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Evaluation of Outdoor Thermal Comfort Between Internal and External Space of Circular Courtyard Building in Hot Humid Climate

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Abstract: Global warming is becoming a common issue that cause global climate change and affect thermal environment of building. In fact, the effectiveness of passive cooling building design such as courtyard building is still not fully explored especially in hot-humid climate. This study is aimed to evaluate the outdoor thermal performance between the internal and external courtyards based on the objective and subjective measurement. Four environmental parameter sensor (air temperature, relative humidity, globe temperature and wind speed) were set at internal and external courtyard to assess the thermal performance of circular courtyard in objective measurement and conducted simultaneously with questionnaire survey in subjective measurement to evaluate the effectiveness of outdoor thermal performance of circular courtyard. Based on the physical measurement, the results show that the internal courtyard is cooler than the external courtyard which the temporal variation of operative temperature in range of 0.2°C to 14.5°C, relative humidity in range of 1% to 51% and wind speed in range of 0 m/s to 2.27 m/s. Meanwhile, thermal comfort assessment by the subjective response shows that majority of respondents felt slightly warm, neutral and slightly cool with comfort temperature 29.8°C, 29.0°C and 28.0°C respectively in morning, while felt hot, warm and slightly warm in the evening with temperature 34.0°C, 33.2°C and 32.6°C respectively. Moreover, the heat stress assessment by Universal Thermal Climate Index (UTCI) showed the average temperature in internal courtyard is in range of 29.9°C which indicate moderate heat stress level and external courtyard is 33.9°C to 37.3°C indicate strong heat stress level. These finding shows that the courtyard building design is able to provide comfortable living space in hot humid climate.

Keywords: Outdoor Thermal Comfort, Circular Courtyard, Hot Humid Climate, Thermal Sensation, Universal Thermal Climate Index

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1. Introduction

Global warming is a problematic issue in the world and caused by the carbon dioxide (CO_2) emission and urbanization of cities. The amount of CO_2 emission in the world is constantly increasing from 29,918 $MtCO_2$ in 2010 to 32,743 $MtCO_2$ in 2019 [1]. It caused the climate of the world has changed tremendously in past decade due to the fast population growth and rapid urbanization of cities, The urbanization rate increases because of the expansion of urban land and it will cause the green space area decrease and cause thermal discomfort to occupants in urban buildings [2]. Meanwhile the thermal stress level will all-time high and will have a negative impact on human beings. Therefore, the semi-open space is essential needed in building to control the thermal level. It is because the semi-open space is partly exposed to the outdoor environment and it means the condition of open space and semi-open spaces are directly influenced by climate change [3]. Therefore, some open spaces of building will design and create a semi-open roof to maintain control thermal environment of building [4]. Thermal comfort in ASHRAE is defined as a ‘ mind state that expresses satisfaction in sensation with the thermal environment ’ [5]. Outdoor thermal comfort is opposed to indoor thermal comfort. Buildings are made for people to live in and must consider the thermal comfort when being designed. Nowadays, outdoor thermal comfort is always considered in building design in the construction industry to optimize the outdoor thermal comfort of the building environment. Malaysia is a country with tropical weather year round and maximum temperatures always in 38°C average throughout a year [6]. In tropical climates, thermal comfort is obtained by reducing temperatures to adequate levels. According to the urban planning aspect, thermal comfort and heat stress are the main parameters affect outdoor spaces which can affect the life quality [7].

This study was aimed to evaluate the outdoor thermal performance between internal and external courtyards based on the objective and subjective assessment. The study was conducted at Tunku Tun Aminah Library (PTTA) UTHM. This building is use a circular courtyard design in middle semi-open space as a way to optimize the outdoor thermal comfort effect. Therefore, this study was focused on the re-evaluation of outdoor thermal comfort and performance between internal and external of circular courtyard building due to the hot and humid climate in Malaysia nowadays is becoming greatly affected the thermal performance of circular courtyard building.

2. Literature Review

2.1 Courtyard building

Courtyard building is defined as the semi-outdoor or outdoor spaces that surround with building’s wall. Semi-outdoor environments are characterized as areas that are placed between the interior and outdoor layers with partly exposure to the outdoor environments such as lobbies, verandas and courtyards [8]. Due to global warming and population growth, semi-open space is widely used to enhance the life quality, health condition and social economy [9]. A study from Zhang points out the semi-open transition spaces will cause thermal parameters analysis become difficult due to the unpredictable characteristics in semi-open space [10]. From the study Nugroho, semi-open spaces in courtyard building nowadays are very important in creating a comfortable environment and providing space for daytime activities, unfortunately these spaces is lack of attention in different type of climate in the previous literature [11]. In hot-humid climate, the elements of courtyard that always be discussed are courtyard orientation, sky view factor from courtyard space, courtyard roof shape and courtyard geometry size [11].

2.2 Notion of Outdoor Thermal Comfort

Outdoor thermal comfort is the opposite of indoor thermal comfort. Outdoor thermal comfort is defined as the comfort level of a man about thermal environment when exposed in outdoor environment at outdoor area [12]. Due to the multifactorial interactions between human and the varying in environment, it become complex in outdoor thermal comfort determination. The different thermal environment will cause people has different reactions and repeated exposure to a different thermal environment can cause a person discomfort in terms of psychological and behavioural in adaptation [12].

2.3 Outdoor Thermal Comfort Measurement

Micro-Meteorological is a physical measurement to measure the microclimatic condition at the surroundings of the occupants during the subjective assessment. Microclimate measurement will take several days to conduct the data collection. This assessment must be conducted by in-situ measurement to collect the microclimatic condition data and field site data such as morphology, building ratio and other physical data that need to be collected to assess the outdoor thermal comfort [13]. The common parameters that are collected from micro-meteorological data are relative humidity, wind speed, air temperature, solar radiation and globe temperature. In thermal comfort study, the general environmental parameters that commonly used are air temperature (T_a), relative humidity (RH), mean radian temperature (T_{mrt}) and wind speed (V_a).

Subjective assessment in thermal comfort is an assessment about the thermal sensation, thermal perception or thermal adaptation in current thermal environment. This assessment is conducted by using face to face interview due to its include the physiological, psychological and social behaviour of the subjects [3]. Its need to be conducted simultaneously with the microclimatic measurement. The objective measurement had been carried out simultaneously with a subjective survey at the same time. The questionnaire that should be conducted to assess the outdoor thermal comfort is needed to design by using ANSI/ASHRAE Standard 55. The procedure of questionnaire is conducted with two parts, there are demographic information such as gender, age, height, clothing insulation level and activity types and thermal sensation from subjects. The external parameters will be considered such as metabolic rate about the activity level and the clothing (Clo) value to analyze the outdoor thermal comfort condition [14].

2.4 Outdoor Thermal Comfort Index

Thermal Comfort Index is the indices that is are used for defining comfort and comfort limits. It can assess past exposures and determine the classification of climate zones. There are several factors of environmental variables is important in thermal comfort indices such as relative humidity, wind speed, air temperature and mean radiant temperature. Besides, it also includes metabolic activity level and clothing insulation. From the previous studies, the majority of thermal comfort indices were used to evaluate indoor thermal conditions and it has been used to investigate thermal comfort perceptions in thermal environments [15]. For the outdoor thermal comfort Indices, the latest study mostly uses the Physiological Equivalent Temperature (PET), Predicted Mean Vote (PMV), Standard Effective Temperature (SET) and Universal Thermal Climate Index (UTCI). Some of the research that studies focused on semi-open space is prefer used PET, OUTSET and UTCI.

3. Materials and Methods

This study was separate in two phase, there are fieldwork measurement and analysis phase. In fieldwork phase, objective and subjective assessment was conducted to investigate the thermal performance in courtyard building. Therefore, four environmental parameters such as air temperature, wind speed, globe temperature and air humidity were used to investigate the thermal environment effect on internal courtyard to external courtyard. Meanwhile, the outdoor thermal comfort was assessed by thermal sensation from subjects.

3.1 Equipment

To conduct this study, some specified instrument was used to investigate the thermal performance surrounding courtyard. To determine the four parameter, the instruments that specified use in outdoor thermal evaluation has Thermo Recorder TR-72U, Thermo Recorder TR-52 and LM-8000 4 in

1 meter kit. Table 1 shows the parameter of equipment used. All instruments were set up at center of internal courtyard and three cardinal directions (east, west and south) of external courtyard and install at 1.1 m height. Figure 1, 2 and 3 shows Thermo Recorder TR-72U, Thermo Recorder TR-52 and LM-8000 4 in 1 meter kit respectively.

Table 1: Parameter of equipment used

Type of equipment used	Parameter	Unit
Thermo Recorder TR-72U	Air temperature	ºC
	Relative humidity	%
Thermo Recorder TR-52	Globe temperature	ºC
LM-8000 4 in 1 meter kit	Wind speed	m/s

Figure 1: Thermo Recorder TR-72U

Figure 2: Thermo Recorder TR-52

Figure 3: LM-8000 4 IN 1 Multi-Function Meter

3.2 Methods

This study was conducted with using the objective and subjective assessment as method of outdoor thermal comfort assessment. The data analysis was based on the comparison between Thermal Sensation Vote (TSV) and Universal Thermal Climate Index (UTCI).

(a) Objective Assessment

Micro-meteorological measurement is the common objective measurement to determine the microclimatic condition in outdoor thermal comfort assessment. This measurement is a physical parameter to characterize the thermal comfort sensation and thermal environment variables, there is air temperature, globe temperature, wind speed and humidity. During objective assessment, parameters data was collected 3 days at the east, west and south of external courtyard respectively. Each location was collected simultaneously with the internal courtyard to investigate the thermal environment effect on internal courtyard space compared to external courtyard. The data analyzed was based on the parameters to calculate mean radiant temperature and operative temperature. Figure 4 shows the plan view of measurement position for instrument setup at courtyard building.

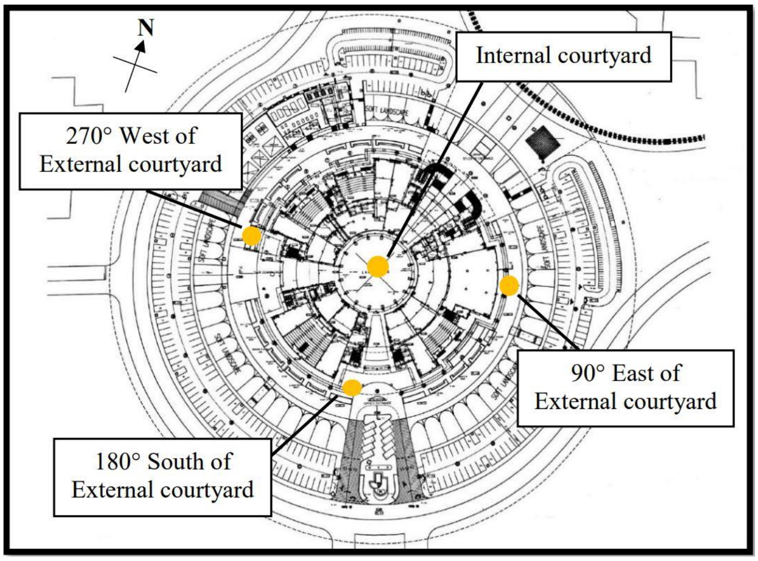

Figure 4: Plan view of measurement position for instrument setup

(b) Subjective Assessment

Subjective assessment is a method that use a face to face questionnaire survey to assess outdoor thermal comfort from subjects. In this assessment method, it purposed to evaluate the outdoor thermal comfort on internal and external courtyard based on subjective assessment. Therefore, this questionnaire was target respondents by up to 100 persons in the study area and both of the internal and external courtyard has 50 subjects to respond questionnaires. All respondents were required stay at study location at least 15 to 20 minutes to adapt the current thermal environment in circular courtyard. The questionnaire recorded the personal information, personal factors and subjective responses. The personal factors part used the open mode method and focus on the clothing type and the metabolic rate of current activity during their answering the questionnaire. The subjective responses part was record the respondent's thermal perception to existing thermal environment, such as air movement sensation, humidity sensation, thermal sensation, satisfaction, acceptability, preference and comfort. The data analyzed was based on the TSV on different operative temperature.

3.3 Equations

In this research, mean radiant temperature was used to calculate the operative temperature in analysis phase. The mean radiant temperature (T_{mrt}) *Eq.1* was obtained and calculated the operative temperature (T_{op}) *Eq.2* of each cardinal direction of external courtyard. The formula of mean radiant temperature as the following:

$$T_{mrt} = [(T_g + 273)^4 + \frac{1.1 \times 10^8 V^{0.6}}{\varepsilon d} \times (T_g - T_a)]^{0.25} - 273 \; Eq. 1$$

Where

T_{mrt} = Mean radiant temperature
T_a = Air Temperature
T_g = Globe temperature
V = Wind speed

The general equation of operative temperature is

$$T_{op} = \frac{(T_{mrt} + (T_a \times \sqrt{10v}))}{1 + \sqrt{10v}} \; Eq. 2$$

where

T_{op} = Operative temperature
T_{mrt} = Mean radiant temperature
T_a = Air Temperature
V = Wind speed

4. Results and Discussion

From the data obtained, there are two assessments were conducted at study location. The data was collected in 3 hours of both morning and evening on day time.

4.1 Analysis of temporal variations of operative temperature at courtyard

Figure 5 (a) and (b) represents the temporal variations of operative temperature between east, west and south of courtyard in morning and evening. Generally, the difference of operative temperature for east and south of courtyard is higher than the west of courtyard in morning. In the evening, the difference of operative temperature for south of courtyard is higher than the east and west of courtyard. It shown that the internal courtyard is cooler than east, west and south of external courtyard. In addition, some improvement is needed to reduce the thermal condition at the external courtyard, such as extend the external shading at east and south of external courtyard to reduce the solar radiation effect to the external courtyard.

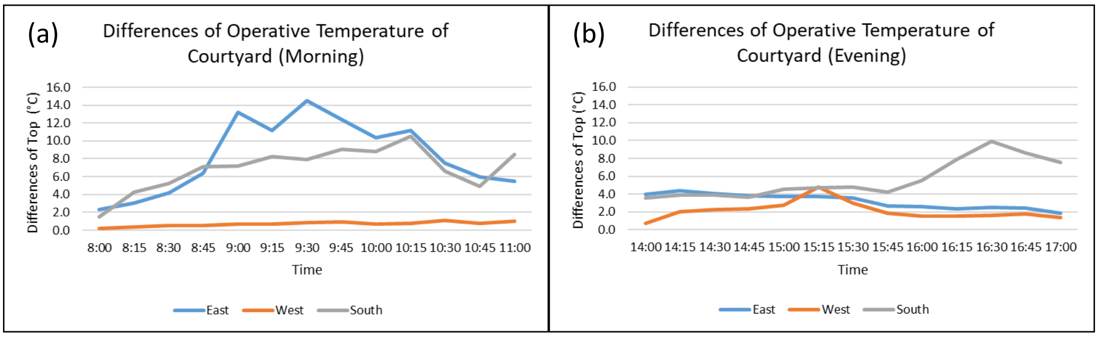

Figure 5: Temperature difference between external courtyard orientation and internal courtyard (a) Internal courtyard (b) External courtyard

4.2 Analysis of TSV proportion in operative temperature

Figure 6 (a) and (b) represents the comparative data about the proportion of thermal sensation vote (TSV) against different operative temperatures between the internal and external courtyard. In Figure 6(a), it can be seen many subjects felt (-2) cool, (-1) slightly cool, (0) neutral and (+1) slightly warm in a range from 26°C to 32°C in the internal courtyard space. Majority subjects which has 26% felt cool and comfort at internal courtyard in day time. Some subjects which has 40% felt slightly warm is due to the increasing in operative temperature in the evening. Figure 6(b) shown many subjects felt (0) neutral, (+1) slightly warm, (+2) warm and (+3) hot in range of operative temperature from 31°C and up to 40°C in external courtyard space. It is because the external courtyard is exposed to the outdoor courtyard and directly affect by the solar heat.

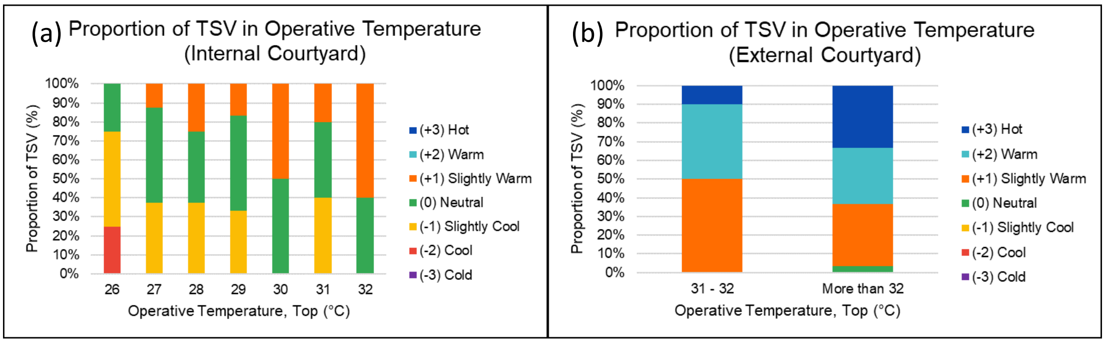

Figure 6: Proportion of TSV in operative temperature (a) Internal courtyard (b) External courtyard

4.3 Analysis of TPV proportion in TSV

Figure 7 (a) and (b) represents the comparative data about the proportion of thermal preference vote (TPV) in different TSV between internal and courtyard. In Figure 7(a), it can be seen majority subjects which has 70% is more prefer no change and satisfied with the current thermal environmental condition of the internal courtyard space. Compared with external courtyard in figure 7(b), it can be seen majority subjects which has 82% is more prefer cooler with the current thermal environmental condition of external courtyard space.

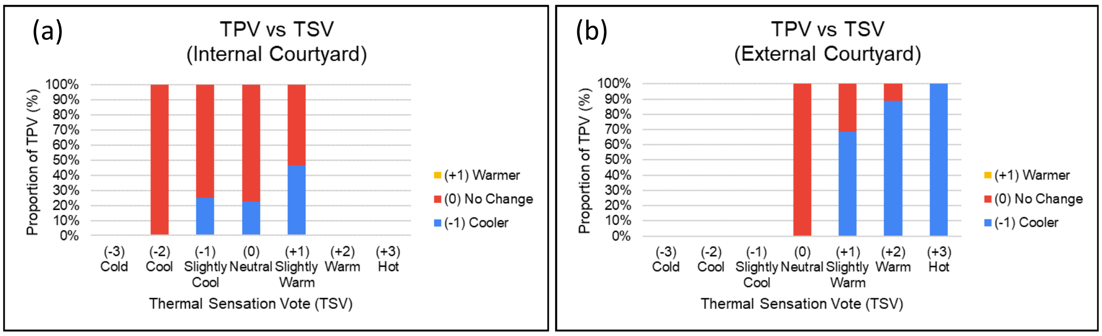

Figure 7: Proportion of TPV vs TSV (a) Internal courtyard (b) External courtyard

4.4 Analysis of TSV proportion between activity category

Figure 8 (a) and (b) represents the comparative data about the proportion of thermal sensation vote (TSV) against different activities of subjects between internal and external courtyard. Figure 8(a) shown majority subjects is felt (-2) cool, (-1) slightly cool, (0) neutral and (+1) slightly warm when doing active and passive activity in the internal courtyard space. For passive activity, 23.8% of subjects felt slightly cool and 38.1% feel both neutral and slightly warm. 48.3% of subjects felt neutral, 24.1% felt both slightly warm and slightly cool and only 3.4% felt cool when active activity. In Figure 8(b), it can be seen many subjects felt (0) neutral, (+1) slightly warm, (+2) warm and (+3) hot when doing active and passive activity in external courtyard space. For passive activity, 46.7% of subjects felt slightly warm, 26.7% felt warm, 20.0% felt hot and 6.7% in neutral. 37.1% of subjects felt both slightly warm and warm and only 25.7% felt hot when active activity.

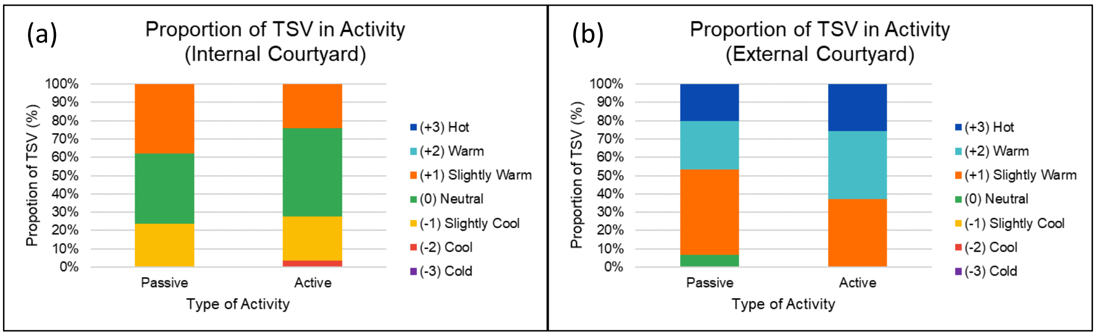

Figure 8: Proportion of TSV in activity category (a) Internal courtyard (b) External courtyard

4.5 Analysis of HSV proportion in operative temperature

Figure 9 (a) and (b) represents the comparative data about the proportion of humidity sensation vote (HSV) in different operative temperatures between the internal and courtyard. In Figure 9(a), it can be seen many subjects felt (-3) too dry, (-1) slightly dry, (0) neutral, (+1) slightly humid and (+2) humid in range of operative temperature from 26°C to 32°C in internal courtyard space. It can be seen the percentage of HSV that sense by 50% of subjects who felt slightly humid is decrease when the operative temperature increase. Figure 9(b) shown that many subjects felt (-3) too dry, (-2) dry, (-1) slightly dry, (0) neutral and (+1) slightly warm in range from 31°C and up to 40°C in external courtyard space. It can be seen the internal courtyard have water pond and cause the air humidity is more humid than the external courtyard.

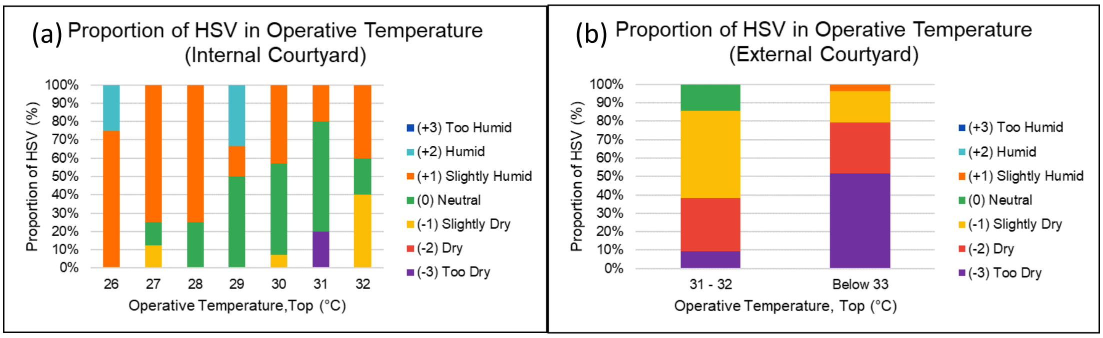

Figure 9: Proportion of HSV in operative temperature (a) Internal courtyard (b) External courtyard

4.6 Analysis of mean result between TSV and UTCI

Table 2 represents the evaluation result between TSV and UTCI. This table also shows the finding from overall research of outdoor thermal comfort in the circular courtyard. Majority of respondents in internal courtyard felt slightly warm, neutral and slightly cool with comfort temperature in range of 28.0°C to 29.8°C in morning and majority of respondent at external courtyard in evening felt hot, warm and slightly warm with temperature in range of 32.6°C to 34.0°C. In term of UTCI, it was found that the average temperature in internal courtyard is in range of 29.9°C indicate moderate heat stress and external courtyard is 33.9°C to 37.3°C indicate strong heat stress.

Table 2: Evaluation mean result between TSV and UTCI

Location	TSV	Mean				UTCI	
		T_a (°C)	RH (%)	V_a (m/s)	T_{op} (°C)	UTCI (°C)	Heat stress range
Internal courtyard	(+1) Slightly warm	29.8	68.5	0.61	29.7	31.6	Moderate heat stress
	(0) Neutral	29.0	68.5	0.61	29.1	30.7	Moderate heat stress
	(-1) Slightly cool	28.0	68.5	0.61	28.0	29.9	Moderate heat stress

External courtyard	(+3) Hot	34.0	50.8	1.23	36.5	37.3	Strong heat stress
	(+2) Warm	33.2	50.8	1.23	33.9	34.7	Strong heat stress
	(+1) Slightly warm	32.6	50.8	1.23	33.4	33.9	Strong heat stress

5. Conclusion

As a conclusion, the circular courtyard design is very effective in thermal environmental condition improvement and also increase the thermal comfort of human subject, so the objectives of this study have been achieved. From the data analyzed for every station of the circular courtyard, it can be seen the thermal environmental condition of the internal courtyard is cooler than the external courtyard which the operative temperature in range of 0.2°C to 4.5°C, relative humidity in range of 1% to 51% and wind speed in range of 0 m/s to 2.27 m/s. This condition is affected by the building height, semi-open space, green vegetation and water pond at the centre of circular courtyard. The finding from the physical measurement shows that the internal courtyard is cooler than the external courtyard. The temporal variations of operative temperature in morning in range of 0.2°C to 14.5°C and evening is 0.8°C to 9.9°C. The finding from subjective response is majority of respondents felt slightly warm, neutral and slightly cool with comfort temperature 29.8°C, 29.0°C and 28.0°C respectively in morning and majority of respondent in evening felt hot, warm and slightly warm with temperature 34.0°C, 33.2°C and 32.6°C respectively. In term of UTCI, it was found that the average temperature in internal courtyard is in range of 29.9°C indicate moderate heat stress and external courtyard is 33.9°C to 37.3°C indicate strong heat stress.

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