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STUDY ON THE OPTIMUM ROOF TYPE WITH 30° ROOF ANGLE TO ENHANCE NATURAL VENTILATION AND AIR CIRCULATION OF A PASSIVE DESIGN

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ABSTRACT

One of the major problems in modern housing design is overheating. Occupants suffer higher indoor temperatures due to a lack of natural ventilation. This issue arises because of poor passive design. A good passive design promotes natural ventilation and provides better indoor air temperatures without reliance on mechanical cooling systems. The roofing system plays an important role in a house's design. Since the roof contributes to 70% of the total heat gain, it is important to investigate its design to reduce the impact of overheating. It has been found that many roofs lack a ventilation system in the top part of the house. These openings in the roof provide areas for trapped hot air to exit into the environment. The openings also enhance natural ventilation and allow for effective air circulation inside the house. The optimum roof is designed to tackle this matter by reducing the overheating inside the house, especially during the hottest hours of the day. The hot air exits based on the differences in air density and due to prevailing wind. In this study, the optimum roof was tested on a small-scale model and verified by simulation using computational fluid dynamic (CFD) software, namely ANSYS 18.0. From the data obtained, it was proven that the opening in the roof reduced the indoor temperature. In conclusion, the optimum roof could improve the passive design and help to reduce overheating inside a house.

Keywords: Computational fluid dynamic simulation; Heat transfer; Optimum roof; Ventilated roof

1. INTRODUCTION

Malaysia is located in the equatorial region and experiences high temperatures with high relative humidity throughout the year. The average solar radiation in this hot, humid climate is between 4.21 kWh/m^2 and 5.56 kWh/m^2, annually (Azhari et al., 2008). Malaysia receives 8.7 hours of sunlight per day (Malaysia Meteorological Department, 2014). The recommended thermal comfort level ranges from 25 to 28°C (Ibrahim, 2004). Based on a previous study on concrete terrace houses in Malaysia, indoor temperatures are only comfortable to the occupants for a few hours every day (Ibrahim et al., 2014a). The same study also discovered that the indoor temperature could reach more than 30°C during the daytime. Increased indoor temperatures in a building are due to poor passive design. Designers should adapt more natural

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ventilation as part of the passive design, especially at the top part of the house. The reason for focusing on the top part of the house is because hot air rises from the bottom part of the house to the upper part due to density differences. The differences between the outdoor air pressure and the indoor environment creates suction. Hence, the hot air naturally passes from inside the house to outside without depending on a mechanical ventilation system.

Poor passive design could lead to overheating. In addition, the occupants in modern low-cost housing suffer overheating due to poor ventilation and roof design problems (Ibrahim, 2004). One research study found that the recorded indoor temperature of a modern low-cost house was higher than recommended for the occupants' level of comfort (Tinker et al., 2004). Due to this, occupants rely on mechanical means to cool their houses, which incur energy consumption costs to power the electrical components. A previous study concluded that openings in the roof's surface could help to reduce the indoor air temperature (Ibrahim et al., 2014a). This study focuses on roofing because it plays an important role in controlling the amount of heat transmitted from the roof surface into the internal area.

2. REVIEW OF THE VENTILATED ROOF DESIGN APPROACH

Modern low-cost houses in Malaysia are mostly designed with a modern roof, which is a flat roof or a roof with a pitch of less than 10° (Ibrahim et al., 2014b). According to Abdul Rahman et al. (2009), a flat roof is considered a poor design choice for hot, humid climates. Previous findings showed that hot air can be extracted from the house through a ventilated roof design (Roslan et al., 2016). Ventilation is one of the passive designs that should be considered during a house's design stage (Kamaruzzaman et al., 2018). One study concluded that natural ventilation is an alternative method to save energy (Ciampi et al., 2005). Natural ventilation offers a free cooling system and could help to provide comfort for the occupants (Heiselberg et al., 2001). Studies of roof ventilation have shown that openings in the roof can help to reduce the indoor temperature up to 8°C compared unventilated roofs (Ibrahim et al., 2014a). The openings in a roof can provide two ways of naturally transferring the hot air from the indoors to the outdoors, known as wind-driven ventilation and stack effect ventilation.

Wind-driven ventilation, or the wind pressure effect, occurs due to air pressure differences, namely the Bernoulli effect. The wind flows from the direction of its source point across a roof surface and creates positive pressure, known as the windward region. Meanwhile on the opposite side of the roof, negative pressure or suction occurs, and this area is known as the leeward region. Figure 1 shows the windward and leeward regions.

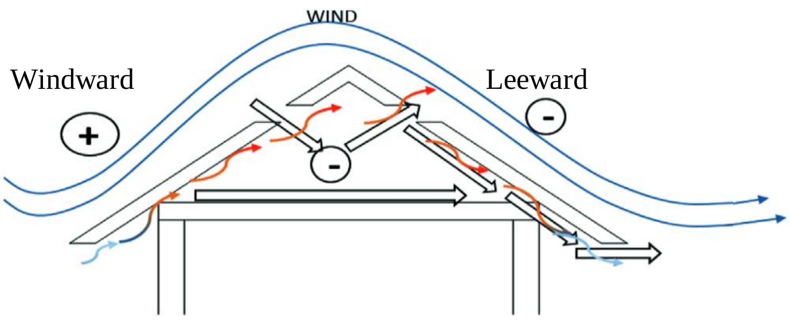
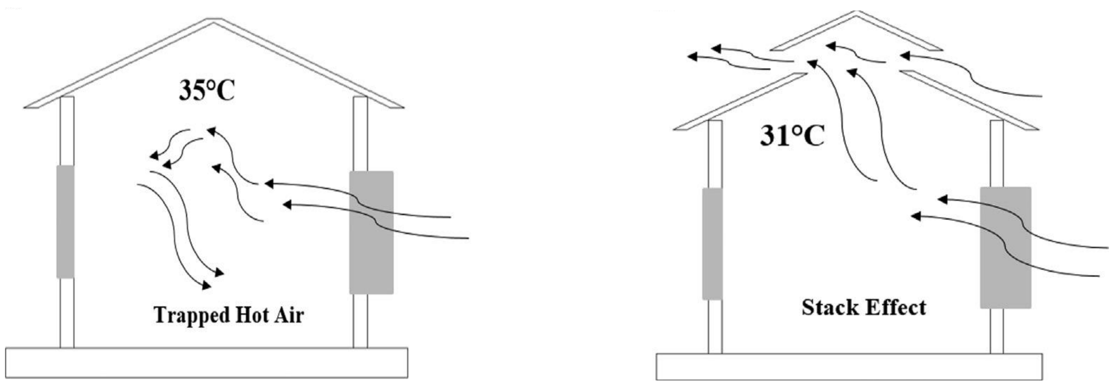


Figure 1 The windward and leeward areas (US Department of Energy, 2011)

The Bernoulli effect occurs with low-slope roofs or lower roof angles. Baskaran (2002) concluded that the lower the roof angle, the higher the local suction pressure along the roof surface. However, the effect of the suction pressure depends on the wind velocity and direction, building orientation, etc. The negative pressure or suction helps to remove the hot air by pulling it from inside the house to the outside environment through openings on the roof's surface.

Unlike the wind pressure effect, the stack effect occurs when hot air travels from the lower areas of the house to the upper part with help from prevailing winds that enter the house and the resulting differences in air pressure density. Hot air rises because of its lower density compared to cold air. The openings at the upper part of the house allow the stack effect to occur. Thus, adapting the stack effect is also recommended in passive design.

Figure 2 shows the condition of air movement inside the house without and with stack effect. Figure 2a illustrates the hot air trapped inside the house. Due to a lack of openings, the stack effect cannot occur. Figure 2b shows that the opening in the roof area allows the stack effect to take place. Many researchers agree that the adaption of a ventilated roof in passive design can minimize the heat transfer from the roof surface and help to reduce the indoor temperature (Endriukaityte et al., 2005; Trinuruk et al., 2007; Qasim et al., 2010; Ibrahim et al., 2014a; Al-Obaidi et al., 2014). Therefore, it could also reduce the energy demand or consumption of electricity to power a mechanical cooling system.



(a) (b)

Figure 2 Condition of air movement: (a) without; and (b) with the stack effect

3. OPTIMUM ROOF DESIGN

The proposed optimum roof was designed to improve the passive design. The roof was designed with a 30° pitch and 50% opening. The 30° roof pitch was chosen because this pitch is recommended for easy maintenance purposes and faster air movement compared to other pitches (Roslan et al., 2016).

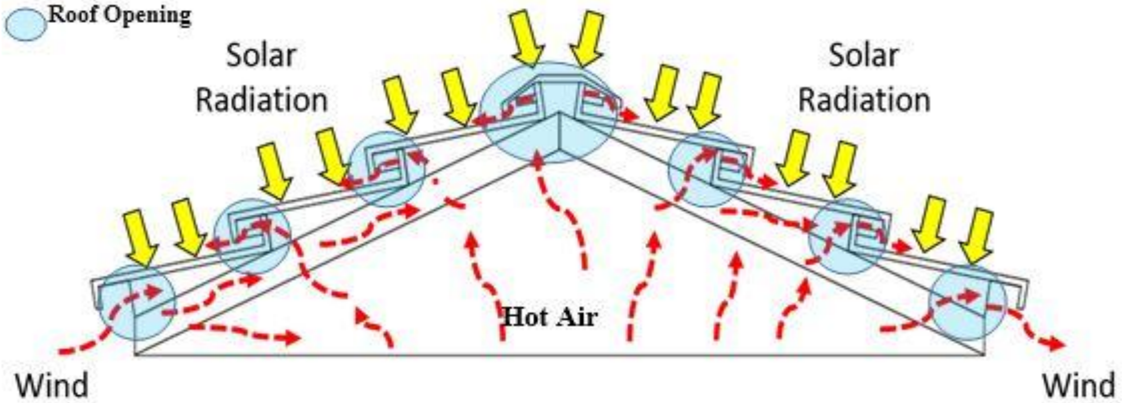


Figure 3 The concept of the optimum roof

Previous research concluded that roofs with 50% or 100% opening on roof surface is adequate to allow air to move through the roof and help to provide an exit for the trapped hot air (Ibrahim et al., 2014a). Due to our region experiencing high annual rainfall, the roof should be designed with 50% opening. The openings on the roof could reduce the temperature up to 7°C compared with normal roofs that have limited openings (Ibrahim et al., 2014a). Figure 3 shows the concept of removing the trapped hot air from the internal area through the opening on roof surface.

The arrangement of the optimum roof was adapted from the traditional *Malay Nypa* roof, and the roof was designed with the recommended minimum flashing height to prevent rain from entering through the opening (Lysaght, 2014). Figure 4 shows the design of the optimum roof.

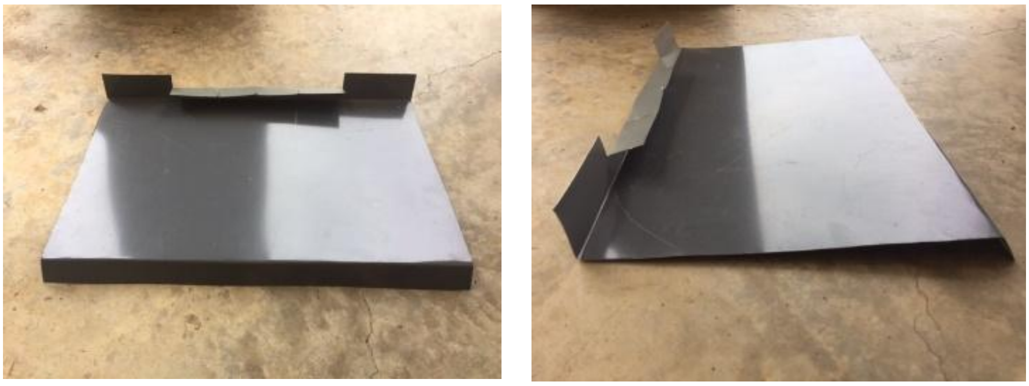


Figure 4 The design of the optimum roof

4. METHODS

A previous study on a small-scale house model was conducted to determine the thermal comfort (Raut et al., 2014). In this study, two small-scale house models were built with dimensions of 1 m height × 1m width × 1 m length. The walls were made from 10-mm-thick plywood. The house models were installed with two different roof designs: a normal roof without opening and an optimum roof with 50% opening. Both were placed under the same environmental conditions and were connected to a data logger via thermocouples. An anemometer was used to record the air velocity and ambient temperature. The study was conducted under two condition:

- Condition 1: windows and door were fully closed
- Condition 2: windows and door were fully opened

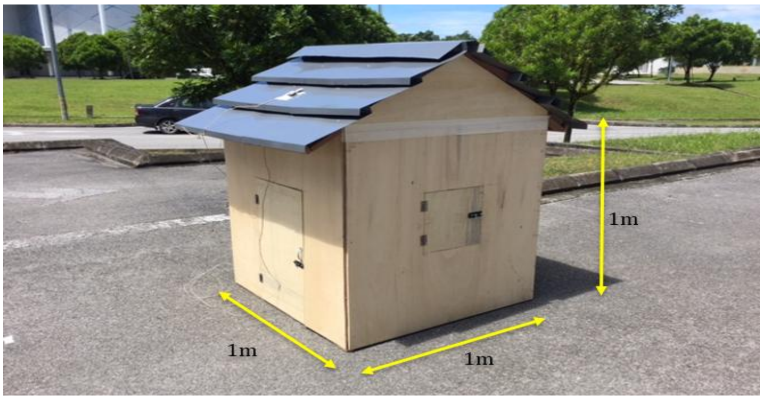


Figure 5 Small scale house model

House models with optimum roof and normal roof underwent both condition and the data was recorded and analyzed. Figure 5 shows the small scale of house model to investigate the performance of optimum roof.

Computational fluid dynamics (CFD) simulation software (Ansys 18.0) was chosen to validate the recorded data from the on-site experiment due to its precision. The software is developed by Ansys Incorporated and the headquarters is located at Canonsburg, Pennsylvania, United States. The acceptable tolerance between the on-site measurement and the CFD must be within 20% (Ali et al., 2014). The differences in air temperature and air flow between the on-site measurement and the simulation typically range from 2–7% (Baharun, 2002). Figure 6 shows the locations of the point nodes. The point nodes P1, P2, P3, and P9 were located outside the house while P4, P5, P6, P7, and P8 were placed inside the house.

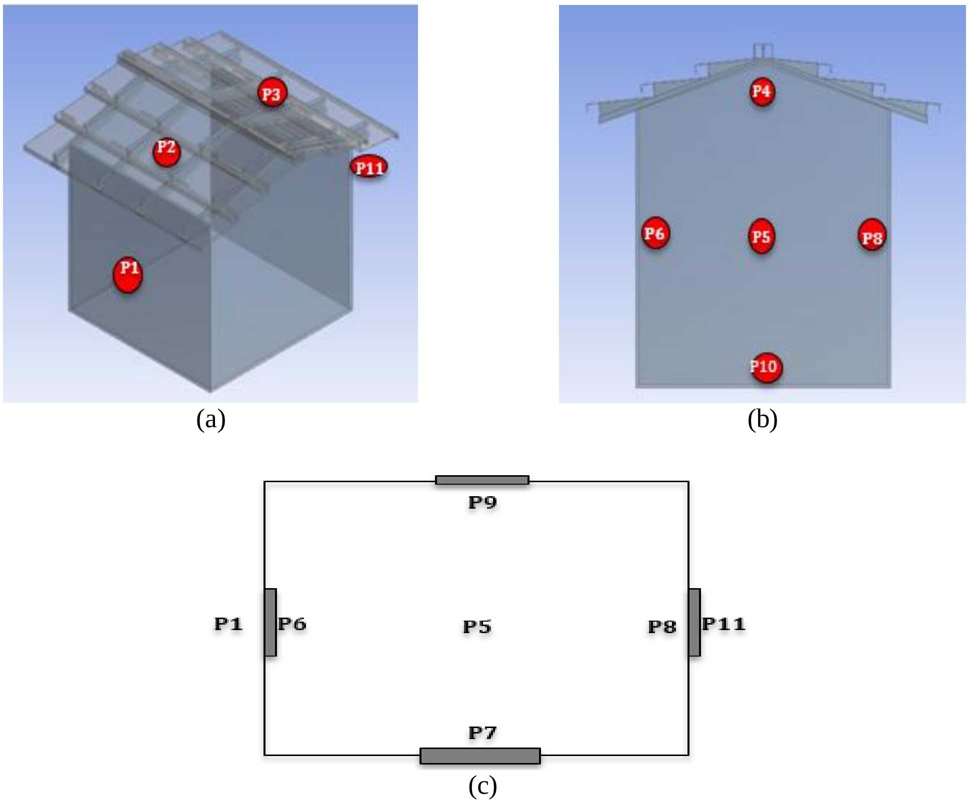


Figure 6 Point nodes: (a) outside house; (b) inside house; (c) in plan view

5. RESULTS AND DISCUSSION

Based on the data obtained, the highest ambient temperature and air velocity recorded at 1:00 pm were 35.33°C and 0.35 m/s, respectively. The measured and simulated air temperature and air velocity for each of the point nodes are presented in Tables 1 and 2, respectively. The mean percentage differences for the air temperature and air velocity were 5.24% and 6.72%, respectively, for the normal roof and 1.41% and 6.39%, respectively, for the optimum roof. All of these are below 10%, which shows that the simulated data for this study are acceptable for further research. To measure the reduction in the indoor temperature, the point at the middle of the house was chosen for comparison.

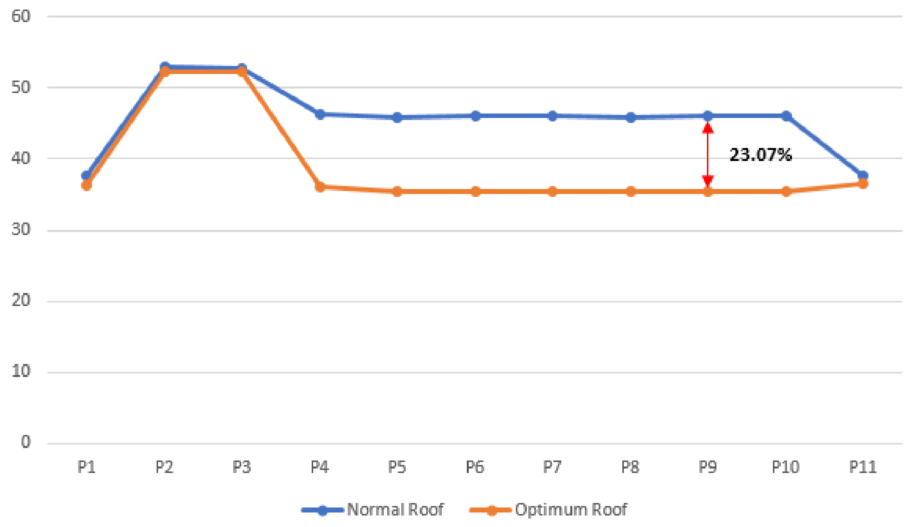
Table 1 Comparison of measured and simulated air temperature between the normal roof and optimum roof

Points		Normal Roof			Optimum Roof		
		Measured (°C)	Simulated (°C)	Percentage Difference	Measured (°C)	Simulated (°C)	Percentage Difference
Fully Closed	P1	37.59	37.67	+0.21	36.24	36.33	+0.25
	P2	53.01	51.64	-2.58	52.25	51.64	-1.17
	P3	52.63	51.57	-2.01	52.18	51.56	-1.19
	P4	46.24	46.85	+1.32	36.18	36.29	+0.30
	P5	45.89	45.92	+0.07	35.49	35.93	+1.24
	P6	45.97	45.94	-0.07	35.50	35.52	+0.06
	P7	46.13	45.91	-0.48	35.49	35.54	+0.14
	P8	45.94	45.95	+0.02	35.49	35.52	+0.08
	P9	46.12	45.94	-0.39	35.48	35.53	+0.14
	P10	46.13	45.84	-0.63	35.45	35.57	+0.34
	P11	37.68	37.71	+0.08	36.48	36.86	+1.04
Fully Opened	P1	36.81	36.88	+0.19	36.34	36.42	+0.22
	P2	51.83	51.64	-0.37	51.81	51.76	-0.10
	P3	51.86	51.72	-0.27	51.78	51.69	-0.17
	P4	36.13	36.24	+0.30	35.28	35.44	+0.45
	P5	36.12	36.03	-0.25	35.26	34.83	-1.22
	P6	36.12	36.05	-0.19	35.25	34.99	-0.74
	P7	36.07	36.03	-0.11	35.23	34.97	-0.74
	P8	36.09	36.05	-0.11	35.16	34.98	-0.51
	P9	36.09	36.04	-0.14	35.24	34.99	-0.71
	P10	36.01	36.00	-0.03	35.04	35.09	+0.14
	P11	36.48	36.55	+0.19	36.11	36.37	+0.72
Mean Percentage Differences				-5.24			-1.41

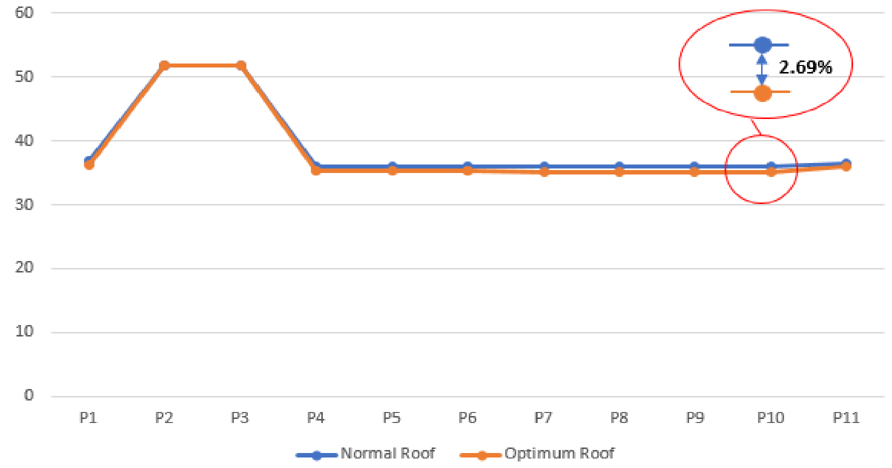
Table 2 Comparison of air velocity between the normal roof and optimum roof

Points		Normal Roof			Optimum Roof		
		Measured (m/s)	Simulated (m/s)	Percentage Difference	Measured (m/s)	Simulated (m/s)	Percentage Difference
Fully Closed	P1	0.37	0.36	-2.70	0.37	0.35	-5.41
	P2	0.32	0.29	-9.38	0.33	0.29	-12.12
	P3	0.37	0.38	+2.70	0.38	0.37	-2.63
	P4	0.00	0.00	0.00	0.16	0.16	0.00
	P5	0.00	0.00	0.00	0.13	0.12	-7.69
	P6	0.00	0.00	0.00	0.12	0.11	-8.33
	P7	0.00	0.00	0.00	0.12	0.10	-16.67
	P8	0.00	0.00	0.00	0.12	0.11	-8.33
	P9	0.00	0.00	0.00	0.12	0.10	-16.67
	P10	0.00	0.00	0.00	0.10	0.10	0.00
	P11	0.36	0.36	0.00	0.35	0.34	-2.86
Fully Opened	P1	0.37	0.36	-2.70	0.37	0.38	+2.70
	P2	0.25	0.25	0.00	0.12	0.13	+8.33
	P3	0.21	0.20	-4.76	0.16	0.17	+6.25
	P4	0.05	0.04	-20.00	0.29	0.30	+3.45
	P5	0.12	0.13	+8.33	0.37	0.38	+2.70
	P6	0.33	0.36	+9.09	0.37	0.38	+2.70
	P7	0.37	0.37	0.00	0.37	0.37	0.00
	P8	0.36	0.38	+5.56	0.36	0.36	0.00
	P9	0.35	0.35	0.00	0.37	0.38	+2.70
	P10	0.14	0.15	+7.14	0.18	0.28	+55.56
	P11	0.37	0.37	0.00	0.37	0.38	+2.70
Mean Percentage Differences				-6.72			+6.39

The indoor air temperature in the fully closed condition was significantly lower at point nodes P9 with a 23.07% reduction for the optimum roof (Figure 7a). The point node P10 recorded the highest reduction compared to the other point nodes for the fully closed condition. In order to have uniform results, point node P7 was also used to measure the difference in air temperature for the house model with the fully opened condition. The indoor air temperature for the optimum roof measured at the same point node was 2.69% lower than the normal roof in the fully opened condition (Figure 7b). This shows that the optimum roof contributes significantly to the reduction of the indoor air temperature, especially under fully closed conditions.



(a)



(b)

Figure 7 (a) Difference between the air temperatures in the fully closed condition; (b) Difference between the air temperatures in the fully opened condition

Since the small-scale house model was built without insulation in the ceiling, most of the heat absorbed by the roof's surface radiated into the lower part of the house. Insulation in the external wall obstructs heat transfer (Linshuang & Hong, 2016). Overall, the normal roof recorded the highest indoor temperature compared to the optimum roof for both fully closed and fully opened conditions. The normal roof under the fully closed condition recorded higher indoor temperatures than the same roof design with the fully opened condition. This is because of the lack of openings on the roof surface and even in the house itself. When hot air rises because it is less dense than cool air, the air cannot exit if there is no ventilation. The hot air becomes trapped inside the house, thus resulting in higher indoor temperatures.

It was found that there was no air velocity inside the house model for normal roof under the fully closed condition. The air velocity from the outside environment could not enter the house because there were no openings on the roof surface, and the door and windows were fully sealed. Without the presence of air movement inside the house, the indoor temperature was higher than the ambient air temperature. The absence of air movement caused the indoor air temperature to exceed the thermal comfort range (Ibrahim et al., 2014b). Air velocity could enhance the internal air circulation, thus reducing overheating inside the house. The optimum roof under the fully closed condition recorded a lower indoor temperature than the normal roof. This is due to the openings on the roof's surface, which allowed the hot air to exit and the wind to enter the house despite the door and windows being fully sealed. Air movement was detected inside the optimum roof house model under fully closed condition. The ventilated roof approach could help to minimize overheating inside a modern house (Roslan et al., 2016).

The data obtained from the on-site experiment and simulation show that the indoor temperature for both the normal and optimum roof under fully closed and fully opened condition was still higher than acceptable thermal comfort range as stipulated by ASHRAE (2013). However, the optimum roof did succeed in reducing the temperature inside the house by up to 10°C compared to the normal roof for the fully closed condition. The temperature was even lower for the house with the fully opened condition.

6. CONCLUSION

This study concluded that the openings on the roof surface provided additional ventilation for the house. The optimum roof works best when the condition of the house is fully closed and fully opened condition. The optimum roof showed its significant reduction of indoor temperature under fully closed condition. This concluded that the openings on the roof surface played an important role in reducing the temperature inside the house. The optimum roof helped to reduce the indoor air temperature by up to 10°C compared to the normal roof.

7. ACKNOWLEDGEMENT

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