INTERNATIONAL JOURNAL OF SUSTAINABLE CONSTRUCTION ENGINEERING AND TECHNOLOGY
VOL. 14 NO. 5 (2023) 170-184

IJSCET

http://publisher.uthm.edu.my/ojs/index.php/ijscet

ISSN : 2180-3242 e-ISSN : 2600-7959

International Journal of Sustainable Construction Engineering and Technology

Investigation of Thermal Comfort for A Naturally Ventilated House: Correlation between Climatic Design Strategy and Thermal Data Analysis

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DOI: https://doi.org/10.30880/ijscet.2023.14.05.013
Received 20 May 2023; Accepted 22 August 2023; Available online 31 October 2023

Abstract: One of the main factors contributing to climate change and global warming is architecture, which accounts for about 50% of the country's greenhouse emissions due to construction and the energy needed to keep buildings operational. Sustainable architecture is believed to reduce emissions, and this approach has been practised with traditional buildings. In Malaysia, a traditional Malay house (TMH) is one of the traditional buildings, and it is initially naturally ventilated with occupant-controlled air ventilation to condition the space. Numerous experimental studies claimed that TMH has demonstrated a good model for contemporary designers to understand climatic and environmental design, building systems, and design adaptability. One of the approaches is to practise climatic design strategies. However, there is a lack of study to determine if TMH is still relevant as a sustainable design that can adapt to current climate conditions. Thus, the study aims to investigate the adaptive indoor thermal comfort of a Negeri Sembilan Malay house in a hot-humid climate determined by the correlation between climatic design strategy and thermal data analysis. This study employed the Predictive Adaptive model by executing two stages of fieldwork: i) local climate background and ii) physical measurement (case study description and environmental data). The data were then analysed using the ACS of ASHRAE 55 and MS 2680:2017. The primary results revealed that 62% of the hourly indoor operative temperature of the case study house was within 80 to 90 % of the acceptability limit. The optimal comfort hourly indoor operative temperature was between 25.5 to 29.5 °C with a prevailing mean outdoor air temperature between 23 to 30 °C, which represents 90% of the acceptability limit range. Moreover, the results also complied with the standards of ACS, where the average hourly indoor operative temperature was less than 31 °C, with a prevailing mean outdoor air temperature less than 32 °C, which was an acceptable indoor state for occupants' comfort. The findings complied with RMK 12 Theme 3, which aims to be a carbon-neutral country by practising sustainable architecture and construction. The design of naturally ventilated houses, such as Negeri Sembilan Malay houses in hot-humid climates, can be a model reference for modern housing design development.

Keywords: Adaptive indoor thermal comfort, climatic design strategy, naturally ventilated house, Predictive Adaptive (PA) model, sustainable design, traditional Malay houses

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1. Introduction

One of the main factors contributing to climate change and global warming is architecture (Gerretsen, 2023; UNEP, 2023; IPCC, 2022). The sector is accountable for about 50% of the country's greenhouse emissions due to construction and the energy needed to keep buildings operational (Stamp, 2020), leading to outdoor thermal discomfort (Gerretsen, 2023; Rodriguez & D'Alessandro, 2019; Morris et al., 2017; Morris, 2016; Morris et al., 2016). As a result, it needs further cooling to regulate indoor thermal comfort (ITC). Sustainable architecture may reduce emissions, which is a re-conceptualisation of architecture in response to many modern concerns about the effects of human activity (Williamson et al., 2015; Hyde, 2008; Sassi, 2006). The approach of sustainable architecture has been practised in the earliest buildings designs, for instance, traditional buildings. In Malaysia, a traditional Malay house (TMH) is one of the examples.

TMH is an initially naturally ventilated building with occupant-controlled air ventilation to condition the space with no mechanical cooling system, i.e., air conditioning installed. It is an excellent and naturally ventilated building, providing natural harmony between people, houses, and the environment. Numerous experimental studies have claimed that Malay houses have demonstrated a good model for contemporary designers to understand climatic and environmental design, building systems, and design adaptability (Hassin & Misni, 2023; Johari & Said, 2021; Yaa'cob et al., 2021; Saad et al., 2019; Ibrahim et al., 2015; Amat & Rashid, 2014; Toe & Kubota, 2014; Toe & Kubota, 2013b). One of the approaches is passive cooling designs, which practise climatic design strategies. These design strategies aim to produce adequate indoor thermal comfort (Shaeri et al., 2018; Nordin & Misni, 2018).

Nonetheless, due to the current global warming phenomenon, there is a need for more studies to determine if TMH is still relevant as a sustainable design that can adapt to current climate conditions (Oleiwi & Mohamed, 2021; Kubota & Toe, 2015). Therefore, the present study aims to investigate the adaptive indoor thermal comfort of a Negeri Sembilan Malay house (NSMH) in a hot-humid climate by determining the correlation between climatic design strategy and thermal data analysis. The idea is to scientifically demonstrate how the climatic design strategy influences the ITC of the house; hence, it can be determined whether NSMH is still relevant as a sustainable design that can adapt to current climate conditions.

2. Indoor Thermal Comfort Evaluation

The Predictive Adaptive (PA) model is a model that defines the relationship between the indoor temperatures measured in buildings and the monthly outdoor mean temperature, which the temperature can be obtained from the nearest approved meteorological station (Parsons, 2020; Efeoma & Uduku, 2014). It could signify the level of indoor thermal condition of the occupants relative to local climate conditions. In addition, the PA model is designed mainly to evaluate buildings with occupant-controlled naturally conditioned spaces or natural ventilation (NV) buildings (Dear & Brager, 2002; Dear & Brager, 1998). Nonetheless, Hassin & Misni (2022), as well as Luo (2020) explained that choosing the appropriate comfort model to evaluate an indoor thermal environment is crucial. ASHRAE (2017) suggested the Adaptive Comfort Standard (ACS) for determining and analysing permissible thermal conditions in NV buildings. ACS includes two sets of operative temperature t_o limits, one for 80% acceptability and one for 90% acceptability. The t_o is an input variable in ACS, simplifying the measurement of human thermal comfort derived from air temperature, mean radiant temperature, and air speed.

In the context of TMH, it is well known for its passive cooling designs. It is a vital strategy for providing natural passage for ventilation and air circulation, impacting the occupants' thermal condition. Thus, the Malaysian Standard for Energy Efficiency and Use of Renewable Energy for Residential Buildings - Code of Practice (MS 2680:2017) is the measurable scale for wind speed. The circulation of air has an impact on indoor thermal comfort. The presence of air movement increases evaporative and convective cooling of the skin, which can help us achieve a higher level of thermal comfort. Based on the air speed rate specified in MS 2680:2017 (Table 1), ASHRAE 55 recommended that the rate be between ≤ 0.25 and 1.0 m/s (Scale 1 to 3) to create a convenient indoor environment.

Table 1 - The measurement scale for air speed based on the MS 2680:2017

Scale	Unit (m/s)	Occupant sensation
1	≤ 0.25	Unnoticed, except at low air temperatures
2	0.25 - 0.5	Feels fresh at comfortable temperatures but draughty at cool temperatures
3	0.5 - 1.0	Generally pleasant when comfortable or warm but causing constant awareness of air movement
4	1.0 - 1.5	Acceptable in warm conditions but can be from slightly to uncomfortably draughty
5	> 1.5	Acceptable only in sweltering and humid conditions when no other relief is available. Requires corrective measures if comfort and productivity are to be maintained

3. Materials and Methods

The Malay house selected as a case study was a NSMH. The applicability of selecting the NSMH and region style was due to the insufficiency of the ITC investigation that encounters the TMH built with *bumbung panjang* tapering ends raised slightly at the *serambi* and an elongated floor plan (Johari & Said, 2021; Oleiwi & Mohamed, 2021; Rizal et al., 2021; Saad et al., 2019; Toe & Kubota, 2014; Toe & Kubota, 2013a; Toe & Kubota, 2013b; Hassan & Ramli, 2010). According to prior research, most experimental ITC studies have focused on the basic design of common *bumbung panjang* and *bumbung limas*. NSMH has a roof with a height angle design; it would have a positive effect as the incident solar radiation angle reaches zero degrees, reducing the solar radiation's penetration into the house (Ramly & Hussain, 2006). The type of roof is very different from the other regions in Malaysia, which the Minangkabau of Indonesia has dramatically influenced (Ismail et al., 2017). Furthermore, a shallow floor plan is more efficient as it permits more airflow inside the structure, allowing for cross-ventilation (Yüksek & Karadayi, 2017). These characteristics differentiate NSMH from the others and symbolise the uniqueness of the *Perpatih* customary community practised by its members (Ismail et al., 2017).

The investigation employed the PA model by executing two stages of fieldwork: i) local climate background and ii) physical measurement (case study description and environmental data). The Adaptive Comfort Standard (ACS) of ASHRAE 55 and MS 2680:2017 were used to verify and analyse indoor thermal comfort and performance. Figure 1 illustrates the methodology framework, and Table 2 lists the case study criteria. Meanwhile, Table 3 indicates the variables/parameters according to the climate and thermal data collection.

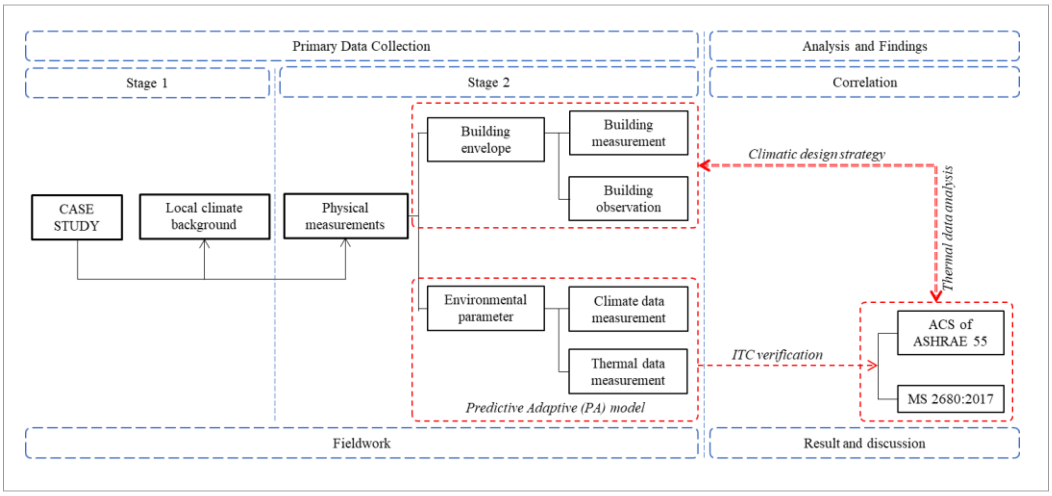

Fig. 1 - Methodology framework

Table 2 - Case study criteria

Criteria	Description
House unit	Single-family house of traditional Malay houses
Yard distribution	Malay house yard (front, side, and back yards are preferred)
Building cooling control	Natural ventilation
Authenticity	Physical requirement elements (minor modification): • Use local low thermal capacity materials of building envelope (wall/floor/roof) • Elevated from the ground (built on stilts) • Large opening of the windows and other openings • Traditional Malay house layout plan (*serambi*, *rumah ibu*, and *rumah dapur* (optional) • Landscaping/edible/native plants surrounding the yard • Strategic orientation of the house
Age of house	Over 80 years old

As previously mentioned, NSMH is one of the TMHs in Malaysia, equivalent to a heritage house. To justify the authenticity and originality of the house, the criteria in Table 2 are applied. The criteria are considered based on the four parameters of the authenticity concept: design, materials, workmanship, and setting, which was introduced by the World Heritage Committee (Ehteshami & Soltaninejad, 2020; Wood, 2020; Nezhad et al., 2015). It ensures the integrity of a building's identity by providing evidence of its physical attributes' existence (Al-Sakkaf et al., 2020). A building with the value of a nation and culture, for instance -- a distinctive physical characteristic of design representing the traditional Malay workmanship -- is justified and referred to as a traditional and heritage building (Feilden, 2003). The fundamental characteristics of TMH are that it is built on stilts, has a single-family house unit, abundant large operable windows, ventilation lattice, a steeply sloping roof with gables ends, occupant-controlled naturally conditioned spaces, and a yard area that is distributed into three main areas: front, side, and rear (Salleh et al., 2016; Teh & Nasir, 2014; Ju et al., 2012; Sahabuddin, 2012). Moreover, the house is constructed using timber, lightweight materials, and other natural materials with low thermal capacity (Ibrahim et al., 2015; Lim, 2010; Misni, 2012).

Despite that, the authenticity requirement of the NSMH typology was referred to because each typology has distinctive characters. Furthermore, the Operational Guidelines of the World Heritage in 2005 defined authenticity as the property's capability to transmit a place's cultural significance. The selected study location for the NSMH in Negeri Sembilan, Malaysia, was based on the areas that practise *Perpatih* customary and have obtained *Tanah Adat* (customary land) (Supaat et al., 2017; Ramly, 1995). The *Tanah Adat* area is a heritage land usually inhabited by the Malays (MDKP, 2023). Thus, the age of the house is presumed to be one of the indicators to ensure its authenticity based on the authenticity concept parameters. Besides, it is intended to ensure that the house's building envelope is adequately morphologically adapted to the surrounding environment (Badarnah, 2017).

Table 3 - Data variables/parameters and gathering instrument

Items	Variables/parameter	Data gathering instrument
Climate data	• Prevailing mean outdoor air temperature (°C) • Relative humidity (%) • Air speed (m/s) • Cloudiness (%) and precipitation (mm)	The nearest approved meteorological station in Negeri Sembilan, Malaysia is at Kuala Pilah and Atherton Estate
Thermal data	In situ measurements (indoor and outdoor): • Air temperature (°C) • Radiant temperature (°C) • Air speed (m/s)	Delta OHM HD32.3 Data logger

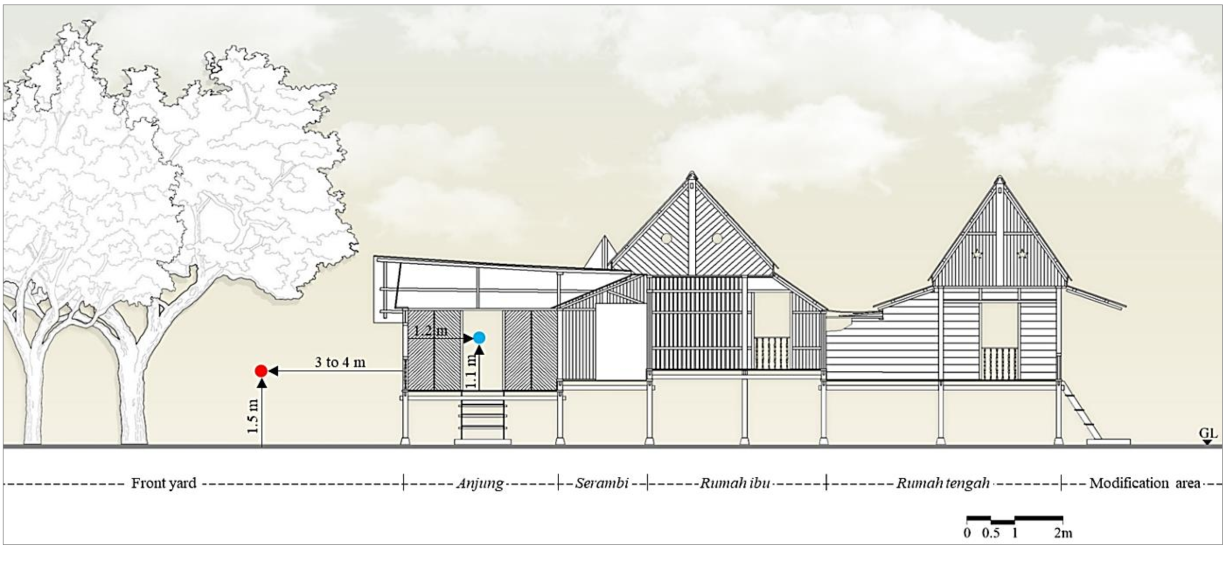

Fig. 2 - Monitoring instrument positions for indoor and outdoor at the case study house

Both the thermal data of indoor and outdoor areas were monitored. As illustrated in Figure 2, the monitoring instrument for the interior data acquisition point was positioned approximately 1.1 m above floor level (ASHRAE, 2017) and 1.2 m from any wall (CLEAR, 2019). At the same time, the outdoor area was measured at 3 to 4 m from the wall of the house and at a height of around 1.5 m (Collow, 2020). Data collection was conducted during overcast and mostly cloudy conditions. It is the typical sky condition in Kuala Pilah, Negeri Sembilan (Weatherspark, 2023), around September 2022 because the weather is the most stable, with medium precipitation and temperature (Weatherspark, 2023; MetMalaysia, 2022). The climate must be in good condition to ensure accurate and practical data in a tropical environment. Therefore, no survey was conducted in rainy or clear sky conditions. This study's scope was only to evaluate the ITC in the ordinary climate of Kuala Pilah.

The data were recorded within 12 hours, from 07:00 to 19.30, at 30-minute intervals, throughout three days. The intention was to obtain and determine the average data. Parsons (2020) stated that one day would be enough for the assessment, whereas ASHRAE (2017) suggested that the timing should span for about two hours or more; thus, no specific number of days is being advocated. In addition, no measurement was taken at night from 20.00 p.m. to 6.30 a.m. This is because the present researcher considered the owner's privacy at night time. Another rationale that the measurement was only taken in the daytime is because it is during the peak time that heat accumulates due to solar radiation and most of the villagers are self-employed or retired. The house must be occupied during the measurement, and windows will always be kept open (ASHRAE, 2017). Besides, the house must also be in fully naturally ventilated mode when the survey is conducted. Therefore, it is reasonable to evaluate the influence of house design on the degree of ITC regulation. Besides, this is to understand the occupants' thermal satisfaction with the ventilation system. Other than that it is to determine the ventilation technique of the house.

4. Results and Analysis

4.1 Local Climate

The selected study location for the NSMH was in Kuala Pilah, Negeri Sembilan, Malaysia. The climate in Kuala Pilah is described as unpleasant, humid, and overcast all year. According to Weatherspark (2023), throughout the year, the temperature ranges typically from 22°C to 32°C, with temperatures rarely falling below 20°C or rising above 34°C. Meanwhile, relative humidity (RH) is between 80% and 100%. The average hourly wind speed in Kuala Pilah varies slightly throughout the year, from 1.1 to 1.7 m/s, and September is one of the second calmest months of the year, with an average hourly wind speed of 1.1 m/s. Kuala Pilah experiences rainfall throughout the year, with an average of 124 mm to 253 mm. Meanwhile, the average cloud cover is between 88% and 90%.

4.2 Case Study Description

NSMH is located at Kg. Cheriau, Mukim Pilah, Senaling, which is situated in the middle of Kuala Pilah district, between Mukim Seri Menanti, Ampang Tinggi, Ulu Muar, Kepis, and Johol. The house is built on Lot 5726 with Longitude 2°41'44" N and Latitude 102°13'39" E, and the elevation is about 112 m above sea level (Figure 3(a)). The location of the house is about 6.9 km from Kuala Pilah town and 3.2 km west of Senaling town. The house is a single-family house and is approximately 128 years old. It still has and maintains the distinctive characteristics of NSMH.

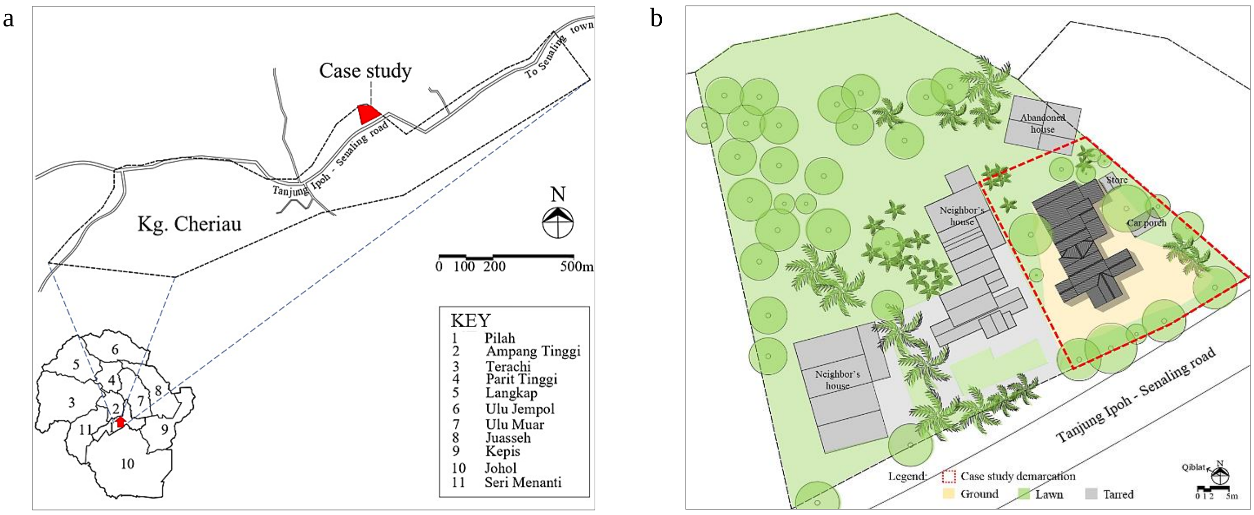

Fig. 3 - (a) The location of the site plan of the case study house at Kg. Cheriau in Mukim Pilah, Senaling, Kuala Pilah; (b) the site plan of the case study house

The site plan in Figure 3(b) illustrates that three houses were built on the same land. The case study house was built on the same land lot as the two houses next door because it was an inheritance from the same family. Nonetheless, the study only involved a NSMH, mainly demarcated in the site plan. The house was built in the typical layout of TMH yards, which is distributed into three main areas: front, side, and rear. It has a total ample outdoor area of 518.33 m^2, which is distributed into the front (201.9 m^2), right side (91.96 m^2), left side (75.43 m^2), and rear (149.04 m^2) of the yards. The front and side yards comprise ground and lawn as the ground is covered; the rear yard is covered with lawn. Crop-bearing trees such as coconut trees and shady trees are planted in the yard. The settlement patterns of Kg. Cheriau, Senaling, depicted in Figure 3(b), are in a linear design setting. It can be identified by the houses facing towards a transportation route, which is the main road known as Tanjung Ipoh-Senaling road.

Fig. 4 - The front elevation of the house with the natural surrounding compound

The typology of the case study was *rumah berserambi dua dan beranjung* (RBDB). The roof structure design is curved slightly at the left and right of the *serambi* (*pangkal and hujung*), has *bumbung cerun bertingkat* (double slope roof) between the roof of the *rumah ibu* and *serambi*, *tebar layar* (gable end) at both ends of the roof, and has *anjung* at the *serambi* (Figure 4). It has five spatial divisions, which are *anjung* (porch), *serambi* (verandah), *rumah ibu* (core or main house), *rumah tengah* (middle house), and kitchen, with a total built-up area of 105.28 m^2. Each spatial division area, floor, and roof heights are varied (Figure 2 and Table 4). Apart from the kitchen, the house was constructed high above the ground. A few modifications and space extensions have been constructed. The kitchen was built later than the main house (original building). Based on the layout plan, there are three bedrooms in the house, and the master bedroom, located at *rumah ibu*, is the original room among those three. The additional bedrooms (bedrooms 2 and 3) were made by demarcating them using plywood as the wall panel at *serambi pangkal* and *hujung*.

The house's front elevation is oriented to face east-south direction, with a direction of qibla 293°30', whereas the house's main entrance is oriented towards the southwest direction. *Anjung, serambi pangkal*, and the right side of the house and the windows face east, where the spaces received abundant sun rays in the morning, especially at *anjung.* In conjunction, the left side of *rumah ibu*, *rumah tengah*, kitchen, and *serambi hujung* received immoderate sun rays beginning from afternoon until evening. This is due to the windows facing the west direction, where the sunset takes place.

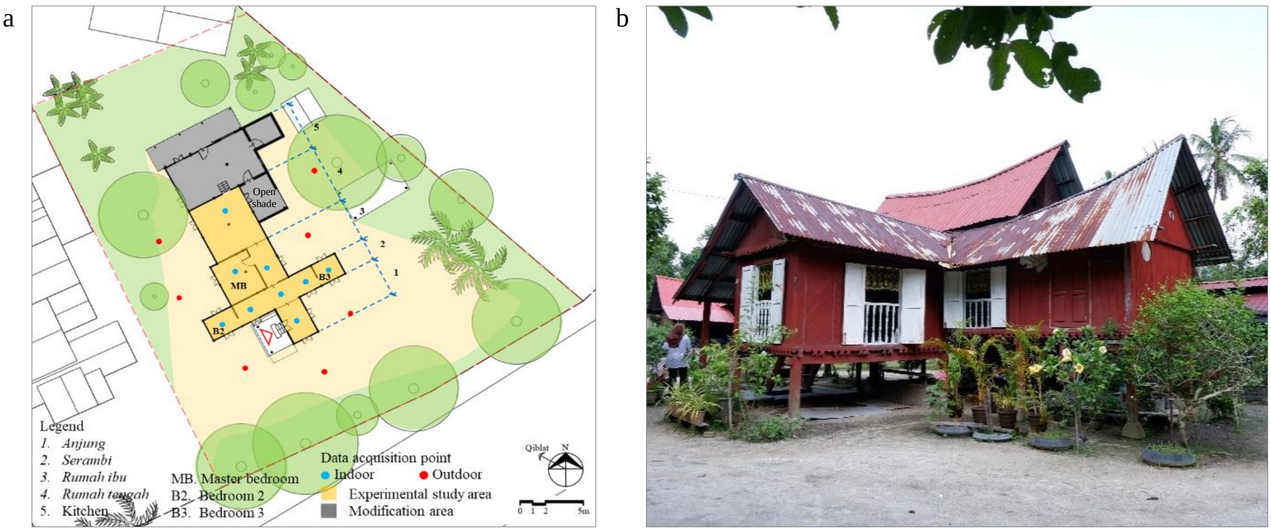

Fig. 5 - (a) The spatial division; (b) front of the house is facing east – the south direction

Table 4 - Area, floor, and roof height according to the spatial divisions

Subject	Original building				Extended and renovation
	Anjung	***Serambi***	***Rumah ibu***	***Rumah tengah***	**Kitchen**
Area (m^2)	7.69	22.90	19.90	23.20	31.59
Floor height (above the ground) (m)	1.12	1.33	1.54	1.32	Constructed direct on the ground
Roof height (from the floor) (m)	2.47 – 2.63	2.78 – 2.30 (*serambi pangkal*) 2.20 (*serambi tengah*) 2.77 – 2.08 (*serambi hujung*)	3.95 – 3.80 – 4.03	4.21 – 4.20 – 4.25	3.85 – 3.65

The house is a fully occupant-controlled and naturally conditioned space. It is designed with plenty of operable windows and ventilated *pagar musang* in each spatial division. The ventilated *kepala tingkap* is only designed for *anjung* and *serambi*. In addition, each space has roof and floor joists as ventilation devices. However, apart from *serambi*, the roofs are designed with ventilated *tebar layar*. As for the wall joist, it is obtainable at *serambi*, *rumah ibu*, and *rumah tengah*. Mechanical ventilation equipment, such as a pedestal fan, is only used when an occasion is being held. However, a pedestal fan is frequently used in the cooking area, which is the kitchen. The floor finishes, walls, and roofing materials in all spatial divisions are rubber mats, wood planks, and zinc sheets. The original material of the house floor is wood plank layered with a rubber mat. According to the house owner, the primordial material for roofing is an *attap* roof made from palm leaves. There is no ceiling in all spaces except in the master bedroom in *rumah ibu*. The plywood covers the ceiling. As for the master bedroom, the ceiling and part of the wall are layered with fabric. Table 5 lists the materials used and depicts the ventilation devices in the spatial division.

Table 5 - The material used for every spatial division

Subject	Original building			
	Anjung	***Serambi***	***Rumah ibu***	***Rumah tengah***
				
Roof and ceiling	Zinc	Zinc	Zinc and plywood covered with fabric	Zinc
Wall	Wood	Wood and plywood	Wood, board, and fabric	Wood
Floor	Wood plank layered with rubber mat			

4.3 Correlation between Climatic Design Strategy and Thermal Data Analysis

Thermal data were collected on the 8th, 9th, and 10th September 2022. All thermal data were recorded in situ based on standard local time (SLT) for indoor and outdoor areas. The data were recorded according to the spatial divisions (original building): *anjung*, *serambi*, *rumah ibu*, *rumah tengah*, and the outdoor area. Figure 5(a) illustrates the various data acquisition points designated to record the data. The average thermal data, based on spatial division, are represented in Table 5, and Figures 6(a)-(b) illustrate the comparison of indoor operative temperature t_o and air speed based on spatial division. Furthermore, the estimated model of indoor operative temperature and air speed based on spatial division is stated in Tables 6 and 7, whereas the relation between the variables is illustrated in Figures 7 to 10 and discussed through linear regression using equation (1).

To verify the indoor acceptability limits using ACS, operative temperature t_o and prevailing mean outdoor air temperature $\overline{t_{pma(out)}}$ is the input variable; equation (2) was applied to get the mean radiant temperature $\bar{t}_r$, whereas equation (3) was used to calculate operative temperature t_o where the prevailing mean outdoor air temperature $\overline{t_{pma(out)}}$ was obtained from the nearest meteorological station, as mentioned in Table 3, which accumulated no more than a month prior to the day of the measurement, as illustrated in Figure 11. As for the MS 2680:2017, it was used to identify the measurable scale of wind flow. Equations (1), (2), and (3) are as follows:

$$y = a + bx \tag{1}$$

where
y = independent variable
a = intercept/constant
b = slope of the line/coefficient
x = dependent variable (target)

$$\bar{t}_r = t_g + 2.42 \times V\left(t_g - t_a\right) \tag{2}$$

where
t_g = globe thermometer temperature
t_a = temperature of the air outside of the globe
V = airspeed cm/sec

$$t_o = \left(t_a + \bar{t}_r\right) / 2 \tag{3}$$

where
t_o = operative temperature
t_a = average air temperature
$\bar{t}_r$ = mean radiant temperature

Table 5 - The average indoor thermal data based on spatial division

Spatial division	Parameters			
	Air temperature (t_a)	Mean radiant temperature ($\bar{t}_r$)	Operative temperature (t_o)	Air speed (V_a)
Anjung	30.10	29.67	29.89	0.18
Serambi	30.39	29.49	29.94	0.11
Rumah ibu	30.59	30.54	30.57	0.16
Rumah tengah	30.61	29.42	30.02	0.16

Table 6 - The estimated model of indoor operative temperature based on spatial division

Spatial division	Indoor operative temperature			
	Regression coefficients	R-Square	Adjusted R-Square	Constant
Anjung	0.92522	0.91626	0.91278	1.00546
Serambi	0.95214	0.95148	0.94946	2.53537
Rumah ibu	0.84541	0.95088	0.94883	5.61953
Rumah tengah	0.8638	0.96207	0.96048	5.10489

Table 7 - The estimated model of indoor air speed based on spatial division

Spatial division	Indoor air speed			
	Regression coefficients	R-Square	Adjusted R-Square	Constant
Anjung	0.00804	0.04364	0.00379	- 0.05935
Serambi	0.01292	0.38678	0.36123	- 0.28385
Rumah ibu	0.03328	0.20258	0.16936	- 0.83495
Rumah tengah	0.03937	0.40265	0.37776	- 1.02139

Table 5 shows the average indoor t_o range from 29.89 to 30.57 °C. It was recorded that the indoor temperature in *anjung* was coolest while *rumah ibu* was warmest compared to other spaces. In addition, *anjung* received the highest rate of average air speed whereas *serambi* received the lowest rate among the spatial divisions. The linear regression in Figure 6(a) shows that the average hourly indoor t_o and outdoor air temperature of the house were closely correlated with R^2 = 0.95574. The average hourly indoor t_o ranged from 25.75 to 33.62 °C, and the corresponding outdoor temperatures ranged from 23.97 to 32.55 °C, where the range of difference was1.07 to 1.78 °C. As for Figure 6(b), the linear regression was based on the overall average hourly indoor air speed of the case study, not based on each spatial division. The regression shows that the average hourly indoor air speed and indoor t_o of the house were slightly less dependent with the $R^2 = 0.42166$, which is R^2 value < 0.5. The average hourly indoor air speed of the house ranged between 0.04 to 0.47 m/s. *Rumah ibu* experienced the highest air speed rate, which was 0.97 m/s (Scale 3) while *rumah tengah* experienced the lowest rate of air speed with 0.02 m/s. Scale 1 was where the occupants barely felt the wind flow in the space.

a b

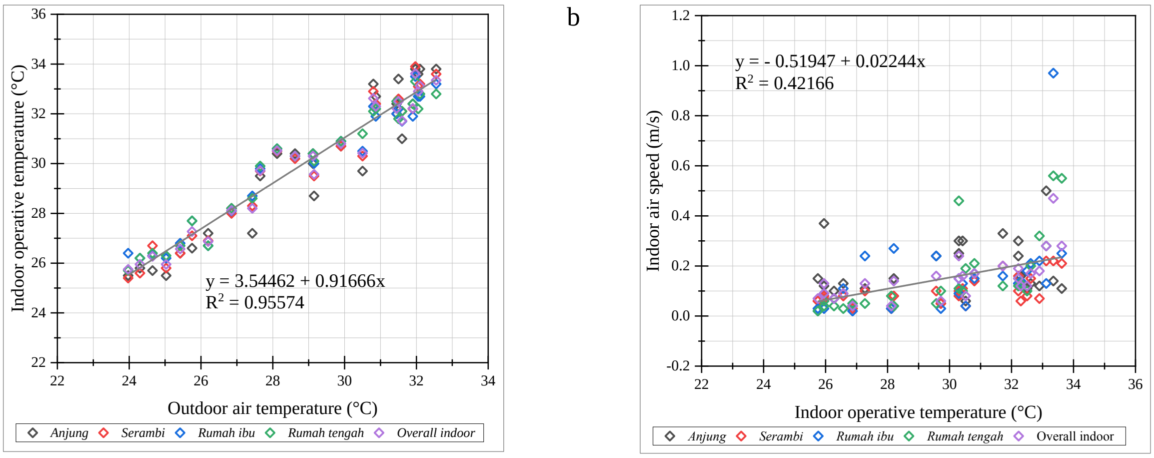

Fig. 6 - Average hourly indoor thermal data of case study (a) indoor operative temperature; (b) indoor air speed

By generally analysing the linear regression of indoor t_o and outdoor air temperature of the spatial divisions in Figures 7(a), 8(a), 9(a), and 10(a), a close correlation was found based on the R^2 value and regression line slopes, in which the R^2 remained > 0.9. Hence, this indicates that the house was in good natural ventilation. The average hourly indoor t_o ranged from 25.4 to 33.9 °C, and the corresponding outdoor temperatures ranged from 23.97 to 32.55 °C, where the range of difference was 1.35 to 1.43 °C. The data recorded that the indoor temperature was warmer compared to the outdoor temperature. Meanwhile, the linear regressions of indoor air speed and indoor t_o were less dependent, which were not too correlated (Figures 7(b), 8(b), 9(b), and 10(b)). This shows that the air speed rate was not the primary factor in regulating indoor temperature, with an R^2 value of < 0.1. The average hourly indoor air speed ranged from 0.02 to 0.97 m/s. This is because September (the month in which the data were gathered) was the second calmest month of the year, with a mean hourly air speed of 1.1 m/s. Based on the measurement scale in MS 2680:2017, all spatial occupants experienced air speed rates between Scale 1 and 3, where occupants felt fresh at comfortable temperatures, but draughty at cool temperatures, which were generally pleasant when comfortable or warm, causing constant awareness of air movement.

a b

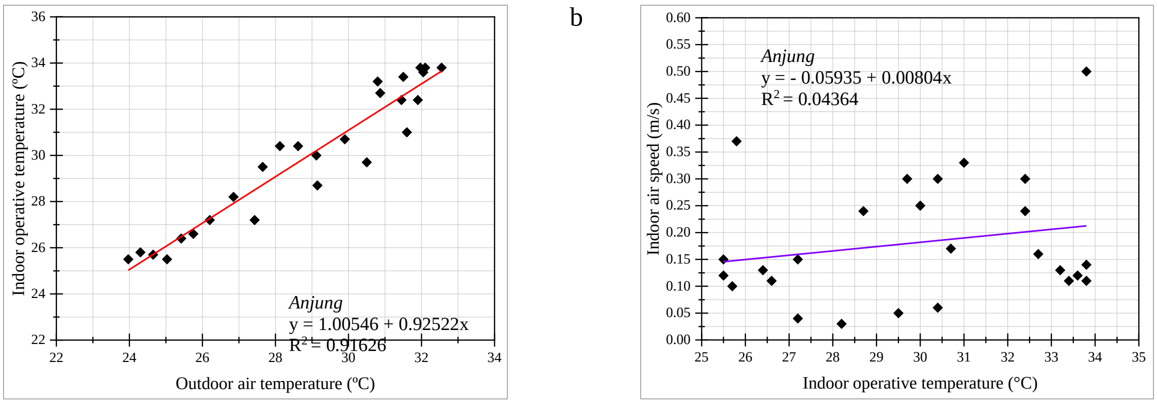

Fig. 7 - Linear regression of *Anjung* (a) indoor operative temperature; (b) indoor air speed

Anjung recorded the least linear relationship for both thermal data. The indoor t_o and air speed were $R^2 = 0.91626$ and $R^2 = 0.04364$, respectively. However, the variances ranging R^2 value of indoor t_o for the other spatial were not considerably different, which were between $R^2 = 0.01059$ to $R^2 = 0.03462$. The average hourly indoor t_o range from 25.5 to 33.8 °C, and the range of difference was ±1.25 °C with outdoor temperatures. The R^2 value of indoor air speed had a significant contrast with other spatial divisions. The range of difference was $R^2 = 0.15894$ to $R^2 = 0.35901$, and the average hourly air speed ranged from 0.03 to 0.37 m/s within Scales 1 and 2. Despite having the least linear relationship, *anjung* recorded the lowest average indoor t_o and most air movement compared to other spaces with 29.89 °C and 0.18 m/s. The fenestration system in this space persuaded low-temperature rates, and the maximal wall openings (full-length operable windows with ventilated *pagar musang* and *tebar layar*) resulted in significant air intakes outside the house, which aided in dispensing warm air into the outdoor area. Therefore, the airflow could freely drift without any deterrents and eradicate warm air from the outdoor areas. Moreover, fewer trees were planted in the front yard; thus, it could provide shade by reducing direct solar radiation.

a b

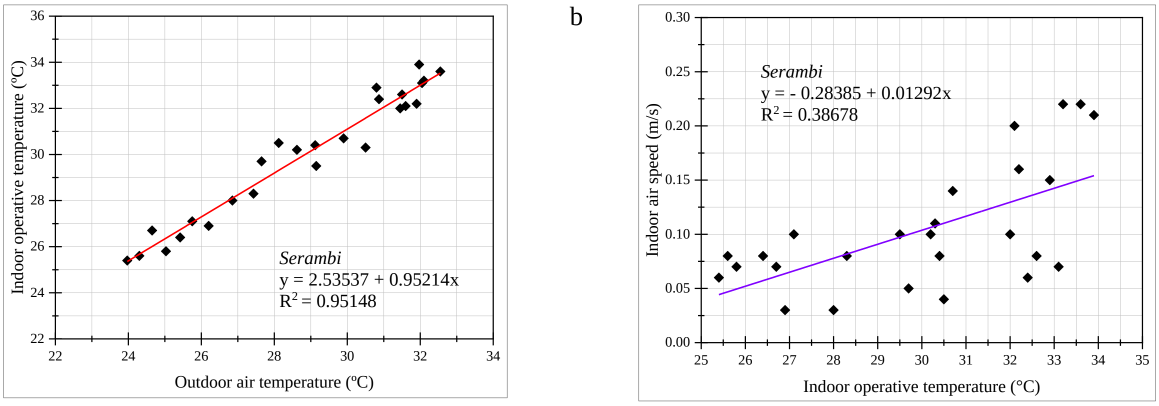

Fig. 8 - Linear regression of *Serambi* (a) indoor operative temperature; (b) indoor air speed

Serambi recorded the second-highest linear relationship for both thermal data. The indoor t_o and airspeed were R^2 = 0.95148 and R^2 = 0.38678, respectively. The variances range R^2 of both thermal data from the highest relation, *rumah tengah,* were not considerably different, which are R^2 = 0.01059 and R^2 = 0.01587. The average hourly indoor t_o ranged from 25.4 to 33.9 °C, and the difference was between 1.35 to 1.43 °C with outdoor temperatures. The average hourly air speed ranged from 0.03 to 0.22 m/s, Scale 1. The average indoor t_o in the *serambi* was 0.05 ºC higher than in *anjung*, 29.94 ºC. Even though this space had rows of full-length operable windows with ventilated *pagar musang*, the average air speed rate was recorded as the lowest among spatial divisions, 0.11 m/s, with a range of differences of 0.05 – 0.07 m/s. The supposed ventilated *tebar layar* at both *serambi pangkal* and *hujung* were sealed. Thus, airflow could not penetrate the house. In addition, the elongated floor layout, which included a partition to create an enclosed area for bedrooms 2 and 3, degraded the wind dispersion in space and lessened the speed rate. Besides, the roof height with zinc roofing was the lowest among the spatial divisions, 2.78 – 2.30 m (*serambi pangkal*), 2.20 m (*serambi tengah*), and 2.77 – 2.08 m (*serambi hujung*). As a result, the warm air was trapped due to the low roof with zinc material and the flooring material, rubber mat.

a b

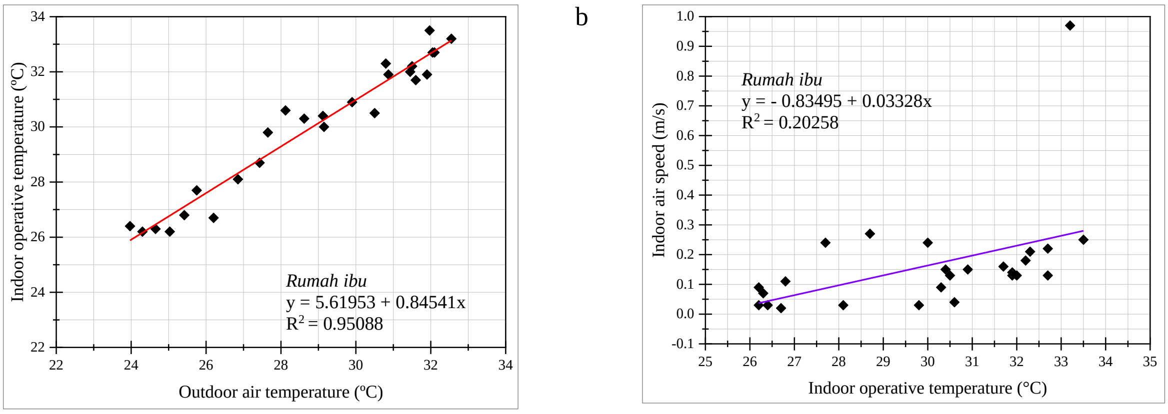

Fig. 9 - Linear regression of *Rumah ibu* (a) indoor operative temperature; (b) indoor air speed

R^2 value at *rumah ibu* recorded R^2 = 0.0006 and R^2 = 0.01119 differences with *serambi and rumah tengah*, respectively, showing that the variances were not significantly different. The indoor t_o was R^2 = 0.95088, and the air speed was R^2 = 0.20258. The average hourly indoor t_o ranged from 26.4 to 33.5 °C, and the range of difference was 0.95 to 2.43 °C with outdoor temperatures. R^2 value of indoor air speed showed R^2 = ± 0.1 disparity with *serambi and rumah tengah*. The average hourly air speed ranged from 0.02 to 0.97 m/s, within Scales 1 and 3. Compared to *anjung*, *rumah* *ibu* recorded only a lower 0.02 m/s differences in average air speed rate; however, average indoor t_o was the highest among the spatial divisions, which was 30.57 ºC. It is indicated that the air speed rate was less influential in regulating the temperature in this space. It received immoderate sun rays beginning in the afternoon until the evening due to the wall and windows facing west, where the sunset took place. Besides, a few trees were planted in the side yard as sunshades, and there was insufficient roof overhang length. Apart from that, there were a substantial number of furnishings in the master bedroom, contributing to heat exchange and thermal radiation. For example, the room had a plywood ceiling and walls layered with fabric. Considering the roof space that covered the ceiling, this degraded the wind dispersion in the space. Thus, stacking up and executing the warm air through the ventilated *tebar layar* and roof joists was impossible. The room's wall was designed with *lubang angin*; unfortunately, it was covered up using plywood and fabric.

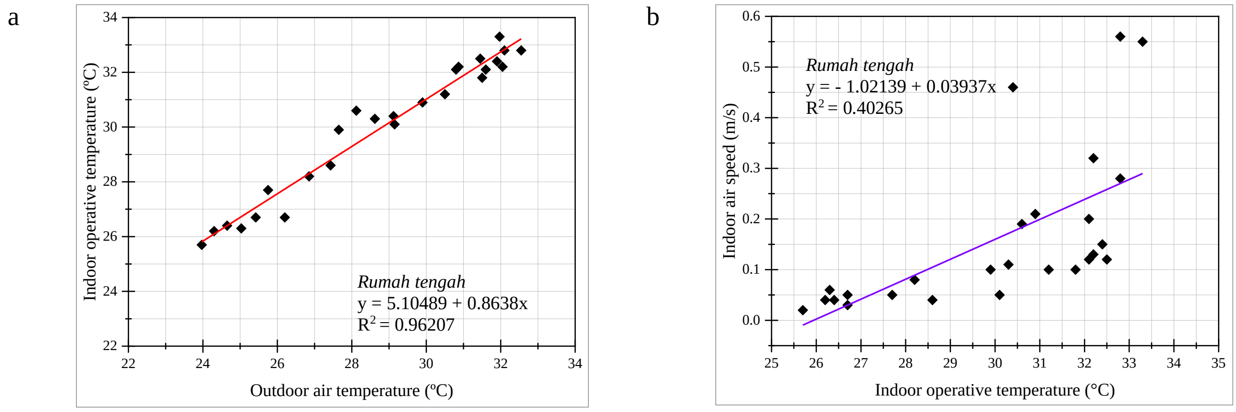

Fig. 10 - Linear regression of *Rumah tengah* (a) indoor operative temperature; (b) indoor air speed

Rumah tengah had a closely correlated linear relationship for both thermal data and the highest among the spatial divisions. It recorded indoor t_o and air speed with R^2 = 0.96207 and R^2 = 0.40265, respectively. This indicates disparity differences in the average hourly indoort_o, which ranged from 25.7 to 33.3 °C, and between 0.75 to 1.73 °C with outdoor temperatures. The average hourly air speed ranged from 0.02 to 0.56 m/s, within Scales 1 and 3. The average indoor t_o recorded the second highest among the spatial divisions with 30.02 ºC and had a similar reading as *rumah ibu*, 0.16 m/s. *Rumah tengah* was the largest area among the spatial units with 23.20 m. It had ample open space with minimal interior partitions, some full-length operable windows with ventilated *pagar musang*, and *tebar layar*. Besides, the roof was the highest among the spatial divisions, i.e., at 4.21 – 4.20 – 4.25 m. Correspondingly, these components and characteristics aided the cool air to distribute freely throughout the interior, even though it was recorded indoors at t_o > 30 ºC. It allowed for the efficient passage of the warm air outflow from a space to an outdoor area. The space below the roof helped cool the house by stacking the warm air and executing it through the ventilated *tebar layar* and roof joist. Furthermore, there were trees planted in the side yard; thus, they could provide shade and reduce the wall's exposure to direct solar radiation.

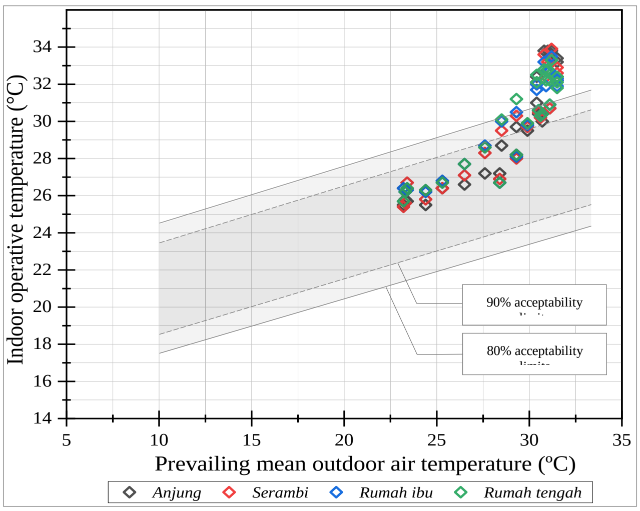

Fig. 11 - Acceptable indoor operative temperature (Δt_o) of the case study

Figure 11 illustrates the allowable indoor t_o based on ACS. According to ACS, it was determined that the average hourly indoor was t_o < 31 °C, with a prevailing mean outdoor air temperature of $\overline{t_{pma(out)}}$ < 32 °C. which was an acceptable indoor state for the occupants' comfort. About 62% of the hourly indoor t_o was within 80 to 90% acceptability limit. In contrast, about 38% of the data were not within the acceptability limit, where the measured data were within 31 to 34 °C with a prevailing mean outdoor air temperature $\overline{t_{pma(out)}}$, of 31 to 32 °C. This situation happened from late morning (11:00) until late afternoon (16:00). Furthermore, the hourly indoor t_o was from 25.5 to 29.5 °C with a prevailing mean outdoor air temperature $\overline{t_{pma(out)}}$, 23 to 30 °C, which was within 90% acceptability limit only. The occupants experienced indoors with a 90% acceptability limit, with only 42% within the six hours. Meanwhile, the hourly indoor t_o was within 29 to 31 °C with a prevailing mean outdoor air temperature $\overline{t_{pma(out)}}$, of 28 to 32 °C, which was within the 80% acceptability limit, with only 27% within the 12 hours. Based on the on-site observation, to regulate their thermal comfort, the occupants spent their day in open shade or where the space had many openings and received abundant wind, for instance, at *anjung*. Apart from that, a pedestal fan was used only when the indoor thermal condition could not be regulated by adjusting the opening because it was too warm.

5. Conclusion

This study scientifically demonstrated the correlation between climatic design strategy and thermal data measurements in a NSMH. It can be deduced that the climatic design strategy influences the ITC of the house. Moreover, it has also been determined that this typology of NSMH is still relevant as a sustainable design that can adapt to current climate conditions. The primary results revealed that about 62% of the hourly indoor to of the case study house was within 80 to 90% of the acceptability limit. Evidently, occupants experienced an excellent indoor environment within the six hours of the day (early to late morning and evening to late evening). Six design strategies of the RBDB typology influence ITC: open plan, opening, roof heights, materials, vegetation, and building orientation. Even if the analysis believes that Malay houses with zinc sheets still exceed comfort standards, in many circumstances, houses with this type of roofing material will have higher indoor temperatures than outdoor ones, especially during the day. Some suggestions are provided for circumventing this particular issue.

The zinc sheet as a roof cover can be replaced with natural materials, for instance, ceramic roof tiles or *kayu berlian* shingles, which are excellent thermal insulators (Smith, 2023; Gaggino et al., 2018). Natural materials can reduce the transmitted heat because they have a low U-value. Thus, it would provide better indoor thermal performance (Miller et al., 2007). Similarly, the colour of the roof should be considered as part of the passive design methods. Most roof tiles in Malaysia are dark in colour, which absorbs more heat (Roslan et al., 2015). Azarnejad and Mahdavi (2015) stated that colour of a surface affects a building's thermal performance. The exposed building envelope to solar radiation generates phenomena of absorption and reflection, surface and ambient temperatures, and heat gains. White surfaces absorb 40%, while dark green, brown, and black surfaces absorb 90% (Stephenson, 1963). To offset the phenomenon, Lenton and Vaughan (2009) suggested increasing the reflection of albedo at the surface. Modifying a building's albedo can help reduce its ambient temperature. Thus, the higher the albedo, the less radiative energy the surface absorbs (Sharma & Chani, 2019).

5.1 Recommendations

Other than ACS, to gain insight and a thorough understanding of the acceptability limit of the house, a simultaneous subjective assessment with physical measurements is recommended. A survey is required to fully evaluate occupant responses to physical settings, which will help verify and identify which thermal conditions give adequate performance to the occupants. A thermal satisfaction (TSV) questionnaire can be used because tools cannot quantify subjective perceptions directly. Moreover, scientific evidence obtained through computer simulation should be provided to fully understand the different approaches that influence the indoor thermal performance of the investigated house. The simulation should be graphically illustrated using computer software such as Computational Fluid Dynamics (CFD), EMVI-met, and Ecotect. The findings of this study complied with RMK 12 Theme 3, which aims to be a carbon-neutral country by practising sustainable architecture and construction. The design of naturally ventilated houses, such as NSMHs in humid climates, can be a model reference for modern housing development which respond well to the local tropical climate. This is vital for guaranteeing that Malaysians' modern house designs are of high quality and meet the demands of a sustainable house. Above all, this experimental study aspires to offer beneficial insights into sensible climatic design approaches of a TMH.

Acknowledgment

The authors would like to thank the house owner, Mr. Razali A. Kadir and his family members, for permitting the researcher and her team to do the measurement and observation. They have also greatly assisted the research and shared information on the history of the house. This research was partially funded by GIP Grant, Universiti Teknologi MARA (600-RMC/GIP 5/3 (172/2021)).

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