentioned problems, cooler air near the floor can be moved upwards via 4 fans mounted at each corner of a chair as shown in Figure 1.

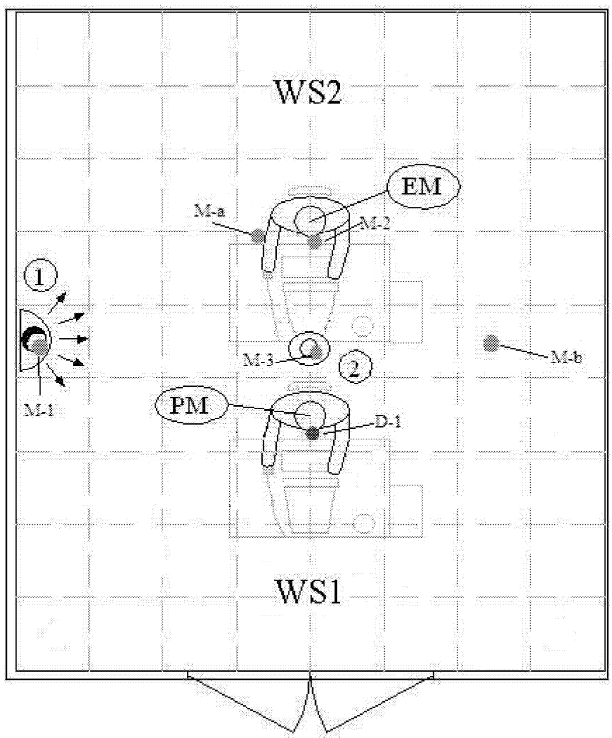
Figure 1. Enhanced displacement ventilation system: chair with attached fans.

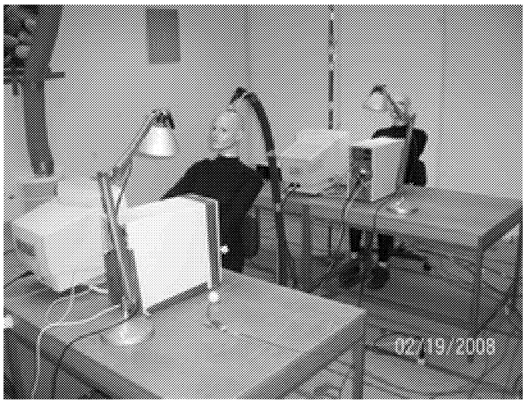
A series of experiments were conducted aiming to study the impact of fans on the pollution distribution in the room and cross-infection between occupants.

2. METHODS

Measurements were performed in a full scale air distribution room at the International Centre for Indoor Environment and Energy, at the Technical University of Denmark, measuring $4.7\times5.4\times2.6m^3$ (W×L×H). The test room is situated in a laboratory hall measuring $10\times11\times8m^3$ (W×L×H) in size.

Two identical workstations were placed in the sealed test room as shown in Figure 2. Each workstation consisted of a desk, a breathing thermal manikin simulating an occupant (75W), a desk lamp (55W), a personal computer with a monitor (143W), and an office chair. Six fluorescent light fixtures were evenly distributed over the ceiling (36W in total). The office area, $12.7m^2$ per occupant, was close to the area of $14.3m^2$ recommended in the standards and guidelines (CEN 1752, 1998). The heat load in the chamber was kept constant.





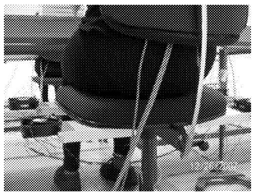
PM - Polluting manikin, EM – Exposed manikin,
1 – Supply unit, 2 – Exhaust unit
Dosing location: D-1
Measuring locations: M-1, M-2, M-3, M-a, and M-b

Figure 2. Climate Chamber layout

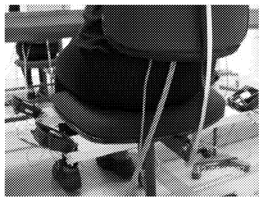
A semicircular floor standing air distribution unit (radius of planar projection 250 mm and height of 1000 mm) placed in the middle of one of the long walls of the office was used for the displacement ventilation. The air from the office was extracted uniformly through a circular diffuser placed at the center of the ceiling. The room air temperature was controlled at 1.1 m above the floor at 22±0.5°C. The temperature in the laboratory hall were kept the same as in the test room. During the experiments, the supply airflow rate from the DV was kept constant at 30 L/s·p.

The thermal manikins used in the study were one with 16 body segments served as a polluting manikin (PM), and the other one with 23 body segments as an exposed manikin (EM). The EM was placed behind the PM, facing the same direction as shown in Figure 2. They were dressed in clothing with thermal insulation estimated 0.50clo (including chair). Their surface temperature was controlled to be equal to the skin temperature of an average person in state of thermal comfort. The breathing mode was switched on for the PM, while the EM was not breathing during the experiments. The breathing cycle for the PM consisted of 2.5s inhalation, 2.5s exhalation and 0.9s pause. The breathing frequency was 10 per minute and the pulmonary ventilation was 6 L/min. One office chair with four fans sizing 80×80×25.4mm^3 (L×W×H), mounted at each corner and one office chair without the fans were used in the experiments. The amount of airflow through the fans could be adjusted easily by varying the power supply voltage. The fans used were 4 normal computer cooling fans with a maximum voltage of 12V and maximum power of 5.76W. The two chairs were swapped between the two manikins according to different experiment conditions.

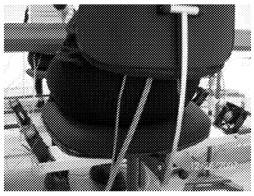
The discharge angle of the flow from the fans was varied to be 0°, 30°, and 60° from the horizontal plane as shown in Figure 3. The four fans were either switched off or switched on with 8V electricity supply (power consumption of approx. 4.5W each). Previous measurements identified that at 8V the airflow rate supplied from the fans was approx. 0.006 m^3/h.



a) 0° discharge angle



b) 30° discharge angle



c) 60° discharge angle

Figure 3. Fan discharge angles

The impact of the fans on the contaminant distribution was studied by means of tracer gases. The air exhaled from the breathing PM was marked by a tracer gas Freon *(location D-1, Figure 2).* The tracer gas concentrations near the EM, location *M-a*, and the ambient tracer gas concentrations in the chamber, location *M-b*, was measured at 0.6m, 0.9m, 1.1m, 1.4m, 1.7m and 2.0m heights under steady-state conditions. Besides, the tracer gas concentrations were also sampled at the supply unit *M-1*, the mouth of the EM *M-2*, and the exhaust unit *M-3*. A gas monitor based on a photo-acoustic infrared detection method was used. The exposure of the manikins was expressed in terms of a normalized concentration: $(C - C_S)/(C_E - C_S)$, where C, C_S, and C_E are the concentration at a point in the room, in the supply air and in the exhaust air, respectively. The uncertainty of the mean with a level of confidence of 95% was calculated based on repeated observations. The uncertainty is presented by means of error bars.

3. RESULTS AND DISCUSSION

Figure 4 presents the concentration of air exhaled by the PM in the air inhaled by the EM (location *M-2)* in case when: (1) fans at the chairs of the PM and the EM were switched off, (2) fans at the chair of the PM switched on (enhances DV) and fans of the chair of the EM were switched off, and (3) fans of the chair of the EM were switched on (enhanced DV) while the fans of the chair of the PM were switched off. The graph in Figure 4 shows the maximum, minimum and mean concentrations obtained from 8 repeated measurements using the tracer gas constant injection technique.

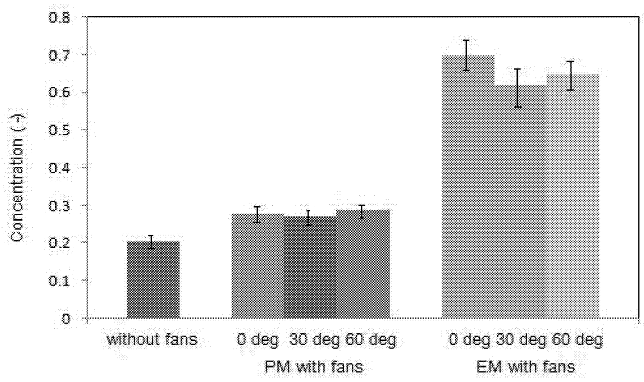


Figure 4. Dimensionless concentration of the contaminant exhaled from PM in the air inhaled by EM

The results in Figure 4 show that when the enhanced DV system was not used, i.e. the fans were switched off (case 1), the contaminant concentration in the air inhaled by the EM is low, i.e. less air exhaled by the PM is transported to the EM. This is due to the fact that the free convection flow around the EM is able to transport clean air from the lower levels upward to the breathing area.

The exposure of the EM to the exhaled air of the PM was increased when either the PM or the EM used the enhanced DV system. This is because the use of the fans caused mixing of the exhaled air with the room air, which increased the pollutant concentration in the room air inhaled by the EM. As compared to the base case when neither manikin used the fans, the exposure of the EM to the air exhaled by the PM increased by approximate 35% when the fans at the chair of the PM were switched ON (case 2), and approximately by 200% when the fans of the chair of the EM were switched ON (case 3). The reason why the EM is prone to more polluted air transported from the PM when it uses the enhanced displacement system, i.e. the fans of its chair are on, will be discussed together with the concentration profiles at location *M-a* and location *M-b* in the following section.

From Figure 4, it is also observed that the angle of the fans does not significantly affect the inhaled air quality of the EM. The mixing caused by the fans when adjusted at different angles and its impact on the exposure of the EM was the same. The impact of the discharge angle of the flow from the fans on local heat loss from the body will be discussed and presented in a following paper.

Figures 5 and 6 present the concentration profiles measured at locations *M-a* and *M-b* at 6 different heights, namely 0.6m, 0.9m, 1.1m, 1.4m, 1.7m, and 2m with three different fan discharge angles.

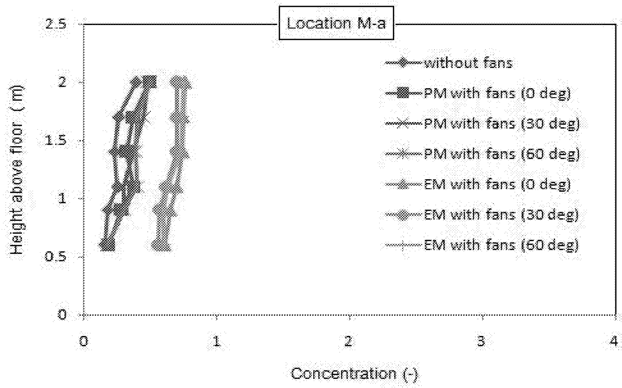


Figure 5. Concentration profiles of exhaled air measured at location *M-a*

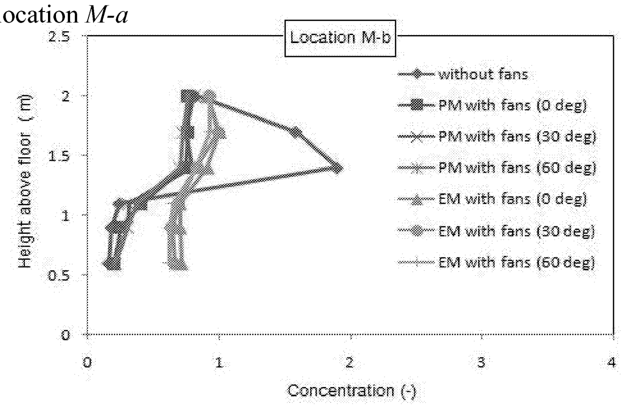


Figure 6. Concentration profiles of exhaled air measured at location *M-b*

When only conventional DV system was used, a typical displacement airflow pattern was observed at the location *M-b*, which was close to the pollution source, i.e. the PM (Figure 6),. The peak of the concentrations of the tracer gas occurred approximately at 1.4m above the floor. This is because the thermal plume from the PM carried the contaminants and dissolved above the stratification level. However, further away from the source PM, at the location *M-a* (Figure 5), the profiles were straightened out. This is because the measuring location *M-a* is close to the EM where clean air was brought upward by the thermal plume generated from the EM. Hence, the readings obtained at location *M-a* were measured in the plume of clean air around the EM.

The use of the fans caused mixing and decreased in the contaminant stratification in the room. .The mixing was less when the fans of the chair of the PM were switched on. In this case the flow generated by the fans assisted the free convection flow around the PM body and strengthened the thermal plume. Thus the exhaled air was transported upward and some of it was evacuated by the exhaust unit placed almost above the PM. Nevertheless a layer of clean air was still preserved above the floor. The free convection flow transported this air upward to the breathing zone of the EM. The use of the fans of the chair of the EM increased the mixing of the air exhaled by the PM with the room air. In this case the pollution stratification at location *M-b* almost disappeared (Figure 6). The pollution concentration at the location *M-a* located near the EM increased almost to the level of the concentration at the location *M-b* (Figure 5). The interaction of flows in the case when the fans of the chair of the PM were switched on was different from the interaction when the fans of the chair of the PM were switched on. This explains the difference in tracer gas concentration measured with the two cases as shown in Figure 4.

From Figures 5 and 6, it is also observed that the change of the fan's discharge angles did not affect the concentration profiles at the locations *M-a* and location *M-b*, which concurs with the finding from Figure 4 about the discharge angle impact on the inhaled air quality of the EM. This is because no matter at which direction the air was discharged from the fans, it would cause a mixing with the room air. Thus, the angle effect can be ignored in terms of the contaminant distribution and the cross infection between the occupants. However, it is believed that the different discharge angles will affect the local thermal comfort on occupants and this will be discussed in a following paper.

4. CONCLUSIONS

The possibility to enhance the performance of DV by moving cooler air from near the floor upward around human body via 4 fans mounted at each corner of a chair was examined with regards to cross-infection. It was found that the transport of exhaled air between occupants increased when the fans were used. No difference was observed in the case when the fans discharged the flow vertically upward or at angle of 30° or 60° against the body. The use of the fans caused mixing of the exhaled air with the room air. The mixing was affected by the interaction of the flow generated by the fans with the free convection flow around manikin's body. These are the primary findings from a large study aiming to identify the most appropriate design strategy for the newly developed enhanced DV system. More detailed study and analysis are still in progress.

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