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Local thermal sensation and comfort study in a field environment chamber served by displacement ventilation system in the tropics

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Received 25 July 2005; received in revised form 28 August 2005; accepted 7 September 2005

Abstract

This paper presents a study of local thermal sensation (LTS) and comfort in a field environmental chamber (FEC) served by displacement ventilation (DV) system. The FEC, 11.12 m (*L*) × 7.53 m (*W*) × 2.60 m (*H*), simulates a typical office layout. A total of 60 tropically acclimatized subjects, 30 male and 30 female, were engaged in sedentary office work for 3 h. Subjects were exposed to three vertical air temperature gradients, nominally 1, 3 and 5 K/m, between 0.1 and 1.1 m heights and three room air temperatures of 20, 23 and 26 °C at 0.6 m height. The objective of this study is to investigate the mutual effect of local and overall thermal sensation (OTS) and comfort in DV environment. The results show that in a space served by DV system, at OTS close to neutral, local thermal discomfort decreased with the increase of room air temperature. The OTS of occupants was mainly affected by LTS at the arm, calf, foot, back and hand. Local thermal discomfort was affected by both LTS and OTS. At overall cold thermal sensation, all body segments prefer slightly warm sensation. At overall slightly warm thermal sensation, all body segments prefer slightly cool sensation.

Keywords: Local thermal sensation; Local thermal comfort; Thermal gradient; Displacement ventilation; Tropics

1. Introduction

In a space served by displacement ventilation (DV) system, supply air at a temperature several degrees below room air temperature is introduced to room space along the floor. The air rises as it is warmed up by heat sources within the occupied zone and exhausted at ceiling level. It is inevitable to create a vertical air temperature difference in the space [1–4]. The Predictive Mean Vote (PMV) model in current standards [5,6] is normally used to predict human thermal sensation based on the ambient environment such as air temperature, air velocity, etc. However, in a thermally non-uniform environment, air temperature, air velocity, humidity and turbulence, etc. are always different at different heights. So PMV will be different by using the parameters at different levels. ASHRAE Standard [5] recommends that operative temperature or PMV shall be measured or calculated at the 0.6 m level for seated occupants. Nielsen et al. [7] used the physical parameters close to the location of the manikin at the height of 1.1 m to calculate the global comfort.

In a thermally non-uniform environment, different body segments are exposed to different ambient environments. This will lead to different thermal sensations and comfort at different body segments. Local thermal sensation (LTS) and local thermal comfort (LTC) of one body segment have impact on the rest of the segments. However, the extent of the impact on different body segments is not always the same. Cooling the lower part of the body caused a decrease in the skin temperature of the finger, forearm, and nose with no significant changes observed at the forehead, cheek, chest and ear [8,9]. Active vasoconstriction was considered to be present in the former but not the latter regions. Olesen et al. [10] showed that the greatest non-uniformity of the skin temperature distribution over the body was partially due to lower temperature at the person's feet, who was clothed in standard clothing

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doi:10.1016/j.buildenv.2005.09.008

(0.6 clo.) and cotton sweat socks (no shoes). When subjects felt optimally comfortable, the trunk was the warmest part of the body and extremities the coolest. Tanaka et al. [11] studied physiological reactions to different vertical (head–foot) air temperature differences in Japan. Six male subjects were exposed to different vertical air temperature differences between the upper and lower parts of the body for 90 min, wearing light clothing (0.69 clo.) at constant air velocity of 0.45 m/s. The lower part of the body was exposed to an air temperature of 25 °C and the upper part of the body to air temperatures of 15, 20, 25, 30 or 35 °C. It was found that the thermal sensations on the upper part of the body and the whole body were similar, and those on the lower part of the body were almost constant under each condition. The lower part of body was exposed to thermally neutral condition and the skin temperatures of the lower extremities were then affected by the upper-body air temperatures. The skin temperatures on the toe and instep increased with increasing upper air temperature. Kawahara et al. [12] investigated thermal comfort in non-uniform thermal environment using an air-conditioning chamber with under-floor air supply and radiator panels in Japan. Sixteen subjects took part in the experiments. The mean equivalent temperature (T_{eq}) around seated subjects was intentionally varied. It was found that the overall thermal sensation (OTS) was generally affected by T_{eq} around upper body.

Some thermal sensation models under thermally non-uniform environment have been developed. Tanabe et al. [13] proposed a method for applying PMV to the passenger compartment, which employs the concept of an average equivalent temperature (AET) as the basis for determining PMV. They found an equivalent temperature (T_{eq}) for three regions of the human body and then calculated a weighted average according to the relative surface area of each as follows: $\mathrm{AET} = 0.1T_{eq}$ (head) $+ 0.7T_{eq}$ (abdomen) $+ 0.2T_{eq}$ (feet). Hagino and Hara [14] investigated the thermal sensation of vehicle occupants. The subjects were six males with normal summer clothing. It was found that whole body thermal sensation vote (TSV) was sensitive to the partial TSV of the forehead and upper arm, which were directly exposed to airflow and solar radiation. A multiple regression equation was obtained for predicting the whole body TSV from partial TSV data as follows: TSV (whole body) = 0.42TSV (forehead) + 0.38TSV (upper arm on window side) + 0.20TSV (tight on window side) + 0.28TSV (instep on window side) + 0.42. Conceição [15] developed a model by dividing the human body into 35 cylindrical and spherical elements with each element made up by 12 layers (one layer for the core, two layers for the muscle, two layers for the fat, seven layers for the skin with the possibility of clothing protection for each element). It can be used to evaluate the global thermal comfort, in steady state and transient conditions, and the local discomfort sensations. Tanabe et al. [16] developed a 65-node thermoregulation model to evaluate thermal comfort under non-uniform conditions. The model has 16 body segments corresponding to the thermal manikin, each consisting of four layers for core, muscle, fat and skin. The 65th node in the model is the central compartment, which exchanges convective heat with all other nodes via the blood flow. Convective and radiant heat transfer coefficients and clothing insulation were derived from the thermal manikin experiments. Zhang [17] developed predictive models of local and OTS and comfort under non-uniform and transient conditions. In the study, local body surfaces of the subjects were independently heated or cooled while the rest of the body was exposed to a warm, neutral or cool environment.

Much information on the relation between thermal comfort and thermal environment has been published, dealing with both human physiological and psychological reactions to a uniform thermal environment. However, thermal sensation and comfort study under non-uniform thermal environment is still limited. Moreover, all the above-mentioned studies were not conducted in a space served by DV system. In an environment with DV system, relatively high velocity and low temperature near the floor may cause local thermal discomfort [18–20]. The local discomfort at body segments will affect OTS and comfort of the occupants. So extensive research is needed to study the mutual effect of local and OTSs and comfort in a space with DV system. The aims of this study are as follows:

(1) To investigate the LTS and comfort of body segments under different room air temperatures (at 0.6 m height) and temperature gradients (between 0.1 and 1.1 m heights) in a space served by DV system.
(2) To study the impact of LTS on OTS.
(3) To study the impact of local and OTSs on LTC.

2. Experimental method

2.1. Experimental procedure

In this study, subjects were exposed to three room air temperatures, nominally 20, 23 and 26 °C, at 0.6 m height and three vertical air temperature gradients, nominally 1, 3 and 5 K/m, between 0.1 and 1.1 m heights. During the experiment, air velocity in the space near the subjects was kept at below 0.2 m/s. Relative humidity (RH) at 0.6 m height and outdoor air provision were maintained at 50% and 10 l/s/p, respectively. The experiment was divided into two stages. In Stage 1, 30 subjects were allowed to adjust their clothing to achieve overall thermal neutrality during the first 2 h. Jackets were available for subjects who wanted to put on more clothing. In Stage 2, other 30 subjects were exposed to room air temperatures of 20 °C with cold sensation and room air temperature of 26 °C with slightly warm sensation. Subjects in this group were not allowed to adjust their clothing during the experiment. For both stages, test conditions were blind to all subjects. Skirts and trousers were compulsory for females and males, respectively, and all subjects were required to wear opened-toe shoes with socks. Subjects were performing sedentary normal office work during the experiment. The duration of each session of the experiment is 3 h. Subjects were requested to complete one set of questionnaire at every 30-min interval during each session.

2.2. Field environment chamber

Fig. 1 shows the field environment chamber (FEC) at the National University of Singapore. The chamber, 11.12 m $(L)\times 7.53$ m $(W)\times 2.60$ m (H), is equipped with an air-conditioning and mechanical ventilation (ACMV) system that is capable of switching between DV and MV modes. An east-facing wall of this chamber comprising of large glass panels which are insulated with aluminium foil externally and furnished with blinds internally to reduce heat conduction and solar radiation.

2.3. Objective measurements

Measurement of room air temperature was carried out using type T thermocouple wire with accuracy of $\pm 0.2\,^{\circ}$C at 0.1, 0.6, 0.8, 1.1, 1.7 and 2.5 m heights. RH was measured using portable sensor with accuracy of $\pm 5\%$ at 0.1, 0.6, 0.8, 1.1, 1.7 and 2.5 m heights. Air velocity was measured at 0.1, 0.6, 0.8 and 1.1 m heights near the subjects using omni-directional hot wire type of anemometer probes with accuracy of 0.01 m/s. Global temperature was recorded at 0.6 m height in the middle of the chamber using black global thermometer. All measurements were recorded continuously throughout each session of the experiment.

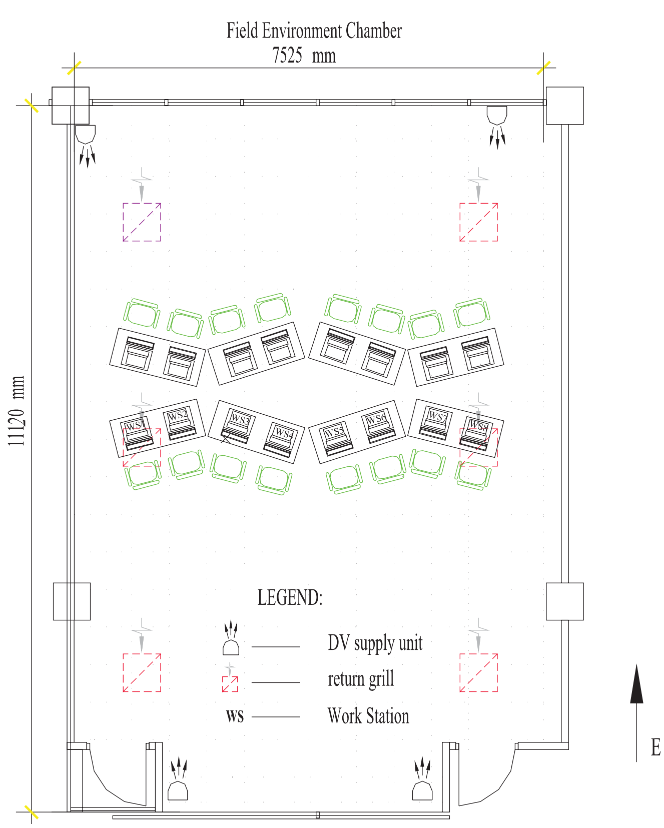

Fig. 1. Layout of the FEC.

2.4. Subjective assessment

The ASHRAE scale, (−3) cold, (−2) cool, (−1) slightly cool, (0) neutral, (+1) slightly warm, (+2) warm and (+3) hot, was used to assess subjects' thermal sensation for overall body and body segments. The ASHRAE scale is based on a measure of how warm or cool occupants feel, which only measures the temperature that occupants perceive. Thermal comfort is that the condition of mind which expresses satisfaction with the thermal environment [5,6]. It is not necessarily dependent only on thermal sensations. Perceptions of thermal comfort may also have to do with expectation, adaptation to conditions and other factors [17]. Although the ASHRAE scale has no direct reference to thermal comfort, it is usually assumed that the three central categories indicate the zone of thermal comfort. However, researchers [21–23] have found that many occupants voting the three central categories on the ASHRAE scale reported that they were not comfortable. Conversely, thermal sensations outside of the three central categories of the ASHRAE scale do not necessarily reflect thermal discomfort. Overall, these findings suggest that thermal sensation cannot be assumed to be equivalent to thermal comfort. Information about thermal sensation alone is not sufficient to evaluate occupants' thermal comfort. It is worth directly asking occupants to evaluate the thermal satisfaction of the temperature. The Bedford scale, (−3) much too cold, (−2) too cold, (−1) comfortable cool, (0) neither warm nor cool, (+1) slightly warm, (+2) too hot and (+3) much too hot, is often used in thermal comfort study. It arose from Bedford's magisterial field study of the winter warmth of workers in light industry [24]. The characteristic of this scale is its combination of warmth and comfort by asking occupants to decide whether they are comfortable at a particular thermal sensation. In this study, the Bedford scale was adopted to assess thermal comfort level.

2.5. Subjects

Sixty subjects, 30 for Stage 1 and 30 for Stage 2, were selected for the experiment. Only college-age students who are acclimatized to the tropical climate were chosen. The anthropometric data of subjects for this study is shown in Table 1.

Table 1
Anthropometric data of subjects

Stage	1			2		
Gender	Females	Males	Total	Females	Males	Total
Numbers	15	15	30	15	15	30
Age (years)	21.7±1.0	23.2±2.8	22.5±2.2	21.8±0.9	24±2.3	22.9±2.1
Height (cm)	160.9±5.6	169.1±7.0	165±7.5	161.9±5.4	172.1±5.0	167±7.3
Weight (kg)	50.6±6.9	63.9±10.8	57.3±11.2	52.1±7.4	66.7±10.4	59.4±11.6

Table 2
Experimental conditions

Stage	Case	Nominal value			Actual value									
		Tr (°C) (0.6 m height)	Δt (K/m)	RH (%)	T_r (°C) (0.6 m height)		Δt (K/m)		RH (%)		V (m/s) (0.1 m height)		Clo. value (clo.)	
					Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
1	1	20	1	50	20.3	0.3	1.4	0.3	52	1.4	0.10	0.03	1.15	0.05
	2	20	3	50	20.0	0.2	3.0	0.3	50	0.7	0.07	0.01	1.13	0.09
	3	20	5	50	19.9	0.2	4.9	0.4	50	1.3	0.09	0.02	1.12	0.1
	4	23	1	50	22.9	0.1	1.3	0.1	54	1.2	0.10	0.04	0.91	0.08
	5	23	3	50	23.0	0.3	3.1	0.2	51	1.0	0.07	0.01	0.89	0.09
	6	23	5	50	23.0	0.3	4.9	0.3	51	0.6	0.08	0.01	0.89	0.07
	7	26	1	50	26.1	0.2	1.0	0.3	53	1.4	0.08	0.02	0.64	0.06
	8	26	3	50	26.2	0.2	3.1	0.2	51	1.2	0.07	0.01	0.64	0.06
	9	26	5	50	25.9	0.2	4.8	0.3	53	1.4	0.08	0.02	0.63	0.06
2	10	20	1	50	20.1	0.2	1.3	0.2	51	1.3	0.12	0.05	0.73	0.1
	11	20	3	50	20.2	0.2	3.3	0.2	51	0.6	0.09	0.01	0.73	0.09
	12	20	5	50	20.0	0.3	4.9	0.2	52	0.6	0.08	0.01	0.77	0.09
	13	26	1	50	26.1	0.2	1.3	0.3	52	1.5	0.08	0.03	0.82	0.13
	14	26	3	50	26.2	0.1	3.1	0.1	53	1.1	0.07	0.02	0.85	0.13
	15	26	5	50	25.9	0.2	4.6	0.2	52	1.1	0.07	0.01	0.8	0.11

3. Results and discussion

3.1. Experimental conditions

Table 2 shows the summary of the nominal and actual experimental conditions. For nominal room air temperatures (T_r) of 20, 23 and 26 °C at 0.6 m height, respective actual values were in the ranges of 19.9–20.3, 22.9–23 and 25.9–26.2 °C. For nominal temperature gradients (Δt) of 1, 3 and 5 K/m between 0.1 and 1.1 m heights, respective actual values were in the ranges of 1–1.4, 3–3.3 and 4.6–4.9 K/m. For nominal RH of 50% at 0.6 m height, actual value was in the range of 50–54%. The results showed that actual experimental conditions were very close to nominal conditions. It appears that the experimental conditions were well monitored during the period of the experiment. Air velocity (V) at 0.1 m height near the subjects was less than 0.2 m/s. For Cases 1–9 in Stage 1, subjects were allowed to adjust their clothing to achieve thermal neutral sensation. For Cases 10–15 in Stage 2, the subjects were not allowed to adjust their clothing. Clothing value for all the cases was in the range of 0.63–1.15 clo. A series of trial tests were conducted before the experiment. The set points of room air temperature (at 0.6 m height), temperature gradient (between 0.1 and 1.1 m heights) and RH (at 0.6 m height) were achieved by adjusting supply airflow rate and temperature with constant heat load for all the cases. The recorded data of trial tests were used as reference for the experiment.

3.2. Profiles of room air temperature and RH

Typical profiles of spatial temperature and RH for Cases 1, 2 and 3 are shown in Figs. 2 and 3, respectively. Results showed that temperature gradients were steeper below 1.1 m height than beyond 1.1 m height. RH at 0.1 m height was the highest and decreased with increase in height. At 0.6 m height, RH was around 50%.

3.3. Local thermal sensation of body segments and overall thermal sensation

3.3.1. Thermal sensation votes at room air temperature of 20 °C

Fig. 4 shows overall and body segments' TSVs for Cases 1–3 and 10–12 at room air temperature of 20 °C. Clothing

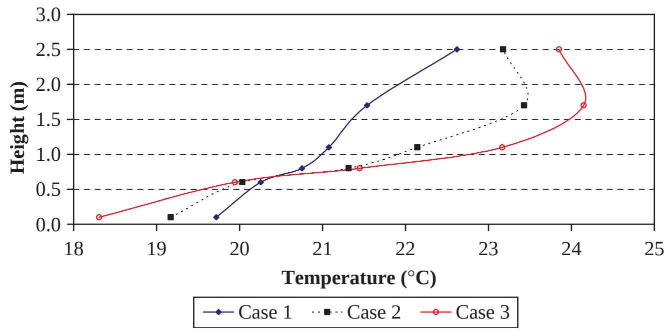

Fig. 2. Temperature profiles for Cases 1–3.

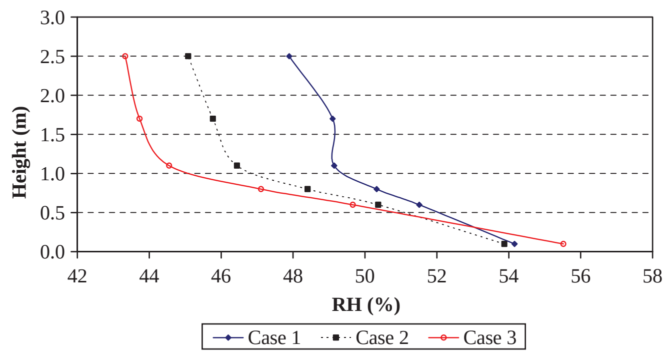

Fig. 3. RH profiles for Cases 1–3.

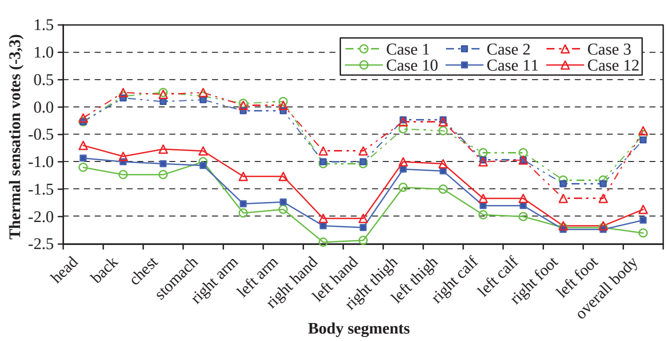

Fig. 4. Thermal sensation votes at room air temperature of 20 °C.

values for Cases 1–3 were in the range of 1.12–1.15 clo. Values of OTS for Cases 1–3 were within the range of −0.6 to −0.43, which is close to neutral. Values of LTS of body segments were in the following ranges of −1.33 to 0.27, −1.4 to 0.17 and −1.67 to 0.27 for Cases 1, 2 and 3, respectively. Among different body segments, the lowest values of LTS were at the feet while the highest at the back or chest for Cases 1–3. The fluctuations of LTS among body segments were in the range of 1.57–1.93.

Clothing values for Cases 10–12 were in the range of 0.73–0.77 clo. For Cases 10–12, values of OTS were within the range of −2.30 to −1.87, which is close to cold sensation. Values of LTS of body segments were in the ranges of −2.47 to −1.0, −2.23 to −0.93 and −2.17 to −0.70 for Cases 10, 11 and 12, respectively. Among different body segments, the lowest values of LTS were at the feet or right hand while the highest at the head or stomach for Cases 10–12. The fluctuations of LTS among body segments were in the range of 1.30–1.47.

3.3.2. Thermal sensation votes at room air temperature of 23 °C

Overall and body segments' TSVs for Cases 4–6 at room air temperature of 23 °C are shown in Fig. 5. Clothing values for Cases 4–6 were in the range of 0.89–0.91 clo. Values of OTS for Cases 4–6 were within the range of between −0.47 and −0.27, which is close to neutral. Values of LTS of body segments were in the ranges of −0.94 to 0.06, −1.0 to 0.07 and −0.97 to 0.13 for Cases 4, 5 and 6, respectively. Among different body segments, the lowest values of LTS were at the feet while the highest at the back or stomach for Cases 4–6. The fluctuations of LTS among body segments were in the range of 1.0–1.1.

3.3.3. Thermal sensation votes at room air temperature of 26 °C

Fig. 6 shows overall and body segments' TSVs for Cases 7–9 and 13–15 at room air temperature of 26 °C. Clothing values for Cases 7–9 were in the range of 0.63–0.64 clo. Values of OTS for Cases 7–9 were within the range of between 0.03 and 0.10, which is close to neutral. Values of LTS of body segments were in the ranges of −0.13 to 0.03, 0.03 to 0.30 and −0.03 to 0.27, respectively. Among different body segments, the lowest values of LTS were at

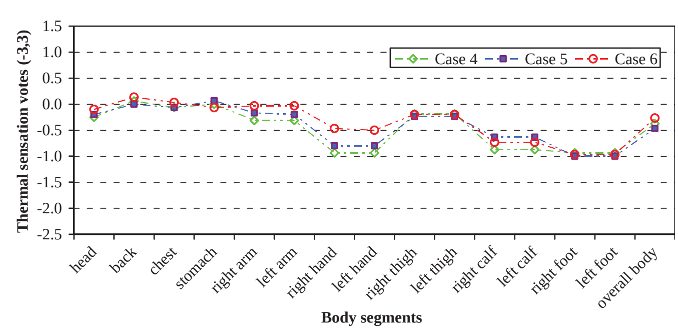

Fig. 5. Thermal sensation votes at room air temperature of 23 °C.

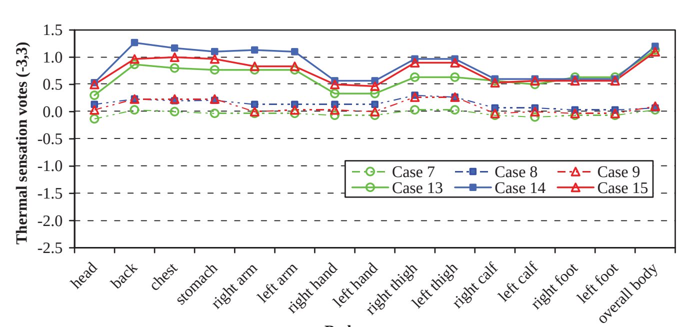

Fig. 6. Thermal sensation votes at room air temperature of 26 °C.

the head, feet or calves while the highest at the back or thighs for Cases 7–9. The fluctuations of LTS among body segments were in the range of 0.16–0.30.

Clothing values for Cases 13–15 were in the range of 0.8–0.85 clo. For Cases 13–15, values of OTS were within the range of 1.1–1.2, which is close to slightly warm sensation. Values of LTS of body segments were in the ranges of 0.30–0.87, 0.53–1.27 and 0.47–1.0 for Cases 13, 14 and 15, respectively. Among different body segments, the lowest values of LTS were at the head or hands while the highest at the back or chest for Cases 13–15. The fluctuations of LTS among body segments were in the range of 0.53–0.73.

3.3.4. Fluctuation of LTS among body segments

For Cases 1–9, values of OTS were close to neutral. However, values of LTS of body segments fluctuated. In addition, the extent of fluctuation was different at different room air temperatures. The fluctuations of LTS among body segments for Cases 7–9 at room air temperature 26 °C were the least in the range of 0.16–0.30. The fluctuations of LTS among body segments for Cases 1–3 at room air temperature 20 °C were the greatest in the range of 1.57–1.9. The results show that even at OTS close to neutral, local thermal discomfort of body segments still may occur. This is consistent with what Fanger (1977) [25] concluded that overall thermal comfort (OTC) was easier to achieve than LTC. At OTS close to neutral, fluctuation of LTS decreased with the increase of room air temperature. Higher fluctuation of LTS leads to higher risk of local thermal discomfort. Therefore, at OTS close to neutral, local thermal discomfort decreased with the increase of room air temperature.

For all the cases under different room air temperatures and temperature gradients, it was observed that values of LTS of upper body segments such as the back, chest and stomach did not fluctuate much in comparison with the values of LTS of lower body segments such as the feet and calves. This demonstrates that in a space served by DV system, it was more difficult to achieve thermal comfort at lower body segments than at upper body segments. This could be attributed to the relatively low air temperature at low level and uneven clothing distribution. The results also show that for Cases 1–9 with OTS close to neutral, values of OTS were in the middle of values of LTS. For Cases 10–12 with cold OTS, values of OTS were close to the lowest values of LTS. For Cases 13–15 with slightly warm OTS, values of OTS were close to the highest values of LTS.

3.4. Applicability of PMV model

The PMV model was developed in uniform thermal environment. The use of DV system leads to the creation of thermally non-uniform environment. Air temperature, velocity, humidity and turbulence are different at different levels in the space served by DV system. So values of PMV at different levels are different. Fig. 7 shows values of PMV at 0.1, 0.6, 0.8 and 1.1 m heights and average actual mean vote (AMV) of thermal sensation for all the cases. The results show that for Cases 1–9 with OTS close to neutral, values of AMV were close to values of PMV at 0.1 or 0.6 m heights. For Cases 10–12 with cold OTS, values of AMV were close to values of PMV at 0.1 m height. For Cases 13–15 with slightly warm OTS, values of AMV were close to values of PMV at 1.1 m height.

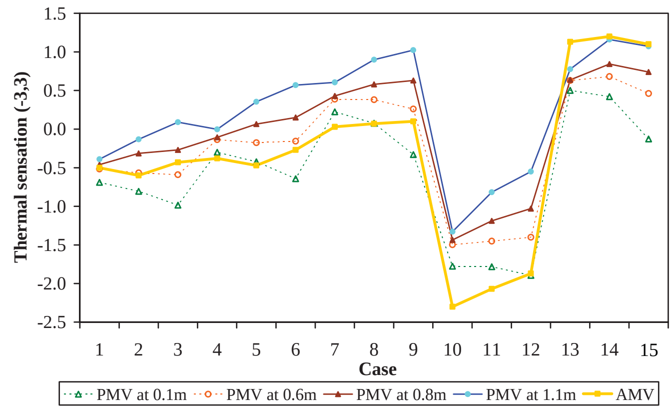

Fig. 7. PMV at specific heights versus AMV.

Table 3 shows the p-values for AMV and PMV at different heights. The results show that only for Case 1 at room air temperature with gradient of 1 K/m, PMV model's prediction was generally accurate as there was non-significant difference between the values of PMV and AMV for each specific height. For the other cases, there was significant difference between values of AMV and PMV at either one level or more than one level. So values of PMV at specific level were not always consistent with the values of AMV. Further research is needed to investigate the applicability of PMV model in the space served by DV system.

3.5. Overall thermal sensation versus local thermal sensation

A stepwise linear regression was employed to investigate the correlation of OTS with LTS. The equation is as follows:

$$\begin{aligned} OTS = {} & 0.324 \times LTS_{arm} + 0.264 \times LTS_{calf} + 0.203 \\ & \times LTS_{foot} + 0.173 \times LTS_{back} + 0.168 \\ & \times LTS_{hand} + 0.118, \text{ adjusted } R^2 = 0.857. \end{aligned}$$

The equation demonstrates that in a space served by DV system, value of subjects' OTS was mainly affected by the values of LTS at the arm, calf, foot, back and hand. Values of LTS of these body segments could be used to predict the OTS. The value of OTS was most sensitive to the values of LTS at the arm and calf.

3.6. Local thermal comfort and overall thermal comfort

Table 4 shows values of LTC of body segments and OTC for all the cases. For Cases 1–9 in Stage 1, subjects were allowed to adjust their clothing to achieve thermal neutrality. Average votes of OTC were within the range of −0.6 to 0.13. For Cases 10–12 in which cold sensation was expected, average votes of OTC were within the range of −2.1 to −1.73. For Cases 13–15 in which hot sensation was expected, average votes of OTC were within the range of 0.8–1.0.

Values of LTC of body segments were in the ranges of −1.2 to 0.3, −1.13 to 0.2 and −1.57 to 0.4 for Cases 1, 2 and 3, respectively. Among different body segments, the lowest values of LTC were at feet while the highest at back or chest for Cases 1–3. The fluctuations of LTC among body segments were in the range of 1.33–1.97. Values of LTC of body segments were in the ranges of −0.88 to 0.06, −0.93 to 0.03 and −1.07 to 0.13 for Cases 4, 5 and 6, respectively. Among different body segments, the lowest values of LTC were at feet or calves while the highest at back, chest or stomach for Cases 4–6. The fluctuations of LTC among body segments were in the range of 0.94–1.2. Values of LTC of body segments were in the ranges of −0.13 to 0.1, 0.03 to 0.3 and 0 to 0.23 for Cases 7, 8 and 9, respectively. Among different body segments, the lowest values of LTC were at feet, calves, hands or arms while the highest at back, chest or stomach for Cases 7–9. The fluctuations of LTC among body segments were in the range of 0.23–0.27. The results show that the profiles of LTC were similar with those of LTS. For Cases 1–9 with OTS close to neutral, values of LTC of body segments fluctuated. The extent of fluctuation was different at different room air temperatures. The results show that fluctuation of LTC decreased with the increase of room air temperature. This is consistent with the previous finding for the LTS of body segments.

Values of LTC of body segments were in the ranges of −2.37 to −1.03, −2.17 to −0.83 and −2.13 to −0.67 for Cases 10, 11 and 12, respectively. Among different body segments, the lowest values of LTC were at the feet or hands while the highest at head, chest or stomach for Cases 10–12. The fluctuations of LTC among body segments were in the range of 1.33–1.47. Values of LTC of body segments were in the ranges of 0.33–0.8, 0.53–1.2 and 0.53–0.97 for Cases 13, 14 and 15, respectively. Among different body segments, the lowest values of LTC were at

Table 3
P-value for actual mean vote and predicted mean value of thermal sensation

Case	Height			
	0.1 m	0.6 m	0.8 m	1.1 m
1	0.111	0.758	0.323	0.058
2	0.344	0.688	0.028	0.001
3	<0.001	0.153	0.175	<0.001
4	0.082	0.047	0.013	0.003
5	0.254	0.039	<0.001	<0.001
6	0.014	0.453	0.007	<0.001
7	0.136	0.007	0.003	0.001
8	0.927	0.002	<0.001	<0.001
9	<0.001	0.140	<0.001	<0.001
10	0.002	<0.001	<0.001	<0.001
11	0.104	0.003	<0.001	<0.001
12	0.873	0.012	<0.001	<0.001
13	<0.001	<0.001	<0.001	<0.001
14	<0.001	<0.001	<0.001	0.669
15	<0.001	<0.001	<0.001	0.341

Table 4
Thermal comfort votes for all the cases

Body segment	Stage														
	1									2					
	Case														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Head	−0.33	−0.17	−0.23	−0.31	−0.17	−0.17	−0.13	0.13	0.17	−1.07	−0.83	−0.67	0.33	0.63	0.63
Back	0.30	0.20	0.27	0.06	0.03	0.13	0.03	0.30	0.23	−1.10	−0.97	−0.80	0.80	1.20	0.97
Chest	0.23	0.10	0.40	0.00	0.03	0.07	0.10	0.23	0.23	−1.10	−0.93	−0.67	0.73	1.13	0.97
Stomach	0.23	0.10	0.40	0.06	0.03	0.07	0.07	0.27	0.23	−1.03	−0.90	−0.70	0.70	1.10	0.90
Right arm	0.03	0.00	0.07	−0.44	−0.23	−0.07	0.00	0.20	0.00	−1.70	−1.60	−1.27	0.70	0.93	0.80
Left arm	0.03	0.00	0.07	−0.44	−0.23	−0.07	0.00	0.20	0.00	−1.70	−1.57	−1.17	0.70	1.03	0.80
Right hand	−0.93	−1.00	−0.70	−0.69	−0.73	−0.47	−0.07	0.17	0.00	−2.37	−2.17	−2.00	0.40	0.63	0.53
Left hand	−0.93	−1.03	−0.70	−0.69	−0.73	−0.47	−0.07	0.17	0.00	−2.27	−2.17	−2.00	0.43	0.63	0.53
Right thigh	−0.30	−0.17	−0.23	−0.31	−0.23	−0.20	0.10	0.23	0.23	−1.33	−1.10	−0.97	0.57	0.87	0.83
Left thigh	−0.37	−0.13	−0.23	−0.31	−0.23	−0.20	0.07	0.20	0.20	−1.33	−1.13	−1.00	0.57	0.87	0.80
Right calf	−0.73	−0.80	−1.03	−0.88	−0.63	−0.70	−0.13	0.03	0.03	−1.80	−1.80	−1.67	0.77	0.57	0.53
Left calf	−0.77	−0.80	−1.00	−0.88	−0.63	−0.70	−0.13	0.03	0.07	−1.80	−1.80	−1.67	0.43	0.57	0.53
Right foot	−1.20	−1.13	−1.57	−0.88	−0.93	−1.07	−0.07	0.10	0.00	−2.20	−2.10	−2.13	0.53	0.53	0.60
Left foot	−1.20	−1.13	−1.57	−0.88	−0.93	−1.07	−0.07	0.07	0.00	−2.20	−2.10	−2.13	0.50	0.53	0.60
Whole body	−0.47	−0.60	−0.50	−0.50	−0.53	−0.37	−0.10	0.13	0.07	−2.10	−1.97	−1.73	0.80	1.00	0.97

Table 5
Correlation of LTC with LTS at different overall thermal sensations

OTS	Close to neutral		Cold		Slightly warm	
Body segment	LTC	R^2	LTC	R^2	LTC	R^2
Head	0.802LTS−0.021	0.604	0.808LTS−0.119	0.805	0.874LTS+0.145	0.592
Back	0.812LTS+0.044	0.662	0.805LTS−0.114	0.742	0.548LTS+0.423	0.319
Chest	0.850LTS+0.059	0.691	0.813LTS−0.078	0.779	0.599LTS+0.353	0.408
Stomach	0.845LTS+0.060	0.677	0.690LTS−0.218	0.669	0.607LTS+0.326	0.418
Arm	0.908LTS−0.013	0.699	0.806LTS−0.179	0.701	0.582LTS+0.301	0.415
Hand	0.904LTS−0.009	0.776	0.823LTS−0.332	0.697	0.809LTS+0.155	0.653
Thigh	0.832LTS−0.010	0.751	0.672LTS−0.326	0.587	0.737LTS+0.136	0.596
Calf	0.853LTS−0.048	0.779	0.634LTS−0.604	0.525	0.673LTS+0.139	0.509
Foot	0.836LTS−0.065	0.740	0.772LTS−0.447	0.702	0.632LTS+0.171	0.504

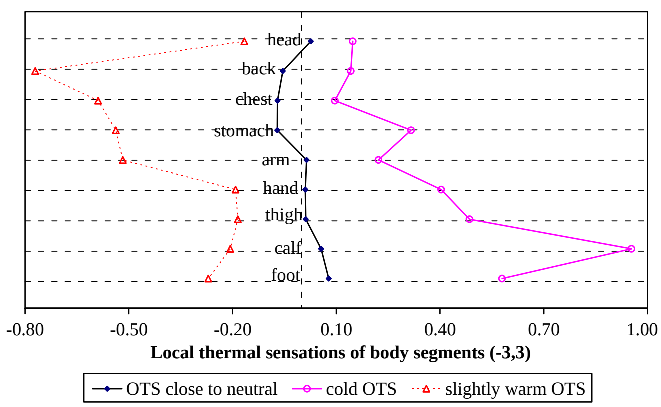

Fig. 8. Values of LTS of body segments at thermal comfort.

feet, calves, hands or head while the highest at back or chest for Cases 13–15. The fluctuations of LTC among body segments were in the range of 0.43–0.67. The results show that the profiles of LTC were similar with those of LTS.

3.7. Local thermal comfort versus local and overall thermal sensations

Table 5 shows the regressions of LTC and LTS of body segments at overall cold, close to neutral and slightly warm sensations. The regressions of the same body segments at different OTS were different. Adjusted R^2 at different OTSs of close to neutral, cold and slightly warm were in the range of 0.604–0.779, 0.525–0.805 and 0.319–0.653, respectively.

When subjects felt neither warm nor cool, value of their thermal comfort level was 0. Values of LTS of body segments at neither warm nor cold are shown in Fig. 8. The values were obtained by setting LTC to 0 in the regression equations of LTC with LTS in Table 5. At cold OTS, values of LTS of body segments at thermal comfort were all positive. The highest was 0.95 at the calf. The lowest was 0.1 at chest. This means all body segments preferred slightly warm sensation. At OTS close to neutral, values of LTS of body segments at thermal comfort were close to 0. The highest was 0.08 at the chest and stomach. The lowest was −0.07 at the foot. The results show that at OTS close to neutral, lower body segments of calf and foot and head preferred slightly warm sensation while upper body parts of stomach, chest and back preferred slightly cool sensation. At slightly warm OTS, values of LTS of body segments at thermal comfort were all negative. The highest was −0.17 at the head. The lowest was −0.77 at the back. This demonstrates body segments preferred slightly cool sensation at slightly warm OTS. In general, the hand and lower body segments of the thigh, calf and foot preferred warmer sensation in comparison with that of upper body parts of stomach, chest and back. One reason is uneven clothing distribution. Another reason is that in non-uniform environment served by DV system, air temperature is lower and velocity is higher at lower level than at higher level.

4. Conclusion

LTS and comfort of body segments were extensively investigated in the FEC served by DV system. Results demonstrate that even at OTS close to neutral, local thermal discomfort of body segments still exists. Local thermal discomfort decreased with the increase of room air temperature. For all the cases under different room air temperatures and temperature gradients, it was observed that values of LTS of upper body segments such as the back, chest and stomach did not fluctuate much in comparison with the values of LTS of lower body segments such as the feet and calves. This shows that in a space served by DV system, it was more difficult to achieve thermal comfort at lower body segments than at upper body segments. The applicability of the PMV model was investigated in the space served by DV system in this study. The results show that values of PMV at specific level were not always consistent with the values of AMV except at room air temperature of 20 °C with temperature gradient of 1 K/m. A regression equation of OTS against LTS of body segments was obtained using stepwise linear regression.

The equation demonstrates that the value of OTS was mainly affected by the values of LTS at the arm, calf, foot, back and hand. The value of OTS was most sensitive to the values of LTS at the arm and calf. The results also indicate that both LTS and OTS had impact on LTC. At cold OTS, all body segments preferred slightly warm sensation. At OTS close to neutral, lower body segments of calf, foot and head preferred slightly warm sensation while upper body parts of stomach, chest and back preferred slightly cool sensation. At slightly warm OTS, body segments preferred slightly cool sensation. In addition, the hand and lower body segments of the thigh, calf and foot preferred warmer sensation in comparison with that of upper body parts of stomach, chest and back.

Acknowledgements

This research is funded by the National University of Singapore, Building and Construction Authority (Singapore) and the Oy Halton Group Ltd. (Finland).

References

[1] Skistad H, Mundt E, Nielsen PV, Hagström K, Railio J. Displacement ventilation in non-industrial premises. Guidebook no. 1: REHVA, 2002.
[2] Xu M, Yamanaka T, Kotani H. Vertical profiles of temperature and contaminant concentration in rooms ventilated by displacement with heat loss through room envelopes. Indoor Air 2001;11(2):111–9.
[3] Yuan X, Chen Q, Glicksman LR. Performance evaluation and design guidelines for displacement ventilation. ASHRAE Transactions 1999;105(1):298–309.
[4] Yuan X, Chen Q, Glicksman LR, Hu Y, Yang X. Measurements and computations of room airflow with displacement ventilation. ASHRAE Transactions 1999;105(1):340–52.
[5] ASHRAE Standard 55. Thermal environmental conditions for human occupancy. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers; 2004.
[6] ISO Standard 7730. Moderate thermal environments—determination of PMV and PPD indices. Geneva: International Organization for Standardization; 1994.
[7] Nielsen PV, Jacobsen TS, Hansen R. Measurement of thermal comfort and local discomfort by a thermal manikin. ASHRAE Transactions 2002;108(2):1097–103.
[8] Bader ME, Mead J. Individual differences in vascular responses and their relationship to cold tolerance. Journal of Applied Physiology 1950;2(11):608–18.
[9] Page J, Brown GM. Effects of heating and cooling the legs on hand and forearm blood flow in the Eskimo. Journal of Applied Physiology 1953:753–8.
[10] Olesen BW, Fanger PO. The skin temperature distribution for resting man in comfort. Archives of Scientific Physiology 1973;27:385–93.
[11] Tanaka M, Yamazaki S, Ohnaka T, Tochihara Y, Yoshida K. Physiological reactions to different vertical (head–foot) air temperature differences. Ergonomics 1986;29(1):131–43.
[12] Kawahara Y, Emura K, Nabeshima M, Bougaki K, Kadoya M. Air-conditioning with underfloor air supply: comfort in non-uniform thermal environment. Building Services Engineering Research and Technology 1999;20(1):1–7.
[13] Tanabe S, Matsunaga K, Sudo F. Evaluation method of thermal comfort in vehicles. Proceedings of 1990 JSAE Autumn Convention 1990;2.
[14] Hagino M, Hara J. Development of a method for predicting comfortable airflow in the passenger compartment. SAE technical paper series, 922131, 1992.
[15] Conceição EZE. Evaluation of thermal comfort and local discomfort conditions by numerical modeling of human and clothing thermal systems. In: Awbi HB, editor. Air distribution in rooms—Roomvent'2000, vol. I. Oxford, UK: Elsevier; 2000. p. 131–6.
[16] Tanabe S, Kobayashi K, Nakano J, Ozeki Y, Konishi M. Evaluation of thermal comfort using multi-node thermoregulation (65MN) and radiation models and computational fluid dynamics (CFD). Energy and Buildings 2002;34:637–46.
[17] Zhang H. Human thermal sensation and comfort in transient and non-uniform thermal environment. PhD thesis. University of California, Berkeley, 2003.
[18] Melikov A, Nielsen J. Local thermal discomfort due to draft and vertical temperature difference in rooms with displacement ventilation. ASHRAE Transactions 1989;95(2):1050–7.
[19] Melikov A, Langkilde G, Derbiszewski B. Airflow characteristics in the occupied zone of rooms with displacement ventilation. ASHARE Transactions 1990;96(1):555–63.
[20] Naydenov K, Pitchurov G, Langkide G, Melikov A. Performance of displacement ventilation in practice. In: Proceedings of Roomvent 2002. Denmark: Copenhagen; 2002. p. 483–6.
[21] Paciuk M, Becker R. Predicted vs. recorded summer thermal responses in air-conditioned and naturally ventilated dwelling in Israel. In: Levin H, editor. Proceedings of indoor air 2002, vol. 5. California: Santa Cruz; 2002. p. 104–9.
[22] Schiller GE. A comparison of measured and predicted comfort in office buildings. ASHARE Transactions 1990;96(1):609–22.
[23] Wong NH, Khoo SS. Thermal comfort in classrooms in the tropics. Energy and Buildings 2003;35:337–51.
[24] Bedford T. The warmth factor in comfort at work. MRC industrial health board. Report no. 76. London; HMSO; 1936.
[25] Fanger PO. Local discomfort to the human body caused by non-uniform thermal environments. The Annals of Occupational Hygiene 1977;20(3):285–91.