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A study of perceived air quality and sick building syndrome in a field environment chamber served by displacement ventilation system in the tropics

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Abstract

This paper presents a study of Perceived Air Quality (PAQ) and Sick Building Syndrome (SBS) using tropically acclimatized subjects 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 subjects, 30 males and 30 females, were engaged in sedentary office work for 3 h. 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. 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 20, 23 and 26 °C at 0.6 m height. The main objective of this study is to evaluate the influence of temperature gradient and room air temperature (at 0.6 m height) on PAQ and SBS in DV environment. It was found that temperature gradient had insignificant impact on PAQ and SBS. Dry air sensation, irritations and air freshness decreased with increase of room air temperature.

Keywords: Perceived air quality; Sick building syndrome; Thermal gradient; Displacement ventilation; Tropics

1. Introduction

The concept of DV is to utilize buoyancy effect to displace warmer stale room air by supplying cooler fresh air at the floor level to create a fresh and cool breathing zone at the occupied level. The air rises as it is warmed up by heat sources within the occupied zone and exhausted at ceiling level. Air temperature is rather uniform at horizontal level except in the region nearer to the supply diffusers. It is observed that vertical temperature gradients always exist in the space with DV system and they are not linear in all the space height [1–4]. In addition, when contaminant source is combined with heat source, the plume will carry the contaminants over the heat source to the upper zone of the room. In a room served by DV system, the ventilation effectiveness is higher than in a room served by Mixing Ventilation (MV) system [3,5]. Numerous studies have demonstrated that Indoor Air Quality (IAQ) in the occupied zone in a room served by DV system is better than by MV system [6–9]. However, subjective study based on tropically acclimatized subjects in DV environment is limited.

A systematic study in non-uniform environment was conducted by Olesen et al. [10]. In this study, 16 subjects (8 females and 8 males) were individually exposed to four different vertical air temperatures (0.4, 2.5, 5.0 and 7.5 K) between head and ankle level with highest temperature at head level. Each experiment was conducted over a period of 3 h. The subjects were sedentary and wore a light standard clothing of 0.6 clo. Subjects felt the air was significantly more stuffy with temperature difference between head and feet of 5 and

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7.5 K than in a uniform thermal environment. It was suggested that it was probably caused by higher temperature around the head. Unfortunately the gradient was not generated by a DV system in these experiments. Another systematic experiment was conducted by Wyon and Sandberg [11]. Experiments were carried out in a chilled/displacement ventilation environment. It was found that thermal discomfort due to dry air was unaffected by thermal gradient, but increased significantly with operative temperature. Discomfort due to dry eyes increased significantly above 2 K/m, but was affected by operative temperature. The values of RH varied in the range of 20–30% during the experiments. In another study, PAQ was compared between DV and MV systems by Brohus et al. [12]. The objective of the study was to see if the high ventilation effectiveness measured chemically also applied when humans were asked directly about how they perceived the air quality. The experiments showed that PAQ in the displacement ventilated room was substantially better than in the case with MV system. A field survey of occupants' response was conducted in eight office buildings with DV system in Denmark [13]. The results showed that the quality of the air perceived by occupants was better at lower operative temperature and PAQ improved when the head felt cool. Fifty percent of those who were dissatisfied with the air quality demanded more air movement. All of the above studies were conducted in the temperate climate. Climate in Singapore is very different from the temperate climate. Because of geographical location and maritime exposure, Singapore's climate is characterized by uniform temperature and high humidity. The minimum and maximum diurnal temperatures in Singapore are in the range of 23–26 °C and 31–34 °C, respectively. The minimum and maximum extreme temperatures are 19.4 and 35.8 °C, respectively. Diurnal RH in Singapore ranges 90% in the early morning to around 60% in the mid-afternoon. Mean value is 84%. During prolonged heavy rain, RH often reaches 100%. Therefore, tropically acclimatized occupants may have different perceptions as compared to temperate occupants. Hence, extensive research is needed to study PAQ and SBS in the space served by DV system in the tropics.

One PAQ study was conducted in a thermal chamber served by DV system in the tropics [14]. The results showed that stronger odor and less acceptable air quality were experienced with increase of room air temperature with no significance. This finding is similar with that of Fang et al. [15] in which the air was perceived as less acceptable with increase of air temperature. The authors suggested the insignificant effect of temperature on PAQ could be due to the relatively small temperature range and the characteristics of tropical occupants. Hence, this more comprehensive study involves tropically acclimatized sedentary occupants in the space served by DV system to investigate the effect of temperature gradient and room air temperature (at 0.60 m height) on PAQ and SBS and corresponding PDs due to PAQ and SBS.

2. Research methods

2.1. Experimental facilities

This study was conducted in a Field Environment Chamber (FEC) as shown in Fig. 1 at the National University of Singapore between July and September 2004. The chamber, 11.12 m (L) × 7.53 m (W) × 2.60 m (H), has an east-facing wall comprising of large glass panels which are insulated with aluminium foil externally and furnished with blinds internally to reduce heat conduction and solar radiation. The chamber is equipped with an Air-Conditioning and Mechanical Ventilation (ACMV) system that is capable of switching between DV and MV modes.

2.2. Experimental design

The experiment was divided into two Stages. In Stage 1, 30 subjects were allowed to adjust their clothing to achieve thermal comfort during the first 2 h. Jackets were available for subjects who wanted to put on more

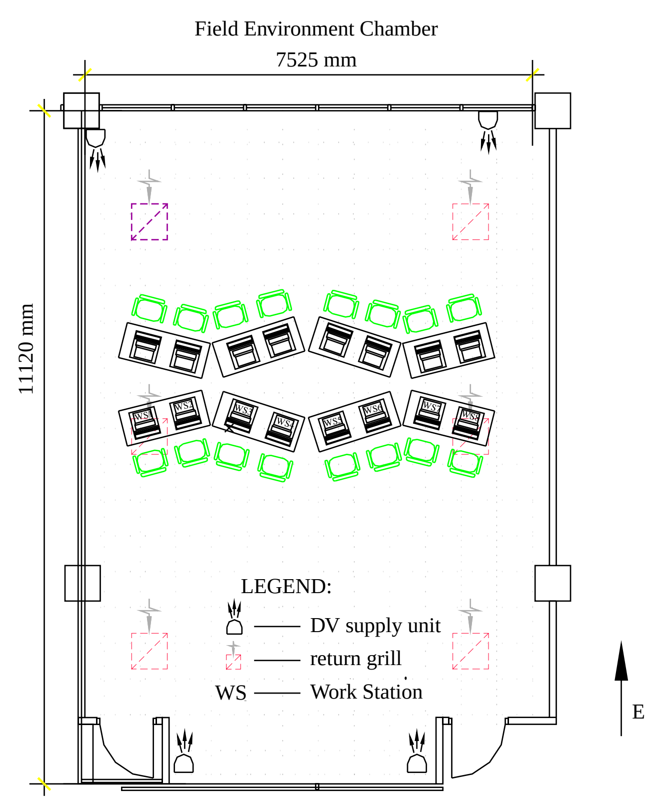

Fig. 1. Layout of the FEC.

clothing. In Stage 2, another 30 subjects were exposed to cold sensation at room air temperatures of 20 °C and slightly warm sensation at room air temperatures of 26 °C. 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 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. RH at 0.6 m height and outdoor air provision were maintained at 50% and 10 l/s/p, respectively. Subjects were performing sedentary normal office work during the experiment. They were requested to complete one set of questionnaire at every 30-min interval during the 3-h exposure.

2.3. Objective measurements

Measurement of room air temperature was carried out using type T thermocouple wire with accuracy of ±0.2 °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 ±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.

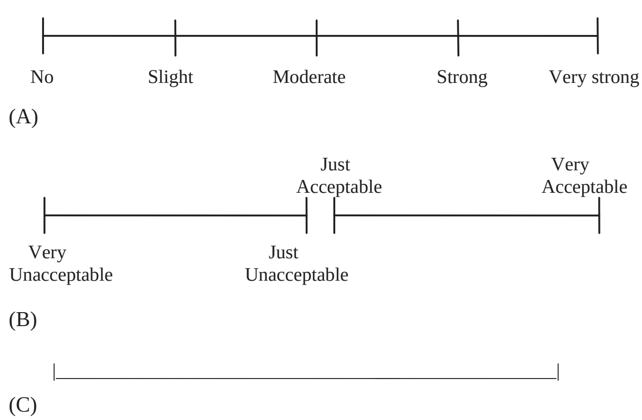

Fig. 2. Scales used for subjective assessment. (A) Continuous scale (divided into four parts). (B) Continuous scale (divided into two parts) (C) Continuous scale (undivided).

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 for the assessment of subjects' thermal sensation for overall body. Thermal comfort was assessed using the Bedford's scale. Visual-analog scales as shown in Fig. 2 were used in the assessment. Scale A was used to assess odor intensity and irritations. Scale B was used to assess PAQ acceptability. Scale C was used to assess dry air sensation and freshness.

2.5. Subjects

A total of 60 subjects, 30 for Stage 1 and 30 for Stage 2, were selected for the experiments. Only students who are acclimatized to the tropical climate were chosen. Table 1 shows the anthropometric data of subjects for this study.

3. Results and discussion

3.1. Experimental conditions

Table 2 shows the summary of nominal and actual experimental conditions. For nominal room air temperatures of 20, 23 and 26 °C, 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 of 1, 3 and 5 K/m, 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%, actual value was in the range of 49.7–53.9%. For nominal outside air provision of 10 l/s/p, actual value

Table 1
Anthropometric data of the subjects

Thermal sensation	Neutral			Cold and slightly warm		
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

Overall thermal sensation	Case	Nominal value				Actual value (0.6 m height)						
		Temp (°C)	Gradient (K/m)	RH (%)	Outside air (l/s/p)	Temp. (°C)		Gradient (K/m)		RH (%)		Outside air (l/s/p)
						Mean	S.D.	Mean	S.D.	Mean	S.D.	
Neutral	1	20	1	50	10	20.3	0.3	1.4	0.3	51.5	1.4	10.9
	2	20	3	50	10	20.0	0.2	3.0	0.3	50.4	0.7	10.4
	3	20	5	50	10	19.9	0.2	4.9	0.4	49.7	1.3	11.0
	4	23	1	50	10	22.9	0.1	1.3	0.1	53.9	1.2	11.2
	5	23	3	50	10	23.0	0.3	3.1	0.2	50.9	1.0	11.4
	6	23	5	50	10	23.0	0.3	4.9	0.3	50.9	0.6	9.8
	7	26	1	50	10	26.1	0.2	1.0	0.3	53.4	1.4	10.5
	8	26	3	50	10	26.2	0.2	3.1	0.2	51.1	1.2	10.9
	9	26	5	50	10	25.9	0.2	4.8	0.3	52.7	1.4	9.1
Cold	10	20	1	50	10	20.1	0.2	1.3	0.2	50.7	1.3	10.7
	11	20	3	50	10	20.2	0.2	3.3	0.2	51.2	0.6	10.9
	12	20	5	50	10	20.0	0.3	4.9	0.2	51.5	0.6	10.3
Slightly warm	13	26	1	50	10	26.1	0.2	1.3	0.3	51.9	1.5	11.0
	14	26	3	50	10	26.2	0.1	3.1	0.1	52.7	1.1	10.9
	15	26	5	50	10	25.9	0.2	4.6	0.2	52.1	1.1	9.1

was in the range of 9.1–11.4 l/s/p. The results showed that actual experimental conditions were very close to nominal conditions. It appears that the experimental conditions were well monitored during period of 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. 3 and 4, 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 of height. At 0.6 m height, RH was around 50%.

3.3. Air temperature, humidity and enthalpy at breathing level as well as Overall Thermal Sensation (OTS)

Table 3 shows room air temperature, humidity and enthalpy at breathing level (1.1 m height) as well as average votes of Overall Thermal Sensation (OTS) for all the cases. For Cases 1–3 with room air temperature of 20 °C (0.6 m height), air temperature at 1.1 m height was in the range of 21.1–23.2 °C and increased with increase of temperature gradient. RH at 1.1 m height was in the range of 49.1–44.6 °C and decreased with increase of temperature gradient. Similar profiles were observed for the other cases. It was observed that Absolute Humidity (AH) at 1.1 m height varied over a narrow band for the cases at the same room temperature

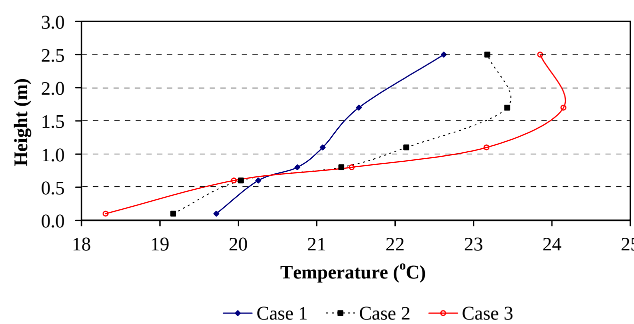

Fig. 3. Temperature profiles for Cases 1, 2 and 3.

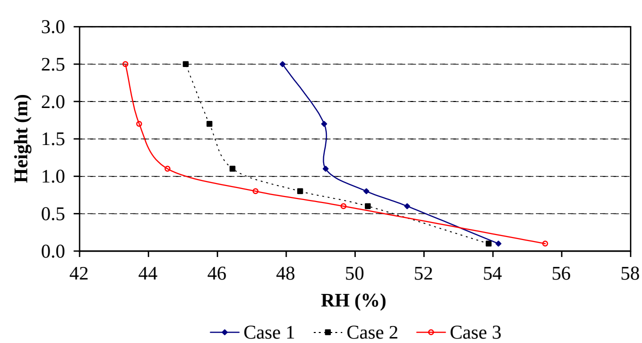

Fig. 4. RH profiles for Cases 1, 2 and 3.

for different temperature gradients. The largest variation was 0.8 g/kg which occurred between Cases 13 and 14 with room air temperature of 26 °C. Average values

Table 3
Air temperature, humidity and enthalpy at 1.1 m height as well as OTS

Case no	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Temp. (°C)	21.1	22.1	23.2	23.6	25.1	25.9	26.5	28.3	28.4	21.0	22.5	23.2	26.9	28.3	28.2
S.D.	0.29	0.07	0.11	0.15	0.10	0.20	0.37	0.13	0.13	0.27	0.44	0.09	0.41	0.22	0.23
RH (%)	49.1	46.4	44.6	50.8	47.3	46.4	52.3	48.1	48.5	47.9	47.2	45.9	49.7	49.2	48.2
S.D.	0.88	0.59	1.00	0.99	0.94	0.46	0.74	0.72	0.68	1.06	0.48	0.77	0.48	1.16	0.62
AH (g/kg)	7.63	7.67	7.88	9.22	9.39	9.67	11.3	11.6	11.7	7.40	8.00	8.12	11.0	11.8	11.5
Enthalpy (kJ/kg)	40.5	41.6	43.3	47.1	49.0	50.5	55.4	57.8	58.4	39.8	42.8	43.8	55	58.5	57.6
OTS	−0.50	−0.60	−0.43	−0.38	−0.47	−0.27	0.03	0.07	0.10	−2.30	−2.07	−1.87	1.13	1.20	1.10
S.D.	0.63	0.56	0.63	0.81	0.63	0.78	0.72	0.52	0.55	0.70	0.83	0.86	0.43	0.48	0.31

of AH at room air temperatures of 20, 23 and 26 °C were 7.78, 9.43 and 11.50 g/kg, respectively which increased with increase of room air temperature. The differences of AH for room air temperature of 20–23 °C and 23–26 °C were 1.64 and 2.08 g/kg, respectively. These were much higher than the variations at the same room air temperature for different temperature gradients. Similar profiles were observed for the values of enthalpy for all cases. The enthalpy difference of 4 kJ/kg between Cases 10 and 12 was the largest variation for cases at the same room temperature with different temperature gradients. Average values of enthalpy, at room air temperatures of 20, 23 and 26 °C, were 41.97, 48.87 and 57.12 g/kg, respectively, which increased with increase of room air temperature. The differences of enthalpy for room air temperature of 20–23 °C and 23–26 °C were 6.9 and 8.25 kJ/kg, respectively. These were much higher than the variation at the same room air temperature for different temperature gradients. For Cases 1–9, the values of OTS were within the range of between −0.6 and 0.10 and close to neutral. For Cases 10–12, the values of OTS were close to cold sensation within the range of between −1.87 and −2.30. For Cases 13–15, the values of OTS were slightly warm within the range of between 1.1 and 1.2.

3.4. Perceived air quality (PAQ)

In this paper, PAQ refers to odor intensity, PAQ acceptability, dry air sensation and air freshness.

3.4.1. Subjective assessment of PAQ

Average votes of PAQ for all cases are shown in Fig. 5. Average votes of odor intensity for all cases were in the range of 0.37–0.83 and this is within the range of no odor (0) and slight odor (1). Average votes of PAQ acceptability were in the range of 0.04–0.39, which is acceptable. This means that PAQ for all cases is still acceptable although the acceptable level is not so high. It is observed that acceptability of PAQ were obviously lower for Cases 13–15 at slightly warm sensation with room air temperature of 26 °C. Average votes of dry air sensation were in the range of −0.01 and 0.24 which was on dry sensation side except for Case 7 with room air temperature of 26 °C and temperature gradient of 1 K/m. This means that RH of 50% is too low for tropically acclimatized subjects. Average votes of air freshness were in the range of −0.16 and 0.32. For Cases 1–12, average votes were above 0 on the fresh side. For Cases 13–15 at slightly warm sensation with room air temperature of 26 °C, average votes were in the range of −0.13 to −0.16 which is below 0 and on the stuffy side.

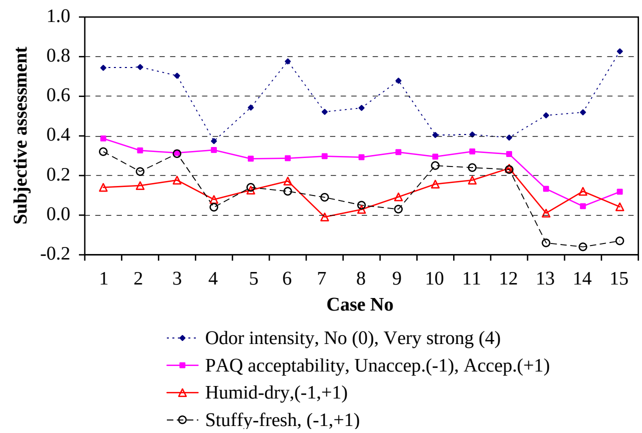

Fig. 5. Subjective assessment of PAQ.

3.4.2. Correlations of PAQ with temperature gradient and room air temperature

Table 4 presents values of correlation coefficient of PAQ with temperature gradient and room air temperature. The results showed that odor intensity ($p = 0.107$), PAQ acceptability ($p = 0.649$), dry air sensation ($p = 0.092$) and air freshness ($p = 0.913$) were insignificantly correlated with temperature gradient. Conversely dry air sensation ($p = 0.007$) and air freshness ($p = 0.003$) significantly decreased with increase of room air temperature. The results also showed that room air temperature had insignificant impact on odor intensity ($p = 0.209$) and PAQ acceptability ($p = 0.132$).

The finding of insignificant impact of temperature gradient on dry air sensation is consistent with that of Wyon and Sandberg [11]. However, dry air sensation significantly decreased with increase of room air temperature. The reason is values of AH increase with increase of room air temperature as mentioned in early section. The finding of insignificant impact of temperature gradient on air freshness differs from that of Olesen et al. [10] in which subjective sensation of air freshness was significantly decreased with increase of temperature difference between head and ankles. In contrast, air freshness significantly decreased with increase of room air temperature which is in accord with the findings of Toftum et al. [16]. A cooling effect in the respiratory tract may help to explain the reason. Total heat transfer is determined by the enthalpy of the inhaled air. With a high indoor air enthalpy, an insufficient cooling may be interpreted as a local warm discomfort in the respiratory tract and leads to the inhaled air being perceived as less fresh. The study of Olesen et al. [10] was not conducted in DV environment. In their study, temperature at breathing level was higher at higher thermal gradient for a certain room temperature. However, there is no information of RH at this level. So the enthalpy at breathing level was unknown. In the present study, temperature at breathing level was higher for gradient of 5 K/m than for 1 K/m. Meanwhile RH at this level was lower for gradient of 5 K/m than for 1 K/m. Differences of enthalpy for these cases at the same room temperature with different temperature gradients were small as shown in Table 3. The small difference of enthalpy was insufficient to be differentiated by the subjects. However, differences of enthalpy for the cases with different room air temperatures were higher than those at the same room air temperature for different temperature gradients. The change of enthalpy for the cases with different room air temperature was substantial. So air freshness significantly decreased with increase of room air temperature in this study. Insignificant impact of room air temperature on odor intensity is similar with that of Fang et al. [15]. However, PAQ acceptability was insignificantly correlated with room air temperature which contrasts with the finding of Fang et al. [15]. It may be explained by the period in which subjects were exposed. In the study of Fang et al. subjects were exposed to the environment only 20 min as compared to 3 h for this present study. The air is perceived least acceptable immediately after people enter a space with air pollution. Adaptation improves acceptability of air quality considerably [17]. In present study, adaptation could occur and subjects accepted the air quality after a long period of exposure. This finding is consistent with the earlier findings in the tropics [14] in which less acceptable air quality was experienced with an increase in room air temperature with no significance.

In summary, the results demonstrated that temperature gradient had insignificant impact on PAQ. Room air temperature had insignificant impact on Odor intensity and PAQ acceptability. Dry air sensation and air freshness decreased with increase of room air temperature.

3.4.3. Percent dissatisfied (PD) of perceived air quality (PAQ)

Tables 5 and 6 show PD of PAQ and summary of chi-square test for all cases, respectively. The vote of odor intensity in the range of no (0) to slight odor (1) is considered satisfied. Beyond this range is considered dissatisfied. The PD of odor intensity was in the range of 10–40%. Room air temperature and thermal gradient

Table 4
Correlations of PAQ with temperature gradient and room air temperature

PAQ	Gradient		Room temp	
	Coefficient	Sig. (2-tailed)	Coefficient	Sig. (2-tailed)
Odour intensity	0.433	0.107	– 0.464	0.209
PAQ acceptability	– 0.093	0.649	– 0.418	0.132
Dry	0.451	0.092	– 0.818	0.007
Freshness	0.031	0.913	– 0.859	0.003

Table 5
Percent dissatisfied of perceived air quality

Case no	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
PD (%)															
Odor intensity	23	27	23	17	17	30	20	27	30	10	13	13	17	17	40
Acceptability	3	10	13	3	10	13	3	10	3	13	10	10	30	43	33
Dry	67	73	70	57	73	63	50	47	50	60	70	77	57	70	53
Freshness	17	30	33	43	43	37	47	50	47	30	30	23	73	63	77

Table 6
Summary of chi-square test for percent dissatisfied of PAQ

PAQ	Test	Gradient					Temp	Temp (20 °C)	Temp (26 °C)
		Neutrality			Cold	Slightly warm	Neutral	Cold-neutral	Neutral- slightly warm
		20	23	26	20	26			
Odor intensity	Chi-square	0.120	2.135	0.818	0.207	5.896	0.532	4.490	0.030
	P	0.942	0.344	0.664	0.902	0.052	0.766	0.034	0.863
Acceptability	Chi-square	1.921	1.921	1.694	0.225	1.261	0.929	0.247	24.801
	p	0.383	0.383	0.429	0.894	0.532	0.628	0.619	<0.001
Dry	Chi-square	0.317	1.843	0.089	1.970	1.944	9.070	0.026	2.240
	p	0.853	0.398	0.957	0.373	0.378	0.011	0.871	0.134
Freshness	Chi-square	2.386	0.367	0.089	0.443	1.406	8.852	0.028	10.163
	p	0.303	0.832	0.956	0.801	0.495	0.012	0.867	0.001

were insignificantly correlated with the PD of odor intensity as shown in Table 6. However, PD of odor intensity was significantly lower at cold sensation than at neutral sensation with room temperature of 20 °C ($p = 0.034$). PD of PAQ acceptability was in the range of 3–43%. It was in the range of 30–43% at slightly warm sensation with room temperature of 26 °C and higher than those at cold and neutral sensations. It was insignificantly affected by room air temperature and thermal gradient. However, PD of PAQ acceptability was significantly higher at slightly warm sensation than at neutral sensation with room temperature of 26 °C ($p < 0.001$). PD of dry air sensation was in the range of 47–73% and insignificantly affected by thermal gradient and thermal sensation. However, it decreased significantly with increase of room air temperature ($p = 0.011$). PD of air freshness was in the range of 17–77%. It was especially high in the range of 63–77% at hot sensation with room temperature of 26 °C. It was insignificantly affected by thermal gradient. However, it increased significantly with increase of room temperature ($p = 0.012$). PD of air freshness was significantly higher at slightly warm sensation than at neutral sensation at room temperature of 26 °C ($p = 0.001$). In summary, the results indicated that PD of PAQ was insignificantly affected by thermal gradient. PDs of odor intensity and PAQ acceptability were insignificantly affected by room air temperature. However, PD of dry air sensation decreased and PD of air freshness increased significantly with increase of room air temperature. For room temperature of 26 °C, PDs of PAQ acceptability and air freshness were significantly higher at slightly warm sensation than at neutral sensation. PD of odor intensity was significantly lower at cold sensation than at neutral sensation with room temperature of 20 °C.

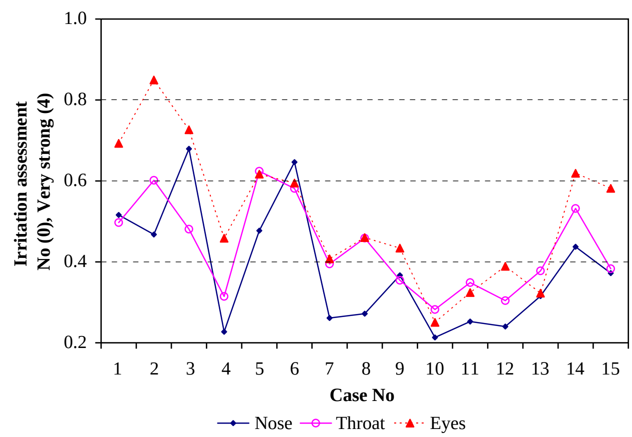

Fig. 6. Subjective assessment of irritations.

3.5. SBS

3.5.1. Irritations

Fig. 6 displays subjective response of irritations of nose, throat and eyes. Average votes of irritation of nose, throat and eyes were in the range of 0.21–0.68, 0.28–0.62 and 0.25–0.85, respectively. All of them were in the range of No (0) and slight irritation (1). Correlations of SBS with room air temperature and thermal gradient are shown in Table 7. The results showed that subjective response of the irritations was insignificantly affected by thermal gradient. Throat irritation was insignificantly related to room air temperature. On the contrary, irritations of nose and eyes decreased significantly with increase of room air temperature ($p = 0.046$ and 0.001, respectively). One possible reason is that more moisture is in the air at higher room temperature and tropically acclimatized subjects are used to relatively high moisture content.

Table 7
Correlations of SBS with room air temperature and thermal gradient

SBS	Gradient		Room temp	
	Correlation	Sig. (2-tailed)	Correlation	Sig. (2-tailed)
Nose irritation	0.439	0.102	– 0.675	0.046
Throat irritation	0.178	0.526	– 0.483	0.188
Eyes irritation	0.285	0.303	– 0.908	0.001
Throat dry	– 0.300	0.278	0.452	0.222
Mouth dry	– 0.404	0.135	0.712	0.031
Lips dry	– 0.208	0.458	0.747	0.021
Skin dry	– 0.482	0.069	0.591	0.094
Eyes dry	– 0.367	0.178	0.587	0.096

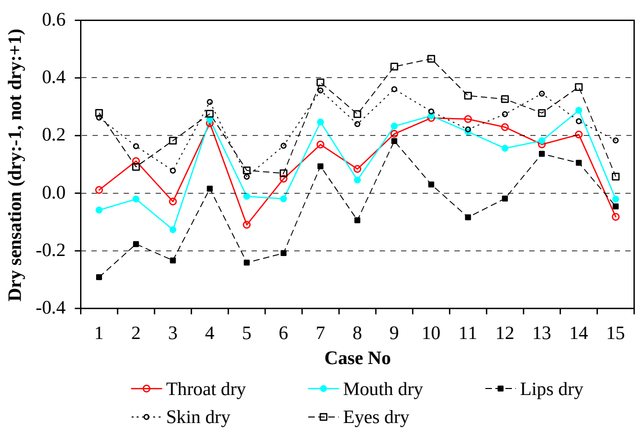

Fig. 7. Subjective assessment of dryness.

3.5.2. Air dry sensation

Fig. 7 displays subjective response of dry air sensation (dry: −1, not dry: + 1). The results indicted that average votes of dry sensation of skin and eyes were in the range of 0.06–0.36 and 0.06–0.46, respectively, which were on not-dry side. It was found that all the dry sensations were insignificantly affected by thermal gradient and room air temperature as shown in Table 7 except that dry sensation of mouth and lips decreased with increase of room air temperature ($p = 0.031$ and 0.021, respectively). This is again due to the higher moisture content at higher room air temperature.

3.5.3. Percent dissatisfied due to SBS

PDs due to SBS and summary of chi-square test are shown in Tables 8 and 9, respectively. PDs due to the irritations, dry air sensation were in the range of 3–33 and 23–77%, respectively. It was found that PDs due to SBS were insignificantly affected by thermal gradient. PD due to throat irritation was insignificantly affected by room air temperature. On the contrary, PDs due to nose and eyes irritations were significantly affected by room air temperature ($p = 0.013$ and 0.047, respectively). The results confirm the previous finding that irritations of nose and eyes decreased significantly with increase of room air temperature. PDs due to throat and skin's dry were insignificantly affected by room air temperature. Conversely, PDs due to mouth, skin and eyes' dry were significantly affected by room air temperature ($p = 0.015$, 0.023 and 0.015, respectively). In addition, most of SBS were insignificantly affected by OTS except that at room temperature of 20 °C, PDs due to nose and eyes' irritations as well as mouth dry were significantly affected by OTS ($p < 0.001$, 0.008 and < 0.036, respectively). The results demonstrated that PDs due to SBS were insignificantly affected by thermal gradient. PDs due to nose and eyes' irritations and mouth, skin and eyes' dry were significantly affected by room air temperature. PDs due to nose and eyes' irritations as well as mouth dry were significantly affected by OTS. PDs due to the other SBS were insignificantly affected by room air temperature and OTS.

4. Conclusion

It has been found by numerous researchers that DV system objectively provides better IAQ than MV. However, literature on subjective study for PAQ and SBS is limited for the tropics. Hence, this study is to conduct an extensive investigation of PAQ and SBS with DV system in the tropics.

The results showed that average votes of dry air sensation for most of the cases were on the dry side. This means that RH of 50% at 0.6 m height is too low for tropically acclimatized subjects. The results demonstrated that thermal gradient had insignificant impact on PAQ, SBS and their corresponding PDs. Dry air sensation, irritations and freshness decreased with increase of room air temperature. One possible reason is that average values of AH and enthalpy at breathing level increased with increase of room air temperature.

Table 8
Percent dissatisfied due to SBS

Case no	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
PD (%)															
Nose irritation	23	17	27	7	20	20	7	3	10	3	3	3	7	13	17
Throat irritation	20	27	10	17	17	17	17	20	10	10	10	13	13	23	17
Eyes irritation	30	33	30	23	27	27	17	20	10	10	13	20	10	17	27
Throat dry	60	47	57	47	67	47	47	53	43	43	47	47	43	43	60
Mouth dry	60	63	67	57	67	57	40	50	40	43	50	50	37	37	57
Lips dry	70	63	63	60	77	63	53	67	43	57	70	57	50	50	53
Skin dry	43	40	47	37	57	40	27	30	23	40	43	43	30	43	37
Eyes dry	27	53	40	50	53	53	30	37	27	23	40	40	40	30	50

Table 9
Summary of chi-square test for PDs due to SBS

SBS	Statistical test	Gradient					Temp	Temp (20 °C)	Temp (26 °C)
		Neutrali			Cold	Slightly warm	Neutral	Cold-neutral	Neutral-slightly warm
		20	23	26	20	26			
Nose irritation	Chi-square	0.900	2.707	1.071	0.000	1.450	8.687	14.406	1.624
	p	0.638	0.258	0.585	1.000	0.484	0.013	<0.001	0.203
Throat irritation	Chi-square	2.756	0.000	1.184	0.225	1.064	0.367	1.422	0.022
	p	0.252	1.000	0.553	0.894	0.587	0.832	0.233	0.881
Eyes irritation	Chi-square	0.104	0.117	1.184	1.259	2.889	6.119	7.107	0.160
	p	0.949	0.943	0.553	0.533	0.236	0.047	0.008	0.689
Throat dry	chi-square	1.165	3.214	0.623	0.090	2.223	0.920	2.135	0.160
	p	0.559	0.200	0.732	0.956	0.329	0.631	0.144	0.689
Mouth dry	Chi-square	0.287	0.833	0.814	0.356	3.258	8.370	4.410	0.000
	p	0.866	0.659	0.665	0.837	0.196	0.015	0.036	1.000
Lips dry	Chi-square	0.394	2.100	3.315	1.496	0.089	3.498	0.383	0.201
	p	0.821	0.350	0.191	0.473	0.957	0.174	0.536	0.654
Skin dry	Chi-square	0.271	2.790	0.341	0.091	1.148	7.566	0.023	2.080
	p	0.873	0.248	0.843	0.955	0.563	0.023	0.880	0.149
Eyes dry	Chi-square	4.444	0.089	0.726	2.460	2.500	8.353	0.594	1.552
	p	0.108	0.956	0.696	0.292	0.287	0.015	0.441	0.213

The differences of AH and enthalpy for room air temperature of 20–23 °C and 23–26 °C are much higher than those at the same room air temperature for different temperature gradients. Thus the small difference of AH and enthalpy for different gradients is insufficient to be differentiated by the subjects. Therefore, thermal gradient had insignificant impact on PAQ, SBS and their PDs. However, dry air sensation, irritations and air freshness significantly decreased with increase of room air temperature due to substantial change of AH and enthalpy for cases with different room air temperature. Odor intensity and its PD were insignificantly affected room air temperature. Room air temperature had insignificant impact on PAQ acceptability. The insignificant effect of room air temperature on PAQ may be due to the relatively small temperature range and the characteristics of tropical occupants. Another possible reason is that adaptation may happen so subjects still accept the air quality after a long period of exposure.

In conclusion, temperature gradient had insignificant impact on PAQ and SBS. This implies that temperature gradient of 5 K/m should not cause detrimental effects for tropically acclimatized occupants in terms of PAQ and SBS although it is beyond the restriction of 3 K/m as specified in present international standard [18]. Odor intensity, PAQ acceptability and corresponding PDs were insignificantly affected by room air temperature. Dry air sensation, irritations and corresponding PDs decreased with increase of room air temperature. Air freshness decreased with increase of room air temperature. With lower room temperature, room air is perceived fresher. On the other hand, energy consumption is higher. Therefore, optimum room condition needs to be explored in the future study in order to balance PAQ, thermal comfort and energy consumption in the space served by DV system.

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