Experimental Investigations of the Indoor Thermal Performance of Open Door System (ODOORS) House Prototype in Tropical Climate

Leng Pau Chung
Faculty of Built Environment & Surveying (Architecture)
Universiti Teknologi Malaysia
UTM Johor Bahru, Malaysia
pcleng2@utm.my

Mohd Hamdan Ahmad
Faculty of Built Environment & Surveying
Universiti Teknologi Malaysia
UTM Johor Bahru, Malaysia
b-hamdan@utm.my

Syed Ahmad Iskandar Syed Ariffin
Institut Sultan Iskandar
Universiti Teknologi Malaysia
UTM Johor Bahru, Malaysia
b-sahmad@utm.my

Khairul Anwar Bin Mohamed Khaidzir
Institut Sultan Iskandar
Universiti Teknologi Malaysia
UTM Johor Bahru, Malaysia
b-anwar@utm.my

Irina Safitri Zen
Institut Sultan Iskandar
Universiti Teknologi Malaysia
UTM Johor Bahru, Malaysia
irinasafitri@utm.my

Roshida Abdul Majid
Faculty of Built Environment & Surveying (Architecture)
Universiti Teknologi Malaysia
UTM Johor Bahru, Malaysia
b-roshida@utm.my

***Abstract*— Natural ventilation represents one of the challenges in Malaysia public housing since the most significant and important parameters reflects the layout design efficiency is the thermal comfort within the indoor environment. This paper investigated the thermal performance of a public housing prototype in Malaysia climate context with the duration of two weeks field measurement. Open Doors House System (ODOORS) is a proposed public housing prototype for the community needs. ODOORS offers a system to provide adequate, affordable, comfortable and quality housing for the hard-core poor in Malaysian, which only requires short construction time, and using readily available materials. It is also versatile for permanent and temporary function. Inspiring by the design concept of traditional Malay house, ODOORS integrating the industrialized building system by utilizing market ready construction materials for construction in order to achieve environmental responsive architecture with mass production building material. The parameters considered in the study were air humidity and air temperature. The result shows that there are significant differences between maximum air temperature of outdoor and indoor from 14% to 24% for total spaces in the prototype. The maximum indoor air temperature recorded as 29.09ºC, which is 14% lower than outdoor air temperature. The air humidity of indoor environment retained 11% - 17% below the outdoor air humidity. Hence, the field measurement presents significant empirical findings about the effectiveness of natural ventilation strategies of ODOORS prototype design.**

***Keywords*— sustainable tropical architecture, natural ventilation, thermal performance, industrialized building system Introduction**

I. Introduction

In tropical climate, thermal performance of the low cost housing concerned by researchers due to its' significant impact to the community. The needs of low cost housing in urban area getting critical, since the migration of population from suburban increasing over the years. Rapid urban development has led to suburban sprawl due to the growth of population. This phenomenon has caused critical health and environmental issues and challenges at various scales, Urban Heat Island (UHI) Phenomenon finds one of them [1]. UHI is one of the most concerned and documented phenomenon of climate change in recent decades [2-4]. Global climate change and urban heat island phenomenon have caused discomfort to living environment due to increases of air temperature, especially low cost housing in urban area of Malaysia [2].

Furthermore, heat islands increase energy consumption for cooling purposes especially in residential sector [5]. Global climate change will increase both outdoor and indoor heat loads, which cause hazards to human's health and affecting work productivity of people[6]. Thanks to the advancement of technology, the mechanical ventilation system is a common technical alternative to problems of increasing air temperatures and humidity of indoor environment, especially in tropical climate country [7]. However, the growing numbers of mechanical ventilation system users increases electricity consumption and hence lead to climate change and UHI, which is the main contributors to ambient heat exposures [8].

The energy consumption as well as thermal and indoor environmental quality in par with the occupants' social characteristics in any specific residential stock [9]. Studies have shown that the lower income groups has higher tendency to spend more on electrical bills due to the inadequacy of thermal qualities of their living environment [10]. In order to reduce the construction cost of low cost housing whilst the price of construction and materials hiking up, the low cost houses often fail to provide basic levels of thermal comfort to the occupants [11]. Studies have shown most of the low cost housing could be ineffective and fail to provide basic thermal comfort to the occupants [11,12]. It is more efficient and cost effective to set clear goals and design-it-green before construction stage. It is costly and less energy efficient to implement green components later in the process of construction [13]. Under the circumstances whereby the population, cost of building materials and construction, inflation rate as well as house and land value are increasing, the needs of alternatives for affordable housing prototype getting more demanding and welcoming by policy makers and stakeholders [14]. By constructing a passive cooled as well as sustainable construction design that utilize local and market ready building materials for people in Malaysia, affordable housing prototype with significant thermal performance could be one of the important criteria and considerations of the design proposal. By fulfilling the criteria as mentioned, ODOORS serve as one of the highly effective thermal performance affordable housing.

II. Malaysia Hot Humid Climate

Malaysia is located within the equatorial zone with stable climatic temperature throughout the year. The diurnal ambient temperature ranging from 27ºC to 32ºC while the nocturnal ambient temperature ranging from 21°C to 27°C. The relative humidity of the air is high throughout the year ranging from 75% to 90% while the wind speed near to the ground nearly static. The prevailing wind flow predominantly from southerly direction. However, the wind speed is relatively low when it is near to the ground level. Malaysia gifted with abundant sunshine up to six hours per day. Most of the sun radiation on ground level is diffuse light due to high cloud cover in Malaysia. In general, the significant characteristic of Malaysia climate is hot and humid climate with long hour of sun radiation, high humidity and temperature, high relative humidity as well as low wind speed.

A number of researchers have studied effect of various housing design parameters on the thermal performance. These parameters included orientation of building, typology of housing, insulations, effect of various microclimates, window types and sizes, effect of shadowing and so forth [15-19]. Most of the research apply virtual simulation model and generative method, which could generate large set of synthetic dataset while some are using scaled models to place in wind tunnels with controlled environment [11,19]. Due to limitations of cost and inflexibility of physical full-scale model, there are limited information was published on thermal performance based on field measurement on full-scale building, especially the new prototype of affordable housing in tropical climate. In this study, the thermal performance study of the prototype housing – ODOORS has conducted.

III. Description of ODOORS Prototype

ODOORS prototype house located in campus compound of Universiti Teknologi Malaysia, Johor Bahru, Malaysia (Figure 2). ODOORS main entrance oriented to east while the rear elevation facing to west. The elongated side facing both south and north to maximize the daylighting and reduce direct heat gain from the sun orientation. ODOORS measures 10.43m x 6.75m with total floor area of 70.08m2.

ODOORS structure are made of kapor timber column and roof beam while the external and internal partition composed by three types of plywood timber door and frame (solid type, solid with small opening and solid with ventilation louvres). Both south and north facing roof gable end are finished with louvred cement board. The roof finished off with corrugated metal roofing with fibre wool as insulation layer. The whole footprint surrounded by 1.6m width perimeter concrete apron. ODOORS consisted of 3 bedrooms, which are master bedroom (bedroom 1), bedroom 2 and bedroom 3 as well as one family area. The living space and dining space shared a space after main entrance. The kitchen, toilet 1 and toilet 2 located parallel with dining and living space which formed a core space of ODOORS. All the façade are operable openings expect external wall of toilet, rooms' partition and core unit partition. (refer to floor plan as shown in Figure 1)

Figure 1: ODOORS consists of core space (shaded – washroom, bathroom and kitchen) and open space (rooms) partitioned with door panels. *circle representing location of field measurement tools setup point from ground level.

Figure 2: Location of ODOORS. Front and rear façade of building facing east and west while the longitudinal elevations are facing North and South.

IV. Methodology of Study

In order to investigate the thermal performance of the ODOORS prototype, field measurement was conducted after the construction. The study is to determine the environmental parameters of ODOORS at UTM Johor Bahru, Malaysia on two consecutive dates from 12 October 2017 to 18 October 2017. The field experiment conducted for 7 days in order to investigate the temporal variation of diurnal and nocturnal for ODOORS.

The field measurement instrumentation consisted of sensors with data logger system. The temporal variation for outdoor and indoor climatic conditions, were monitored by data logger as shown in Figure 1 (shaded circle). Other than the indoor sensor data logger, a HOBO weather station was set up 10m away from ODOORS to record the real-time weather data. Outdoor climatic conditions were collected 2.0m above ground using HOBO U30 weather station. Other than outdoor climatic data, all the indoor data were collected 1.2m above the floor, which is at human body level. Data for solar radiation, wind velocity, air temperature, and humidity were obtained using weather station while indoor climatic data were collected with Delta Ohm thermal comfort data logger and compact data logger. Delta Ohm HD31 Thermal Data Logger and Delta Ohm HD3114B Thermal Data logger were set up at living space and master bedroom (or bedroom 1) while HOBO U12 data logger (air temperature and humidity) were set up at bedroom 2 and bedroom 3. The time intervals for each automatic measurements by data logger is 15 minutes, and hence, the thermal performance were investigated from 00:00hr to 23:00hr. All the data logger and weather station were carefully calibrated with thermal data logger beforehand in order to generate reliable result. Table 1 denotes the details of field measurement, which includes subject spaces, data type, equipment used, measurement interval time, and height of measurement point.

In this study, in order to investigate the worst case scenario, all the operable openings (door of ODOORS) were closed. There is only natural ventilation happened across louvres at both gable end. No electrical devices, heating and cooling appliances and lighting, which would adding or reducing heating or cooling load to the indoor environment were utilised throughout the field measurement.

TABLE I. THE MEASUREMENT ITEMS AND METHOD

Room	Data Type	Equipment	Interval	Height
Living Space	Air temperature, Humidity, wind speed	Delta Ohm HD31 Thermal Comfort Data Logger	15 minutes	1.2m above the floor
Master Bedroom/ Bedroom 1	Air temperature, Humidity, wind speed	Delta Ohm HD3114B Thermal Comfort Data Logger	15 minutes	1.2m above the floor
Bedroom 2	Air temperature, Humidity	HOBO U12 Data Logger (Air temperature and humidity)	15 minutes	1.2m above the floor
Bedroom 3	Air temperature, Humidity	HOBO U12 Data Logger (Air temperature and humidity)	15 minutes	1.2m above the floor
Outdoor	Wind speed, air temperature, solar radiation, humidity	HOBO U30 weather station	15 minutes	2.0 m above the floor

V. Thermal performance of ODOORS

5.1 Field Measurement: Outdoor Climatic Condition

In this study, the overall measurements summarized into outdoor climatic condition, thermal performance for living space, bedroom 1, bedroom 2, and bedroom 3. Daily climatic variations in the tropical climate fluctuating between 23.4°C to 33.8°C throughout the measurement period. Conscious architectural design strategies is important criteria for tropical climatic building design. According to Figure 3, the outdoor air temperature ranged from 23.4°C to 33.8°C while the humidity ranged from 13% to 97% throughout the measurement. The highest outdoor air temperature recorded as 33.8°C at 2pm on 16 October 2018 and during this measurement period the humidity at minimum point of 17%. The lowest outdoor air temperature was reported, as 23.4 ºC at 0600hr and the average air temperature was about 27.41 º C. The highest air relative humidity was indicated as 97% at 07:00hr of 17 October 2017 while lowest diurnal relative humidity, which was 13% at 16:00hr of 16 and 18 October 2017. According to the collected data, minimum daily diurnal humidity ranged from 13% to 29%, and around 71.4% of the min daily diurnal humidity happened at 16:00hr. When the diurnal outdoor air temperature reached the highest point of the day, the air humidity will be at minimum level (Figure 3). Temperature and air humidity affect occupant's comfort level. High humidity and heat contains more water in air where the odours molecule would be carried further and lead to thermal discomfort. According to Hyde, the neutral air temperature needs to be maintain at 28.6°C – 29.3°C [20]. However the data collected indicated that the diurnal measured outdoor air temperature between 0800hr to 1800hr was above the required thermal comfort air temperature.

Solar intensity data on 16 October 2017 emphasized 132 MJ/m² at 1400hr while the air temperature measured as the highest throughout the field measurement (33.8°C) (Figure 5). Daily patterns of mean wind velocity in the daytime (from 0800hr to 1800hr) are between 0.24m/s to 3.38m/s. However, the mean of air speed is slightly higher than the nocturnal air speed, which is between 0m/s to 0.05m/s especially between 00:00hr to 06:00hr. Thus, the air movement in the daytime is more significant compare to night-time. The measured outdoor air movement in the daytime deduce that cross ventilation strategy could improve the internal air temperature via design layout with multiple operable openings applied [21].

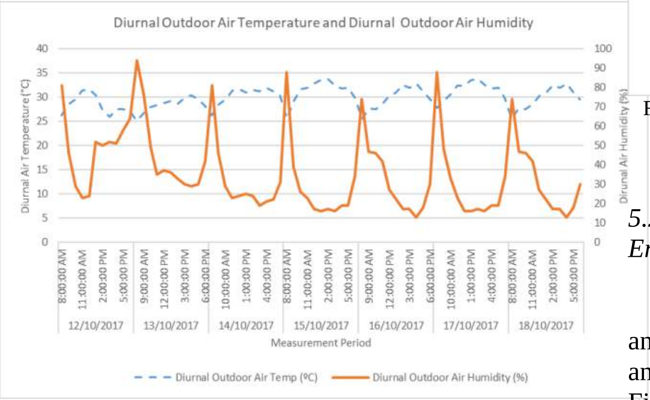

Figure 3: Relationship between Diurnal outdoor air temperature and diurnal outdoor air humidity

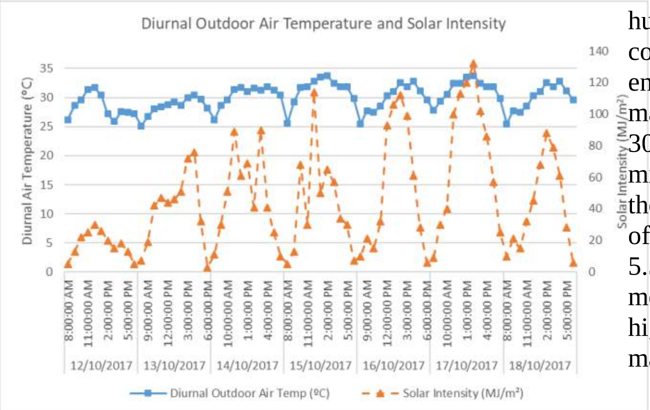

Figure 4: Outdoor diurnal air temperature and solar intensity throughout the field measurement period

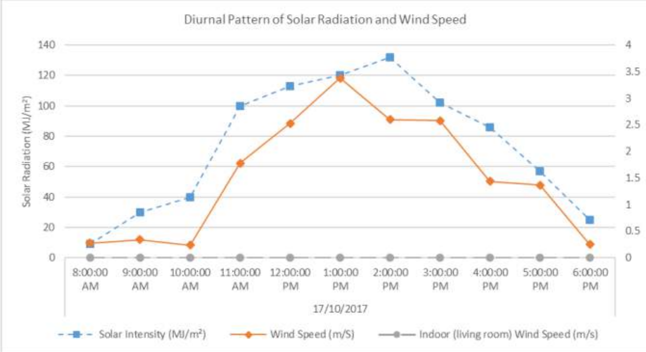

Figure 5: Diurnal pattern of Solar Radiation and Wind Speed at 17 October 2017 (Data obtained 2m above ground on site at the U30 HOBO Weather Station, 17 October 2017)

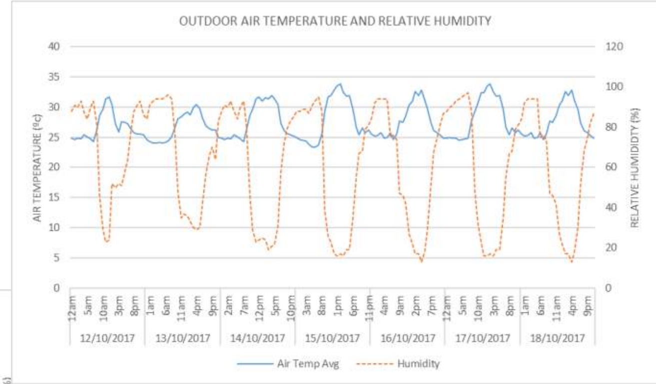

Figure 6: Outdoor air temperature and relative humidity from 12 October 2017 to 18 October2017

5.2 Field Measurement: Indoor Thermal Environment

According to the measured air temperature and humidity data, the relationship between indoor and outdoor air temperature of ODOORS is shown in Figure 7, The deviation of outdoor and indoor temperature data is minor throughout the field measurement. It is clear that the fluctuation of both humidity and air temperature for outdoor climatic condition is dynamic compared to indoor environment. The percentage of deviation between maximum and minimum outdoor air temperature is 30.76% while the deviation of maximum and minimum living space air temperature is 11.69%. In the other hand, the max and min humidity deviation of outdoor is approximately 86.6% while it is only 5.54% for indoor environment. According to the measurement, the outdoor air temperature could be as high as 33.8°C since the solar intensity at its maximum of 132MJ/m² at 1400hr.

During the morning and late evening (2000hr – 0700hr), the air temperature of indoor environment and outdoor climate is similar with 0.2-0.4°C difference. At 17 October 2017, the average diurnal air temperature (0800 – 1800hr) for outdoor climate ranged from 27.8°C at 0800hr and 33.8°C at 1400hr. However, the air temperature range for living space ranged from 25.08°C at 0800hr to 26.35°C at 1600hr. The mean diurnal air temperature for outdoor climate and living space are 31.43°C and 25.69°C respectively. The indoor living space is 18.26% lower than outdoor climate condition at the selected day with maximum air temperature throughout measurement. With the increase of solar radiation, outdoor air temperature also increased and reached it highest value at 1400hr with a value of 33.8°C and gradually drop to 29.8°C before radiation diminishing at 1900hr. Throughout the daytime measurement on 17 October 2017, the max diurnal air temperature deviation happened on 1300hr and 1400hr with differences of 7.85°C. The maximum air temperature of indoor environment (living space) occurred at 1600hr with value 26.35°C when outdoor air temperature is 31.8°C. The indoor environment thermal performance able to maintain at thermal comfort range (24.75°C to 28.03°C) may due to the fact that the space is oriented towards the east with the least evening sun exposure.

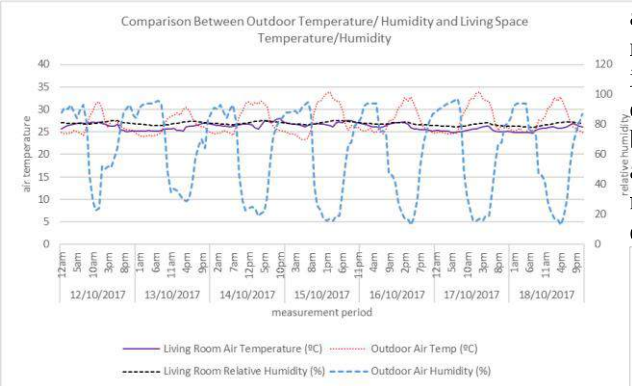

Figure 7: Comparison between outdoor versus living space's temperature and relative humidity

For bedroom 1, bedroom 2 and bedroom 3, the average air temperature throughout field measurement recorded as 27.36°C, 27.62°C and 27.52°C respectively (Figure 8, 9 and 10). The maximum air temperature for bedroom 1 recorded as 37.71 C at 0900hr of 15 October 2017, while bedroom 2 and 3 recorded as 32.75 C and 31.92 C at 1500hr on 14 October 2017. When the outdoor air temperature marked the higehst value of 33.8°C and the highest solar radiation recorded as 132MJ/m² on 17 October 2017, the indoor environment air temperature for bedroom 1, 2 and 3 marked as 28.75°C, 29.25°C and 31.92°C respectively. In the hottest day (17 October 2017), the indoor air temperature ranged from 25.95°C to 29.23°C, which is still within acceptable comfort range by Nicol's comfort formula. According to Nicol's comfort formula indicates, the diurnal mean indoor air temperature above 29.5°C considered as exceeding comfort zone [22]. Both statements have indicated that indoor air temperature indirectly influenced by the outdoor air temperature, whereby the increases of air temperature could be affected by other factors such as air convection due to heat trap since the measurement were taken in enclosed condition. The indoor thermal environment of bedroom 2 and 3 received direct solar heat gain in the evening and the enclosed environment has restricted the airflow, which has led to accumulation of solar heat trap.

Furthermore, mean relative humidity for living space, bedroom 1, bedroom 2 and bedroom 3 throughout field measurement recorded as 80.54%, 82.57%. 80.40% and 81.30% respectively (Figure 7, 8, 9 and 10). In comparison with mean outdoor humidity throughout field measurement, the mean outdoor air humidity is 23.44% to 25.46% lower than the mean indoor air humidity. The dynamic fluctuation of the outdoor air humidity caused by the air radiation and wind velocity condition, whereby the indoor humidity remains essentially the same for several hours due to the heat gain from outdoor condition during the daytime. During the hottest hour (1400hr at 17 October 2017), the humidity of indoor environment ranged from 76.62% to 79.23% where the bedroom 1, 2 and 3 marked as 76.62%, 77.53% and 78.33% respectively while the living and outdoor marked as 79.23% and 17%. The humidity for living is slightly higher than bedroom 1, 2 and 3. The results emphasized the high relative humidity at living and bedroom 3 since the lower limit of humidity is approximately 80%. The slightly higher humidity may enhanced by air flow and circulation of air in the enclosed room.

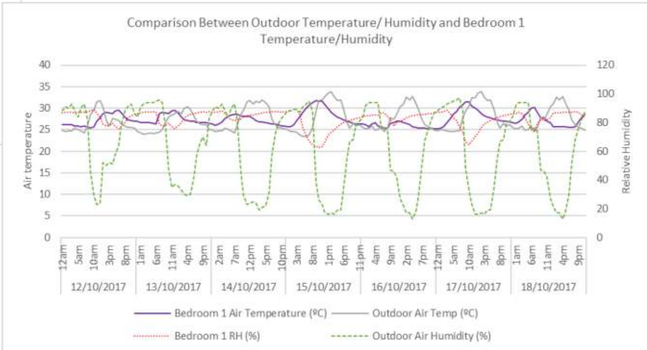

Figure 8: Comparison between outdoor versus bedroom 1 air temperature and relative humidity

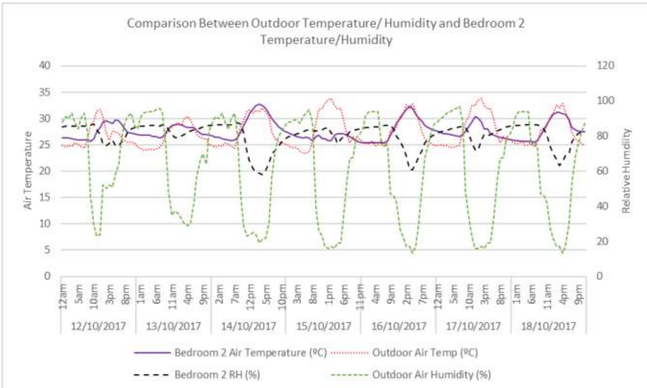

Figure 9: Comparison between outdoor versus bedroom 2 air temperature and relative humidity

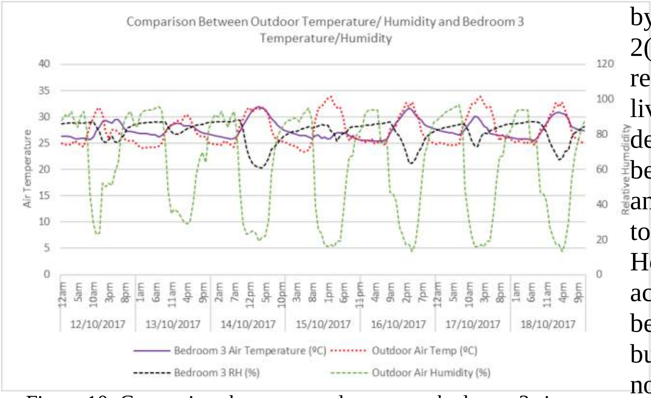

Figure 10: Comparison between outdoor versus bedroom 3 air temperature and relative humidity

VI. FACTORS INFLUENCING THE PROFILE OF AIR TEMPERATURE IN ODOORS

The main interest of this study is to investigate the thermal performance of ODOORS as in it's effectiveness to provide the thermal comfort to the occupants. The measurement hypothesized that thermal performance of ODOORS could be achieved with it's passive tropical architecture design feature: Long overhang of roof, louvres gable end, multiple opening as building envelope and the use of timber door and white metal roofing were applied as building construction material for ODOORS. In this section, the comparison between outdoor air temperature versus deviation value of outdoor and living room air temperature; the comparison between outdoor air temperature versus deviation value of outdoor and Bedroom 1, bedroom 2 and bedroom 3's air temperature were studied.

Figure 11 shows the relationship between deviation of the indoor environment thermal performance during min and max outdoor air temperature and min and max indoor air temperature. It has shown that air temperature for bedroom 2 and 3 has significant differences between outdoor and indoor air temperature throughout the measurement, while bedroom 1 possess the least differences between outdoor and indoor thermal performance during the day with highest and lowest air outdoor temperature. Both variation pattern of deviation for min and max outdoor air temperature are similar. The similar pattern could be caused by the position of the room since ODOORS is detached building exposed to direct radiation and heat gain.

In the other hand, Figure 12, 13, 14 and 15 were structured in this study in order to investigate the relationship between outdoor air temperature and deviation of outdoor temperature versus indoor thermal performance for living space, bedroom 1, bedroom 2 and bedroom 3. The linear regressions of outdoor and indoor temperature deviation is constructed. According to the four figures, R^2 of living space show the results of R^2=0.9287, followed by bedroom 2 (R^2=0.7312) and bedroom 2(R^2=0.6068) and bedroom 3 (R^2=0.6727). The results deduced that the thermal performance of the living space remains in comfort zone with consistent deviation with outdoor climate condition. For bedroom 1, 2 and 3, correlation between deviation and outdoor air temperature is significant and closed to the linear trendline at air temperature below 27°C. However, when the outdoor air temperature increases accordingly, the correlation between both parameters became insignificant and dynamic. Back to the building physical location, living space positioned at northeast orientation while bedroom 3 is facing south-west. Bedroom 1 is facing north-west and bedroom 2 positioned at north elevation. Since the morning sun's solar intensity is lower compared to evening, the heat gain for living space could be lower compared to bedroom 3 and bedroom 1. The inconsistency of variation pattern shown by figure 13, 14 and 15 have indicated that heat transferred from air convection and radiation happened when direct sunlight contributes to increases of air temperature in order for the indoor and outdoor air to achieve equilibrium. Thus, orientation of building is one of the important factor as it could influence the indoor thermal performance.

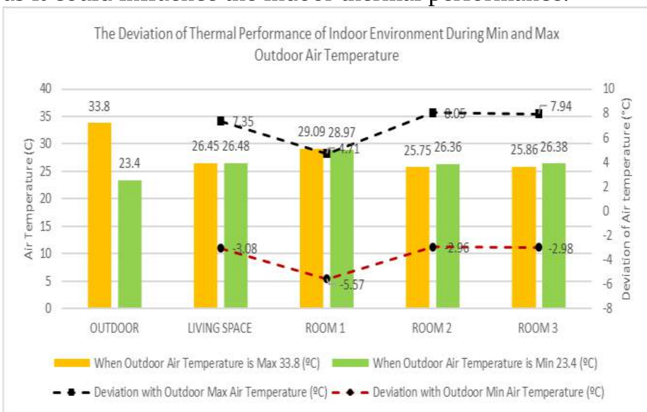

Figure 11: The deviation of thermal performance of indoor environment during min and max outdoor air temperature

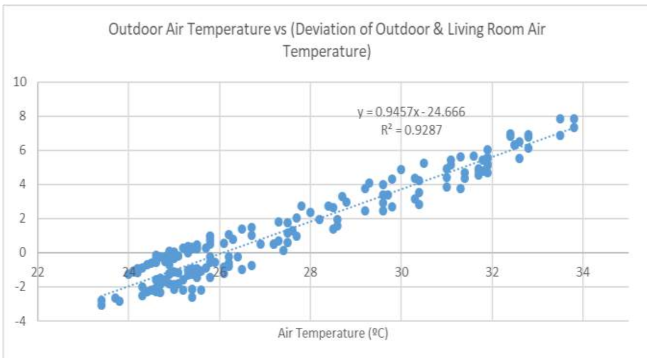

Figure 12: Linear regression of outdoor air temperature versus differences of outdoor and living room air temperature.

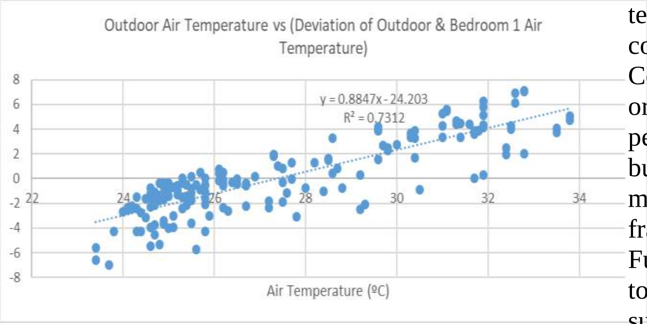

Figure 13: Linear regression of outdoor air temperature versus differences of outdoor and bedroom 1 air temperature.

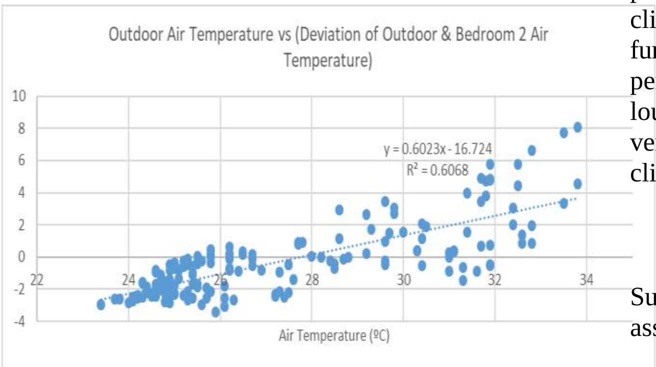

Figure 14：Regression of outdoor air temperature versus differences of outdoor and bedroom 2 air temperature.

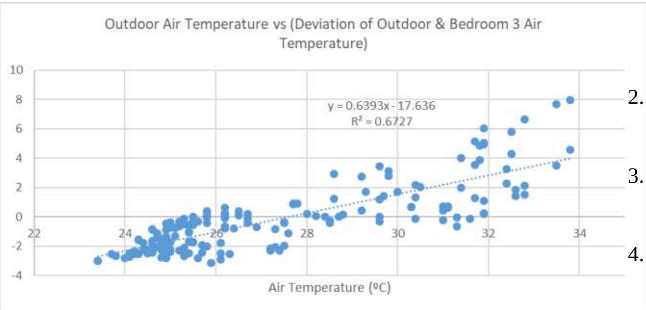

Figure 15：Regression of outdoor air temperature versus differences of outdoor and bedroom 3 air temperature.

VII. CONCLUSION

The aim of the study is to investigate the thermal performance of ODOORS since it is a new prototype housing developed based on tropical climate and traditional houses architectural feature. The wisdom of the past, which has gradually substituted with adaptive modern architectural feature from the west were applied and modified as new prototype housing for people. The field measurement investigated the thermal environment and the thermal performance of the prototype house from 12 – 18 October 2017, which was conducted after the construction of prototype. In general, the average air temperature for living space, bedroom 1 to 3 ranged from 25.52ºC to 27.62 ºC while during the max outdoor air temperature hour with value 33.8 ºC, the indoor environment thermal performance ranged from 25.95 ºC to 29.25 ºC. The diurnal indoor air temperature for ODOORS considered within the comfort zone below 29.5 ºC according to Nicole Comfort Formula. Other than that, the position and orientation of space directly influenced the thermal performance of the building. In compared to concrete building, ODOORS constructed from fully open-market available component (door panel and door frame) which is low thermal conductivity material. Furthermore, the used of reflective and light colour tone of low overhang roof enabled most of the sunlight reflected and enabled the envelope to be protected from climate condition. Hence, the findings proved that ODOORS is thermally perform in tropical climate. In order to improve the thermal condition, further experiments needed to examine on thermal performance of ODOORS with operable openings or louvred section on door panel to improve the natural ventilation in buildings in hot and humid tropical climate.

ACKNOWLEDGEMENT

The authors would like to thank Institut Sultan Iskandar for the financial support and assistance from research grant.

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