Conference Paper

Field Survey of Thermal Comfort and Sleep Quality in the Bedrooms with Different Cooling Strategies in Malaysia

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Abstract

This study aims to determine the indoor comfort temperature before sleep and after wake up in air-conditioning (AC) mode with different adaptive cooling strategies. Two units of guest rooms on the university campus were used with a total of 20 participants. The arbitrary-controlled AC setting (case 1) and control of thermostat setting by 3°C higher than case 1 with installing of cool bed padding (case 2) were employed as cooling strategies in this study. The measurement parameters were indoor and outdoor air temperatures, globe temperature, relative humidity, air velocity, and AC electricity consumption. The questionnaire survey has also been distributed twice a day for "before going to bed" and "after waking up" during measurement simultaneously. It was observed that thermal sensation vote (TSV) indicated for both cases were within $-1 \leq TSV \leq 1$ and respondents might accept the present condition for both cases. Mean thermal preference (TP) in both cases either "before going to bed" and "after waking up" was found mostly close to "0 no change" ($0.1 \leq TP \leq 0.3$) for all cases. Overall comfort (OC) ranged between 4.7 and 4.9 for both cases, indicating for "comfortable." However, air movement sensation (AMS) shows respondent felt weak airflow inside the room for all ventilation strategies. The skin moisture sensation (SMS) shows value pointed to neutral feeling for all cases. The comfort temperature obtained by Griffiths' method was approximately 24°C and 25°C that for case 1 and case 2, respectively.
Meanwhile, most of the respondents experienced calmness during sleeping and satisfied with their sleep in both cases. Sleep efficiency index (SEI) shows case 2 was higher rather than case 1. It seems the second adaptive cooling strategy might effective for reducing AC energy consumption by about 32% and increase 2% of SEI without affecting respondents' thermal comfort.

Keywords: thermal comfort, sleep quality, air-conditioning

1. Introduction

The use of air-conditioners (AC) for space cooling is one of the major causes of energy consumption and CO2 emissions in Malaysia. Thus, the proper and efficient use of AC systems that realizes comfort and healthy indoor environment as well as reduces energy consumption is strongly needed. However, according to previous studies that had conducted in Malaysia, the pre-set temperatures of AC for space cooling in dwellings [6, 16], offices [2, 9], and educational classroom [17] are much lower than values recommended by Malaysian governments. In dwellings, most of the AC used for sleeping purpose [6, 10, 16]. Long duration of AC usage may lead to rise of energy consumption. However, more research and solution should be considered in addition to provide awareness and guidelines. For instant, Wang et al. [15] studies the energy saving of AC's through experiment when the temperature was set at high level of 27 °C for cooling operation, the energy saving rate was 18.7%. Japan Cool Biz campaign has promoted not only the recommendation of indoor air temperature of 28 °C for cooling but also the style change of clothes in offices to reduce the thermal insulation during hot and humid weather [8]. However, this guideline might not be suitable for occupants in other regions since thermal perception of occupants is different according to their acquisitions and culture. Therefore, in this study we will clarify the preference of indoor thermal environment before sleep and after waking up of resident of Malaysia by actual measurement and questionnaire survey. In particular, we focus on methods that compatible with night time AC energy consumption reduction and indoor thermal environment improvement of the occupant behaviour. We are aiming for the adaptive cooling strategies in houses, those can reduce energy consumption as well as greenhouse gas emission, can improve the thermal comfort and sleep quality, and can be applied for ordinary people.

2. Research Methodology

2.1. Data collection

The field survey was conducted in two units of guest rooms with AC mode (Figure 1) in Universiti Teknologi Malaysia Kuala Lumpur campus (UTMKL) from 10th November 2017 until 9th January 2018. Two different cooling strategies were applied for both investigated rooms with the AC use. First strategy (case 1) is known as arbitrary-controlled AC setting, where respondents freely change the AC setting temperature based on their preference. In addition, the AC fan mode setting was continuously set as low speed mode all through the night. An ordinary cotton bed clothing has been used as bedcover for all respondent throughout the duration of measurement. In contrast, second strategy (case 2) is known as AC setting temperature by 3°C higher than the case 1 for each respondent. To compensate this high setting temperature, the bed clothing was replaced with a special "cool" bed padding made from 70% polyetheylene, 20%

polyester, 10% nylon, 95% back polyster, 5% nylon mesh, 100% polyster padding which produced by a Japanese company (Figure 2b). We also fixed the high-speed mode of AC setting. Besides that, respondents are required to wear a sleep quality device (Garmin wristwatch) during the measurements. In this field study, 10 males and 10 females of present and former university students were participated. All respondents are required to sleep in the investigated room for three consecutive nights.

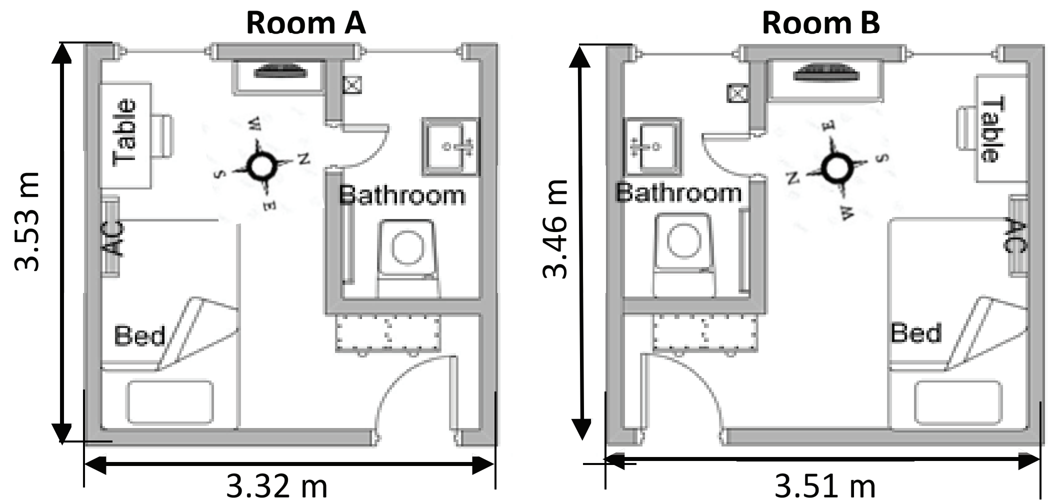

Figure 1: Plan layout of the investigated rooms.

Table 1 shows the specification of instruments used during field measurements. The field measurements include four indoor environmental parameters: air temperature (T_a), globe temperature (T_g), relative humidity (*RH*), and air velocity (V_a). All parameters were measured at 0.7 m above the floor level that the same height of bed. In addition, T_a at 0.4 m (near to floor) and at 2 m (near to ceiling) was measured as well. All of these instruments were attached to a stand as shown in Figure 2a. We also measured AC power consumption as shown in Figure 2c. All instruments were measured within 1-minute interval. All sensors are calibrated and tested all sensors before the data collection. The remote-control unit for setting AC temperature and fan mode was shown in Figure 2d. A sleep quality device was shown in Figure 2e. Outdoor air temperature was obtained from weather station located in UTMKL on the rooftop of Malaysia-Japan International Institute of Technology (MJIIT) building. The information of this weather station can be referred in Swarno et al. [13].

2.2. Questionnaire survey

The questionnaire survey was designed based on [2, 5] Damiati et al. (2016), Imagawa and Rijal (2014) for thermal comfort survey while for sleep quality survey was referred to

Table 1: Specification of instruments.

Instrument	Parameter	Sensor type	Resolution	Accuracy and tolerance
ONSET HOBO (U12-013)	Air temp. Globe temp. Relative humidity	External sensor External sensor with 40mm black sphere Internal sensor	0.03 °C	±0.35°C [0 ° to 50 °C] ±2.5% RH (from 10% to 90%)
KANOMAX Climomaster hot-wire anemometer	Air velocity	Needle probe 6542-2G	0.03% RH	±2% of reading ± 0.0125 m/s (from 0.10 to 30.0 m/s)
Power quality analyser (KE6315-03)	AC power consumption	Load current clamp sensor	0.01 m/s	±0.3%rdg±0.2%f.s. + accuracy of clamp sensor (power factor 1, sine wave, 407□0Hz

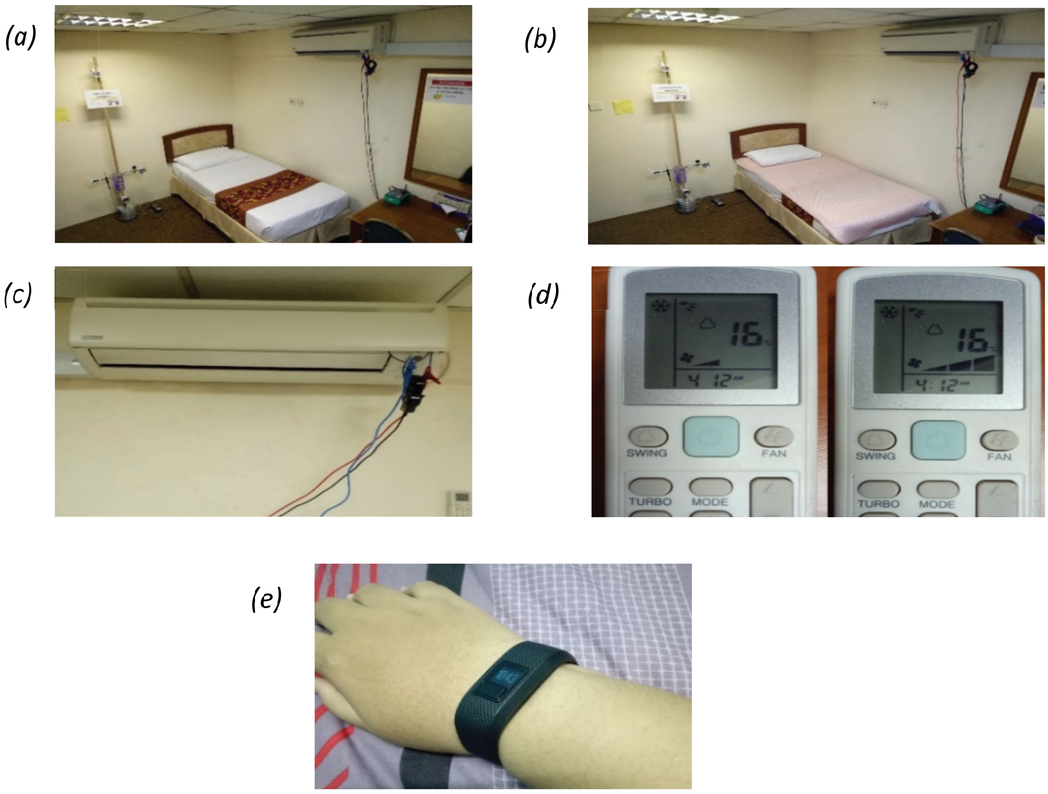

Figure 2: Investigated room conditions during field survey: (a) room's setting of the first strategy, (b) room's setting for second strategy, (c) AC electricity consumption been monitored and measured, (d) AC fan mode setting for case 1 and 2, (e) Garmin wristwatch wear by respondents to monitor their sleep quality.

Lan et al. [7].The survey included the demographic information of respondents, thermal sensation, acceptance and preference, overall comfort, air movement sensation, and skin moisture sensation. The thermal sensation was assessed using ASHRAE 7-point scale (ASHRAE Standard 55, 2017), 2-point scale of thermal acceptance, 5-point scale of thermal preference, and 6-point scale of overall comfort. We also evaluated the air movement sensation scale using 4-point and 5-point of skin moisture sensation scale. All aforementioned scale was presented in Table 2. Besides that, questions about respondents' sleep quality have been asked in this questionnaire survey. The sleep quality survey included sleep calmness, sleep satisfaction, enough of sleep and how many woke up last night as shown in Table 3. We have collected 120 votes from 20 respondents for both cases.

Table 2: Scales of thermal comfort surveys for thermal sensation, thermal preference, and overall comfort.

Thermal sensation		**Thermal acceptance**		**Thermal preference**		**Overall comfort**		**Air movement sensation**		**Skin moisture sensation**	
No.	**Scale**	**No.**	**Scale**	**No.**	**Scale**	**No.**	**Scale**	**No.**	**Scale**	**No.**	**Scale**
-3	Cold	1	Accept-able	-2	Prefer much warmer	6	Very comfort-able	1	No airflow	-2	Very dry
-2	Cool	0	Un-accept-able	-1	Prefer slightly warmer	5	Comfort-able	2	Weak airflow	-1	Dry
-1	Slightly cool			0	No change	4	Slightly comfort-able	3	Moderate airflow	0	Neutral
0	Neutral			1	Prefer slightly cooler	3	Slightly un-comfort-able	4	Strong airflow	1	Sticky
1	Slightly warm			2	Prefer much cooler	2	Un-comfort-able			2	Very sticky
2	Warm					1	Very un-comfort-able				
3	Hot										

Table 3: Scales of sleep quality based on questionnaire survey.

Sleep calmness		**Sleep satisfactions**		**Enough of sleep**		**How many woke up last night**		**Reason for woke up**	
No.	**Scale**	**No.**	**Scale**	**No.**	**Scale**	**No.**	**Scale**	**No.**	**Scale**
1	Very restless	1	Not at all	0	No	1	Never	1	Feeling hot
2	Quite restless	2	Not much	1	Yes	2	Once	2	Feeling cold
3	Neither calm nor restless	3	Moder-ately			3	Twice	3	Noises
4	Fairly calm	4	Fairly			4	Three times	4	Urgency of urination
5	Very calm	5	Fully			5	More than three times	5	The bed was un-comfor-table
								6	Others

3. Results

3.1. Indoor thermal environment

The summary results of all parameters during period of measurement were displayed in Table 4. The mean and standard deviation of outdoor temperature (T_o) was about 27°C±1 for both cases. T_a was almost similar for all heights at approximately 25°C except at 2.0 m with 1°C high for the first case. In contrast, the value of T_a for case 2 is about 1°C higher compared to first case for all condition of height. However, we used T_a at 0.7 m that near to the bed for further analysis. Meanwhile, globe temperature shows approximately identical with T_a for both cases. It indicates that almost no heat radiation affected indoor temperature. Furthermore, mean relative humidity shown in case 2 were almost similar with case 1. Meanwhile, the mean air velocity was below 0.1 m/s, which indicates low condition for an indoor setting (Damiati et al., 2016). The AC power consumption was reduced at approximately 32% in case 2. This is because of increasing 3°C of thermostat setting from case 1.

Table 4: Mean values of climatic parameters during period of measurements.

Case	Variables	T_o(°C)	T_a(°C) [FL + 2.0 m]	T_a(°C) [FL + 0.7 m]	T_a(°C) [FL + 0.4 m]	T_g(°C)	RH (%)	V_a(m/s)	Power consumption (kW)
1	Mean	27.2	25.8	24.6	24.6	24.7	72	0.07	0.34
	Min	22.2	18.6	16.7	16.9	17.4	43	0.00	0.00
	Max	34.6	31.7	29.8	29.6	29.9	89	0.19	0.92
	S.D.	1.0	1.4	1.7	1.7	1.7	5	0.02	0.20
2	Mean	27.1	26.4	25.7	25.7	25.7	74	0.09	0.23
	Min	22.7	18.0	16.7	16.6	17.0	48	0.00	0.00
	Max	34.9	31.1	29.8	29.7	29.8	88	0.17	0.90
	S.D.	0.8	1.3	1.4	1.5	1.4	4	0.03	0.13

Min: minimum; Max: maximum; S.D.: standard deviation; FL: floor level; T_o: outdoor temperature; T_a: indoor air temperature

3.2. Subjective evaluations

Table 5 shows the summary of subjective evaluation for both cooling strategies. The mean of thermal sensation vote (*TSV*) for case 1 and 2 “before go to bed” was -0.7 and -0.1 and “after waking up” was -0.8 and -0.4, respectively. It indicates for both cases were within -1 ≤ *TSV* ≤ 1 that respondents might accept the present condition for both cases. The similar trend also observed for thermal acceptance (*TA*) with mean almost 1.0 for all cases. Meanwhile, the mean of the thermal preference (*TP*) in both case either "before go to bed" or "after waking up" was voted almost "0 no change" ($0.1 \leq TP \leq 0.3$). Besides, the mean values of overall comfort (*OC*) show that respondent voted almost "5 comfortable" ($4.7 \leq OC \leq 4.9$) for both cases. However, air movement sensation (*AMS*) shows most of respondent voted "2 weak airflow" inside the rooms for both conditions although we fix the AC setting of high speed fan mode in case 2. It seems that the air movement inside the rooms might not influence the respondents. The mean skin moisture sensation (*SMS*) value ranged between -0.3 and -0.1, indicating as neutral feeling for all cases.

Table 5: Subjective distribution of respondent perceptions in each case.

Case	n	Variable	Before go to bed						After waking up					
			TSV	TA	TP	OC	AMS	SMS	TSV	TA	TP	OC	AMS	SMS
1	60	Mean	-0.7	1.0	0.2	4.9	2.1	-0.3	-0.8	0.9	0.3	4.8	2.1	-0.2
		S.D.	0.7	0.0	0.6	0.6	0.5	0.5	1.0	0.3	0.6	0.8	0.6	0.6
2	60	Mean	-0.1	1.0	-0.2	4.7	2.3	-0.1	-0.4	1.0	0.1	4.7	2.3	-0.1
		S.D.	0.7	0.2	0.6	0.8	0.7	0.3	0.8	0.2	0.6	0.7	0.7	0.4

n: number of samples; *TSV:* thermal sensation votes*; TA*: thermal acceptance; *TP:* thermal preference*; OC:* overall comfort; *AMS*: air movement sensation; *SMS*: skin moisture sensation; S.D.: standard deviation.

3.3. Comfort temperature

Comfort temperature can be obtained by Griffiths' method [3, 18]. The Griffiths' method was used to estimate comfort temperature, T_c by applying following equation.

$$T_c = T_a + (0 - TSV) / \alpha \quad (1)$$

where T_a is the indoor air temperature (°C), *TSV* is the thermal sensation votes, 0 indicated neutral condition and α is the constant rate of thermal sensation change with room temperature.

In order to apply the Griffiths' method, Sabri et al. (2017) and Humphreys et al. (2013) used the constants of Griffiths' constants 0.25, 0.33, and 0.50 for 7-point thermal sensation vote (*TSV*). Thus, comfort temperatures were estimated here by using these constants. Table 6 shows the descriptive statistics of comfort temperature calculated by using Griffiths' method for each case. The results of estimated mean comfort temperature using Griffiths' constant 0.50 shows almost similar to T_a. Thus, constant value of 0.50 was selected to estimate the comfort temperature. It is consistent with previous studies [11].

Table 7 shows the calculated mean comfort temperature by using Griffiths' and mean temperature when *TSV* and *TP* equal to zero which means *TSV* is "neutral" and *TP* is

TABLE 6: Descriptive statistics of comfort temperature by using different Griffiths' constants.

Case	Variables	Before go to bed			After waking up		
		T_c (°C)			T_c (°C)		
		α = 0.25	α = 0.33	α = 0.50	α = 0.25	α = 0.33	α = 0.50
1	Mean	25.4	24.7	23.9	26.0	25.3	24.4
	S.D.	3.5	3.1	2.8	4.1	3.5	3.1
2	Mean	24.6	24.5	24.4	26.5	26.2	25.8
	S.D.	3.5	3.2	2.8	3.8	3.2	2.7

T_c: comfort air temperature; α: Griffiths' constant; S.D.: standard deviation

"no change". The value of T_c in case 2 was about 1°C higher than case 1. It indicates that respondent can tolerate with indoor thermal condition although AC thermostat setting was set to 3 °C higher than case 1. Such condition might due to using cool bed padding and increase the AC fan setting to high speed mode.

TABLE 7: Comfort temperature based on the Griffiths' method and mean temperature for given votes.

Case	Variable	Comfort temperature, T_c (°C)											
		Before go to bed						After waking up					
		n	Griffiths' method Mean	n	TSV = 0 Mean	n	TP = 0 Mean	n	Griffiths' method Mean	n	TSV = 0 Mean	n	TP = 0 Mean
1	Mean	60	23.9	19	23.1	38	23.7	60	24.4	23	23.5	39	24.8
	S.D.		2.8		2.9		2.8		3.1		3.3		3.1
2	Mean	60	24.4	37	23.8	45	24.3	60	25.8	37	25.1	45	25.2
	S.D.		2.8		3.1		3.0		2.7		2.6		2.6

n: number of samples; *TSV*: thermal sensation vote; *TP*; thermal preference; S.D.: standard deviation

3.4. Sleep quality

In this section, respondents' sleep quality has been discussed. In order to analyse sleep quality, we only considered second and third night of measurements since the first night was only for an adjustment so that respondents may adapt with the room conditions. Table 8 shows the distribution of sleep quality based on questionnaire survey for both cooling strategies. The mean values of each variables showed almost similar for both case. Respondents generally voted "4 fairly calm" for sleep calmness and "4 fairly" satisfy with their sleep for both case. Meanwhile, respondents averagely woke up once during sleeping period for both case. This is because respondents averagely voted for "4 urgency of urination" for case 1 and 2. However, respondents were in a good health condition during the field measurement. Respondents might drink or take a bath before they went to sleep in order to comfort their body before went to sleep. Nevertheless, respondents were satisfied with their sleep and obtained enough sleep during period of measurements.

Table 8: Mean values of sleep quality based on questionnaire survey for each case.

Case	**n**	**Variables**	Sleep calmness	Sleep satisfactions	Enough of sleep	How many woke up last night	Reason of woke up
1	40	Mean	4.1	4.0	0.9	2.2	3.9
		S.D.	0.6	0.8	0.3	1.2	1.7
2	40	Mean	4.2	4.1	0.9	2.1	4.2
		S.D.	0.7	0.7	0.3	1.2	1.7
n: number of samples; S.D.: standard deviation							

Table 9 shows the proportion of votes for sleep calmness; sleep satisfaction, enough of sleep, how many woke up last night and reason for woke up for each case. The highest proportion of sleep calmness for case 1 and 2 were scale of “4 fairly calm” for both case that is 0.68 and 0.53 respectively. For sleep satisfaction, respondents voted the most was “4 fairly” satisfied with their sleep with proportion of 0.55 (case 1) and 0.45 (case 2). While for enough of sleep, the highest proportion of votes was “1 yes”. The highest proportion of votes for how many respondents woke up last night in case 1 was 0.33 (“1 never” and “2 once”) and 0.43 (“1 never”) for case 2. The results indicate proportion of respondents that never woke up last night was higher in case 2 rather than case 1. Besides that, the highest proportions of votes for reason of woke up were 0.30 and 0.39 (“6 others”) for both cases. However, since sleep calmness (“4 fairly calm” and “5 very calm”) and sleep satisfaction (“4 fairly” and “5 fully”) were the most voted, we may conclude that the respondents were satisfied with their sleep for the given thermal environment.

Besides that, the mean values of sleep quality variables of each case as shown in Table 10. The sleep efficiency index (*SEI, %*) was calculated by using equation (2) as below [14].

$$SEI = (SPT - WASO) / SPT \tag{2}$$

Where *SPT* refers to total duration of sleep and *WASO* is total duration of wake up recorded by Garmin wristwatch. Meanwhile, time in bed (*TIB*) referred to the duration of sleep starts from the primary sleep period during which participants were trying to sleep in bed until they woke up according to the our manually record for each respondent. The mean of *TIB* was 417 minutes (case 1) and 389 minutes (case 2). While for *SPT*, the mean values of case 1 and 2 were 395 and 367 minutes respectively. For *WASO*, the mean of case 1 was higher than 5 minutes compared to case 2. Although the results

TABLE 9: Proportion of votes for sleep calmness, sleep satisfaction and enough of sleep for each case.

Case	n	Sleep calmness		Sleep satisfaction		Enough of sleep		How many woke up last night		Reason of woke up	
		Scale	Prop-ortion	Scale	Prop-ortion	Scale	Prop-ortion	Scale	Prop-ortion	Scale	Prop-ortion
1	40	1	0.00	1	0.00	0	0.08	1	0.33	1	0.04
		2	0.03	2	0.08	1	0.93	2	0.33	2	0.26
		3	0.10	3	0.10			3	0.23	3	0.11
		4	0.68	4	0.55			4	0.05	4	0.25
		5	0.20	5	0.28			5	0.08	5	0.04
										6	0.30
2	40	1	0.00	1	0.00	0	0.10	1	0.43	1	0.04
		2	0.00	2	0.00	1	0.90	2	0.20	2	0.09
		3	0.15	3	0.25			3	0.25	3	0.30
		4	0.53	4	0.45			4	0.10	4	0.13
		5	0.33	5	0.30			5	0.03	5	0.04
										6	0.39

n: number of samples

show the respondents' sleep duration of case 1 was higher than case 2 when referred to *TIB* and *SPT*, the *WASO* of respondents seems decreased in case 2. Besides that, an independent sample t-test was conducted to compare the sleep efficiency index between case 1 and 2 (Table 11). There was a significant difference of *SEI* between case 1 and 2. The results indicates that the *SEI* of respondents increased by 2% in case 2 compared to case 1. Specifically, the cooling strategies proposed in case 2 may improve sleep quality of respondents.

TABLE 10: Mean values of sleep variables of each case.

Case	n	Variables	TIB (Minutes)	SPT (Minutes)	WASO (Minutes)	SEI (%)
1	40	Min	270	246	1	80
		Max	570	579	61	100
		Mean	417	395	12	96
		S.D.	85	87	12	4
2	40	Min	240	219	1	95
		Max	537	490	20	100
		Mean	389	367	7	98
		S.D.	75	72	6	2

n: number of samples; Min: minimum; Max: maximum; S.D.: standard deviation; *TIB*: time in bed; *SPT*: total duration of sleep recorded by Garmin wristwatch; *WASO*: total duration of wake up recorded by Garmin wristwatch.

TABLE 11: Independent sample T-test of sleep efficiency index (*SEI*) with case 1 and 2.

	n	Case	Mean (%)	S.D. (%)	t	df	sig. (2-tailed)
Sleep efficiency	40	1	96.4	4.1	-2.4	49.5	0.02
index (SEI)	40	2	98.1	1.5			

n: number of samples; S.D.: standard deviation, t: t-value, df: degree of freedom, sig. (2-tailed): correlations of 2-tailed significant level.

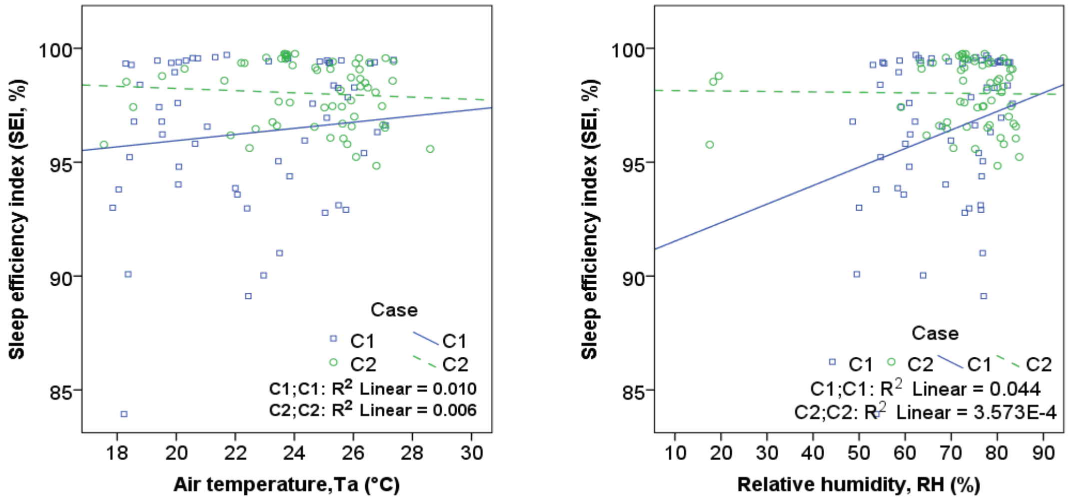

Figure 3: Relationships between sleep efficiency index (*SEI*) and air temperature (T_a) and relative humidity (*RH*) during respondents sleep in the rooms.

Besides that, the relationship between *SEI* with T_a and *RH* were examined (Figure 3). The *SEI* seems to be increased when T_a and *RH* increased during case 1 compared to case 2, *SEI* looks decreased as the T_a and *RH* increased. However, there is no statistically significance were found in those relationships. Based on the sleep variables of the Garmin wristwatch, Figure 4 illustrates the mean of sleep variables for two measurement nights (night 2 and 3) between *SPT* and *SEI* in case 1 and 2 for individual respondents. The mean of *SEI* of individual respondents in case 2 shows higher compared to case 1. This means that cooling strategies proposed in case 2 provide better sleep quality to respondents in AC conditioned rooms.

4. Conclusions

In this study, we employed two different cooling strategies to investigate the thermal comfort before sleep and after waking up in AC mode in two guest rooms at university campus. The summary of finding as follow:

1. Based on subjective evaluations, most of respondents were thermally comfortable in both cases. This is because, *TSV* indicated for both cases were within -1 ≤ *TSV* ≤

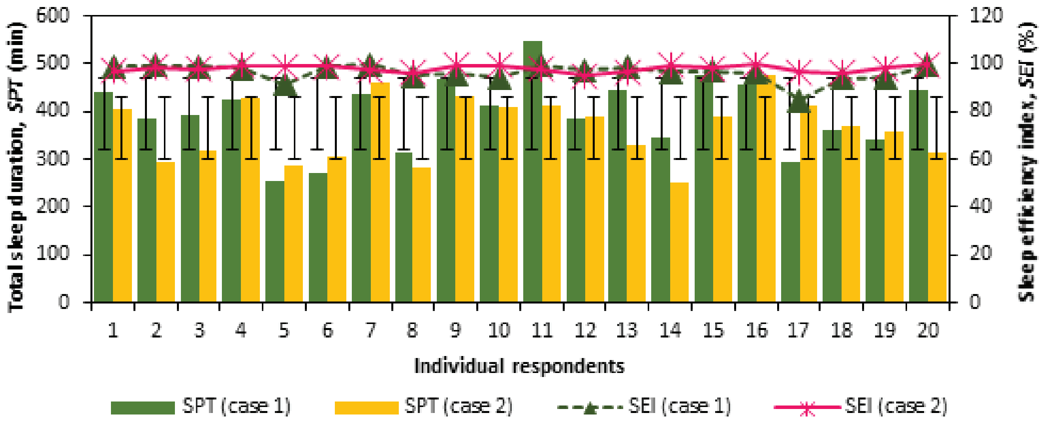

Figure 4: Mean total sleep duration, *SPT* according to Garmin wristwatch and mean sleep efficiency index (*SEI*) of individual respondents for two measurements night.

1 and respondents might accept the present condition for both cases. Respondents preferred "no change" for indoor thermal environment either "before go to bed" and "after waking up". *OC* shows respondent voted for "5 comfortable" for both cases. However, *AMS* shows respondent felt weak airflow inside the room although we change the AC fan mode to high speed. The *SMS* shows value pointed almost neutral (-0.3 $\leq$ *SMS* $\leq$ -0.1) for all cases.

2. Based on Griffiths' method, the value of comfort temperature in case 2 was about 1°C higher than case 1. It is indicating respondents can tolerate with indoor thermal condition AC thermostat setting was 3°C higher than case 1. Such condition might be due to use of cool bed padding and increase the AC fan mode setting to high speed.

3. Based on sleep quality survey, most respondents were experienced calmness during sleeping and satisfied with their sleep. This refers to the highest proportion of the votes were "4 fairly calm" and "5 very calm" for sleep calmness and "4 fairly" and "5 fully" for sleep satisfactions for both case 1 and 2. However, *SEI* shows in case 2 relatively higher for each respondent compared to case 1. This shows that cooling strategies proposed in case 2 provide better sleep quality for respondents in AC conditioned rooms.

4. The recommended adaptive cooling strategies (case 2) with use of cool bed padding and AC thermostat setting of 3°C higher than case 1 with high AC fan mode may reduce AC energy consumption about 32% without affecting respondents' thermal comfort and may increase their sleep quality as well.

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