

# Indoor Thermal Environment of Various Semi-Enclosed Atrium Configurations of Institutional Building in Tropical Climate

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## ABSTRACT

The consideration of local climate is essential for the application of atrium in building. Different strategies and approaches in atrium configuration are required for different climates in ensuring its effectiveness. Nevertheless, the final aim is still similar which is to provide a comfortable environment for the users. Hence, this study was executed to examine the effects of top and side configurations on the indoor thermal environment of semi-enclosed atrium in the tropical climate. The methodologies involved field measurement and questionnaire survey. The field measurements were executed at two different configurations of semi-enclosed atriums in the tropical climate of Malaysia. Meanwhile, the questionnaire surveys were executed simultaneously with the field measurements in obtaining the users' thermal sensation and satisfaction. The findings indicated that the top configuration had more influence to the indoor thermal environment compared to the side configuration as it determined the amount of solar heat penetration into the atrium area. Meanwhile, the side configuration influenced the air velocity inside the atrium. The Faculty of Engineering and Built Environment's atrium that has opaque top finishes was found to have the average indoor operative temperature of less than 30 °C throughout the day, though the average outdoor air temperature was more than 30 °C. It also had more hours with neutral thermal sensation felt by the users compared to the Faculty of Economics and Management's atrium that has transparent materials for the top finishes. The study is useful in guiding the selection of appropriate strategy for an atrium in tropical climate.

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## 1. Introduction

In building, atrium is known as a top-lit internal space that has several storeys surround it (Curl, 2006). The numerous functions and benefits of atrium in the social and environmental aspects have made this strategy is widely applied in various building typologies such as the office, institutional and commercial buildings. One of the social benefits of atrium is an area for organizing events, socializing and gathering (Hung, 2003). The ample area provided by an atrium, as well as its

location in building which is normally at the front or centre, has made it as a focal point and a node. In addition, the spaces or rooms around it have also made an atrium as a strategic place for activities and events. Besides that, an atrium may also become a starting point in distributing the circulation within the building (Adams et al., 2010).

Besides social benefits, an atrium also provides many environmental benefits if the strategy is appropriate for the climatic condition where it is situated. The environmental

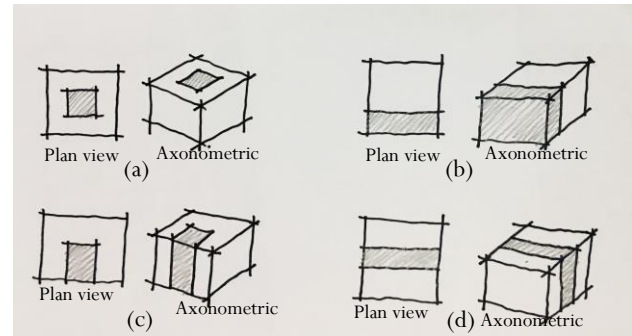
benefits of atrium have been widely studied, and the aspects are various such as the daylighting strategy (Sharples and Lash, 2007; Jorgensen et al., 2012; Ghasemi et al., 2015; Huang et al., 2015; Acosta et al., 2018; Song, 2007; Mohsenin & Hu, 2015) the ventilation strategy (Acred and Hunt, 2014; Yusoff et al., 2019), the energy usage (Wang et al., 2017; Aldawoud & Clark, 2008; Vethanayagam & Abu-Hijleh, 2019), and the indoor thermal environment (Abdullah and Wang, 2012; Chu et al., 2017; Abdullah, Meng, Zhao, & Wang, 2009; Hussain & Oosthuizen, 2012; Hussain & Oosthuizen, 2013; Lu et al., 2019; Taleghani, Tenpierik, & van den Dobbelsteen, 2014).

Due to its various social and environmental benefits, the application of atrium is not restricted to certain climatic condition. The application of atrium in tropical climate of Malaysia is also very wide. It is applied in various building typologies such as the commercial, institutional and office buildings. Nevertheless, different climatic condition requires different approach in the atrium application to ensure the environmental benefits are achieved. Hence, it is important to understand the appropriate strategy for a particular climatic condition. Otherwise, instead of providing environmental benefits, the atrium may become a liability to the building, such as increasing the energy usage, as well as the maintenance and operational costs.

The application of atrium at commercial and office buildings is common. There are already many studies conducted for the atrium at such building typologies such as the studies by Ghasemi et al. (2015), Huang et al. (2015), Mohsenin and Hu (2015), Yusoff et al. (2019), Wang et al. (2017), Abdullah and Wang (2012), Abdullah et al. (2009), Asfour (2020) and many others. However, the study of atrium at institutional building is still lacking, though the application of it in such building is mushrooming nowadays. Hence, two atriums that are located at the institutional building which is National University of Malaysia (UKM) were selected for this study. They were selected due to the different atrium characters though located within similar institution and having similar functions. Details of these two atriums are elaborated in the methodology section.

### 1.1 Atrium Configuration

There are four generic forms of atrium which are categorized by the location in building. They are the centralized, attached, semi-enclosed and linear forms (Hung and Chow, 2001), as shown in Figure 1.



**Figure 1** The four generic forms of atrium, which are a) centralized, b) attached, c) semi-enclosed, and d) linear

Each atrium has its own configuration, depending on its connection with the adjacent spaces within the building. The location and configuration of an atrium have significant effect to the indoor environmental condition of the atrium space. The study by Aldawoud (2013) indicated that the energy usage for a narrow and elongated rectangular atrium was higher than a square shaped atrium.

Besides location, the environmental strategy can also be considered to classify an atrium. In general, the atrium can be classified into two, namely the fully enclosed atrium and the semi-enclosed atrium. This classification is based on the daylighting and natural ventilation strategies. The semi-enclosed atrium is an atrium that has openings whether at the facade or roof, which allow for air exchange between the indoor and outdoor. The ventilation mode that is normally applied at the semi-enclosed atrium is either fully naturally ventilated or hybrid, which is by incorporating a mechanical fan. It is different from the fully enclosed atrium, which is normally air-conditioned. The indoor environmental effects provided by the fully-enclosed atrium and semi-enclosed atrium are also different. The former strategy provides greenhouse effect, which is favorable by cold and temperate climates, whilst the latter offers chimney effect, which is appropriate for tropical climate.

In term of the daylighting strategy, the amount of daylight into the atrium area is determined by the building massing and orientation, as well as the openings such as skylight, void and window (Asfour, 2020). An atrium can be either top-lit, side-lit or both. The top-lit atrium normally uses transparent or translucent roof material that enables certain amount of daylight penetration. Such example is the utilization of skylight at the roof of the atrium. Nevertheless, the ratio of the skylight or glazing area impacts the heating and cooling loads of the atrium area (Aldawoud & Clark, 2008; Tabesh & Sertyesilisik, 2016). Excessive glazing is inappropriate for hot climate as it increases the amount of heat gain, which subsequently escalates the indoor air temperature (Asfour, 2020). In addition, a multi-storey atrium with top glazing that is located in hot and humid climate will also suffer a high air temperature stratification at the highest level (Abdullah et al., 2009).

In summary, by combining the ventilation and daylighting strategies, the atrium can be classified into four categories which are fully enclosed top-lit, fully enclosed side-lit, semi-enclosed top-lit and semi-enclosed side-lit. All these strategies have different effects to the indoor environmental condition of atrium. Nevertheless, the semi-enclosed side-lit atrium was found to provide better indoor thermal comfort than the other atrium strategies for tropical climate (Abdullah and Wang, 2012). Though Abdullah and Wang (2012) had already investigated the thermal comfort in semi-enclosed side-lit and top-lit atriums, the methodology used was numerical simulation only. There was no survey executed on the actual thermal sensation felt by the users of the atriums. Similarly, other studies of the indoor thermal comfort in atrium which are by Hussain and Oosthuizen (2012), Hussain and Oosthuizen (2013), Abdullah et al. (2009), Chu et al. (2017), Lu et al. (2019), and Taleghani et al. (2014) also did not execute field survey on the actual users' thermal sensation. Hence, this paper intends to examine the effects of top and side configurations on the indoor thermal environment of semi-enclosed atrium using the field measurement and questionnaire survey methods. The findings from this study take into account the actual users' thermal sensation and satisfaction of the atrium's indoor environmental condition.

## 2. Methodology

Two research methods were utilized for this study namely the field measurement and the questionnaire survey. The field measurement was executed with the purpose of obtaining the outdoor and indoor environmental data of the selected atriums. The environmental data of the field measurement were used to calculate the indoor operative temperature and the predicted indoor comfort temperature. Meanwhile, the questionnaire survey was conducted concurrent with the field measurement, with the purpose of deriving the users' thermal sensation and satisfaction regarding the indoor thermal environment of the selected atriums.

### 2.1 Building Selection

Two institutional buildings with different configurations of atriums had been selected for this study. Though the atriums' configurations are different but they have similarity, in which both of them are classified as semi-enclosed and centralized atrium. The two institutional buildings are Faculty of Engineering and Built Environment (FKAB), and Faculty of Economics and Management (FEP) of National University of Malaysia (UKM). The atriums of those buildings serve the similar purpose which is as communal area for socializing and gathering. In addition, the events or activities held at the atriums are also for the academic purposes such as educational talk and exhibition. Those buildings are located within the main campus

of National University of Malaysia. The distances between those buildings are approximately 2.6 km from each other (Figure 2).

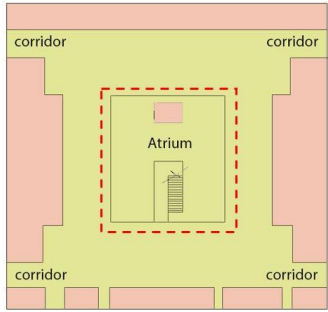
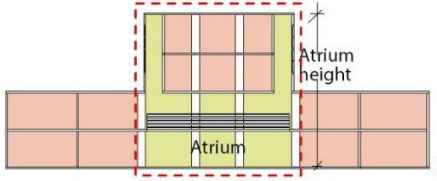
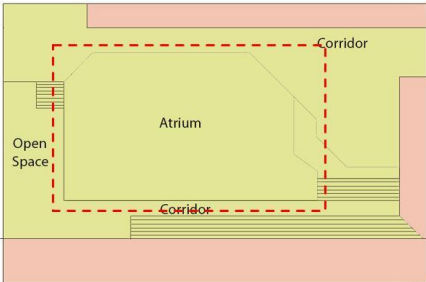
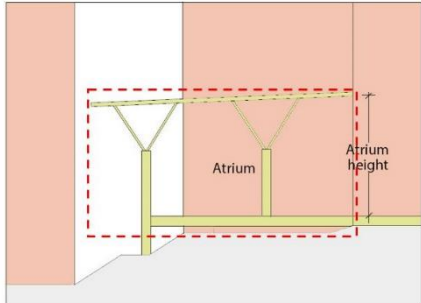


**Figure 2** The locations of the selected buildings (GoogleMap, 2020)

The atrium at FKAB has the area of 159.3 m<sup>2</sup> (Table 1). There are many rooms and spaces that surround the atrium, which function as laboratories and offices. There are also corridors that connect the atrium with the outdoor. Besides being as passageway, the corridors also allow the outdoor air to flow into the atrium. The atrium has a total height of 12 m from the ground level (Table 1). However, the 12 m height includes the spaces like vertical shafts that are located at the sides of the atrium. On the other hand, the height of the centre of the atrium is only 6 meter from the ground level. The penetration of daylight into the atrium is via the glass louvers that are located at the vertical shafts. Nevertheless, the artificial lightings are still installed at the spaces and corridors around the atrium due to the low lighting level at the areas especially during the cloudy days. Besides daylighting, the glass louvers also allow for natural ventilation, especially the stack effect ventilation due to their heights from the ground level.

The FEP's atrium is similar to FKAB's atrium which it is also surrounded by other spaces and rooms. However, the floor area of the atrium is larger than the FKAB's atrium, which is 343.4 m<sup>2</sup> (Table 1). In contrary to the FKAB's atrium, there is one side of the FEP's atrium that is adjacent to a small courtyard. Nevertheless, the other sides are similar to the FKAB's atrium which are adjacent to rooms. The atrium is also naturally ventilated via the corridors that link the atrium with the outdoor. Nevertheless, the ventilation in the atrium is also aided by mechanical fans. These ceiling fans function only when there is a large crowd at the atrium due to event. In comparison to the FKAB's atrium, the FEP's atrium has lower height which is 5.8 m from the ground level (Table 1).

**Table 1** Simple Layout Plans and Cross Sectional Views of the Selected Atriums

Atrium	Simple Layout Plan	Simple Cross Sectional View	Area / Height
FKAB			Area: 159.3m <sup>2</sup>  Height : 12m
FEP			Area: 343.4m <sup>2</sup>  Height : 5.8m


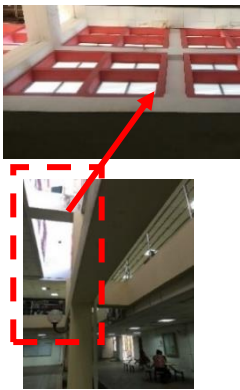
Note: The atrium area is indicated by the red dashed lines.

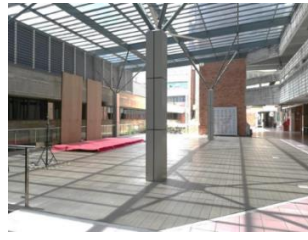
**2.2 Top and Side Configurations of Selected Atriums**

different in term of the surrounded spaces, the amount and locations of the openings, as well as the locations of corridors that function as the air flow paths.

Table 2 shows the top and side configurations of the atriums. The top configurations of the atriums are dissimilar in term of the design and materials. Meanwhile, the side configurations are

**Table 2** Top and Side Configurations of the Atriums

Atrium	Top Configuration	Side Configuration	Description
FKAB			<u>Top:</u> -The ceiling is finished with gypsum boards. <u>Side:</u> -There are spaces like vertical shafts with glass louvers on both sides of the atrium. -There are corridors at two sides that connect the atrium with the outdoor.
FEP			<u>Top:</u> -The top is made of transparent roofing material which is clear polycarbonate



skylight. The skylight is supported by high tensile rolled steel structure.

Side:

- There are three sides that face the building blocks. While the other one side faces a small courtyard.
- There are corridors at two sides that connect the atrium with the outdoor.

**2.3 Field Measurement**

The field measurements for the selected atriums were executed at different times. The measurement for the FKAB's and FEP's atriums were conducted for five days in March 2018 and four days in April 2019, respectively. Both measurements started from 9 am to 5.59 pm. The duration for the field measurement was considered acceptable as it was also similar to the study executed by Huang et al. (2019). Though there was almost a year gap between each field measurement, the outdoor environmental data indicated no major difference, except for the wind velocity as shown in Table 4. This is due to the climatic condition of Malaysia which has constant air temperature and relative humidity all year round. The outdoor environmental data for both field measurements were derived from the weather station that was located at the roof top of the FKAB's building. The indoor environmental data for the field measurements were recorded at the interval of 5 minutes. The data were then averaged to develop the average hourly data from 9 am to 5 pm.

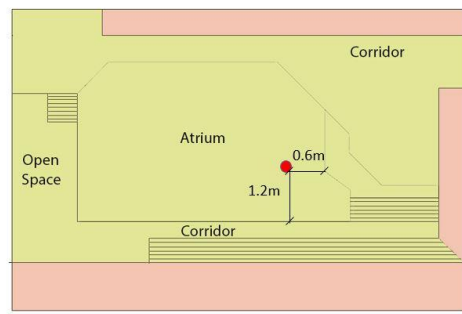
The indoor measurement tool that was utilized for the field measurement was Delta Log10. It is able to measure the environmental parameters such as relative humidity, air velocity, mean radiant temperature and air temperature. It has

the measurement accuracy of  $\pm 0.1$  °C for the air temperature,  $\pm 0.1$  °C for the mean radiant temperature,  $\pm 0.05$  m/s for the air velocity and  $\pm 2.5$  % for the relative humidity. The calibration of measurement tool was executed prior to each field measurement. The calibration was executed by placing the instrument in parallel with the other measuring instrument when conducting the measurement. The measured data of both measurement tools were compared and the percentages of deviation were calculated.

The calibration of the tool for the measurement at the FKAB's atrium indicated that the percentage of deviation for the air temperature was 0.2 %, for the mean radiant temperature was 0.2 %, for the air velocity was 6 % and for the relative humidity was 6 % also. Meanwhile, for the measurement at the FEP's atrium, the calibration resulted in 0.2 % deviation percentage for air temperature, 0.2 % for mean radiant temperature, 10 % for air velocity and 5 % for relative humidity. During the field measurement, the tool was placed at the height of 1.1 m from the floor level, which is considered acceptable for the sitting and standing positions (ASHRAE, 2017). The location of the measurement tool at each atrium is depicted in Table 3. These locations were selected based on the safety factor of the tool due to the active usage of the atriums.

**Table 3** Location of Measurement Tool

Atrium	Location of Measurement Tool	Photo
FKAB		
FEP		



## 2.4 Questionnaire Survey

The questionnaire surveys for both atriums were executed concurrently with the field measurements. The survey form had two sections. The first section was regarding the respondent's background such as gender, age, height, weight and attire, while the second section examined the respondent's thermal sensation and satisfaction of the atrium's indoor environment. The ASHRAE thermal sensation scale (1: cold, 2: cool, 3: slightly cool, 4: neutral, 5: slightly warm, 6: warm, 7: hot) was utilized in the thermal sensation evaluation (ASHRAE, 2017). Meanwhile, for the respondent's satisfaction, the 7-likert scale (1: very dissatisfied, 2: dissatisfied, 3: slightly dissatisfied, 4: neutral, 5: slightly satisfied, 6: satisfied, 7: very satisfied) was employed. The determination of acceptability by the users towards the indoor thermal environment can be categorized into two, namely the range between the 'neutral' to the 'very satisfied' thermal sensations, or a slightly wider range, which is in between the 'slightly dissatisfied' to 'very satisfied' thermal sensations (ASHRAE, 2017). Nevertheless, in this study, the acceptability percentages of the users were derived within the range of 'neutral' to the 'very satisfied' thermal sensations. The total numbers of respondents were 164 and 102 for FKAB's and FEP's atriums, respectively.

The respondents' data for the FKAB's and FEP's atriums were almost similar as majority of the users were the students and staff. Only small percentages of the users were visitors. For the weight and height categories of both atriums, majority of the respondents were found to be within 40 to 80 kg, and 150 to 170 cm high, respectively. The frequency of usage for both atriums was also similar where most respondents were the frequent users of the atriums. The questionnaire also required the respondent to select the clothing type that he or she was wearing during the survey. The results indicate that the respondents' attires of the FKAB's and FEP's atriums were quite formal to suit the regulation set by the university. Nevertheless, none of the respondents were found to wear thick clothes due to the climatic condition of Malaysia which is constantly hot and humid. Hence, the range of clothing values for the respondents of both atriums were between 0.57 to 1 clo (ASHRAE, 2017). The activities executed by the respondents at both atriums were either walking slowly, sitting or standing, and none of them were found running. Hence, the metabolic rates of the respondents were within the range of 1.0 to 2.0 MET

(ASHRAE, 2017).

## 3. Results

The results are presented on the outdoor and indoor environmental data of the selected atriums, the predicted indoor comfort temperature, as well as the thermal sensation and satisfaction of the users.

### 3.1 Outdoor and Indoor Environmental Data of Selected Atriums

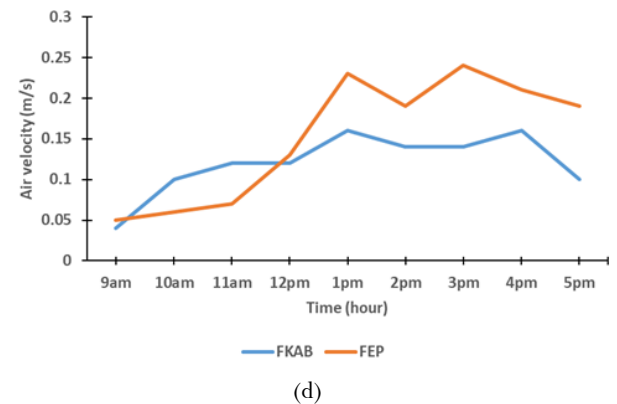
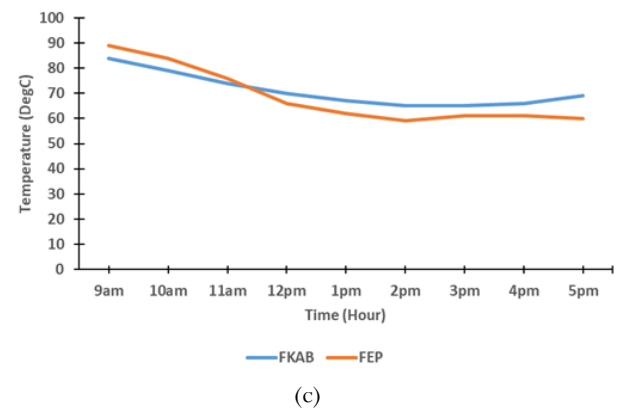
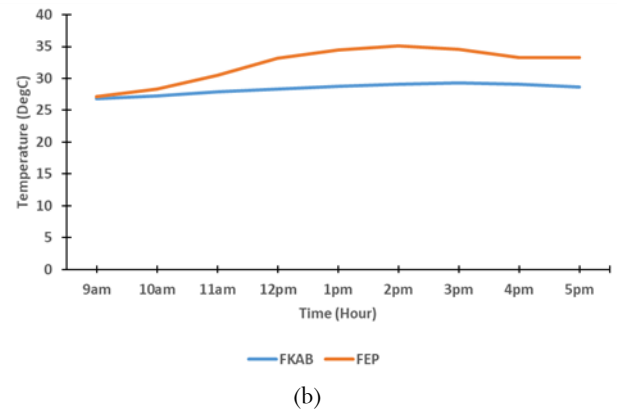
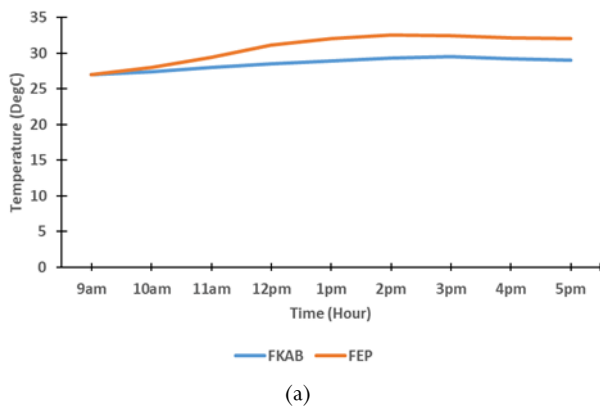
The average outdoor environmental data of the selected atriums are tabulated in Table 4. From the table, it shows that there is no significant difference between the outdoor environmental data of the atriums, except for the average wind velocity. Malaysia is tropical climate country that has almost constant air temperature and relative humidity all year round. The average outdoor air temperature ( $T_o$ ) was recorded to be within the range of 27 °C to 34 °C, while the average outdoor relative humidity was within the range of 58 % to 94 %. Meanwhile, the outdoor wind velocity for FKAB's and FEP's atriums indicated almost similar values where they were around 0.4 m/s to 2.2 m/s.

**Table 4** Average Outdoor Environmental Data of Selected Atriums

Time	Average Outdoor Air Temperature, $T_o$ (deg C)		Average Outdoor Wind Velocity, $V_o$ (m/s)		Average Outdoor Relative Humidity, RH (%)	
	FKAB	FEP	FKAB	FEP	FKAB	FEP
9am	27.7	27.8	0.42	0.46	86	94
10am	29.7	30.0	0.86	0.67	78	85
11am	30.9	32.0	1.44	1.04	70	77
12pm	30.9	33.0	1.62	1.20	68	70
1pm	32.5	33.5	1.98	1.29	62	69
2pm	33.3	34.0	1.96	1.53	58	66
3pm	33.5	33.2	2.20	1.74	58	68
4pm	32.0	32.3	2.27	1.52	61	69
5pm	30.1	31.4	1.99	1.34	68	72

The results of the indoor environmental data are depicted in Figure 3. The results in Figure 3(a) show a similar trend of both atriums, where the indoor air temperature increased from morning to afternoon, became peak in the afternoon, and decreased from the afternoon to evening. Nevertheless, the average indoor air temperature of FKAB's atrium was found to be less than 30 °C at all times compared to the FEP's atrium. The lowest average indoor air temperature was recorded at 9 am, which was 27 °C for both atriums. Meanwhile, the highest average indoor air temperature was recorded at 3 pm for the FKAB's atrium, with the reading of 29.5 °C. On the other hand, the FEP's atrium had recorded the highest indoor air temperature at 2 pm, with the reading of 32.6 °C. Figure 3(b) demonstrates the average indoor mean radiant temperature of the selected atriums. The results indicate that the FKAB's atrium had lower average indoor mean radiant temperature compared to the FEP's atrium. Similar to average indoor air temperature, the recorded average indoor mean radiant temperature of FKAB's atrium had also not exceeded 30 °C for the entire times.

The average indoor relative humidity of the selected atriums is depicted in Figure 3(c). The results show that the average indoor relative humidity indicated similar pattern for all atriums where the highest relative humidity was found to be at 9 am, and it continued to decrease until late afternoon. Meanwhile, from 3 pm onwards, the average indoor relative humidity started to increase. The average indoor relative humidity was found to be higher in FKAB's atrium at most of the times compared to the FEP's atrium. The average indoor air velocity for all atriums is demonstrated in Figure 3(d). The results show that the average indoor air velocity at FEP's and FKAB's atriums were less than 0.3 m/s at all times. At most of the times, lower average indoor air velocity was recorded at the FKAB's atrium compared to the FEP's atrium.



**Figure 3** (a) Average indoor air temperature, (b) Average indoor mean radiant temperature, (c) Average indoor relative humidity, and (d) Average indoor air velocity, of the selected atriums

The measured indoor environmental data are important in calculating the indoor operative temperature. The operative temperature is the temperature that is sensed by the people, where it includes the air temperature, mean radiant temperature and air velocity. The operative temperature of the atrium is utilized in comparison to the thermal sensation and satisfaction felt by the users of the atrium, as well as the predicted indoor comfort temperature. The formula suggested in ANSI/ASHRAE Standard 55 (ASHRAE, 2017) was utilized in calculating the indoor operative temperature ( $T_{op}$ ), which is as below:

$$T_{op} = A T_a + (1 - A) T_{mrt} \quad (1)$$

where  $T_{op}$  is the indoor operative temperature,  $A$  is the value as a function of the average air speed,  $T_a$  is the indoor air temperature, and  $T_{mrt}$  is the mean radiant temperature. The value of  $A$  was referred to the suggested value by ANSI/ASHRAE Standard 55 (ASHRAE, 2017). Hence, the derived indoor operative temperature ( $T_{op}$ ) of the selected atriums is shown in Table 5.

**Table 5** Average Indoor Operative Temperature ( $T_{op}$ ) of the Selected Atriums

Time (Hour)	$T_{op}$ (deg C) of FKAB's Atrium	$T_{op}$ (deg C) of FEP's Atrium
9 am	26.9	27.0
10 am	27.3	28.2
11 am	27.9	29.9
12 pm	28.4	32.1
1 pm	28.8	33.0
2 pm	29.2	33.9
3 pm	29.4	33.3
4 pm	29.1	32.6
5 pm	28.8	32.7

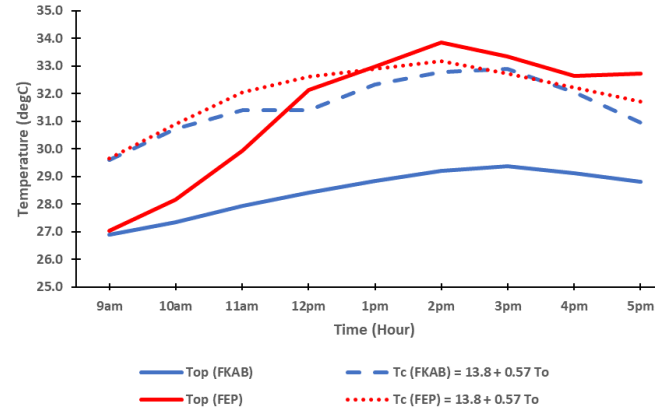
Besides calculating the indoor operative temperature ( $T_{op}$ ), the measured environmental data of the atriums were also used to calculate the predicted indoor comfort temperature of the atriums ( $T_c$ ). The adaptive thermal comfort (ATC) equation had been used to determine the predicted indoor comfort temperature. The reason for using this thermal comfort model is due to the condition of the atrium which is naturally ventilated. The ATC model is more appropriate for a naturally ventilated building compared to the PMV model due to the constantly changing environment (He et al., 2017). The ATC index embraces the principle that human has the ability to adapt himself or herself in achieving thermal comfort condition. The adaptability can be in the aspect of behavioral adjustment, psychological adaptation and physiological acclimatization (Brager and Dear, 1998). In contrary to the other thermal comfort indexes, the ATC equation is simpler and user-friendly where the main influencing parameter to the indoor comfort temperature is the outdoor air temperature.

The ATC index equation for naturally ventilated building in tropical climate based on the ASHRAE RP-884 database had been specifically developed by Toe and Kubota (2013). Humphreys et al. (2013) had also developed an ATC equation for naturally ventilated building, which was also based on the ASHRAE RP-884 database. However, the equation by Humphreys et al. (2013) was based on the database of various climates, while Toe and Kubota (2013) focused only the tropical climate. The developed equations by both studies are similar in the y-intercept value, but slightly different in the value of the slope of the function. Hence, for this study, the equation

developed by Toe and Kubota (2013) had been used, which is as below:

$$T_c = 13.8 + 0.57 T_o \quad (2)$$

where  $T_c$  is the predicted indoor comfort temperature, and  $T_o$  is the mean outdoor air temperature. The results of the predicted indoor comfort temperature ( $T_c$ ) for all atriums are depicted in Figure 4. These results are discussed in section 4, in conjunction with the field measurement and questionnaire survey results.



**Figure 4** Comparison of indoor operative temperature ( $T_{op}$ ) and predicted indoor comfort temperature ( $T_c$ ) of the atriums

### 3.2 Thermal Sensation and Satisfaction of Selected Atriums

In this section, results are presented for the respondents' thermal sensation and satisfaction that were derived from the questionnaire surveys at the atriums of FKAB and FEP. Figure 5 depicts the percentages of thermal sensation of the users for the indoor operative temperature at the FKAB's atrium. The results show that at most of the time, majority of the users felt neutral except at 3 pm and 4 pm. Other than feeling neutral, many users also felt slightly warm being in the atrium area. Nevertheless, there were also some users that felt slightly cool and cool, in which this can be found at all times except at 12 pm. Meanwhile, there were also users who felt hot being in the atrium which were at 2 pm and 3 pm.

The thermal sensations of the users of FEP's atrium are depicted in Figure 6. The results indicate that in average, the thermal sensation that was felt mostly by the users throughout the measurement was either neutral or slightly warm. Most users felt neutral at 9 am, 10 pm, 1 pm, 2 pm and 4 pm. At the other times, the dominated thermal sensation was slightly warm. However, there were also users who felt hot, which was at 3 pm. In general, the morning hours at the atrium provided better indoor thermal environment compared to the afternoon hours.



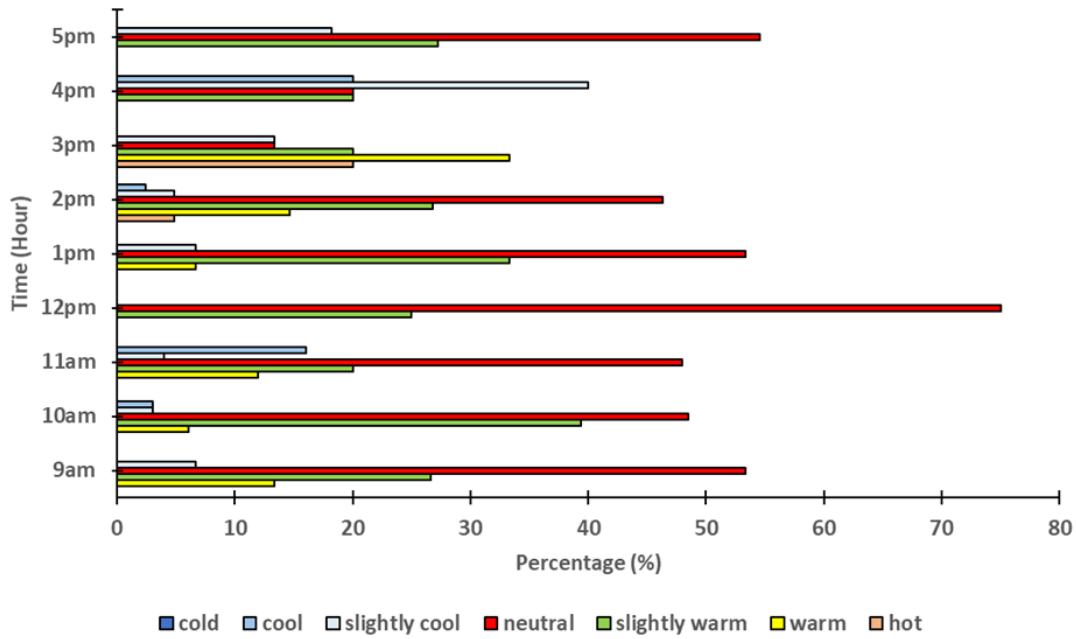


Figure 5 Thermal sensation of the users of FKAB's atrium

Figure 7 demonstrates the percentages of users' satisfaction of the indoor temperature at the FKAB's atrium. It is found that at most of the time, the users felt either neutral or slightly satisfied with the indoor temperature at the atrium area. In addition, the users who felt neutral, as well as satisfied and above are found to be more than those who felt dissatisfied and below at all times,

except at 3 pm. Hence, it is found that the indoor operative temperature of FKAB's atrium is acceptable by the users at most of the times, as shown in Table 6. These results are in accordance with the results in Figure 5, where majority of the users felt neutral thermal sensation.

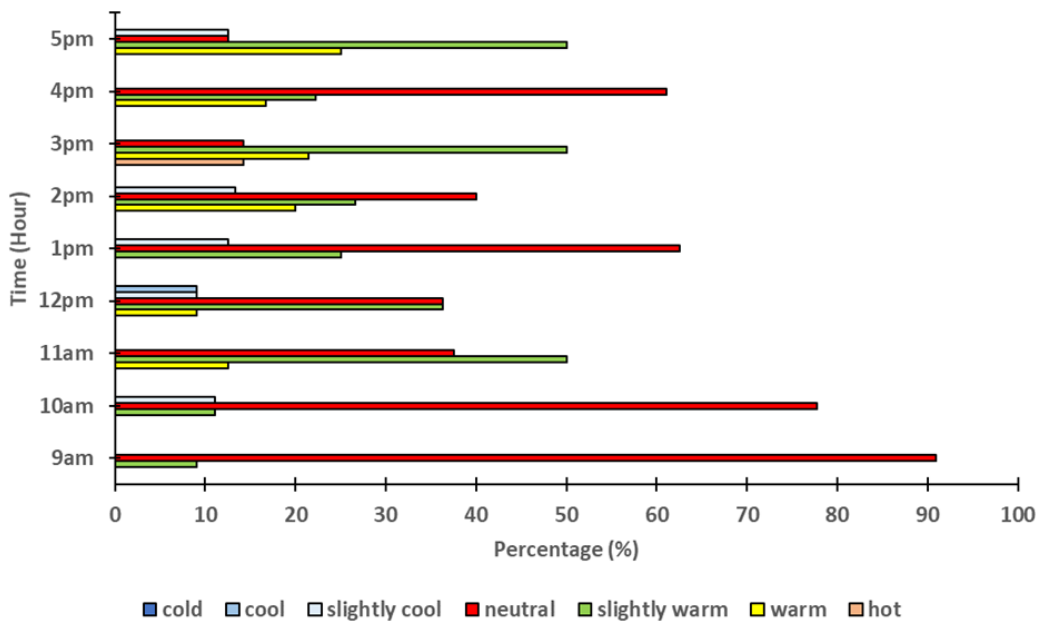


Figure 6 Thermal sensation of the users of FEP's atrium

The results of users' satisfaction of the indoor temperature at the FEP's atrium are presented in Figure 8. The results show that during the morning hours till noon, most users felt neutral,

as well as satisfied and above with the indoor air temperature, except at 10 am and 12 pm, where some of them felt slightly dissatisfied. On the other hand, from 1 pm till 5 pm, the

number of users who felt slightly dissatisfied and below increased. This is in line with the results in Table 6, where during this time, the acceptability level is below 80 %. The worst condition was found to be at 3 pm, where most users felt

slightly dissatisfied, and even some of them did feel very dissatisfied. When comparison is made to the results in Figure 6, it is found that most users felt slightly warm thermal sensation.

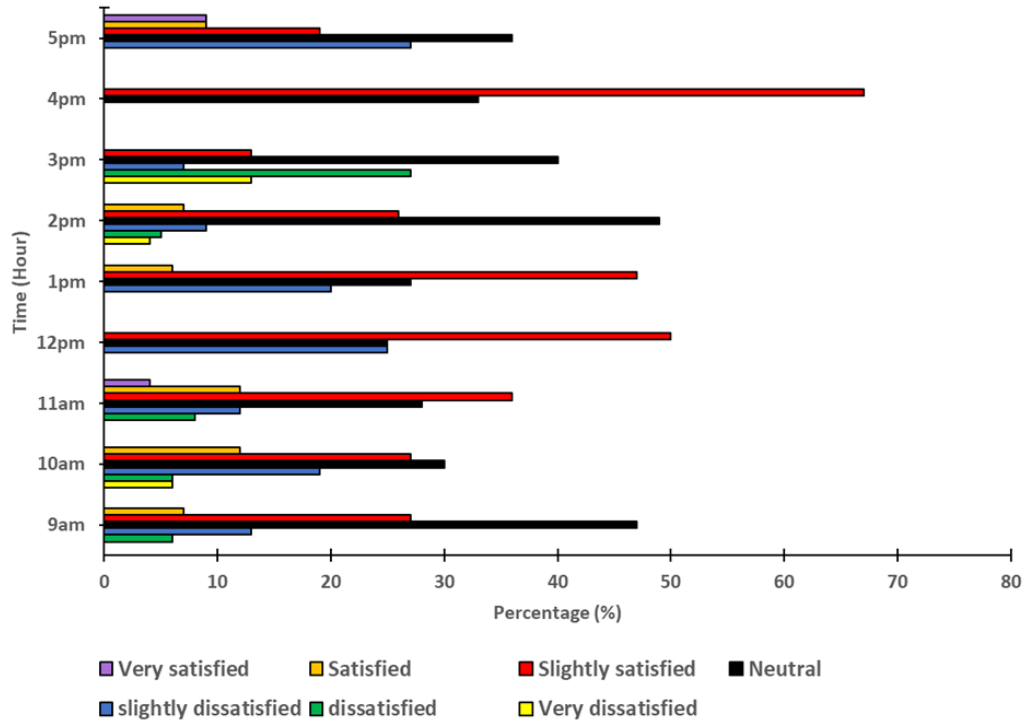


Figure 7 Users' satisfaction of the indoor operative temperature of FKAB's atrium

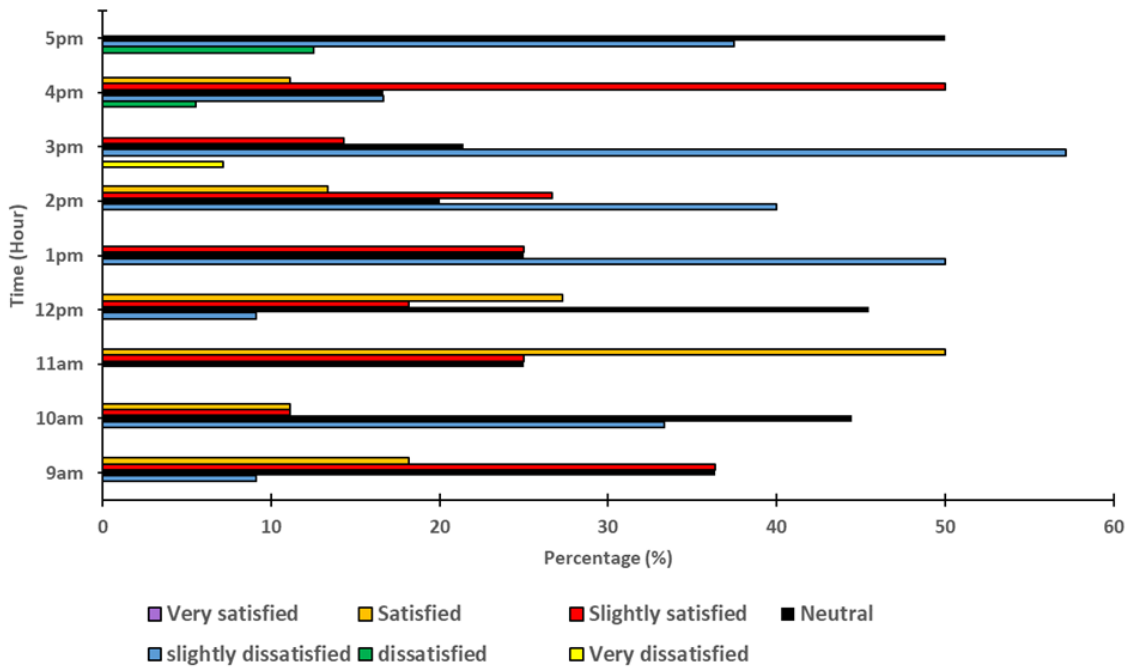


Figure 8 Users' satisfaction of the indoor operative temperature of FEP's atrium

Table 6 presents the acceptability percentages of the users of FKAB's and FEP's atriums of the indoor operative temperature. As mentioned earlier, the acceptability percentages of the users were calculated within the range of 'neutral' to the 'very satisfied' feelings. It is recommended by ASHRAE (ASHRAE, 2017) that the indoor thermal condition is within the comfort zone if the acceptability level achieved is 80 % or more. From the tabulated results, it is found that out of nine hours measurements in both atriums, the FKAB's atrium achieved more hours with the acceptability percentage compared to the FEP's atrium. Nevertheless, the worst condition was found to be at 3 pm for both atriums.

**Table 6** Acceptability Percentages of the Users of FKAB's and FEP's Atriums of the Indoor Operative Temperature

Time (Hour)	Percentage of Acceptability (%)	
	FKAB's Atrium	FEP's Atrium
9 am	81	91
10 am	69	67
11 am	80	100
12 pm	75	91
1 pm	80	50
2 pm	82	60
3 pm	53	36
4 pm	100	78
5 pm	73	50

#### 4. Discussion

The results of the indoor environmental data of the selected atriums show similar pattern where the average indoor air temperature increased from morning to noon, and decreased during the evening. Though the average outdoor air temperature recorded the reading of more than 30 °C started from 11 am for both atriums, it was found that the average indoor air temperature of FKAB's atrium remained below 30 °C throughout the day. In contrary, the average indoor air temperature of FEP's atrium started to be more than 30 °C from noon hours and remained high throughout the day. This pattern was also similar to the average indoor operative temperature of FKAB's atrium where it remained below 30 °C through the day. The comparative analyses of the users' thermal sensation also indicated that FKAB's atrium had more hours with majority of the users felt neutral compared to FEP's atrium. Even, there was one time, which was at 4 pm, where majority of the FKAB users felt slightly cool. The FKAB's atrium indicated seven hours with dominated neutral thermal sensation, while FEP's atrium indicated five hours only. For the FEP's atrium, majority of the users felt slightly warm at the other hours. Meanwhile, for the users' satisfaction, it is found that the FKAB's atrium had more hours where the users felt satisfied with the indoor operative temperature compared to the FEP's atrium.

Many previous studies had been executed on the indoor thermal comfort for naturally ventilated buildings in the tropical climate

using various methods. The studies had suggested on various ranges of comfort temperature such as 27.4 °C to 28.8 °C (Hwang et al., 2006),  $26.9 \pm 1.3$  °C (López-Pérez et al., 2019),  $30.2 \pm 0.2$  °C (Djamila et al., 2013), and 26 °C to 28.9 °C (Daghigh, 2015). Hence, it can be summarized that the indoor thermal comfort temperature for the naturally ventilated building in tropical climate is within the range of 26 °C to 30.4 °C. In comparison to the average indoor operative temperature of the atriums, it was found that the FKAB's atrium was within the suggested thermal comfort temperature at all measurement times. Meanwhile, for the FEP's atrium, the indoor thermal environments were found to be outside the suggested thermal comfort range started from 12 pm. Nevertheless, there were users who still felt neutral or slightly cool at the times outside of this suggested thermal comfort range. This is due to the findings from the previous studies which stated that some people in naturally ventilated building can accept higher and wider range of comfortable indoor operative temperature (Lau et al., 2019; Hwang et al., 2006; Mishra and Ramgopal, 2014).

The results from the ATC equation by Toe and Kubota (2013) show higher predicted indoor comfort temperature ( $T_{c}$ ) compared to the thermal comfort range of 26 °C to 30.4 °C suggested by the previous studies. Nevertheless, the average indoor operative temperature at the FEP's atrium was still above the predicted indoor comfort temperature at most of the times. In contrary, the average indoor operative temperature of the FKAB's atrium was found to be below the predicted indoor comfort temperature at the entire times.

The field measurement and questionnaire survey results show that the top and side configurations of the atrium play significant role in determining the indoor thermal environment. The top of the FKAB's atrium is made of opaque material compared to the FEP's atrium. This opaque material reduces the solar heat penetration into the atrium. On the other hand, the presence of skylight at the top of the FEP's atrium has allowed more solar irradiation into the indoor area. Hence, the side-lit strategy applied at the FKAB's atrium is found to provide better indoor thermal environment compared to the top-lit strategy as at FEP's atrium. This finding is also in accordance with the study by Abdullah and Wang (2012) which stated that the side-lit atrium with clerestory windows provided better thermal comfort than the fully transparent top-lit atrium for tropical climate.

The top configuration determines the penetration of solar heat into the building, while the side configuration influences the ventilation of the building (Huang et al., 2019). Though both atriums are semi-enclosed, but the side configurations have different approaches. The similarity of these atriums is their locations which are at the centre of the building, and surrounded by rooms or spaces. Hence, the corridors that connect the atriums with the outdoor function as the air flow paths. Nevertheless, though FEP's atrium is also located in the middle, it has an adjoining small courtyard at one side.

The results of indoor air velocity measurements have demonstrated that the FEP's atrium had recorded higher average

indoor air velocity compared to the FKAB's atrium. Though the outdoor wind speed was recorded to be higher for FKAB's atrium, the side configuration of the atrium also plays important role in determining the air that flows in and out of the atrium. The locations of the corridors are significant in determining the cross ventilation that occurs inside the atrium, as they function as the air flow paths. Based on the layout plans of the atriums, the corridors of FKAB's and FEP's atriums are located at two sides only. However, the FEP's atrium has more advantages in term of natural ventilation as it has the adjoining small courtyard which helps to enhance the natural ventilation. Nevertheless, the FKAB's atrium has openings at the top of the walls which enable the stack ventilation to occur when the cross ventilation is ineffective. In overall, the summarization of the comparative analyses between the two atriums are presented in Table 7.

**Table 7** Summary of comparative analyses between FKAB's and FEP's atriums

Criteria	FKAB's Atrium	FKAB's Atrium
Average indoor operative temperature	Remained below 30 °C throughout the measurement time	Started from 12 pm and above, the $T_{op}$ was more than 30 °C
Users' thermal sensation	Out of 9 hours, there were 7 hours that neutral thermal sensation dominated	Out of 9 hours, there were 5 hours that neutral thermal sensation dominated
Users' satisfaction	Out of 9 hours, there were 4 hours that most users felt slightly satisfied and 5 hours that they felt neutral	Out of 9 hours, there were 2 hours that most users felt slightly satisfied, 3 hours that they felt neutral, 3 hours for slightly dissatisfied, and 1 hour for very dissatisfied
Thermal comfort range for hot humid climate suggested by literature	Within the suggested thermal comfort range at all the measurement times	Outside the suggested thermal comfort range started from 12 pm
Adaptive thermal comfort equation	The average indoor operative temperature was below the predicted indoor comfort temperature at the all times	The average indoor operative temperature was above the predicted indoor comfort temperature at most of the times

## 5. Conclusion

This study examines the indoor thermal environment of two different approaches of top and side configurations of semi-enclosed atriums. The top of FKAB's atrium is fully covered

with opaque material, while the top of FEP's atrium is fully finished with transparent material. Meanwhile, both atriums are located in the middle of the building, and they are surrounded by rooms or spaces. The corridors of the FEP's and FKAB's atriums are found to be only at two sides. Nevertheless, the FEP's atrium has the advantage of having adjacent courtyard which helps to enhance the natural ventilation. From the investigation, the indoor thermal environment of FKAB' atrium was found to be at neutral thermal comfort condition felt by the users at most of the times compared to the FEP's atrium. The average indoor air and operative temperatures of FKAB's atrium were also found to be less than 30 °C at all times, though the average outdoor air temperatures were more than 30 °C. Hence, the findings of the study indicate that both top and side configurations of an atrium have significant roles in determining the indoor thermal environment. The findings also show that the top configuration has an effect to the solar heat penetration which influences the indoor air temperature. Meanwhile, the side configuration affects the natural ventilation inside the atrium, which influences the indoor air velocity. In addition, the findings also indicate that the top configuration of the atrium has more influence to the indoor thermal environment than the side configuration. Hence, for the tropical climate, it is important to reduce the solar heat penetration as much as possible into the atrium area, but at the same time does not compromise on the daylighting aspect. In addition, it is also important to enhance the cross ventilation inside the atrium area for the thermal comfort in tropical climate.

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