A thermal comfort study on displacement ventilation in the tropics

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ABSTRACT

This paper presents the performance of a displacement ventilation system in a thermal chamber with tropical subjects. The chamber is served by an Air-Conditioning and Mechanical Ventilation (ACMV) system in either Mixing or Displacement Ventilation modes. In the experiments, tropical subjects were surveyed with respect to their thermal sensations under different room conditions in either displacement ventilation or mixing ventilation. Objective measurements such as room air temperature, air velocity and relative humidity were measured at different heights in the chamber. The results show that the room neutral temperature for a displacement ventilation system is higher than the conventional mixing ventilation system. Subjects in the tropics can accept supply air temperature as low as 16.2°C and relative humidity as high as 77% with room temperature of 23°C.

INDEX TERMS

Thermal comfort; Neutral temperature; Relative humidity; Displacement ventilation; Tropics

INTRODUCTION

Mixing Ventilation (MV) systems are commonly used in air-conditioned buildings in Singapore to maintain comfortable living conditions for their occupants. However, a Displacement Ventilation (DV) system, which is not popular locally, has greater control of temperature and concentration of pollutants in the occupied zone within an acceptable level, while allowing higher temperature and build-up of pollutants to rise beyond the occupied zone. Hence, this leads to a reduction in energy required to air-condition the space and provision of better air quality at the occupant's level.

The DV system has been widely used in the Scandinavian countries particularly for the ventilation of industrial buildings. In these countries, there have been extensive researches on the performance of the DV system. However, there are very few studies on the DV system in the tropics. The results from these researches in the temperate countries may not be directly applicable to countries in the tropics, such as Singapore, due to the vast differences in climate, people and the air-conditioning and mechanical ventilation (ACMV) systems. Hence, the objective of this study is to assess the thermal comfort performance of DV system in the tropics.

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METHODS

The experiments were carried out in a thermal chamber, 6.6 m (L) × 3.7 m (W) × 2.6m (H), at the School of Design and Environment, National University of Singapore. This chamber is located within another air-conditioned room to ensure minimal external environmental interference. The fresh air provision is maintained at about 6 l/s per person throughout all the experiments.

Thermal Chamber Layout

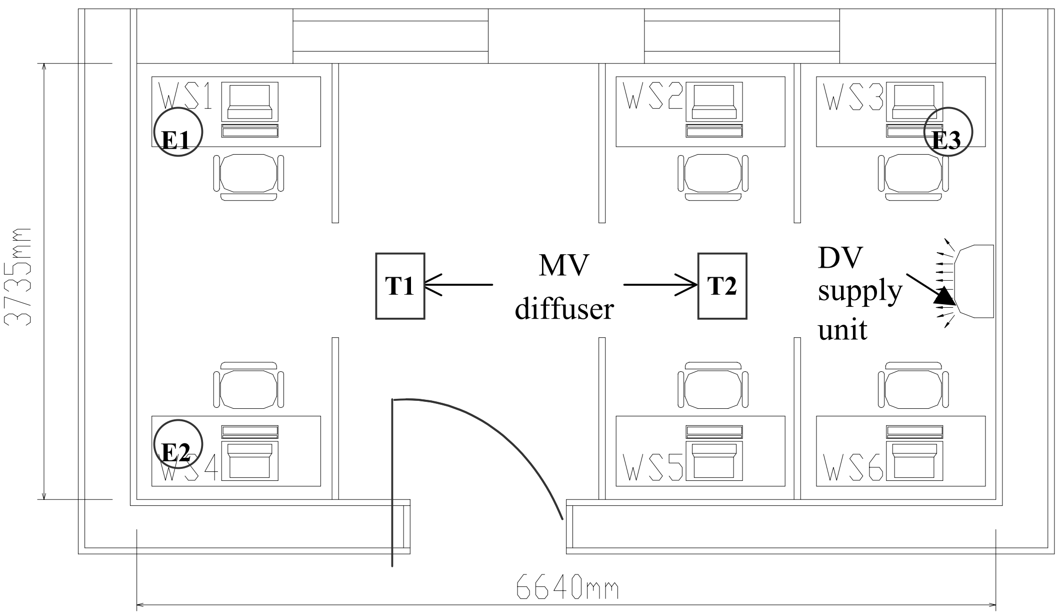

Figure 1 Thermal chamber layout. (Note: WS denotes workstation and E denotes extract grille.)

Figure 1 shows the layout of the chamber. There are six workstations inside the chamber. In the DV mode, the air is supplied from a floor standing low velocity semicircular supply unit, as shown in Figure 1, at one end of the chamber and extracted via two ceiling grilles, E1 and E2. In the MV mode, the air is supplied from two square ceiling diffusers, T1 and T2, and extracted via two grilles, E2 and E3, positioned diagonally at two corners of the chamber.

Experimental Procedures

Twelve (five males and seven females) subjects dressed up in typical office wear participated in these experiments. They were allowed to put on additional clothing to maintain thermal neutrality during the course of the experiment. Subjects in groups of six performed sedentary work under different test conditions for 2 h. During these experiments, subjects were surveyed about their thermal sensation, thermal comfort acceptability, inhaled air quality and its acceptability.

Thermal Comfort Indices

ASHRAE's seven point thermal sensation scale was adopted for the purpose of describing the thermal sensation: (–3) cold, (–2) cool, (–1) slightly cool, (0) neutral, (+1) slightly warm, (+2) warm and (+3) hot. The continuous scale for thermal comfort acceptability is classified as (–1) Very Unacceptable, (0) Just Unacceptable/Just Acceptable and (+1) Very Acceptable.

RESULTS AND DISCUSSION

Average room air temperature, relative humidity, clothing value, overall AMV and thermal comfort acceptability for all experimental cases are shown in Table 1.

Table 1 Average room parameters, Clo value, overall AMV and comfort acceptability

Parameters \ Case	1	2	3	4	5	6	7	8	9	10	11
Ventilation Mode	DV	DV	DV	DV	DV	DV	DV	MV	MV	MV	MV
Average Ts (°C) Standard Deviation	16.2 ±0.3	17.7 ±0.2	18.9 ±0.1	20.3 ± 0.2	16.8 ±0.09	18.7 ±0.08	20.4 ±0.32	15.7 ±0.02	17.8 ±0.31	17.3 ±0.05	17.9 ±0.11
Average Tr (°C) Standard Deviation	23.1 ±0.1	23.1 ±0.1	23.1 ±0.1	23.2 ±0.09	22.2 ±0.03	24.2 ±0.13	26.2 ±0.18	22 ±0	22.9 ±0	24 ±0.07	26.1 ±0
Average RH (%) Standard Deviation	55.6 ±1.2	61.9 ±0.9	68.1 ±1.0	77 ±1.4	65 ±0.6	65 ±0.2	64.7 ±2.9	65.9 ±3.61	70.4 ±0.49	66.5 ±5.09	64.7 ±1.06
Average Clo Value Standard Deviation	0.53 ±0.17	0.59 ±0.20	0.49 ±0.15	0.53 ±0.15	0.56 ±0.16	0.47 ±0.13	0.5 ±0.20	0.6 ±0.16	0.47 ±0.14	0.53 ±0.18	0.44 ±0.10
Overall AMV Standard Deviation	-0.38 ±0.6	-0.06 ±0.88	-0.32 ±0.61	0.19 ±1.01	-0.43 ±0.70	-0.19 ±0.98	0.79 ±0.88	0 ±0.87	-0.17 ±1.02	0.09 ±0.87	0.57 ±1.03
Thermal Acceptability Standard Deviation	0.32 ±0.36	0.36 ±0.38	0.37 ±0.35	0.36 ±0.45	0.19 ±0.38	0.25 ±0.33	0.14 ±0.40	0.35 ±0.39	0.38 ±0.47	0.37 ±0.40	0.26 ±0.45
Percentage of Subjects Unaccetaptable with Thermal Comfort	12.5	8.3	4.8	16.7	16.7	16.7	33.3	16.7	16.7	16.7	25

Ts = Supply Air Temperature, Tr = Room Air Temperature, RH = Relative Humidity, AMV = Actual Thermal Mean Vote, DV= Displacement Ventilation, MV= Mixing Ventilation.

Effect of Different Supply Temperature on Thermal Comfort

For Cases 1–4, room temperature was maintained at around 23°C while the air supply temperature was varied from 16.2 to 20.3°C, as shown in Table 1. The average comfort acceptability votes were within a narrow range of 0.32–0.37. The overall thermal Actual Mean Vote (AMV) ranged between 'slightly cool' and 'slightly warm' with inclination towards the 'slightly cool'. All these four cases fulfilled the less than 20% unacceptability criterion (ASHRAE Standard 55, 1992) with Case 4 having the highest unacceptability votes and Case 3 the lowest. The result shows that the room conditions for all the four cases with different supply air temperatures are in the comfort zone and satisfy the unacceptability criterion of the ASHRAE Standard.

In order to investigate the suitable range of supply air temperature, the thermal sensation and acceptability of subjects seated closest to the supply unit in these four cases, as shown in Table 2, were analysed since this group of subjects was most susceptible to draft risk.

Table 2 Average overall AMV and comfort acceptability for the workstation nearest to the supply unit

Case	1	2	3	4
Overall AMV Standard Deviation	-0.41 ±0.71	0.11 ±0.91	-0.3 ±0.84	0.38 ±1.15
Thermal Acceptability Standard Deviation	0.3 ±0.44	0.35 ±0.40	0.37 ±0.46	0.3 ±0.46

The results show that the overall AMV ranged between –0.41 and 0.38; comfort acceptability ranged between 0.3 and 0.37. This shows that subjects can accept supply air temperature as low as 16.2°C, without feeling thermal discomfort when seated at about 0.4 m from the DV supply unit with average air velocity of 0.08 m/s. This temperature is below the recommended temperature of 18°C (Jackman, 1990; Yuan *et al.*, 1999). The supply airflow rate can be reduced with a lower supply air temperature for the same cooling load in the space. Thus, the size of the air handling unit and ductwork will decrease accordingly. The initial investment and operation cost will be reduced and less fan energy will be consumed. The optimum supply air temperature for energy-saving purpose without sacrificing thermal comfort for the DV system in the tropics needs to be further investigated.

Effect of Room Humidity on Thermal Comfort

Cases1–4 have room relative humidity in the range 55.6–77% with room temperature around 23°C. Subjects at the workstation furthest away from the DV supply unit are least affected by supply temperature and exposed to almost constant room temperature around 23°C with average air velocity of 0.07 m/s. Hence, relative humidity is the governing factor for any variations in the results of thermal sensation for these cases.

Table 3 Average overall AMV, comfort acceptability and velocity for the workstation furthest away from the supply unit

Case	1	2	3	4
Overall AMV Standard Deviation	-0.21 ±0.56	0.34 ±0.84	0.48 ±0.39	0.66 ±0.93
Thermal Acceptability Standard Deviation	0.41 ±0.36	0.38 ±0.44	0.41 ±0.47	0.28 ±0.50
Velocity (m/s)	0.07	0.08	0.07	0.07

Thermal sensations of these four cases varied (p = 0.04) with overall AMV ranging from ‘slightly cool’ (–0.21) to ‘slightly warm’ (+0.66), respectively, as shown in Table 3. Case 4 has slightly lower comfort acceptability (0.28). The results show that as RH increases from 55.6 to 77%, the comfort acceptability generally decreases. However, in terms of thermal comfort, 77% RH at 23.2°C room temperature is still perceived as acceptable for subjects in the tropics. It exceeded the recommended condition of ASHRAE Standard 55a (75%, 23.2°C), ISO Standard 7730-94 and Singapore Standard SS-CP13 (70%, 23.2°C). This reveals that subjects in the tropics can accept higher RH when they are exposed to the normal air-conditioning room temperature. The higher threshold level of acceptable RH leads to lower energy required to remove the latent heat load in a hot and humid climate.

Effects of Varying the Room Temperature on Thermal Comfort

In Cases 5–7, room temperature ranged between 22.2 and 26.2°C with a constant RH of about 65%. Table 1 shows that AMVs (p = 0.00005) ranged between 'slightly cool' and 'slightly warm'. The average comfort acceptability votes for these cases were similar, ranging between 0.14 and 0.25. Cases 5 and 6 satisfied the 20% unacceptability criterion except for Case 7. This could be due to the high room temperature of 26.2°C.

Comparison of Neutral Temperature between DV and MV Systems

The relationship between thermal sensation and room temperature for DV cases was investigated by linearly regressing the overall AMV and the room temperature for Cases 1–7. Figure 2 shows a reasonable regression with an R^2 value of 0.73. When exploring the neutral room temperature of the DV cases, the overall AMVs were plotted against the room temperature as shown in Figure 2. The room neutral temperature for the DV cases was found to be 23.8°C. The same analysis was applied to the MV cases (Cases 8–11) and the results are shown in Figure 2. The overall AMVs and the room temperature have good correlation with an R^2 value of 0.80. The room neutral temperature for MV cases is found to be 23°C. The results show that the DV system produces cooler sensation than the MV system when the room temperature is below 24.8°C. This implied that to obtain the equivalent thermal sensation, the DV system consumes less energy than the MV system. Hence, the DV system has energy-saving potential in the tropics over the MV system.

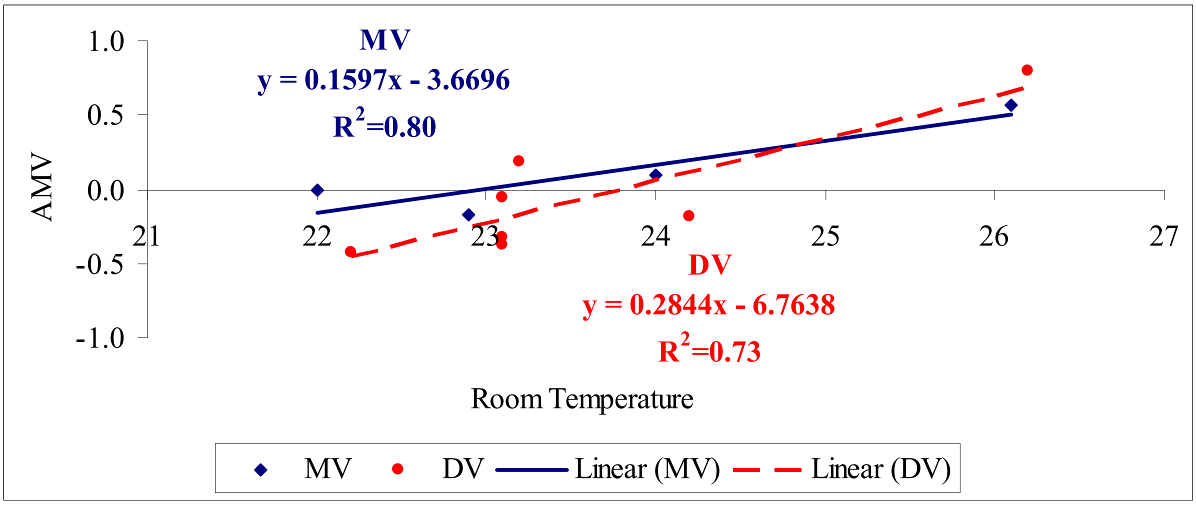

Figure 2 Neutral room temperature for displacement ventilation (DV) and mixing ventilation (MV) systems.

CONCLUSIONS

It is observed that tropical subjects can accept a relatively high RH level and low supply air temperature with the DV system. When the room temperature is maintained at about 23°C, the supply air temperature for the DV system can be as low as 16.2°C without sacrificing their thermal sensations for the tropical subjects. Tropical subjects are thermally acceptable with air temperature of 23.2°C and RH of 77%. This RH level exceeded the recommended thresholds stipulated by the International and Singapore Standards. Tropical subjects may be accustomed to the hot and humid climate. Hence, the range of acceptable RH level may be wider than subjects in the temperate climate. Air velocity in the space plays a very important role to promote thermal comfort in a hot and humid environment. Higher air velocity leads to higher heat transfer coefficients. This will be helpful for the occupants in hot and humid environment to promote thermal comfort against the background of skin wettedness ratio. However, higher air velocity may increase draft risk in the space with the DV system. Therefore, further research work is needed to determine the comfort zone for tropical subjects in air-conditioned space. This study found that the room neutral temperatures for DV and MV systems are 23.8 and 23°C, respectively. Hence, the DV system can produce a cooler sensation than the MV system. All these findings show evidence of the energy-saving potential for the DV system in the tropics.

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REFERENCES

ASHRAE (1992). *Standard 55—Thermal Environmental Conditions for Human Occupancy*. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

ASHRAE (1995). Standard 55a—Addendum to Thermal Environmental Conditions for Human Occupancy. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

ISO (1994). *Standard 7730—Moderate Thermal Environments—Determination of PMV and PPD Indices*. Geneva: International Organization for Standardization.

Jackman, P. (1990). *Displacement Ventilation*. Bracknell, Berks.: Building Services Research and Information Association.

SISIR (1999). Singapore Standard CP13—Code of Practice for Mechanical Ventilation and Air-Conditioning in Building. Singapore: Singapore Institute of Standards and Industrial Research.

Yuan, X., Chen, Q. and Glicksman, L. (1999). Performance evaluation and design guidelines for displacement ventilation. *ASHRAE Transactions* **104** (2), 298–309.