Indoor air quality on displacement ventilation in the tropics—a chamber study

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ABSTRACT
This paper presents the indoor air quality performance of a displacement ventilation system in a thermal chamber. This study consists of two sets of experiments. In the first experiment, the thermal chamber was operated under displacement ventilation (DV) mode with the relative humidity (RH) set at about 65% while the ambient temperature (AT) at 1.3 m height varied from 22 to 26ºC. In the second experiment, all the conditions are the same except that the ventilation strategy is changed to mixing ventilation (MV). Tropical subjects were surveyed with respect to the perceived air quality and Sick Building Syndrome (SBS) symptoms. It was found that with an increase in temperature, subjects perceived stronger odour and less acceptable air quality. Some level of adaptation effect existed in this study as subjects experienced less odours and more acceptable air quality after 60 min of exposure at T_{room} = 22ºC and more acceptable air quality at 26ºC. On the whole, there is no significant difference between DV and MV modes for all subjects' votes. DV mode shows a very clear stratification of carbon dioxide concentration even in a recirculated system as compared to the MV mode.

INDEX TERMS
Displacement ventilation; Perceived air quality; SBS symptoms; Temperature

INTRODUCTION
Since displacement ventilation (DV) was first applied to a welding industry in 1978, it has been gaining popularity in Scandinavia. In comparison with conventional mixing ventilation (MV), DV can provide better IAQ, achieve considerably higher ventilation efficiency and better energy efficiency. However, research on DV has been mainly conducted in Scandinavian countries. There is limited research on DV system in the tropics. Moreover, as the climate, subjects and system's configuration in the tropics are not the same with those in the Scandinavian countries, the results of such research may not be applicable.

This study is conducted to investigate whether displacement ventilation is applicable and how it performs in terms of indoor air quality in the tropics. This is achieved by conducting a preliminary study with both objective measurements and subjective assessment in a thermal chamber.

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METHODS

This study consists of two sets of experiments. In the first experiment, the thermal chamber was operated under displacement mode with the relative humidity (RH) set at about 65% while the ambient temperature (AT) at 1.3 m height varied from 22 to 26ºC. In the second experiment, all the conditions are the same except that the ventilation strategy is changed to mixing mode. All the experiments were conducted with the outside air provision of about 6 l/s per person.

Chamber Setup

The experiments were carried out in a thermal chamber of size 6.6 m (L) × 3.7 m (W) × 2.6 m (H). The Air-Conditioning and Mechanical Ventilation (ACMV) system is capable of controlling the air temperature and airflow rates by adjusting the off coil temperature and fan speed with the aid of the computer controller to reach the required room conditions. The ventilation strategy of the chamber can be in either MV or DV mode.

Figure 1 shows the layout of the six workstations in the chamber with two fixed windows on the wall to simulate a typical office environment. In the DV mode, the air is supplied from a floor-standing low velocity semi-circular unit at one end of the chamber and extracted from two ceiling grilles, E1 and E2. In MV mode, the air is supplied from two square ceiling diffusers, T1 and T2, and extracted from two ceiling grilles, E2 and E3.

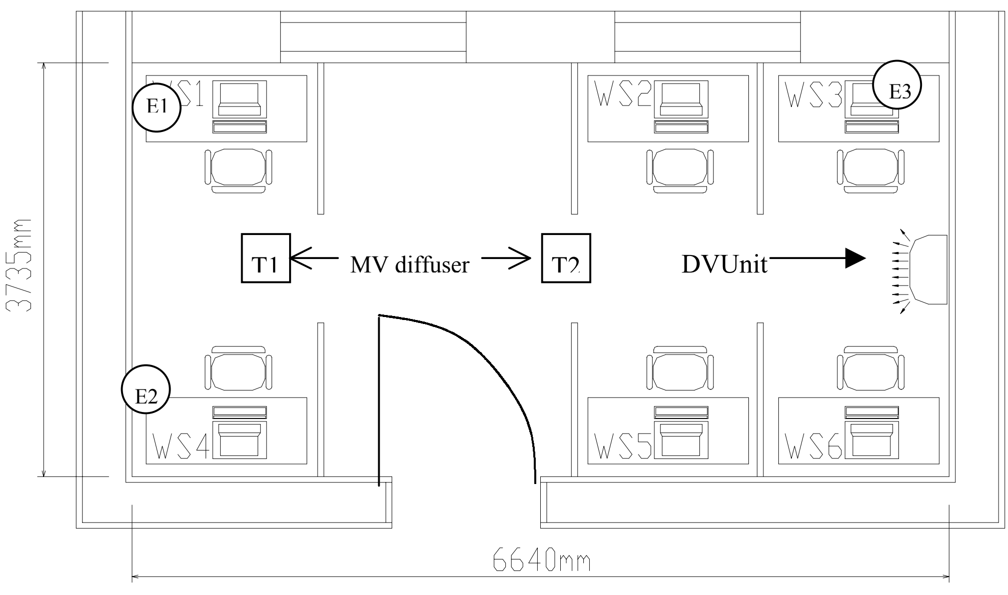


Figure 1 Chamber layout. (Note: WS denotes workstation and E denotes extract grille.)

Equipment

Table 1 shows the measured parameters and instruments used in the experiments.

Table 1 Parameters measured and instruments used in the experiments

Parameter	Instrument	Accuracy
Temperature	Type T thermocouple wire	±0.2°C
Room air relative humidity	Portable RH sensor	±5% RH
Dew point temperature	Dew-point hygrometer	±0.15°C
Supply and return airflow rate	Hood and vane anemometer	±1%
CO_2, formaldehyde, TVOC concentration	Photoacoustic Spectrometer Multi-Gas Analyser	±2%

Experiment Procedure

The durations for the DV and MV experiments were 2 and 1 h, respectively. Twelve (five males and seven females) college-age students participated in all these experiments. Subjects would arrive at the chamber 30 min prior to the experiment. There will be a briefing session followed by the completion of a set of questionnaires. During the experiments, subjects had to complete a set of questionnaire every 10 min. The scope of the questionnaire includes personal particulars, thermal sensation, thermal comfort acceptability, odour sensation, inhaled air quality acceptability, air movement at different parts of the body and its acceptability, environment assessment, personal sensation and types of clothing. The students were subjected to the conditions in the thermal chamber as shown in Table 2.

Table 2 Conditions of experiments for both displacement and mixing modes

Ventilation mode	DV		MV	
Case no.	1	2	3	4
T_s (ºC)	16.8	20.4	15.7	17.9
T_r (ºC)	22.2	26.2	22.0	26.1
RH (%)	65.0	64.7	65.9	64.7
q_v (l/s)	181	69	87	64

Note: T_s = supply temperature, T_r = room temperature (1.3 m height), RH = relative humidity (1.3 m height), q_v = supply airflow rate.

RESULTS

Experiments with Displacement Ventilation Mode

Table 3 shows the results of the questionnaire's survey. The scale for odour sensation is from 0 to 4 with 0 as 'no odour' and 4 as 'very strong odour while the other responses are between –1 and +1. The results in Table 3 show that with higher room temperature, subjects tend to perceive stronger odour and less acceptable air quality. However, statistical analysis shows that there is no significant difference between these conditions. As for the *Environment assessment*, results of *t*-test show that the condition of 26ºC is significantly different from the other condition. Subjects feel stuffy ($p = 0.01$) and dry ($p = 0.04$) when they were exposed to 26ºC.

Table 3 Results of the subjective assessment for both displacement and mixing modes

Response \ Case no.	1 Mean	1 SD	2 Mean	2 SD	3 Mean	3 SD	4 Mean	4 SD
Indoor air quality								
Odour sensation (0,4)	0.64	0.56	0.83	0.87	0.64	0.57	0.81	0.83
IAQ acceptability (–1, +1)	0.42	0.35	0.31	0.49	0.44	0.40	0.38	0.45
Environment assessment								
(–1) Air humid/air dry (+1)	0.08	0.30	0.28	0.27	0.13	0.29	0.24	0.33
(–1) Air stuffy/air fresh (+1)	0.25	0.31	–0.07	0.45	0.17	0.48	0.10	0.53

The effect of adaptation of perceived air was also studied. The result is shown in Table 4. In Case 1, subjects experienced fewer odours after 60 min of exposure, though a statistically significant effect did not exist. However, subjects perceived higher level of odour after 60 min of exposure in Case 2 though it is not statistically significant. Subjects felt that the air was more acceptable after 60 min of exposure in both cases, and significant effect was found in Case 1 ($p = 0.03$).

Table 4 Means of 0 and 60 min for displacement mode

Subjective response	Case 1		Case 2	
	0 min	60 min	0 min	60 min
Odour sensation (0, 4)	0.96	0.64	0.71	0.83
IAQ acceptability (–1, +1)	0.29	0.42	0.29	0.31

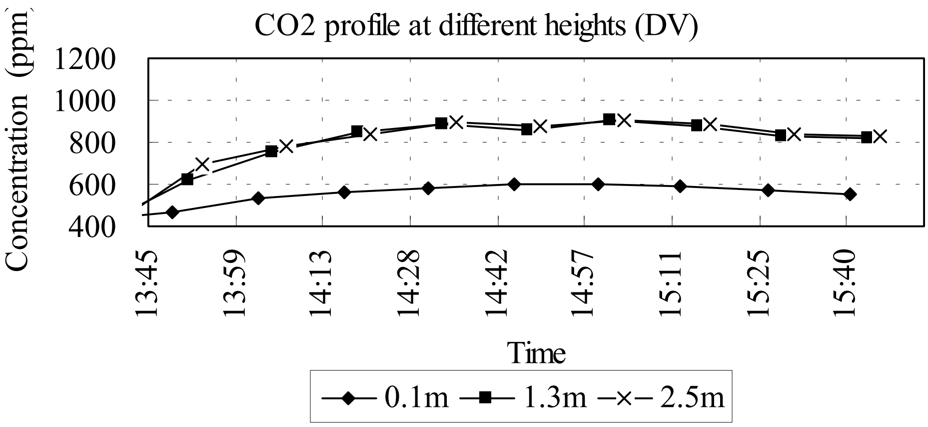
Comparison between DV and MV Modes

Results of statistical test show that there is no significant difference between DV and MV modes in terms of subjects' vote with similar room conditions.

The profile of carbon dioxide (CO_2) concentration showed that stratification of CO_2 is more significant in the DV mode than in the MV mode as shown in Figure 2. The CO_2 profile for the DV mode showed that $C_{0.1m}$ is significantly lower than $C_{1.3m}$ and $C_{2.5m}$ in a recirculated system with about 36% outdoor air. The CO_2 profile for the MV mode showed that it is rather uniform from the floor to ceiling level. This is the characteristics of mixing ventilation strategy. It is observed that the absolute concentrations of CO_2 at all the heights in the chamber with the DV system are lower than those of MV although the fresh air provision rate and the number of subjects remain the same. This implies that DV system is better in extracting CO_2 and subjects in the chamber served by the DV system will be exposed to lower level of CO_2 as compared to the MV system.

DISCUSSIONS

Statistical analysis showed that the impact of temperature on odour intensity was not significant. This is consistent with the studies by Fang *et al.* (1998a,b). In those studies, the impact of both humidity and temperature on the acceptability of perceived air quality was significant and the air was always perceived as less acceptable with increasing temperature



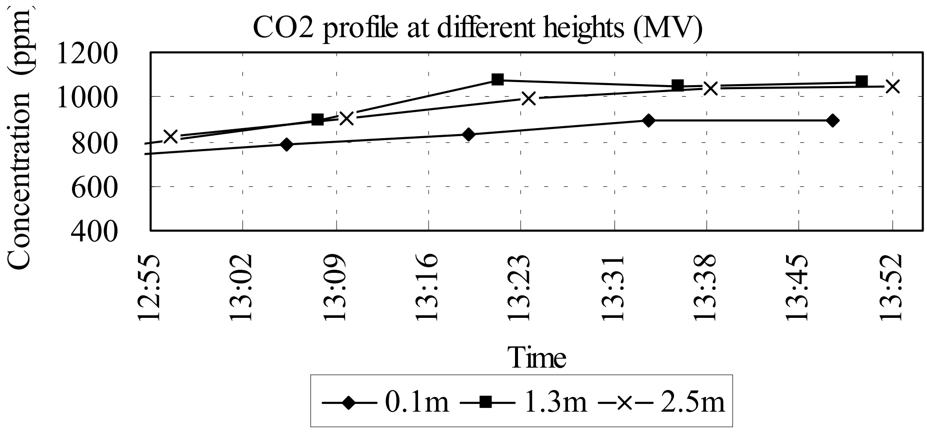


Figure 2 CO_2 profiles at different heights for DV mode (upper) and MV mode (lower).

and humidity. However, in this study, it was found that the impact of temperature on the acceptability of air was not significant. The insignificant result might be because of the small sample size (12 subjects participated in this study, compared with 36 subjects of Fang *et al.*'s). It could also be due to the small range of temperature (22–26ºC, practically adopted at local tropical area). In Fang *et al.*'s study, the temperature ranged from 18 to 28ºC. In addition, the people in the tropics are subjected to changes in temperature and humidity when they move between their office environment (22ºC, 55–65% RH) and the outdoor environment (33ºC, 80–100% RH). When people were frequently subjected to these changes in the temperature and humidity, they could be less sensitive to the perceived air quality. Hence, in this study with such a small temperature range and a constant RH level, it is reasonable that the subjects could not tell the difference between the DV conditions. In future study, a larger temperature and humidity range with larger sample size should be considered.

In this study, there is no significant difference between DV and MV in terms of SBS symptoms. This could be due to the low pollutant level inside the chamber. In the entire study, the formaldehyde concentration was always zero and that of the total volatile organic compounds (TVOC) did not exceed the threshold level of 3 ppm (Ministry of the Environment). The subjects will not be able to show any SBS symptoms due to such low level of pollutants. Hence, future study needs to have a higher pollutant level.

Despite the fact that statistically significant difference did not exist, some less significant results did present some useful results that DV system to some extent provides a better indoor air quality than mixing ventilation. The subjects indicated consistently less headache, less sleepy at 22ºC and less tired, less sleepy at 26ºC with the DV system. The perceived lesser symptoms with the DV system could be due to the lower CO_2 level. In DV mode, the concentration of CO_2 at 1.3 m height was about 850 ppm as compared to MV mode with 1050 ppm.

CONCLUSIONS

With the higher temperature of 26ºC, subjects experienced stronger odour and less acceptable air quality but the effect was not statistically significant. The insignificant effect of temperature on perceived air quality could be due to the small temperature range and the characteristics of tropical area and people. Some level of adaptation effect existed in this study as subjects experienced less odours and more acceptable air quality after 60 min of exposure at T_{room} = 22ºC and more acceptable air quality at 26ºC. There is no significant difference between DV and MV systems for all subjects' votes when the room conditions were the same. This could be due to the low pollution level inside the chamber. Concentration stratification is more significant in the DV mode than in the MV mode. The concentrations of all heights of DV are lower than those of MV although the fresh air provision rate and the number of subjects remain the same. Despite the fact that a statistically significant difference did not exist, some less significant results did present some useful results that DV system to some extent provides a better indoor air quality than mixing ventilation. As this is only a small scale pilot study, future intensive experiments with more subjects, larger temperature range and higher pollutant level will be necessary to ensure that the results be statistically significant.

ACKNOWLEDGEMENTS

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