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Thermal Comfort Survey in Office Buildings in Bandung, Indonesia

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The comfort state of office building's occupants is crucial since its related to the worker's productivity. This comfort temperature of people from tropical climate might be different from temperate climate area. This study aimed to investigate thermal comfort and adaptive behaviour of occupants in office buildings with different ventilation modes: air-conditioned, mixed-mode, and free running. On February and March 2015, approximately 400 responses has been obtained through field surveys in three office buildings Bandung, Indonesia. The results has shown quite different comfort range between occupants in three ventilation modes: 24.7 °C, 26.3 °C, and 27.5 °C operative comfort temperature for FR, CL, and MM accordingly.

Keywords: Thermal comfort, Ventilation mode, Tropical climate, Office building

Introduction

Preserving thermal comfort is particularly a challenge in office buildings, where the buildings are not only exposed to solar heat from the sun, but also gained significant internal heat caused by occupancy. In other hands, the trade-offs between energy consumption and occupant comfort has been quite dilemmatic. Aside from the usual air conditioning system, there have been alternative solutions offered to be applied in building ventilation system, such as natural ventilation and mixed mode ventilation. The latter system claimed to have advantages over the former, such as: reduced heating, ventilation and cooling (HVAC) energy consumption, reduced health symptoms due to higher outdoor air ventilation rates, higher occupant satisfaction due to improved comfort, and increased flexibility due to the use of distributed mechanical systems and controls.

Even in the same office space, it is not an easy task to maintain an optimum temperature setting, since each of occupants has different thermal sensation and behavior. Many studies (Meester et al., 2013; Hiller, 2012; Tanner & Henze, 2014) has been done and proved that occupant behavior has remarkable impact on their thermal comfort. Several activities could be identified as attempts to maintain comfort state, such as drinking water; changing clothes; and operating windows, fans, or air conditioner.

It is also important to know that the comfort expectations of a tropical population and people from temperate or cold climate are different. A recent study in Brazilian climate context (Vecchi et al., 2014), which varies considerably from tropical to temperate climate, indicated that it is possible to find significant percentages of thermal acceptability data outside of the zone proposed by ASHRAE 55 (2013) adaptive model. From other previous field studies in the United Kingdom (Humphreys et al., 2013), India (Indraganti, 2011), and Singapore (Yang et al., 2013), it is noted that temperatures well above 30°C are not considered uncomfortable in some cases, while it normally would considered as uncomfortable in many other places.

This study therefore would attempt to: 1) analyse occupants' comfort temperature in office buildings with free running mode (FR), mixed mode (MM), and mechanical air conditioning for cooling (CL) in Bandung, Indonesia; 2) investigate occupants' adaptive behaviour in maintaining thermal comfort; and 3) compare the comfort temperature results with related standards.

Investigation Method

Investigated buildings

The survey had been conducted on February and March 2015, in three office spaces in Bandung, Indonesia. 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 (Bureau of Statistics, 2003). Two of the office spaces were located inside of ITB campus area, while the other one was located inside of CIMB tower, a private bank company in urban area of Bandung. The detail of all investigated office is shown on Table 1.

Table 1 Investigated buildings

Items/ Buildings	**Office 1 (CL)**	**Office 2 (MM)**	**Office 3 (FR)**
Ventilation type	AC Central	AC split-unit + windows	Natural ventilation (windows)
Total storey	12F + 1B	2F + 1 B	4F
Investigated office	Level 8	Level 2	Level 2
Orientation	N-W	S-N	S-N
Overhang roof	n/a	Available	Available
Façade	Curtain walls + ACP	Curtain walls + operable windows	Brick walls + operable windows

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

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 digital thermo recorders (resolution 0.05°C, accuracy ±0.25 °C: 0°C to 50°C). This instrument comes with two external data channels. One of these channels attached to TMC-HD1 external air temperature sensor tipped with a 40 mm black sphere to measure globe temperature. Outdoor temperatures 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 (resolution 0.01 m/s, accuracy ± 0.0125 m/s: 0.10 to 30.0 m/s).

Each equipment and sensor was set up in a retort stand, attached to a clamp, approximately 1.1 meters height above floor level. These retort stands were placed around 1 meter radius of the occupants' working place. Surface temperatures were measured from each cardinal directions inside of the room, using the IR-300 infrared thermometer (resolution 0.1°C, accuracy ±0.3°C: -55°C to 220°C).

Thermal comfort survey

Personal parameters such as occupants' clothing insulation value and thermal perceptions were surveyed through questionnaires. Thermal Sensation Vote (TSV) in this study uses the ASHRAE-55 seven point scale (ASHRAE, 2010), which was translated to local language for each surveys in Indonesia, as shown in Table 2. Another scale used in this study was the 4-point air movement vote and 5-point thermal preference.

476 questionnaires were distributed to three groups of occupants in different office spaces Bandung, and 400 responses were collected. There were 16, 20, and 18 subjects from offices B1, B2, and B3 respectively. Each respondent voted 6 to 10 times throughout the study. Physical thermal environment parameters were measured during three to five working days in each location. At the measured days, the questionnaires were distributed every morning (10:00-11:00) and afternoon (14:00-15:00). Physical data from each instrument during these hours was taken as an average value for each thermal index.

Table 2 Scale and translation

Thermal sensation vote			**Air movement vote**			**Thermal Preference**		
Scale	**English**	**Indonesian**	**Scale**	**English**	**Indonesian**	**Scale**	**English**	**Indonesian**
-3	Cold	Sangat dingin	1	No movement	Tidak ada	-2	Much cooler	Jauh lebih dingin
-2	Cool	Dingin	2	Weak	Lemah			
-1	Slightly cool	Agak dingin	3	Moderate	Sedang	-1	Slightly cooler	Sedikit lebih dingin
0	Neutral	Netral	4	Strong	Kencang	0	No Change	Tidak berubah
1	Slightly warm	Agak hangat				1	Slightly warmer	Sedikit lebih hangat
2	Warm	Hangat						
3	Hot	Panas				2	Much warmer	Jauh lebih hangat

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). This study uses the globe thermometer method and calculates T_{mrt} using Equation (1) (ASHRAE, 2005).

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

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) (Nicol et al., 2012).

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

Results

Physical parameters

The results from field survey were then compiled and the mean values from each parameter were obtained, as seen on Table 3. The average outdoor temperature was between 26.3°C (FR) and 28.7°C (MM). The lowest average temperature was in CL mode, 25.5°C; while indoor air temperature in FR and MM were quite similar, 26.7°C and 26.5°C accordingly. Globe temperatures were quite similar with air temperature in all offices; only slightly higher than air temperature for CL and MM, while the average globe temperature in FR was similar with air temperature. Relative humidity (*RH)* in CL and MM were lower than total average, which is 56%, while in FR mode it is slightly higher on 62%. Average air velocity in all offices was low, since it were all less than 0.20 m/s, even in FR mode. Average clothing insulation was quite similar in all office, with overall average of 0.57 clo.

Air temperature was correlated with other temperature index, and they were all have significantly high correlation values in all three modes, as seen on Table 4. The scatter plot on Figure 1 showed that air temperature and globe temperature were similar in FR, while in other modes globe temperature seems to be higher.

Table 3 Average value of objective and subjective evaluation

Mode	Variable	T_{out} (°C)	T_a (°C)	T_g (°C)	*RH* (%)	V_a (m/s)	I_{cl} (clo)	*TSV*	*TA*	*TP*	*AMV*	*AMA*
FR	**Mean**	26.3	26.7	26.7	62	0.07	0.58	1.0	0.7	-0.3	1.8	0.5
	N	159	159	159	159	159	159	159	158	159	159	158
	S.D.	0.8	0.2	0.2	2	0.01	0.14	1.4	0.7	0.9	0.8	0.9
MM	**Mean**	28.7	26.5	27.1	54	0.17	0.59	-0.1	0.7	-0.1	2.1	0.5
	N	150	150	150	150	150	150	150	150	150	150	150
	S.D.	1.6	1.3	1.3	4	0.03	0.15	1.3	0.7	0.8	0.7	0.8
CL	**Mean**	27.6	25.5	25.8	47	0.14	0.52	-0.2	1.0	-0.1	2.2	0.9
	N	91	91	91	91	91	91	91	91	91	91	91
	S.D.	1.0	0.4	0.4	3	0.03	0.13	1.2	0.3	0.7	0.5	0.5
Total	**Mean**	27.5	26.4	26.6	56	0.12	0.57	0.3	0.8	-0.2	2.0	0.6
	N	400	400	400	400	400	400	400	399	400	400	399
	SD	1.6	1.0	0.9	7	0.05	0.14	1.4	0.6	0.8	0.7	0.8

CL: Cooling, FR: Free-running, MM: Mixed-mode, T_{out}: Outdoor air temperature, T_a: Indoor air temperature, T_g: Globe temperature, *RH*: Indoor relative humidity, V_a: Air velocity, I_{cl}: Clothing insulation value, *TSV*: Thermal sensation vote, *TA*: Thermal acceptance, *TP*: Thermal Preference, *AMV*: Air movement vote, *AMA*: Air movement acceptance, N: Number of sample, S.D.: Standard deviation

Table 4 Correlation of T_a with T_g, T_{mrt}, and T_{op}

Mode	Items	T_a: T_g	T_a: T_{mrt}	T_a: T_{op}
FR	r	1.00	0.98	1.00
	N	159	159	159
MM	r	1.00	0.98	1.00
	n	150	150	150
CL	r	1.00	0.98	0.99
	N	91	91	91

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

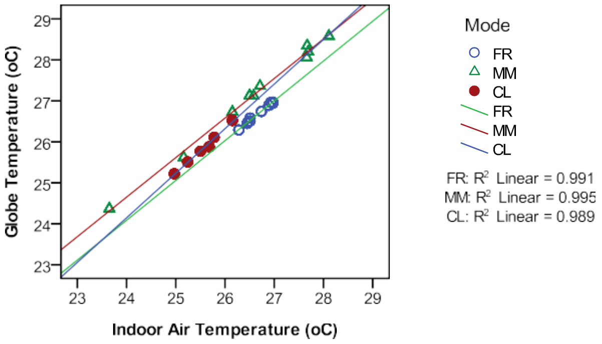


Figure 1 Correlation between globe temperature and air temperature

Thermal sensation

The occupants were asked about both thermal sensation vote and thermal preference. These two scales have to be corresponding between each other, then comparison of results from both scale in this study as seen on Figure 2. It showed as the occupants vote for warm sensation, they will prefer cooler condition, and vice versa. Table 3 shows that average thermal sensation vote were in cool side of 7-point ASHRAE scale for 2 buildings: -0.2 (S.D.=1.2) in CL and -0.1 (S.D.=0.8) in MM; while FR mode average result was on warm side of the scale: 1.0 (S.D.=1.4). However, all average results of *TP* scale were negative, which means occupants from all buildings seems to prefer cooler condition in average.

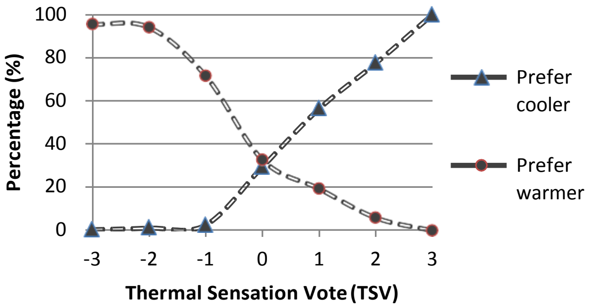


Figure 2 Relation of TSV and TP scale for all modes

To clarify thermal comfort zone, TSV results from this study were analysed using Probit regression method (Finney, 1971) for each modes. It started with ordinal regression with Probit as the link function and globe temperature as covariate. The results from MM mode are shown in Table 6. Mean temperature in the table was calculated by dividing the constant by regression coefficient. Using the following function for each *P*, then plotting it into proportions, the area of each comfort votes of TSV are divided by curves in Figure 3.

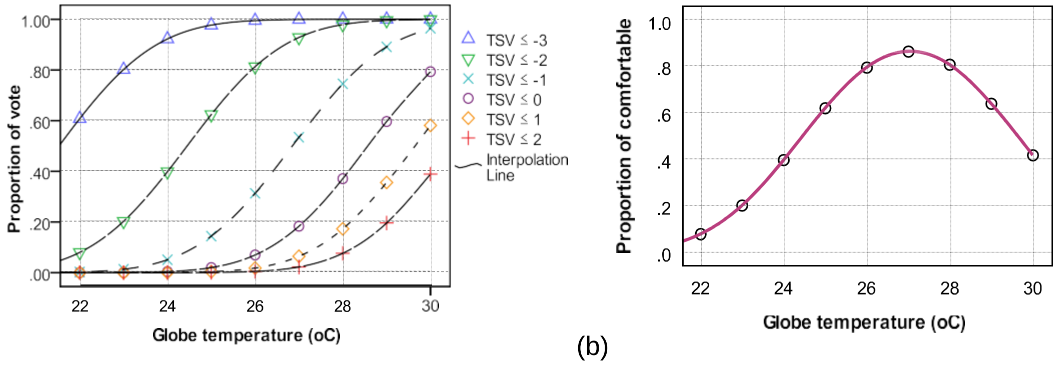
$$\text{Probability} = \text{CDF.NORMAL (quant, mean, S.D.)} \qquad (3)$$

Where the "quant" is globe temperature (^{o}C); the mean and S.D. are given in Table 5.

Table 5 Equation of probit analysis using globe temperature on TSV

Equation*	Mean (^{o}C)	S.D.	N	R^2	SE
$P_{(\leq-3)} = 0.574\ T_g - 12.35$	21.5	1.743	150	0.32	0.079
$P_{(\leq-2)} = 0.574\ T_g - 14.03$	24.4				
$P_{(\leq-1)} = 0.574\ T_g - 15.41$	26.8				
$P_{(\leq0)} = 0.574\ T_g - 16.40$	28.6				
$P_{(\leq1)} = 0.574\ T_g - 17.01$	29.6				
$P_{(\leq2)} = 0.574\ T_g - 17.50$	30.5				

$P_{(\leq-3)}$ is the probit of proportion of the votes that are -3 and less, $P_{(\leq-2)}$ is the probit of the proportion that are -2 and less, and so on; S.D.: standard deviation of the cumulative normal distribution; N: number of sample; R^2: Cox and Snell R^2; S.E.: standard error of the regression coefficient; * regression coefficient is significant ($p < 0.001$).



(a) (b)

Figure 3 Proportion of TSV or comfortable over globe temperatures in mixed mode (MM)

The highest line (blue triangle points) was defining area of probability for TSV -3 (cold) and TSV -2 (cool), and so on until the lowest line for TSV 3 (hot) based on ASHRAE 7-scale. Using TSV -1, 0, and 1 as represents of comfortable, the Probits was transformed into proportions, a bell-curve of Figure 3b. The proportion of people comfortable at the optimum is high, a bit over 80%. The temperature range which over 80% are comfortable is around 26 to 28 °C.

<u>Comfort temperature</u>

The climatic data range results of field survey were quite narrow, so it would be unreliable to use the regression method for calculating comfort temperature. Therefore this study will use Griffiths' method to calculate comfort temperature based on TSV (Griffiths, 1990; Nicol et al., 2012; Humphreys et al., 2013; Damiati et al., 2015)

$$T_{ci} = T_a + \frac{(0 - C)}{\alpha} \qquad (4)$$

Here T_{ci} indicates comfort temperature (^{o}C), based on T_a which is indoor air temperature (^{o}C). C is thermal sensation vote on a scale where 0 is neutral condition. α indicates the constant rate of thermal sensation change with room temperature. In this case 0.5 is used as the constant, as applied by Humphreys et al. (2013) at 7-point thermal sensation scale.

From this equation, comfort temperatures were obtained for each modes in 4 thermal index: T_a, T_g, T_{mrt} and T_{op}. Figure 4 showed that the 4 temperature index has similar results in FR mode. CL and MM has similar pattern with comfort air temperature as the lowest value, comfort mean radiant temperature slightly higher, while globe and mean radiant temperature were quite similar to each other, a middle value of the other two indexes. Each average temperature of occupants' comfortable state for each scale we use in questionnaire were also analysed, as seen on Table 6.

The results corresponded quite well with Griffith's method, where comfort air temperatures were 26.0°C, 24.7°C, and 26.8°C for CL, FR, and MM.

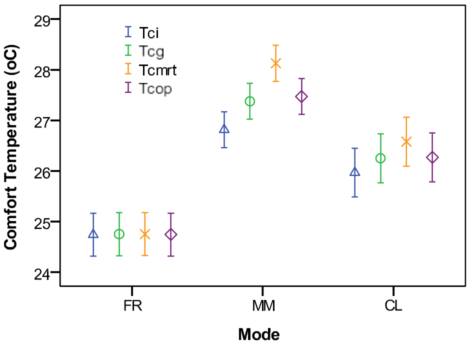


Figure 4 Comfort temperature in FR, MM, and CL ventilation modes

Table 6 Griffith's comfort temperatures and mean temperature for the given votes

Mode	Variable	Griffith's method			*TSV* = 0			*TP* = 0			*OC* = 5 or 6		
		n	Mean	S.D.	n	Mean	S.D.	N	Mean	S.D.	n	Mean	S.D.
FR	T_a	159	24.7	2.7	42	26.7	0.2	65	26.7	0.2	87	26.7	0.2
	T_g	159	24.8	2.7	42	26.7	0.2	65	26.7	0.2	87	26.7	0.2
	T_{mrt}	159	24.8	2.7	42	26.7	0.2	65	26.7	0.2	87	26.7	0.2
	T_{op}	159	24.7	2.7	42	26.7	0.2	65	26.7	0.2	87	26.7	0.2
MM	T_a	150	26.8	2.2	45	26.7	1.2	71	26.4	1.4	105	26.6	1.3
	T_g	150	27.4	2.2	45	27.3	1.2	71	26.9	1.3	105	27.1	1.2
	T_{mrt}	150	28.1	2.2	45	28.0	1.1	71	27.7	1.3	105	27.9	1.2
	T_{op}	150	27.5	2.2	45	27.4	1.2	71	27.0	1.3	105	27.2	1.2
CL	T_a	91	26.0	2.3	35	25.5	0.4	60	25.5	0.4	81	25.6	0.4
	T_g	91	26.2	2.3	35	25.8	0.4	60	25.8	0.4	81	25.8	0.4
	T_{mrt}	91	26.6	2.3	35	26.1	0.5	60	26.2	0.5	81	26.2	0.5
	T_{op}	91	26.3	2.3	35	25.8	0.4	60	25.8	0.5	81	25.9	0.5

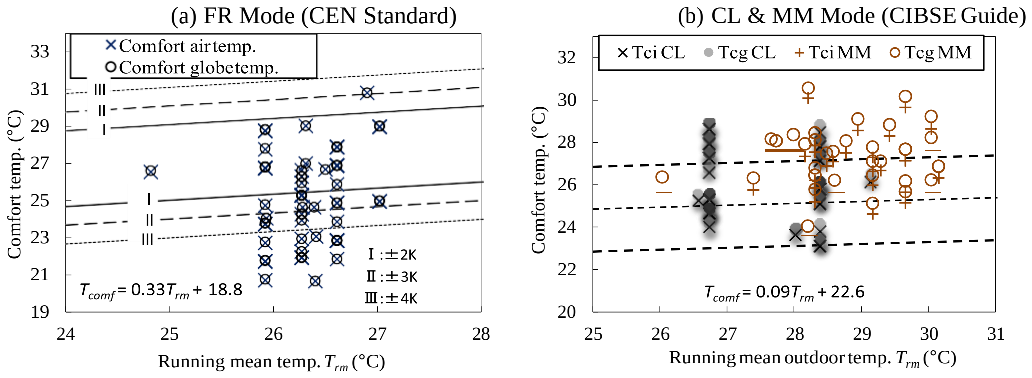
CL: Cooling, FR: Free-running, MM: Mixed-mode, T_a: Indoor air temperature (°C), T_g: Globe temperature (°C), T_{mrt}: Mean radiant temperature (°C), T_{op}: Operative temperature (°C), *TSV*: Thermal sensation vote, *TP*: Thermal preference, *OC*: Overall comfort, N: Number of sample, S.D.: Standard deviation.

Comparison to related standards

Since the field measurements of this study were conducted daily, the results of FR mode were compared with Equation (5) from CEN EN15251 which predicts comfort temperature zones in free-running mode based on daily running mean temperature (CEN, 2007).

$$T_{comf} = 0.33\,T_{rm} + 18.8 \qquad (5)$$

Where T_{comf} is comfort temperature (^{o}C), and T_{rm} is daily running mean temperature (^{o}C). The comfort air temperature and comfort globe temperature in this study was plotted based on mean outdoor temperature during field measurement hours. As seen on Figure 6a, the results of FR mode fell mostly within the comfort zone, however there were also some points fell below the comfort zone (Figure 6b).


(a) FR Mode (CEN Standard)

(b) CL & MM Mode (CIBSE Guide)

Figure 5 Comparison with the adaptive model

Meanwhile there is no international adaptive standards to define comfort temperature zones in mechanically cooled buildings, because outdoor air infiltrations are assumed to be minimized. There is still a correlation found between outdoor and indoor air temperature in HVAC buildings, although not as significant as in free-running modes. Therefore comfort zones for CL and MM mode were plotted using Equation (6) from the CIBSE guidelines, specified for cooled buildings (Humphreys & Nicol, 2006).

$$T_{comf} = 0.09\,T_{rm} + 22.6 \qquad (6)$$

On Fig. 6b, equation (6) was plotted in dotted lines, along with upper and lower limits which were using ±2*K* from the original equation. The results from this study fell within and above the CIBSE comfort zone. Some of higher comfort temperature compared to the guidelines might be caused by regional differences, since CIBSE was developed on European countries database.

Adaptive behavior

Based on direct observation and questionnaire results on Figure 5, the occupants tend to adapt in thermal environment condition mainly by using window blinds in CL mode. This might be affected by the all glass curtain walls façade. While in FR mode, most occupants adapt by drinking beverages and opening windows or doors. In MM mode, most occupants also adapt by drinking water; another option was using AC and window openings.

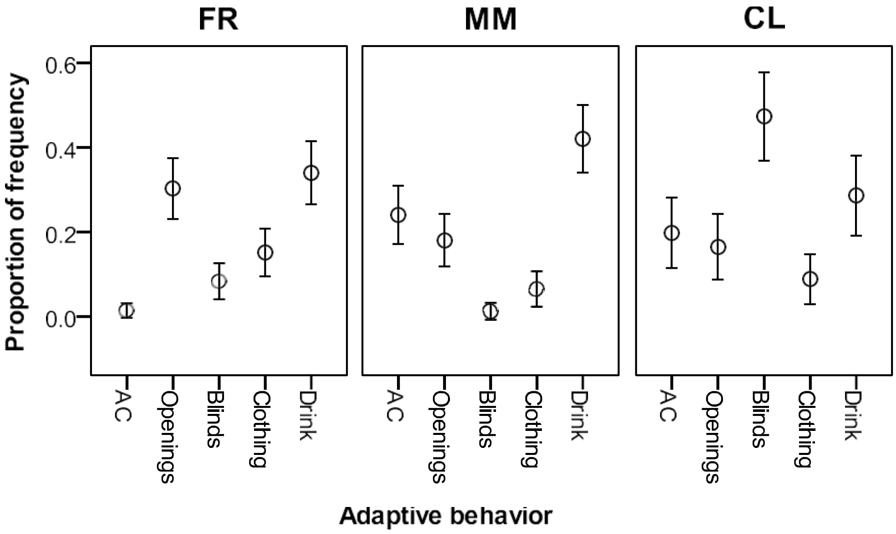


Figure 6 Occupants' adaptive behaviour in FR, MM, and CL ventilation modes

Discussions

The results from this study in CL mode is slightly higher than previous studies, where comfort temperature was estimated at 24.2°C for air-conditioned mode in Singapore (de Dear et al., 1991). FR mode has quite low comfort temperature compared to previous study by Rijal et al. (2015) where comfort temperature in free-running buildings during summer in Kanto region of Japan was 26.8°C (Rijal et al., 2015). Meanwhile MM corresponds with another study in Malaysia by Daghigh et al. (2009) where comfort temperature was estimated 26.6–27.6°C for air conditioned mode with window-opening arrangements. This might be an additional evidence of overcooling issue in mechanically cooled buildings, especially in tropical climate regions.

Conclusions

The field study in three ventilation modes of office buildings in Bandung leads to these conclusions:

- Using Griffith's method, the operative comfort temperature in the offices are 24.7 ^{o}C (S.D.=2.7 ^{o}C), 26.3 ^{o}C (S.D.=2.3 ^{o}C), and 27.5 ^{o}C (S.D.=2.2 ^{o}C) for FR, CL, and MM accordingly.
- Some adaptation method which most of occupants used to maintain their thermal comfort in investigated buildings were operating window blinds (CL mode), drinking beverages, opening windows or doors, and using AC (in CL and MM mode).
- Compared to related standards, the comfort temperatures in MM and CL were a bit higher than CIBSE guide; while in FR mode most of the results are within the CEN standard area and only small portions fell under the range.

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