

COMFORT TEMPERATURE IN AIR CONDITIONED OFFICE BUILDINGS: CASE STUDY OF INDONESIA AND SINGAPORE

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ABSTRACT

Air-conditioning system has been a basic feature in many office buildings, especially in tropical climate where buildings are exposed to solar radiation all year round. However, air conditioning is a leading source of energy consumption. Efficient energy consumption is highly desirable for commercial, for-profit entities occupying offices. A field study in two countries; Indonesia and Singapore, has been conducted to investigate office building occupants' thermal comfort. In 2015, questionnaire survey as well as physical parameter measurements were collected from each country. Analysis shows that occupants of air-conditioned building with window-opening behaviour has higher comfort temperature, compared to cooling mode only. The results of this study could be used to better understand comfort temperature in tropical countries.

Keywords— Thermal comfort, Office building, Tropical climate, Air conditioning, Mixed mode

1. INTRODUCTION

Nearly half of the total electricity usage in buildings was for the sake of providing a thermally comfortable air condition, as reported from air-conditioning (AC) usage in tropical countries [1],[2]. Energy consumption increases as lower temperature setting are used. In some countries, this has led to “minimum temperature setting campaigns” such as Japan’s Cool Biz, promoting minimum AC setting of 28°C for cooling [3], and the Malaysian government promoting a minimum temperature of 24°C in its offices [4]. However, building occupants’ comfort should be taken into account concurrently with these energy saving measures. This is also considered important in office buildings since workers’ productivity would be at stake [5]. Meanwhile, there was no such temperature recommendation for energy-saving campaigns in Indonesia and Singapore, two south-east Asian countries with tropical climate.

Preceding research studies has been conducted on office workers in other climatic conditions. A survey in 2006 concluded that 81% of workers in the UK find it difficult to concentrate on their work, taking up to 25% longer time to complete tasks if the ambient temperature is higher than the

norm, while 24°C is the maximum air temperature recommended by the World Health Organisation for workers’ comfort [6]. Thermal comfort is also the second highest cause of worker dissatisfaction, with 50% of workers dissatisfied with thermal environmental conditions [7].

Meanwhile in tropical climate, there were some instances when people actually feel cold inside of an air-conditioned buildings, despite having a warm outdoor climate [8]. The evidence of overcooled buildings issues were shown through previous climate-chamber field studies in the hot humid climate of Hongkong by Chan et al. [9], Mui [10], Lai et al. [11], Lee et al. [12] and 12 years ago in Singapore by Sekhar [13]. Overcooled office buildings is a serious issue because of the resource consumption through energy waste, HVAC operation and maintenance, as well as environmental damage. Continuous feedback is needed to ensure technology is used efficiently, meets society’s needs, and does not cause harm.

Addressing the overcooling issue, the objectives of this study were: 1) to investigate comfort temperature of office buildings with mechanical air conditioning system in Indonesia and Singapore; 2) to compare comfort temperatures expressed in 4 thermal index: air temperature, globe temperature, mean radiant temperature, and operative temperature; and 3) to compare the comfort temperature results with related available guidelines.

2. INVESTIGATION METHOD

2.1. Location and investigated buildings

Located within 5–10° latitude of the equator, Indonesia and Singapore are classified as tropical rainforest climate, based on Köppen–Geiger climate classification system [14]. The climate is generally hot-humid with a year-round air temperature of approximately above 18°C. Throughout the year, both countries experience average precipitation of at least 60 mm or 2.4 inches [14]. Tropical rainforest climate has no natural seasons, because it is dominated by the doldrums low-pressure system all year round. Climate in Bandung is cooler than most of other Indonesian cities and is classified as humid, due to its elevation. The average temperature is 23.6°C throughout the year [15]. Meanwhile in Singapore, the temperature hovers around a diurnal range of a minimum of 23°C and a maximum of 32°C [16].

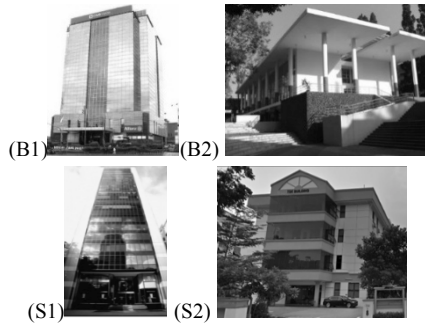


Fig. 1 Office buildings facade in Bandung: B1 and B2 and Singapore: S1 and S2

As seen in Fig. 1, there were four buildings included in this study; two buildings in each country. In Indonesia, these were an office in the urban area of Bandung (B1); and a building inside of Institut Teknologi Bandung, Ganesha Campus (B2). In Singapore there were Tong Building (S1); and TSK Building (S2). All of the buildings provides air conditioning for the occupants, although occupants' access to temperature control settings were different. B1 and S1 both use centralized AC system, while B2 and S2 use split unit AC where the occupants have more control over temperature settings and the flexibility to turn AC on or off. More preliminary design parameters of each buildings are listed in Table 1. This study covers both medium high-rise buildings (B1 and S1) and low-rise buildings (B2 and S2).

Table 1 General information of investigated buildings

Items/ Buildings	B1	B2	S1	S2
Ventilation type	AC Central	AC split-unit + windows	AC central	AC split-unit
Total Storey	12F + 1B	2F + 1 B	19F + 1 B	4
Orientation	N-W	S-N	S-E	N-E
Overhang roof	n/a	available	n/a	n/a
Façade	Curtain walls + ACP	Operable glass windows	Curtain walls	Curtain walls + ACP

AC: Air Conditioning, F: Floor, B: Basement, N: North, S: South, E: East, W: West, ACP: Aluminium Composite Panels

2.2. Thermal measurements

Since thermal comfort affected by physical and personal parameters, both were measured simultaneously in this study. There was no interference or control over the thermal environment, since this study aims to investigate occupant response to typical conditions. Air temperature, globe temperature, and relative humidity were measured every 10 seconds using HOBO thermo recorders. The basic function of this instrument is to record air temperature and relative humidity and also comes with two external data channels. One of these channels attached to TMC-HD1 external air temperature sensor tipped with a 40mm black sphere to measure globe temperature. Outdoor temperature were also recorded using the same instrument, equipped with solar-radiation shield, located outside of the investigated building. Simultaneously, air velocity was measured in 10 second intervals using hot wire anemometer attached with an

omnidirectional probe. Both equipment are illustrated in Fig. 2.

Each equipments' sensor was set up in a retort stand, attached to a clamp, approximately 1.1 meters height above floor level. The measurements include both movable and static stands. The static stand would be attached with anemometer and placed in the middle of the measured room. Meanwhile, the movable stand would be placed about 1 meter away from the subject who is answering the questionnaire survey. The stand would be moved after approximately 20 minutes, after the subject finished filling up questionnaire. Surface temperatures were measured from each cardinal directions inside of the room, using the IR-300 infrared thermometer. Specifications of each mentioned instruments as listed on Table 2.



Fig. 2 Retort stands with thermo recorder and hot wire anemometer

Table 2 Specification of the instruments

Instrument	Resolution	Accuracy
Thermometer with data logger (HOBO U12-13)	0.05°C	±0.25°C [0°C to 50°C]
Anemometer (Kanomax 6501-0G)	0.01 m/s	± 0.0125 m/s [0.10 to 30.0 m/s]
Infrared Thermometer (IR-300)	0.1°C	±0.3°C [-55°C to 220°C]

2.3. Thermal comfort survey

Personal parameters such as occupants' metabolic rate, clothing insulation value, and thermal perceptions were surveyed through questionnaires. The questionnaire collected information such as socio-demographics, thermal sensation, acceptability, preference, overall comfort vote, adaptive behavior, and clothing worn on that time. Thermal Sensation Vote (TSV) in this study uses the ASHRAE-55 seven point scale [17], which was translated to local language for each surveys in Indonesia, as shown in Table 3. Another scale used in this study was the 4-point air movement vote.

340 questionnaires were distributed to four groups of occupants in four different buildings in Bandung and Singapore, and 255 responses were collected. In Bandung, there were 16 and 20 subjects from offices B1 and B2 respectively; while in Singapore there were respectively 8 and 6 respondents from offices S1 and S2. Basic information such as age and gender were obtained from the questionnaire. The combined male to female ratio across all study locations is 52:48, which is quite balanced. 48% of occupants were aged between 20-29 years old, 34% between 30-39 years old, 12% between 40-49 years old, and 6% are more than 50 years old.

All field measurements mentioned in this study were conducted between January and March 2015. Physical thermal environment parameters were measured during three to five days in each location. At the measured days, the questionnaires were distributed every morning (10:00-11:00) and afternoon (14:00-15:00). All of the physical data

from each instruments during these hours was taken as an average value for each thermal index. Due to permission issues, the duration and repetition quantity of subjective questionnaire survey were different between each country. The respondents in Singapore only gave their thermal votes once in the first day of measurements, while Indonesian respondents voted 6 to 10 times throughout the study.

Table 3 Scale and translation

Thermal sensation vote			Air movement vote		
Scale	English	Indonesian	Scale	English	Indonesian
-3	Cold	Sangat dingin	1	No movement	Tidak ada
-2	Cool	Dingin	2	Weak	Lemah
-1	Slightly cool	Agak dingin	3	Moderate	Sedang
0	Neutral	Netral	4	Strong	Kencang
1	Slightly warm	Agak hangat			
2	Warm	Hangat			
3	Hot	Panas			

2.3. Calculation of mean radiant and operative temperature

Mean radiant temperature (T_{mrt}) and operative temperature (T_{op}) are derived from air temperature (T_a), globe temperature (T_g), and air velocity (V_a). Other than globe thermometer method, there is also the integral radiation measurement method to obtain mean radiant temperature. However a recent study by Thorsson et al. revealed that there is only relatively small differences between both methods, even in an outdoor setting [18]. This study therefore uses the globe thermometer method and calculates T_{mrt} using Equation (1) [19].

$$T_{mrt} = \left[(T_g + 273)^4 + \frac{1.1 \times 10^8 V_a^{0.6}}{\varepsilon D^{0.4}} (T_g - T_a) \right]^{\frac{1}{4}} - 273 \quad (1)$$

ε refers to emissivity of the globe, taken as 0.95 for a black globe, and D diameter of the globe which is 0.04 meter.

T_{op} is a combination of air temperature and mean radiant temperature, a weighted average value of both to express their joint effect. The weighting factors are radiative and convective heat transfer coefficients at the occupant's clothed surface. At indoor condition when air speeds around 0.10 m/s, T_{op} is approximated with Equation (2) [20].

$$T_{op} = 0.5 (T_a + T_{mrt}) \quad (2)$$

3. RESULTS AND DISCUSSIONS

3.1. The modes

During field measurement, the occupants in B2 opened windows while using air conditioning. Initially this could be seen as adaptive behavior in an air-conditioned building, but it may also categorizes this building as using "concurrent mixed mode" ventilation. According to CBE definitions, concurrent mixed-mode is air-conditioning system and operable windows operate in the same space and at the same time [21]. Because B2 was recorded to have opened windows during field measurement, it is

assumed that the occupants use natural ventilation simultaneously with air conditioning. From this realization we decided to differentiate the four air-conditioned buildings into Mixed-Mode (MM): office B2; and Cooling (CL): office B1, S1, and S2.

3.2. Evaluation of thermal environment

Thermal environment data in both outdoor and indoor space of each buildings were compiled and analysed. Mean outdoor temperatures ranged between 27.2 to 30.1°C in Bandung, closely mirroring Singapore's 27.0 to 30.3°C. Indoor air temperature in office S1 Singapore which was using centralized AC system showed an average minimum temperature of 21.6°C, 3 degrees lower than the mean indoor air temperature for all offices. The highest mean indoor temperature recorded was 27.7°C in office B2, Bandung, which used split-unit AC together with operable windows. Globe temperature were recorded to be slightly higher than air temperature had an average value of 25°C (Table 4). Average air velocity in all offices were less than 0.20 m/s, as expected in indoor condition.

Table 4 Mean and standard deviation of objective and subjective evaluation data

Country/ Building	Var	T_{out} (°C)	T_a (°C)	T_g (°C)	RH (%)	V_a (m/s)	TSV	I_{cl} (clo)	
Indonesia	n	91	91	91	91	91	91	91	
	B1	Mean	27.6	25.5	25.8	47	0.14	-0.2	0.52
		SD	1.0	0.4	0.4	3	0.03	1.2	0.13
	B2	n	150	150	150	150	150	150	150
		Mean	28.7	26.5	27.1	54	0.17	-0.1	0.59
		SD	1.6	1.3	1.3	4	0.03	1.3	0.15
Singapore	n	32	32	32	32	32	8	32	
	S1	Mean	29.1	22.2	22.2	62	0.03	-1.9	0.75
		SD	1.1	0.5	0.5	1	0.03	1.0	0.44
	S2	n	24	24	24	24	24	6	24
		Mean	28.4	24.5	24.6	69	0.07	-1.5	0.83
		SD	0.9	0.5	0.6	2	0.03	0.8	0.38
All	n	297	297	297	297	297	255	297	
	Mean	28.5	24.8	25.0	59	0.11	-0.5	0.61	
	SD	1.1	1.8	2.0	8	0.06	0.8	0.12	

T_{out} : Outdoor air temperature, T_a : Indoor air temperature, T_g : Globe temperature, RH: Indoor relative humidity, V_a : Air velocity, TSV: Thermal sensation vote, I_{cl} : Clothing insulation value, n: Number of sample, SD: Standard deviation

To investigate the relation between indoor air temperature and the other 3 thermal index: globe temperature, mean radiant temperature, and operative temperature; correlation coefficients were calculated. They are all equal to one, indicating all of them are significantly correlated (Table 5). Unlike T_{mrt} and T_{op} which were obtained from calculation, T_a and T_g were directly measured with instruments. As representative, Fig. 3 shows scatter-plot between T_a and T_g . There is almost no difference between them, except the linear regression line was slightly tilted because T_g usually a bit higher than T_a . From regression analysis we obtained the following equation to predict T_g by T_a :

$$T_g = 1.072 T_a - 1.469 \quad (3)$$

(n = 297, $R^2 = 0.99$, S.E. = 0.006, $p < 0.001$)

n: Number of sample, R^2 : Coefficient of determination, S.E.: Standard Error of the regression coefficient, p: Significant level of regression coefficient.

Table 5 Correlation coefficients of T_a and other thermal index

Mode	Items	$T_a: T_g$	$T_a: T_{mrt}$	$T_a: T_{op}$
CL (B1,S1,S2)	r	1.00	0.99	0.99
	n	147	147	147
MM (B2)	r	1.00	0.98	1.00
	n	150	150	150

CL: Cooling, MM: Mixed-mode, T_a : Indoor air temperature, T_g : Globe temperature, T_{mrt} : Mean radiant temperature, T_{op} : Operative temperature, r: Correlation coefficient, n: Number of sample. Note: all correlation coefficients are significant ($p < 0.001$)

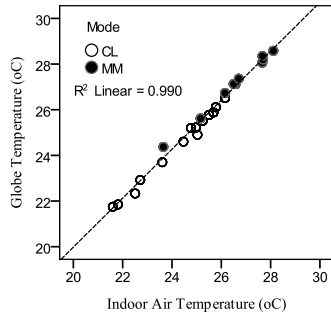


Fig. 3 Relation between globe temperature and indoor air temperature

3.3. Evaluation of thermal sensation

Individual votes of occupants thermal sensation were taken as an average value from each buildings and categorized into modes. Mean TSV from all buildings was -0.5, with 0.77 standard deviation (Table 4). According to ISO 7730-2005, this is classified as category B, where predicted mean vote (PMV) is in between ± 0.5 and percentage of dissatisfied occupants is predicted to be less than 10% [22]. However by analyzing each building's daily results separately, most of the average votes are negative on the 7 point scale, indicating that respondents experience cool thermal sensations overall. The lowest was -1.9 from office S1 with mean clothing insulation value 0.75 clo and 0.12 clo standard deviation. The only positive average TSV values were from first and third measurement sessions in office B2 Bandung, 0.74 and 0.11 when average T_a were at 27.7°C and 27.1°C. TSV from each modes was correlated to all thermal index, and the results on Table 6 shows that correlation coefficient in CL mode were the same, 0.40 for all indexes. Compared to CL, results from MM respondents shows higher correlation coefficient between TSV and 4 thermal index, with only slight differences between each index.

Table 6 Correlation coefficients of TSV and 4 thermal index

Mode	Items	$TSV: T_i$	$TSV: T_g$	$TSV: T_{mrt}$	$TSV: T_{op}$
CL (B1,S1,S2)	r	0.40	0.40	0.40	0.40
	n	105	105	105	105
MM (B2)	r	0.53	0.54	0.52	0.53
	n	150	150	150	150

CL: Cooling, MM: Mixed-mode, T_a : Indoor air temperature, T_g : Globe temperature, T_{mrt} : Mean radiant temperature, T_{op} : Operative temperature, TSV: Thermal sensation vote, r: Correlation coefficient, n: Number of sample. Note: all correlation coefficients are significant ($p < 0.001$)

3.4. Comfort temperature

Neutral temperature refers to the air temperature, which on average, a large sample of people would feel "just right" or "neutral" [23]. In this study neutral temperature is referred to as comfort temperature, because both require occupants' neutral thermal comfort vote. As seen on Table 3, the range of climatic parameters were quite narrow and it would be unreliable to use the regression method with TSV results [20]. Another way to calculate comfort temperature based on actual votes is by using the Griffiths' method [20], [24], [25]:

$$T_c = T + \frac{(0 - TSV)}{a} \quad (4)$$

T_c indicates comfort temperature (°C), expressed in four thermal indices, by substituting the T which is temperature (°C) with T_a , T_g , T_{mrt} , and T_{op} ; to obtain T_{ci} , T_{cg} , T_{cmrt} , and T_{cop} accordingly. a indicates Griffith's constant, which is the rate of thermal sensation change with room temperature. In this case 0.5 is used as the constant, as applied by Humphreys et al. at 7-point thermal sensation scale [25]. All individual votes and temperature data were substituted into the equation to calculate individual comfort temperatures. Average comfort air temperature (T_{ci}) in Bandung offices were 26°C in B1 and 26.8°C in B2; while in Singapore it was 25.6°C in S1 and 26.7°C in S2 respectively. As seen on Fig. 4, there are negligible differences between comfort temperatures by gender. Most error bars of each index overlap each other except for T_{cmrt} and T_{ci} of male respondents.

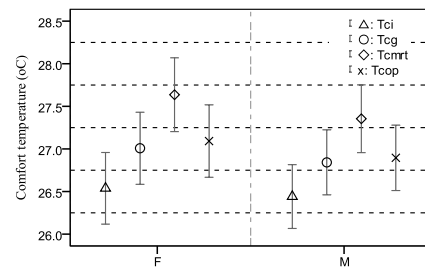


Fig. 4 Average comfort temperatures by gender, with 95% confidence interval

3.5. Comparison of comfort temperatures by modes

After obtaining comfort temperatures from all buildings, the results from mixed mode where occupants operating the windows were compared with cooling mode. Window-opening behaviour has affected occupants' comfort temperature, as shown on Table 7. Average comfort mean radiant temperature in MM mode was 28.1°C, while in CL mode it was 26.6°C. Standard deviation was 2.2°C and 2.3°C for both modes respectively. These results are slightly higher than previous studies by de Dear et al., where comfort temperature was estimated at 24.2°C for air-conditioned mode in Singapore [26]. Meanwhile it corresponds with another study in Malaysia by Daghig et al. where comfort temperature was estimated 26.6–27.6°C for air conditioned mode with window-opening arrangements [27].

Table 7 Average comfort temperatures in CL and MM

Mode (Building)	Variable	n	Mean (°C)	SD (°C)
CL (B1,S1,S2)	T_{ci}	105	26.0	2.3
	T_{cg}	105	26.3	2.3
	T_{cmrt}	105	26.6	2.3
	T_{cop}	105	26.3	2.3
MM (B2)	T_{ci}	150	26.8	2.2
	T_{cg}	150	27.4	2.2
	T_{cmrt}	150	28.1	2.2
	T_{cop}	150	27.5	2.2

CL: Cooling, MM: Mixed-mode, T_{ca} : Comfort air temperature, T_{cg} : Comfort globe temperature, T_{cmrt} : Comfort mean radiant temperature, T_{cop} : Comfort operative temperature, n: Number of sample, SD: Standard deviation

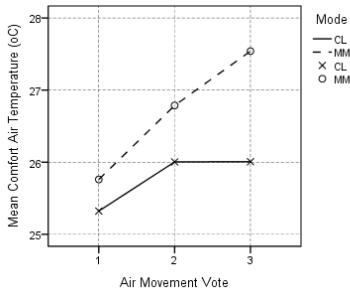


Fig. 5 Comparison of mean comfort temperature and mean air movement votes by modes

Because the windows are opened, it is possible that the occupants sensed higher air movement speed. This is in spite of the instruments recording air velocities of lower than 0.20 m/s, which could be due to the limited number of instruments, being positioned in the centre of the room and away from the windows at the perimeters. From Fig. 5, air movement vote seems to have positive correlation with comfort temperature in mixed-mode operation, but not as significant in fully air-conditioned operation. Even though in mixed mode (window-opening), there is no vote for “4. Strong air movement”, but there are votes for “1. No air movement” (refer to Table 3).

3.6. Comparison of comfort temperature with related guideline and standard

So far there is no adaptive international standards to define comfort temperature zones for heated or cooled modes, since outdoor air infiltration is assumed to be minimized. There is still a correlation found between indoor and outdoor air temperature in buildings with HVAC systems [28], [29]. Normally people adapt to their regional thermal environments as well as their accommodations and working places. An adaptive comfort temperature zone by CIBSE guidelines for heated or cooled ventilation mode is used to compare the results of this study, as shown in Equation (5) [29].

$$T_{comf} = 0.09 T_{rm} + 22.6 \quad (5)$$

T_{comf} is comfort temperature (°C) and T_{rm} is outdoor daily running mean temperature (°C). Results from equation (5), including $\pm 2K$ upper and lower limits were plotted on Fig. 6. The comfort air temperature and comfort globe

temperature in this study was plotted based on mean outdoor temperature during field measurement hours. Most of this study’s datapoints fall within these limits, but those indicating higher comfort temperatures can be attributed to regional differences, due to the CIBSE’s European database.

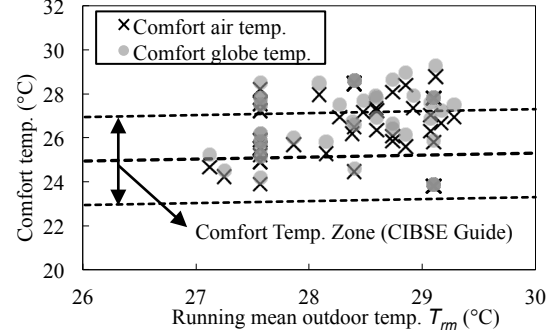


Fig. 6 Comparison of individual mean comfort temperatures with CIBSE Guide

There is no local standards about thermal comfort in office buildings in Indonesia, while Singapore uses a standard regulation SS 554:2009, which recommends indoor operative temperature between 24 to 26°C, with an acceptable limit of at least 8 hours [30]. In comparison with the standard, comfort temperatures in S1 and S2 falls within the acceptable limit stipulated for operative temperature. However overcooling issues seems apparent at these buildings, especially office S1 where the occupants have fewer adaptive options. The mean indoor air temperatures recorded to be the lowest compared to other buildings, while the mean of clothing insulation values were rather high in comparison to others. On side note, the design of building façade might also affect its default indoor condition. As listed on Table 1, all subject buildings in this study use curtain walls on its façade, except for B2, which uses operable glass windows and overhang roof, the latter useful for sunshading in tropical climates. These features possibly has made it possible for the B2 office to be occasionally operated in free running mode.

4. CONCLUSIONS

A combined analysis of thermal comfort case study of air-conditioned office buildings in Bandung and Singapore leads to these findings:

- Air temperature, globe temperature, mean radiant temperature, and operative temperature has no significant difference in expressing comfort temperature with Griffiths’ method. From this result we concluded it is safe to use only one of these indexes, because of the lack of difference between them.
- By grouping the buildings into mixed mode (MM) and cooling (CL), occupants of mixed mode has slightly higher operative comfort temperature between 25.3 – 29.7°C; while in cooling mode, operative comfort temperature was between 24.0 – 28.6°C. There is an indication of overcooling case in fully air-conditioned mode.

- Compared to relevant guidelines by CIBSE, about half of the mean individual comfort temperatures fell above the upper limits. Since CIBSE guide was developed based on European data, this means comfort temperature might be affected by different characteristics of tropical climates, despite of HVAC system in the buildings.

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