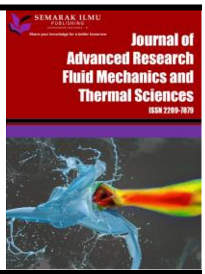
SEMARAK ILMU PUBLISHING

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage:
https://semarakilmu.com.my/journals/index.php/fluid_mechanics_thermal_sciences/index
ISSN: 2289-7879



Field Assessment of The Indoor Thermal Environment and Thermal Comfort Levels for Naturally Conditioned Residential Buildings in The Tropical Climate

Zeyad Amin Al-Absi[1,2,*], Mohd Isa Mohd Hafizal[1,♣], Mazran Ismail[1]

[1] Universiti Sains Malaysia, School of Housing, Building and Planning, 11800, Penang, Malaysia
[2] Sana'a University, Faculty of Engineering, Department of Architecture, Sana'a, Yemen

ARTICLE INFO

Article history:
Received 18 May 2022
Received in revised form 5 October 2022
Accepted 14 October 2022
Available online 5 November 2022

Keywords:
Adaptive model; indoor thermal environment; naturally conditioned building; thermal comfort; building orientations

ABSTRACT

As we spend most of our time in indoor spaces, half of the energy consumption in buildings is used to improve the indoor thermal environment to achieve thermally comfortable conditions. However, studies showed that people in naturally ventilated buildings have a broader thermal comfort zone. Additionally, people in hot areas can tolerate higher indoor temperatures. Therefore, this work investigates and evaluates the indoor thermal environment and the thermal comfort level in naturally conditioned buildings. Field measurements were conducted in various residential spaces in different buildings. The measurements were used to calculate the operative temperature (T_{op}), which was utilized to evaluate the thermal comfort level based on the adaptive models and taking into account the effect of the various orientations. The results showed that maximum T_{op} ranged between 27.70 ℃ and 35.50 ℃, depending mainly on the space's orientation. Additionally, the thermal discomfort time ranged between 0% and 73%. The South & East, Southeast, South, and East orientation were more critical during the study period, while the North, Northeast, and Northwest orientations achieved better indoor thermal conditions. However, these results can vary throughout the year, depending on the sun's path. This study revealed that the daily average heat gain to the building from the Southeast and South orientations is higher than that from the East and West orientations due to the longer exposure time to solar radiation.

1. Introduction

In developed countries, people used to spend 85-90% of their time in indoor environments [1–4]. As a result, around 50% of the building's energy is used to maintain healthy and comfortable indoor thermal conditions [5,6]. Thermal comfort level and occupant well-being are important aspects of the operation of buildings and have a primary role in indicating the quality of the living environment [5,7,8]. Therefore, building design should provide more thermal stability to enhance

* *Corresponding author.*
E-mail address: zeyadarch@gmail.com
♣ *Corresponding author.*
E-mail address: hafizal@usm.my

https://doi.org/10.37934/arfmts.100.3.5166

thermal comfort levels [9]. Thermal comfort is “the condition of mind that expresses satisfaction with the thermal environment” [10,11]. The absence of thermal comfort can cause occupants’ dissatisfaction and might affects their performance, productivity, and health [7].

The literature shows two main approaches to determining a proper thermal environment for occupants in buildings: Fanger’s steady-state model and the adaptive thermal comfort model. Fanger’s steady-state model is widely used to determine the thermal perception of occupants in air-conditioned spaces by predicting the mean thermal sensation, *i.e.,* Predicted Mean Vote (PMV), and the percentage of dissatisfaction, *i.e.,* Predicted Percentage Dissatisfaction (PPD), for the occupants in the space [5]. This model was derived from experimental data collected in a climatic chamber with a controlled indoor environment and standardized personal clothing and activities. PMV model addresses the primary variables that influence thermal comfort state, which include four environmental-based variables, namely dry-bulb air temperature, mean radiant temperature, humidity, and airspeed, and two personal variables, namely metabolic rate and clothing insulation.

However, field thermal comfort studies that assessed the actual acceptability of the thermal environment in buildings showed that the PMV model might underestimate or overestimate the thermal comfort level of spaces with a non-uniform thermal condition, like in naturally conditioned buildings [5,10]. People in naturally ventilated buildings have a wider acceptance range compared to mechanically conditioned buildings [12]. As a result, the adaptive thermal comfort model was developed to address the thermal perception of people in naturally conditioned buildings, which relates the acceptable temperature range to the outdoor air temperature [5,10]. This model depends on an active relationship between people and the surrounding environment, allowing people to adapt to the indoor environment when discomfort conditions occur in order to restore their thermal comfort. This adaption is usually achieved by a two-way reaction, *i.e.,* adjusting themselves to the environment (*e.g.,* clothing, position, activities) and adjusting the environment to suit their needs (*e.g.,* fans, curtains, opening windows) [13–16]. Furthermore, people’s adaption to the environment is not only behavioural adaptations (clothing, windows, fans, etc.), but it is also physiological adaptations (acclimatization) and psychological adaptations (expectations) [17].

1.1 Adaptive Thermal Comfort Models for Naturally Conditioned Buildings

Several models were developed and are available to calculate the thermal comfort temperature for naturally conditioned buildings. For instance, Toe and Kubota [14] used the ASHRAE RP-884 database to develop an adaptive thermal comfort equation for naturally conditioned buildings in hot-humid climates. They proposed an equation for the indoor neutral operative temperature (T_{op}) based on the monthly mean outdoor temperature (T_{mmo}) as follows

$$\text{Neutral } T_{op} = 0.53\ T_{mmo} + 14.5 \quad (1)$$

Furthermore, they found that comfort T_{op} is preferred to be 0.7 ℃ below the neutral T_{op}. However, they mentioned that even though occupants can tolerate high neutral temperatures in hot climates, they still prefer cooler conditions. Furthermore, the British standard [18] defines the acceptable range of T_{op} for naturally conditioned buildings based on three categories of buildings, as presented in Table 1, while the acceptable T_{op} can be calculated based on the outdoor running mean temperature (T_{rmo}) as follows

$$\text{Acceptable } T_{op} = 0.33\ T_{rmo} + 18.8 \quad (2)$$

Table 1
Acceptable temperature range for naturally conditioned buildings [18]

Category	Explanation	Acceptable range
I	High level of expectation and is recommended for spaces occupied by very sensitive and fragile persons with special requirements like handicapped, sick, very young children and elderly persons	T_{op} ± 2
II	Normal level of expectation and should be used for new buildings and renovations	T_{op} ± 3
III	An acceptable, moderate level of expectation and may be used for existing buildings	T_{op} ± 4

The Chartered Institution of Building Services Engineers (CIBSE) published the limits of thermal comfort: avoiding overheating in European buildings, TM52 [19], which recommends using the comfort range provided by the BS EN 15251 for category II (*i.e.,* a maximum temperature of 3 ℃ above the comfort temperature obtained by Eq. (2)). Moreover, the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) standard provides a method to define acceptable thermal conditions in naturally conditioned buildings [10]. The upper limit of the acceptable T_{op} (with 80% acceptability) can be determined based on the prevailing mean outdoor temperature (T_{pmo}) using Eq. (3). The standard permits using the T_{mmo} if data is unavailable to calculate the T_{pmo}. Furthermore, if airspeed increases above 0.3 m/s, the standard allows increasing the upper limit of the acceptable T_{op} by 1.2 ℃, 1.8 ℃, and 2.2 ℃ for average airspeeds of 0.6 m/s, 0.9 m/s, and 1.2 m/s, respectively.

$$\text{Upper limit (80\% acceptability) } T_{op} = 0.31\, T_{pmo} + 21.3 \quad (3)$$

It should be noted that all the above models of calculating the acceptable thermal condition are for naturally conditioned buildings (*i.e.,* no mechanical cooling in use) and that the occupants are free to adapt themselves (*i.e.,* clothing, activities, etc.) and their conditions (*i.e.,* openable windows, fans, etc.). Additionally, the ASHRAE standard requires the T_{pmo} to be between 10 °C (50 °F) and 33.5 °C (92.3 °F) [10].

1.2 Thermal Comfort in Malaysia

Malaysia has a tropical, hot-humid climate, with a uniform diurnal temperature throughout the year (*i.e.,* less than 2 ℃ annual difference) [20–22]. In 2019, the average outdoor temperature was 27.63 ℃, while the average maximum and minimum outdoor temperatures were 32.67 ℃ and 24.24 ℃, respectively [23]. Therefore, it has a climate that can meet the requirements set by the ASHRAE standard to use the adaptive model. Furthermore, regarding the available Malaysian standards for thermal comfort, the MS 1525, Energy efficiency and use of renewable energy for non-residential buildings - Code of practice [24], provides the required comfort temperature for air-conditioned buildings only, which should be between 24℃ and 26℃. However, the Building Sector Energy Efficiency Project (BSEEP) has published the building energy efficiency technical guideline for passive design [25], which adopts the following adaptive model comfort equation for the Malaysian climate, which is based on the outdoor air temperature (T_o)

$$\text{Comfort } T_{op} = 18.9 + 0.255\, T_o \quad (4)$$

They defined the upper limit of T_{op} for the 90% acceptability as T_{op} + 2.5 °C. On the other hand, the MS 2680, Energy efficiency and use of renewable energy for residential buildings - Code of practice [26], provides an equation that can be used to estimate the indoor comfort temperature for naturally conditioned residential buildings based on the T_{mmo} as follows

$$\text{Comfort } T_i = 13.8 + 0.57\ T_{mmo} \tag{5}$$

Moreover, various thermal comfort studies for Malaysia were conducted in chambers and actual buildings and reported the neutral and comfortable temperatures and comfort ranges. For instance, Abdulshukor [27] studied the thermal comfort of Malaysians and found that the neutral temperature in a chamber was 28.3 °C, while the comfort temperature was 28.2 °C. Furthermore, the study reported differences in the thermal comfort temperatures between Malays and Chinese, *i.e.,* 28.7 °C and 27.6 °C, respectively, and between males and females, *i.e.,* 28 °C and 28.3 °C, respectively. Besides, this study found that the Malaysian comfort zone is between 25 °C and 28.5 °C to 29.5 °C (*i.e.,* depending on relative humidity). In another study by Dahlan *et al.,* [28], a field thermal comfort study was conducted in naturally ventilated high-rise hostels near Kuala Lumpur. They reported a neutral temperature of 30.93 °C when using linear regression of subjects' thermal sensation votes (TSV) with the T_{op}, and 29.87 °C when using the optimum thermal comfort model. Hussein *et al.,* [29] conducted a field thermal comfort study in air-conditioned and non-air-conditioned buildings (*i.e.,* mechanically ventilated with fans) located in Selangor and Johor Bahru. The obtained neutral temperature using linear regression of TSV with T_{op} were 24.4 °C and 28.4 °C for the air-conditioned and non-air-conditioned buildings, respectively, while the acceptable ranges of temperatures were 23.1 °C to 25.6 °C and 26.0 °C to 30.7 °C, respectively.

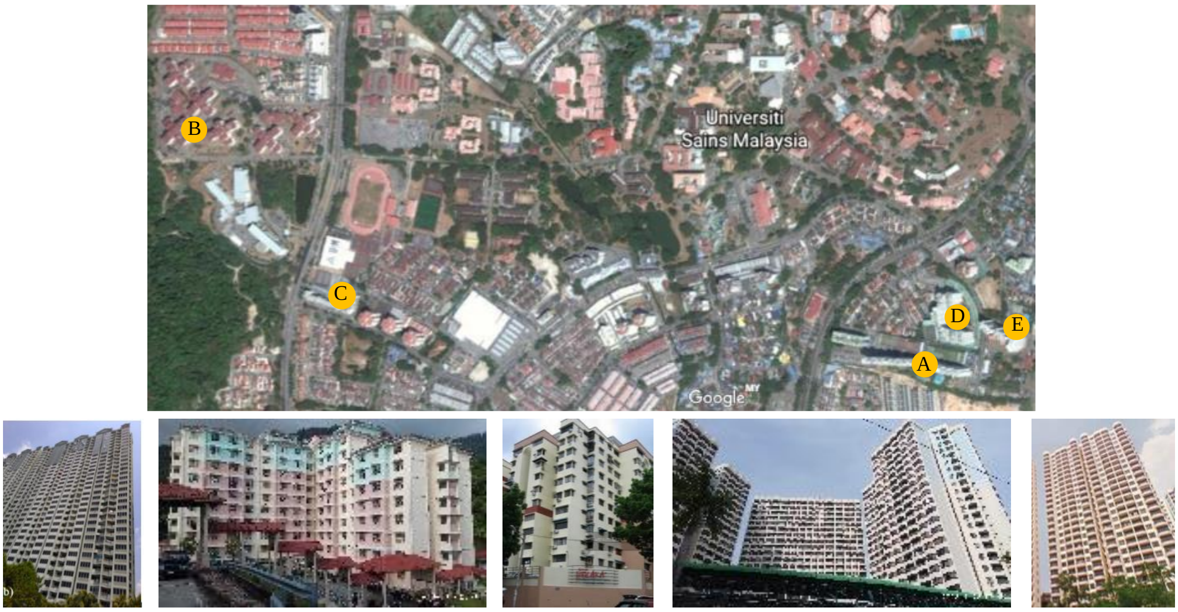
Djamila *et al.,* [30] performed a field thermal comfort study over one year long in non-air-conditioned residential buildings in Kota Kinabalu. Based on 890 responses, the neutral temperature, *i.e.,* obtained using linear regression of TSV with T_i, was 30.1-30.2 °C, while the acceptable indoor temperature range for 80% acceptability was 27.0 °C - 32.5 °C. Furthermore, Damiati *et al.,* [31] conducted a field thermal comfort study in 13 offices located in Malaysia, Singapore, Indonesia, and Japan, which had various ventilation modes, *i.e.,* Free-Running (FR), Mixed-Mode (MM), and Cooling (CL). In Malaysia, the obtained comfort temperature range, using linear regression of TSV with T_{op}, was between 24.5 °C and 30 °C, with an optimum temperature of 27 °C. Besides, they reported a mean comfort temperature of 25.7 °C. However, the ventilation mode in Malaysian offices was CL.

Based on the above studies, it can be observed that the comfort and neutral temperatures in naturally conditioned buildings were higher than that in air-conditioned buildings, which reflects the tolerance of Malaysians to higher temperatures in tropical climates. The upper limit of the comfort temperature range reached up to 30-32 °C, while the comfort temperature was, on average, 28 °C in most studies. However, to which level the naturally conditioned buildings can offer thermal comfort conditions for the occupants throughout the day and under different orientations. It is well known that the outdoor heat gain in buildings is a combination of T_o and incident solar radiations, which can differ between day and night times and under different orientations. Therefore, this work investigates and evaluates the thermal comfort level in naturally conditioned residential buildings. Various residential spaces in different buildings were selected and used to conduct measurements for the environmental parameters. The operative temperature was then calculated and used to evaluate the thermal comfort level based on the adaptive thermal comfort models.

2. Methodology

2.1 Building Selection

A total of ten different non-air-conditioned bedrooms in five different residential buildings were selected on Penang Island to conduct field indoor environmental measurements. Some considerations were taken into account during the selection of the buildings, including different buildings' locations, orientations, and height levels. Although multiple medium and high-rise residential buildings were selected, the selection was limited to those buildings that were accessible by permission from their owners or the management. Figure 1 shows the locations and views of the selected buildings.



N-Park (A) Desasiswa Restu (B) T. Pekaka (C) Sunny Ville (D) E-Park (E)

Fig. 1. Location and external view of the selected buildings for the field measurements [20]

2.2 Measurements and Instrumentations

Two external factors affect the buildings' indoor thermal environment through the envelope, namely the T_o and solar radiation. In the tropical climate, T_o has uniform patterns throughout the year with slight increases during the dry season, i.e., typically from February to May. On the other hand, the incident of solar radiation on buildings' envelopes can cause overheating of the adjacent spaces, resulting in thermal discomfort [24]. Based on the sun path of Penang Island, the maximum incident solar radiation on the south-oriented and north-oriented spaces, which are the favourable orientation for buildings in Malaysia, occurred on December 21 and June 21, respectively; see Figure 2. Therefore, the field measurements were conducted from December to March, in which the south-oriented wall was exposed to direct solar radiation, while the north-oriented wall was not exposed to direct solar radiation, in order to evaluate the influence of the incident solar radiation on the indoor thermal environment.

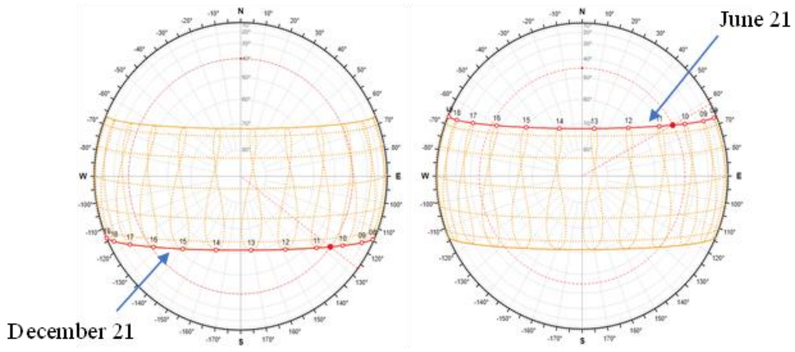


Fig. 2. Sun path charts for Penang [32]

According to ASHRAE [33], the measurements were taken from the middle of the space at 1.1 m above the floor. They were recorded continuously with an interval of 10 minutes [34, 35] using an HD32.3 data logger produced by Delta Ohm Srl, Italy (Figure 3). The measurements included the environmental parameters of thermal comfort, namely, air temperature, air velocity, relative humidity, and globe temperature (*i.e.,* to calculate mean radiant temperature) [36]. Table 2 provides the characteristics of the instrument's sensors. It should be noted that although the residents in the buildings were free to use the rooms and practice any means of personal activities or environmental controls, such as opening or closing windows and curtains, applying natural ventilation, and using fans, most of the rooms were not in use during the measurements due to presence of the instrument in the rooms. However, the owners were asked to enter the rooms and operate the windows and fans as usual. The aim was to collect measurements that reflect the actual conditions in various buildings during regular use rather than limiting them to one fixed thermal condition.

(a) (b)

Fig. 3. (a)The instrument used in this research and (b) an example of its installation in the middle of the rooms

Table 2
Sensors used with the HD 32.3 data logger instrument

Sensor	Measurement	Measurement range	Accuracy	Resolution
HP3217.2R	Temperature	-10 to 100℃	1/3 DIN	0.1°C
	Humidity	0 to 100%RH	±1.5%RH	0.1%RH
AP3203.2	Air speed	0.1 to 5 m/s	±0.2 m/s (<1) ±0.3 m/s (>1)	0.01 m/s
TP3276.2	Globe thermometer sensor Ø=50mm	-10 to 100℃	1/3 DIN	0.1°C

Furthermore, the outdoor weather data was obtained from the Malaysian meteorological department for the Bayan Lepas weather station at Penang International Airport, which is located within 8 km from the locations of the selected buildings. Additionally, visual observation of the daily weather was conducted by the researchers in line with the field measurements to identify and record the sunny, cloudy, or rainy weather.

2.3 Thermal Comfort Evaluation

The comfort temperature used in the adaptive thermal comfort models is based on the T_{op}, which combines the effects of the air temperature and radiant temperature while taking into account the influence of the air velocity [10,35]. T_{op} is an index used in thermal comfort models and studies to represent the comfort temperature and range. It can be calculated using the following equation [10]

$$T_{op} = A\,T_i + (1-A)\,T_r \tag{6}$$

where T_i is the air temperature, T_r is the mean radiant temperature, and A can be selected from Table 3 based on the average air velocity in space. Additionally, the T_{op} can also be calculated in a sufficient approximation by simple averaging of the T_i and T_r if the difference between them is smaller than 4 °C or if the air velocity is smaller than 0.2 m/s [37].

Table 3
Required "A" values to calculate T_{op} based on the average air velocity [10]

Average Air velocity	<0.2 m/s	0.2 to 0.6 m/s	0.6 to 1.0 m/s
A	0.5	0.6	0.7

All adaptive thermal comfort models estimate the comfort temperature with reference to the outdoor air temperature. As mentioned previously, the field measurements were conducted between December and March. Figure 4 shows the monthly average T_o, global solar radiation (GSR), and relative humidity (RH) for the study period.

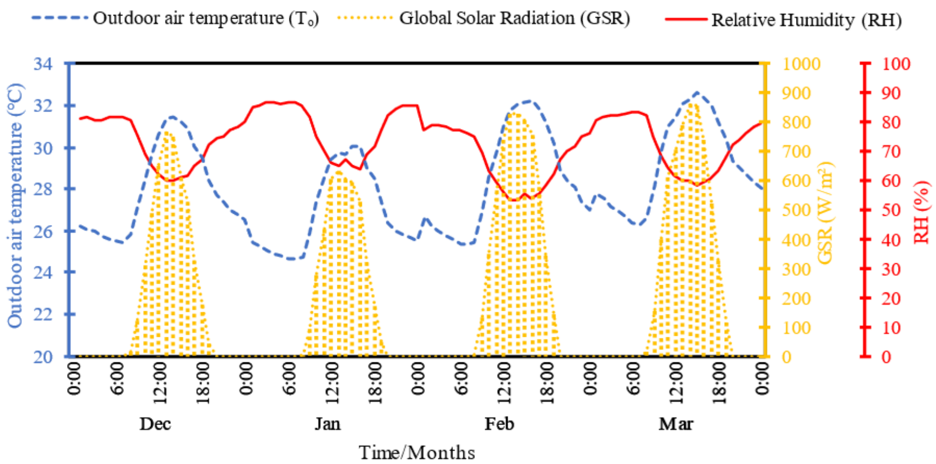


Fig. 4. Monthly average outdoor air temperature (T_o), global solar radiation (GSR), and relative humidity (RH)

The BS EN 15251, ASHRAE standard 55, and MS 2680 models were adopted to calculate the required comfort temperature using Eq. (2), Eq. (3), and Eq. (5), respectively. Based on these equations, the comfort temperature was calculated with reference to the monthly mean outdoor temperature and is presented in Table 4. As can be seen, the required comfort temperature is calculated using the three thermal comfort models and the obtained average comfort temperature for the study period was 28 ℃, while the average upper limit of the comfort temperature was 30℃. It is noticed that these results agreed well with the results obtained by the field thermal comfort studies.

Table 4
Calculation of the comfort temperature for the study period with regard to the outdoor air temperature

			Dec	Jan	Feb	Mar	Average
Monthly mean outdoor temperature	T_{mmo}	℃	27.95	26.86	28.51	29.25	-
MS 2680	T_{op}	℃	29.73	29.11	30.05	30.47	30
ASHRAE Standard 55 (Upper limit)	T_{op}	℃	29.96	29.63	30.14	30.37	30
BS EN 15251 (Comfort temperature)	T_{op}	℃	28.02	27.66	28.21	28.45	28
BS EN 15251 (Upper limit)	T_{op}	℃	30.02	29.66	30.21	30.45	30

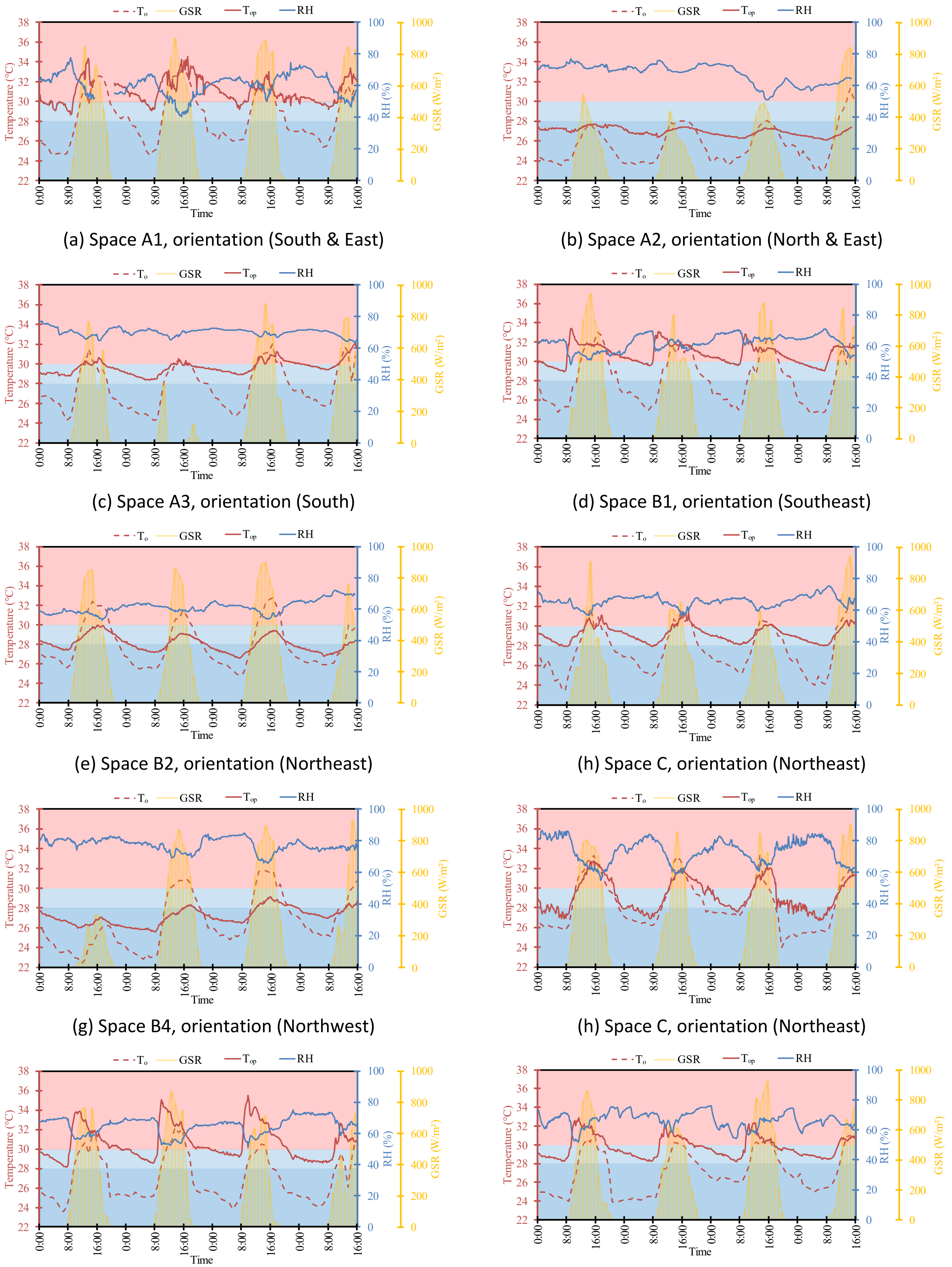
To evaluate the thermal comfort level in the investigated spaces, three levels were adopted based on the thermal comfort temperature limits that were calculated using the thermal comfort models for naturally conditioned buildings in Table 4, as follows example

i. Thermal comfort (TC) zone: T_{op} is below or equal to 28 ℃,
ii. Relative thermal comfort (RTC) zone: T_{op} is above 28 ℃ and below/equal to 30 ℃,
iii. Thermal discomfort (TD) zone: T_{op} is above 30 ℃.

3. Results and Discussion

Field measurements for the indoor environment of the selected buildings were conducted in this study. Figure 5 illustrates the T_o, GSR, T_{op}, and RH for all the investigated spaces. The figure's background was divided into three coloured areas, representing the TC zone, RTC zone, and TD zone. Generally, the maximum T_o reached between 32 ℃ and 34 ℃ in most cases, while it did not increase higher than 28 ℃ in a few cases, such as in Spaces A2, Figure 5 (b). This is attributed to the weather condition, which can be confirmed by the GSR that reached around 900 W/m² on sunny days compared to an average of 500 W/m² on cloudy days. Furthermore, the RH was, on average, between 60% and 80%. However, the fluctuation of the RH was different between the case studies (*i.e.,* high fluctuation, such as in Space C and low fluctuation, such as in Space A2). The RH fluctuation is linked to indoor temperature fluctuation. RH describes the water vapour percentage in the air. Therefore, when the air temperature increases, the air expands, and the spaces that hold water molecules increase, resulting in lower RH and vice versa.

Moreover, the T_{op} fluctuation was observed in most cases, which is linked to the continuous changes in weather conditions. Additionally, different fluctuation profiles of T_{op} were obtained between the case studies due to many factors, including different measurement periods and weather conditions, spaces' orientation, floor height, window-to-wall ratio (WWR), and the status of the windows and curtains (*i.e.,* opened or closed). Generally, the spaces can be grouped based on the T_{op} profile into three main categories; spaces with T_{op} mainly above the upper comfort limit (i.e., above 30 ℃), such as in Spaces A1, B1, and D, spaces with T_{op} mostly below the upper comfort limit, such as in Spaces A2, A3, B2, B3, and B4, and spaces with T_{op} fluctuating above and below the upper comfort limit, such as in Spaces C and E.

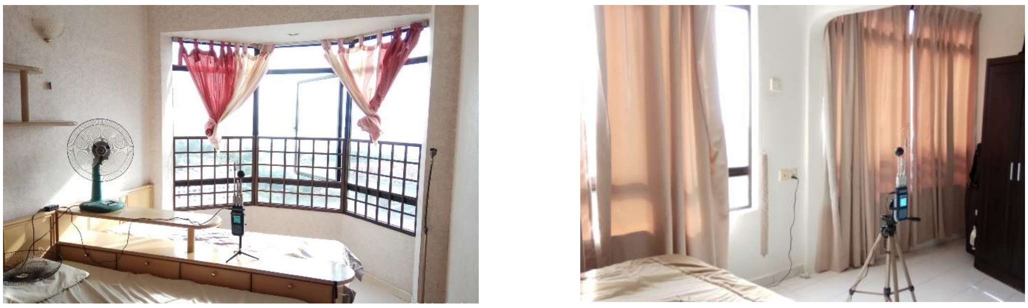


(a) Space A1, orientation (South & East)
(b) Space A2, orientation (North & East)
(c) Space A3, orientation (South)
(d) Space B1, orientation (Southeast)
(e) Space B2, orientation (Northeast)
(h) Space C, orientation (Northeast)
(g) Space B4, orientation (Northwest)
(h) Space C, orientation (Northeast)
(i) Space D, orientation (East)
(j) Space E, orientation (East)

Fig. 5. The outdoor air temperature (T_o), global solar radiation (GSR), indoor operative temperature (T_{op}), and relative humidity (RH) for all the investigated spaces

The effect of the incident solar radiation on the buildings' façades in increasing the T_{op} can be seen obviously in Figure 5. For instance, a higher T_{op} fluctuation was observed in the spaces with an orientation toward the East, South, and Southeast. These spaces were exposed to solar radiation during the study period. Therefore, the incident solar radiation can penetrate through the fenestration to the indoor environment and/or conduct as heat through the opaque envelope of the building, which increases the T_{op}. In contrast, all spaces with orientations related to the North, which did not expose to solar radiation during the study period, had lower T_{op}, such as in Spaces B2 and B4. For the case of Space C, even though it has an orientation to the Northeast, it had high T_{op} with a high average daily fluctuation of 5-6 ℃, Figure 5 (h). This space is on the uppermost floor and only separated by an attic from the roof. Besides, the sky condition was mainly sunny during the measurement in this space. Therefore, due to heat gain from the roof, the T_{op} in this space reached higher records than the other spaces with a similar orientation. Moreover, the lower minimum T_{op} recorded in this space can be attributed to achieving good cross-natural ventilation due to the fully opened windows, curtains, and door (*i.e.,* the unit was unoccupied during the study period).

The T_{op} profile in spaces A2 and B4, Figure 5 (b) & (g), shifted down by an average of 1-2 ℃, producing the lowest T_{op} records among all spaces. This is attributed to the effects of the cloudy and rainy weather. On the other hand, in space B1, Figure 5 (d), space D, Figure 5 (g), and space E, Figure 5 (j), a step increase in T_{op} was noticed around 8:00, which is linked to the effects of the direct sun rays during the sunrise (*i.e.,* East oriented spaces). Additionally, in space D, the steep increase in T_{op} reached around 36 ℃, which can be linked to the penetration of direct solar radiation into the space during the sunrise due to the fully opened curtains, as shown in Figure 6 (a). Additionally, the instrument was installed in the middle of space, which received direct solar radiation during sunrise, causing the high T_{op}. In contrast, the window's curtains were almost closed in Space E, Figure 6 (b), resulting in lower T_{op} compared to Space D despite the comparable weather conditions. Penetrating direct solar radiation into the space can cause local discomfort for the occupants, suggesting the need to close the window's curtains to avoid these adverse effects related to the East orientation.



(a) (b)

Fig. 6. (a) Penetration of solar radiation through the window into the room during the sunrise in the East-oriented room due to fully opened curtains (Space D) and (b) closing window's curtains to prevent solar radiation penetration into the room in the East-oriented room (Space E)

It is worth mentioning that no measurements were conducted in a space with the absolute west orientation due to difficulty finding an accessible west-oriented space. However, it can be observed that the spaces with Southwest and Northwest orientations had lower T_{op} compared to those that faced South and East. This is in line with Ahmad *et al.,* [38] and Ling *et al.,* [39], who found that the west wall received less solar radiation than the East and the South walls. This was attributed to the lower exposure time to the solar radiation for the west wall (*i.e.,* around 4-5 hours) compared to the south wall (*i.e.,* an average of 7 hours). Besides, the frequent occurrence of cloudy and rainy weather during the afternoon is higher in Malaysia [24, 39], which can lower the temperature profiles for West-oriented spaces.

Figure 7 illustrates the Max, Avg., Min, and fluctuation of T_{op} throughout the study period of each space. Based on the figure, the Max T_{op} reached above 30 °C (*i.e.,* the upper limit of the relative thermal comfort zone) in seven of the ten investigated rooms, and it was above 32 °C in six of them. Space D had the highest Max. T_{op}, *i.e.,* 35.50 °C, followed by Space A1, Space B1, Space C, Space E, Space A3, and Space B3, i.e., 34.56 °C, 33.40 °C, 32.86 °C, 32.75 °C, 32.10 °C, and 31.35 °C, respectively. The orientation of the rooms from the one with the highest Max T_{op} to the one with the lowest Max T_{op} is as follows: East, South & East, Southeast, East, North, South, Southwest, Northeast, Northwest, and North & East. The rooms with the highest Max T_{op} have orientations toward the East, South, and West detractions, except for Space C, which had a high Max T_{op} due to its location on the uppermost floor level, as mentioned earlier. In contrast, the other rooms with Max T_{op} below 30°C have orientations toward the North, Northeast, and Northwest.

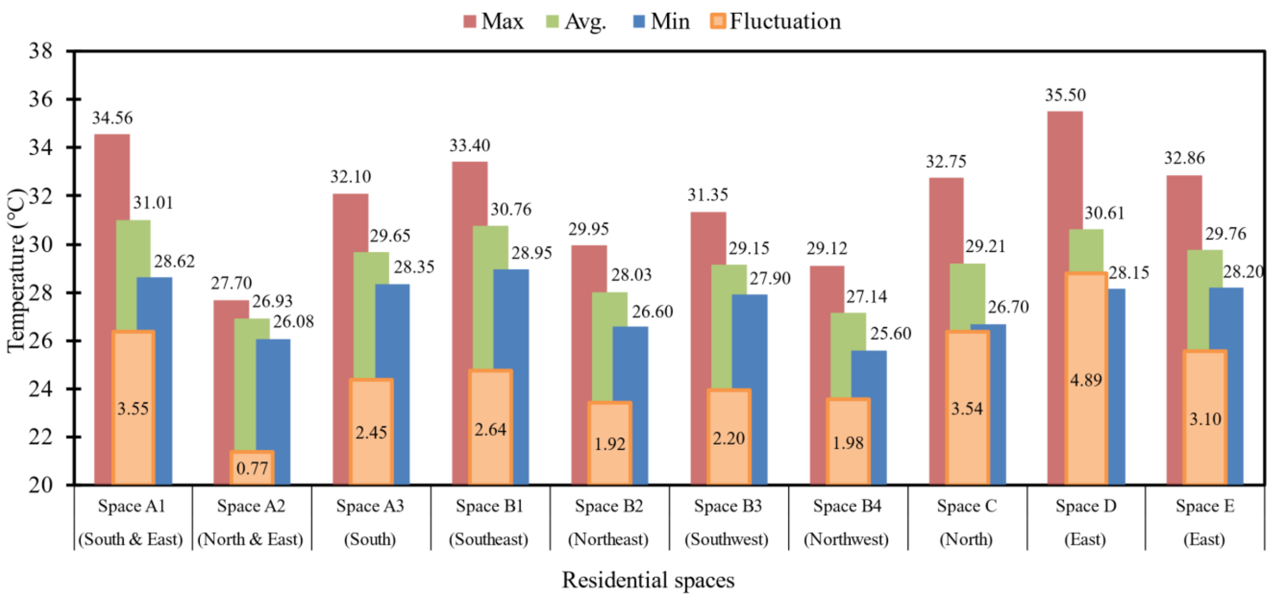


Fig. 7. Max, Avg., Min, and fluctuation of T_{op} throughout the study period of each space

On the other hand, Space A1 had the highest Avg. T_{op}, followed by Space B1, Space D, Space E, Space A3, Space C, Space B3, Space B2, Space B4, and Space A2. The orientations of these rooms are as follows: South & East, Southeast, East, East, South, North, Southwest, Northeast, Northwest, and North & East. Interestingly, Space A1 had the highest Avg. T_{op} while Space D had the highest Max. T_{op}. This reveals that space with an orientation towards the East can receive direct solar radiations only in the early morning, which penetrate into the space due to the sun's lower position during the sunrise, only if the window's curtains were opened, resulting in high Max T_{op} (see Space D). In contrast, a space with an orientation towards East & South or Southeast will receive solar radiation for a more extended period, i.e., from sunrise until the sun starts to set, resulting in a higher Avg. T_{op}.

Furthermore, only five of the ten investigated rooms had Min T_{op} below 28 °C (*i.e.,* the upper limit of thermal comfort zone), which are Space A2, Space B2, Space B3, Space B4, and Space C. These spaces have the following orientations; North & East, Northeast, Southwest, Northwest, and North, respectively). All these spaces were not exposed to solar radiation during the study period, resulting in lower T_{op} profiles, except for Space B3 with the Southwest orientation, which had a lower T_{op} profile due to the presence of the clouds during the afternoon in Malaysia.

By calculating the time in which the T_{op} was within the TC zone, RTC zone, and TD zone, the results are illustrated in Figure 8. As shown in the figure, only spaces oriented to the North, Northeast, and Northwest had time within the TC zone, while most of the other spaces with South, East, and West orientations were within the RTC zone. Additionally, more time within the TD zone was obtained in the South- and Southeast-oriented spaces (*i.e.,* 70 - 73%), followed by East-orientated spaces (*i.e.,* 35 - 52%). However, no TD time was obtained in the North-, Northeast-, and Northwest-oriented spaces, except for Space C, which had heat gain through the roof. Furthermore, the figure illustrates how the windows with closed curtains can reduce the TD time, as in Space E, compared to opened curtains, as in Space D, despite their orientations to the East.

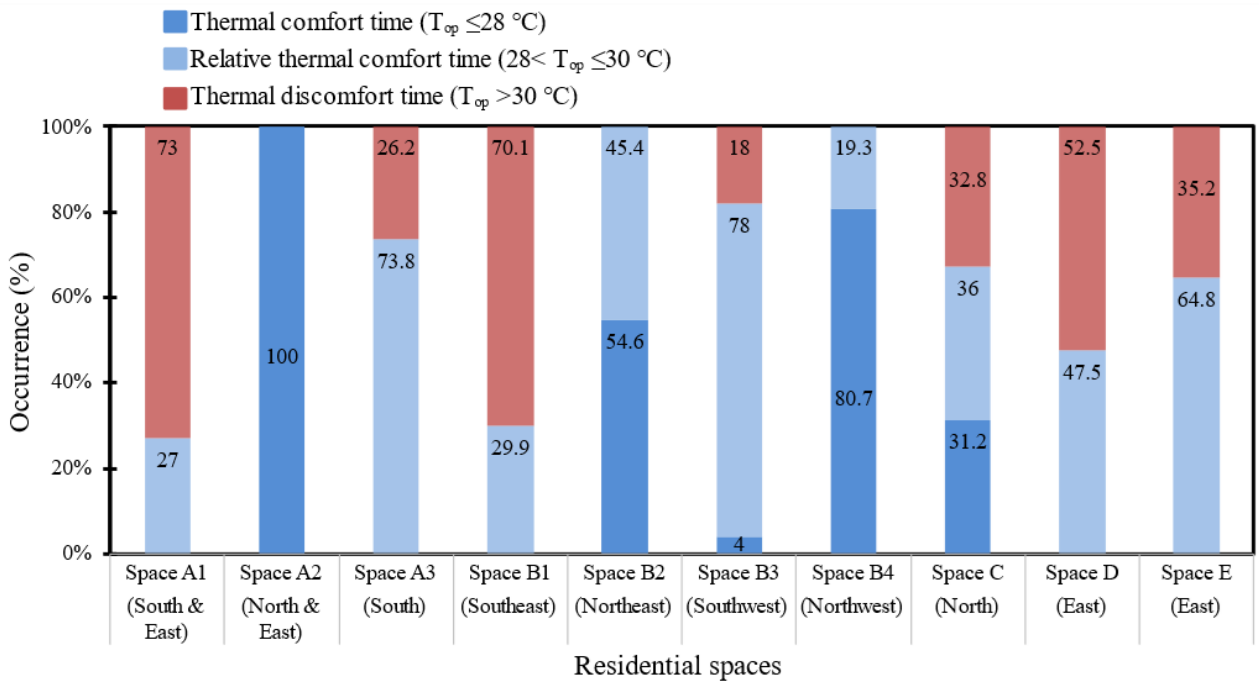


Fig. 8. Percentage of the time in which the T_{op} was within the Thermal comfort zone, Relative thermal comfort zone, and Thermal discomfort zone

Furthermore, Figure 9 shows the thermal comfort evaluation for the spaces based on the daytime (*i.e.,* 07:00 to 19:00) and night-time (19:00 to 07:00). The figure confirms that spaces with orientations to the South & East, Southeast, and South had the worst thermal comfort conditions throughout the study period, especially during the daytime. Additionally, spaces with orientations to the East had thermal discomfort conditions during the daytime, while the indoor thermal conditions improved significantly during the night-time.

As discussed earlier, the field measurements were conducted for all spaces within the period in which the sun is tilted to the Southside, which increased the solar radiations received by spaces with orientations toward the South, while no solar radiations were received in spaces with orientations related to the North. Additionally, the sun's position in the sky during the sunrise and sunset is low, which increases the depth of the solar radiation's penetration into the spaces resulting in more heat. However, the East orientation was more critical than the West orientation due to the higher chances of cloudy weather in the afternoon time in Malaysia. Furthermore, it is evident that the most critical parameter that affects the heat gain in all spaces is exposure to direct solar radiation. Therefore, those spaces with North-based orientations might get higher heat gain when the sun is tilted to the Northside (*i.e.,* from April to August). Finally, it should be noted that although the windows were opened during the measurements in some spaces to allow cool night ventilation to reduce the internal heat, adequate cross-night natural ventilation is not achieved easily. Therefore, applying effective night mechanical ventilation might help to reduce indoor temperatures and remove the trapped heat during the daytime.

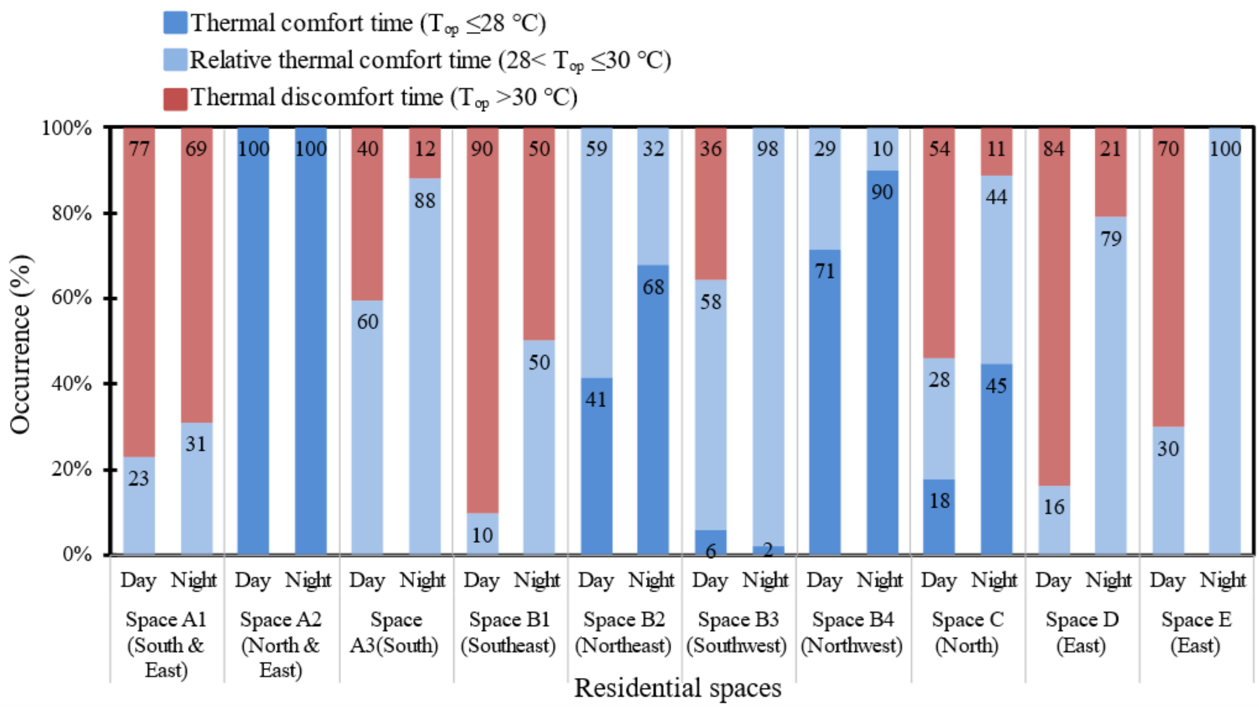


Fig. 9. Percentage of the time in the day and night in which the T_{op} was within the Thermal comfort zone, Relative thermal comfort zone, and Thermal discomfort zone

4. Conclusions

This study involved field measurements in various residential spaces. The aim was to investigate and evaluate the indoor thermal environment and the thermal comfort level based on the adaptive thermal comfort models for naturally conditioned spaces (*i.e.,* no Air-conditioning). The mean conclusions were as follows

i. Most of the spaces recorded high T_{op}, with T_{op} peaks exceeding 32 °C, especially for the East-oriented spaces, which reached up to 35.50 °C. However, the average T_{op} in many of the spaces was below 30 °C (i.e., the upper limit of the comfort condition). Additionally, some of the spaces showed low T_{op} profiles with T_{op} peaks below 30 °C and average T_{op} around 28 °C.
ii. The spaces with orientations to the South & East, Southeast, South, and East were more critical during the study period since they received direct solar radiation. The Southeast and South orientations resulted in longer heat gain time throughout the day, which was more critical than the East orientation that resulted in heat gain during the early morning. The West orientation was less critical on the heat gain to the spaces due to the high potential for the occurrence of cloudy weather. In contrast, all spaces with orientation to the North, Northeast, and Northwest showed better indoor thermal environments since they did not expose to solar radiation during the study period.

iii. Most spaces with orientations to the South & East, Southeast, South, and East were in the thermal discomfort zone for about 50 – 70% of the time. In contrast, spaces with orientation to the North, Northeast, and Northwest showed thermal comfort conditions throughout the day (i.e., 0% thermal discomfort time).
iv. Using some of the passive techniques, such as closing the curtains and applying cross ventilation, can significantly reduce the heat gain and improve the indoor thermal environment.

Finally, this work revealed that the most critical parameter in the heat gain to the buildings is the exposure to solar radiation. In the studied area, the East- and West-oriented spaces receive solar radiation during sunrise and sunset, respectively, throughout the year. In contrast, the South- and North-oriented spaces receive solar radiation throughout the daytime depending on the sun's path (*i.e.,* to the Southside during October-February or to the Northside during April-August). Therefore, the daily average heat gain to the building from the South and North Orientatios might be higher than that from the East and West orientations.

Acknowledgement
The authors would like to thank Universiti Sains Malaysia for providing financial support through Research University Grant number (1001/PPBGN/814285) and USAINS Holding Sdn. Bhd. For Industrial Grant (R176) (Contract Research) of the Post-Doctoral Programme. The first author also acknowledges support from the Department of Architecture, Faculty of Engineering, Sana'a University.

References
[1] Pisello, A. L., I. Pigliautile, M. Andargie, Christiane Berger, P. M. Bluyssen, S. Carlucci, G. Chinazzo et al. "Test rooms to study human comfort in buildings: A review of controlled experiments and facilities." *Renewable and Sustainable Energy Reviews* 149 (2021): 111359. https://doi.org/10.1016/j.rser.2021.111359
[2] Fahmy, M., M. Morsy, H. Abd Elshakour, and A. M. Belal. "Effect of thermal insulation on building thermal comfort and energy consumption in Egypt." *Journal of Advanced Research in Applied Mechanics* 43, no. 1 (2018): 8-19.
[3] Al-Absi, Zeyad Amin, Mohd Isa Mohd Hafizal, Mazran Ismail, Hanizam Awang, and Abdullah Al-Shwaiter. "Properties of PCM-based composites developed for the exterior finishes of building walls." *Case Studies in Construction Materials* 16 (2022): e00960. https://doi.org/10.1016/j.cscm.2022.e00960
[4] Tan, Huiyi, Keng Yinn Wong, Hong Yee Kek, Kee Quen Lee, Haslinda Mohamed Kamar, Wai Shin Ho, Hooi Siang Kang et al. "Small-scale botanical in enhancing indoor air quality: A bibliometric analysis (2011-2020) and short review." *Progress in Energy and Environment* 19 (2022): 13-37. https://doi.org/10.37934/progee.19.1.1337
[5] Ma, Nan, Dorit Aviv, Hongshan Guo, and William W. Braham. "Measuring the right factors: A review of variables and models for thermal comfort and indoor air quality." *Renewable and Sustainable Energy Reviews* 135 (2021): 110436. https://doi.org/10.1016/j.rser.2020.110436
[6] Sidik, Nor Azwadi Che, Tung Hao Kean, Hoong Kee Chow, Aravinthan Rajaandra, Saidur Rahman, and Jesbains Kaur. "Performance enhancement of cold thermal energy storage system using nanofluid phase change materials: a review." *International Communications in Heat and Mass Transfer* 94 (2018): 85-95. https://doi.org/10.1016/j.icheatmasstransfer.2018.03.024
[7] Ganesh, Ghogare Abhijeet, Shobha Lata Sinha, Tikendra Nath Verma, and Satish Kumar Dewangan. "Investigation of indoor environment quality and factors affecting human comfort: A critical review." *Building and Environment* 204 (2021): 108146. https://doi.org/10.1016/j.buildenv.2021.108146
[8] Shaari, Abdul Muin, Kamil Abdullah, Mohd Faizal Mohideen Batcha, Hamidon Salleh, and Makatar Wae-Hayee. "Effect of Converging Duct on Solar Chimney." *CFD Letters* 12, no. 3 (2020): 89-97. https://doi.org/10.37934/cfdl.12.3.8997
[9] Al-Absi, Zeyad Amin, Mohd Hafizal Mohd Isa, and Mazran Ismail. "Assessment of Building Façade Thermal Performance for the Potential Application of Phase Change Materials (PCMs) in Malaysia, a Case Study." In *ICACE 2019*, (2020): 129-141. https://doi.org/10.1007/978-981-15-1193-6_15

[10] American Society of Heating, Refrigerating and Air-Conditioning Engineers. *Thermal Environmental Conditions for Human Occupancy: ANSI/ASHRAE Standard 55-2017 (Supersedes ANSI/ASHRAE Standard 55-2013) Includes ANSI/ASHRAE Addenda Listed in Appendix N*. Ashrae, 2017.

[11] Putra, Nandy, Evi Sofia, and B. Ali Gunawan. "Evaluation of Indirect Evaporative Cooling Performance Integrated with Finned Heat Pipe and Luffa Cylindrica Fiber as Cooling/Wet Media." *Journal of Advanced Research in Experimental Fluid Mechanics and Heat Transfer* 3, no. 1 (2021): 16-25.

[12] Fohimi, Nor Azirah Mohd, Muhammad Hanif Asror, Rosniza Rabilah, Mohd Mahadzir Mohammud, Mohd Fauzi Ismail, and Farid Nasir Ani. "CFD Simulation on Ventilation of an Indoor Atrium Space." *CFD Letters* 12, no. 5 (2020): 52-59. https://doi.org/10.37934/cfdl.12.5.5259

[13] Al-Absi, Zeyad Amin, and Noor Faisal Abas. "Subjective assessment of thermal comfort for residents in naturally ventilated residential building in Malaysia." In *IOP Conference Series: Materials Science and Engineering* 401, no. 1 (2018): 012009. https://doi.org/10.1088/1757-899X/401/1/012009

[14] Toe, Doris Hooi Chyee, and Tetsu Kubota. "Development of an adaptive thermal comfort equation for naturally ventilated buildings in hot–humid climates using ASHRAE RP-884 database." *Frontiers of architectural research* 2, no. 3 (2013): 278-291. https://doi.org/10.1016/j.foar.2013.06.003

[15] Humphreys, M. A., H. B. Rijal, and J. F. Nicol. "Updating the adaptive relation between climate and comfort indoors; new insights and an extended database." *Building and environment* 63 (2013): 40-55. https://doi.org/10.1016/j.buildenv.2013.01.024

[16] Al-Absi, Zeyad, and Abas, Noor. (2019). "Adaptive Behavior Of Residents For Thermal Comfort In High-Rise Residential Building, Malaysia. " *in: J. Wahid, A.A. Abdul Samad, S.S. Ahmad, P. Pujinda (Eds.), Eur. Proc. Multidiscip. Sci., Future Academy*, (2020): 404-414. https://doi.org/10.15405/epms.2019.12.39

[17] De Dear, Richard, and Gail Schiller Brager. "Developing an adaptive model of thermal comfort and preference." *ASHRAE Trans*. 104, (1998): 145-167.

[18] Comite'Europe'en de Normalisation, C. E. N. "Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics." *EN 15251* (2007).

[19] Nicol, Fergus. "The Limits of Thermal Comfort: Avoiding Overheating in European Buildings." *CIBSE TM52:2013*. *Cibse*, (2013).

[20] Al-Absi, Zeyad Amin, Mohd Isa Mohd Hafizal, Mazran Ismail, Ahmad Mardiana, and Azhar Ghazali. "Peak indoor air temperature reduction for buildings in hot-humid climate using phase change materials." *Case Studies in Thermal Engineering* 22 (2020): 100762. https://doi.org/10.1016/j.csite.2020.100762

[21] MMD, "Malaysia's climate. " *Malaysian Meteorol. Dep.* (2020). http://www.met.gov.my/pendidikan/iklim/iklimmalaysia?lang=en (accessed June 11, 2020).

[22] Al-Absi, Zeyad Amin, Mohd Isa Mohd Hafizal, Mazran Ismail, and Azhar Ghazali. "Towards Sustainable Development: Building's Retrofitting with PCMs to Enhance the Indoor Thermal Comfort in Tropical Climate, Malaysia." *Sustainability* 13, no. 7 (2021): 3614. https://doi.org/10.3390/su13073614

[23] Malaysian Meteorological Department. "Annual report 2019." *Malaysian Meteorological Department, Selangor,* (2019).

[24] Standard, Malaysian. "Energy efficiency and use of renewable energy for non-residential buildings-Code of practice." (2014).

[25] Tang, C. K., and Nic Chin. "Building energy efficiency technical guideline for passive design." *Public Works Department Malaysia, Kuala Lumpur* (2013).

[26] Malaysian Standard, MS 2680:2017. "Energy efficiency and use of renewable energy for residential buildings - Code of practice." *Department of Standards Malaysia,* (2017).

[27] Abdulshukor, Abdulmalik Bin. "Human thermal comfort in tropical climates." *University of London, University College London (United Kingdom)*, (1993).

[28] Dahlan, Nur Dalilah, Phillip John Jones, Donald Kneale Alexander, E. Salleh, and Dylan Dixon. "Field measurement and subjects' votes assessment on thermal comfort in high-rise hostels in Malaysia." *Indoor and Built Environment* 17, no. 4 (2008): 334-345. https://doi.org/10.1177/1420326X08094585

[29] Hussein, Ibrahim, M. Hazrin A. Rahman, and Tina Maria. "Field studies on thermal comfort of air-conditioned and non air-conditioned buildings in Malaysia." In *2009 3rd International Conference on Energy and Environment (ICEE)*, (2009): 360-368. https://doi.org/10.1109/ICEENVIRON.2009.5398622

[30] Djamila, Harimi, Chi-Ming Chu, and Sivakumar Kumaresan. "Field study of thermal comfort in residential buildings in the equatorial hot-humid climate of Malaysia." *Building and Environment* 62 (2013): 133-142. https://doi.org/10.1016/j.buildenv.2013.01.017

[31] Damiati, Siti Aisyah, Sheikh Ahmad Zaki, Hom Bahadur Rijal, and Surjamanto Wonorahardjo. "Field study on adaptive thermal comfort in office buildings in Malaysia, Indonesia, Singapore, and Japan during hot and humid season." *Building and Environment* 109 (2016): 208-223. https://doi.org/10.1016/j.buildenv.2016.09.024

[32] Sun-Path chart, (2017). http://andrewmarsh.com/apps/releases/sunpath2d.html (accessed December 31, 2017).

[33] Hoovestol, Ryan A., and Ted R. Mikuls. "Environmental exposures and rheumatoid arthritis risk." *Current rheumatology reports* 13, no. 5 (2011): 431-439. https://doi.org/10.1007/s11926-011-0203-9

[34] Rijal, H. B., M. A. Humphreys, and J. F. Nicol. "Adaptive model and the adaptive mechanisms for thermal comfort in Japanese dwellings." *Energy and Buildings* 202 (2019): 109371. https://doi.org/10.1016/j.enbuild.2019.109371

[35] Ling, Haoshu, Chao Chen, Shen Wei, Yong Guan, Caiwen Ma, Guangya Xie, Na Li, and Ziguang Chen. "Effect of phase change materials on indoor thermal environment under different weather conditions and over a long time." *Applied Energy* 140 (2015): 329-337. https://doi.org/10.1016/j.apenergy.2014.11.078

[36] James, Appah–Dankyi, and Koranteng Christian. "An assessment of thermal comfort in a warm and humid school building at Accra, Ghana." *Advances in Applied Science Research* 3, no. 1 (2012): 535-547.

[37] AC08013621, Anonymus, ed. "Ergonomics of the thermal environment-Instruments for measuring physical quantities. " *ISO*, (1998). https://doi.org/10.3403/02509505

[38] Ahmad, M. Hamdan, Dilshan R. Ossen, and Chia Sok Ling. "Impact Of Solar Radiation On High-Rise Built Form In Tropical Climate." In *The 5th International Seminar on Sustainable Environment Architecture*, (2004).

[39] Ling, Chia Sok, Mohd Hamdan Ahmad, and Dilshan Remaz Ossen. "The effect of geometric shape and building orientation on minimising solar insolation on high-rise buildings in hot humid climate." *Journal of Construction in Developing Countries* 12, no. 1 (2007): 27-38.