



Faculty of Engineering

Ventilated Roof for Modern Low-cost House in Hot Humid Climate

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Ventilated Roof for Modern Low-cost House in Hot Humid Climate

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DECLARATION

I declare that the work in this thesis was carried out in accordance with the regulations of Universiti Malaysia Sarawak. Except where due acknowledgements have been made, the work is that of the author alone. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

.....

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ABSTRACT

The overheating of indoor air temperature is one of the major concerns in a modern house design especially for the low-cost housing. Most of the occupants will feel uncomfortable when the indoor temperature is exceeding the level of thermal comfort. This result of the need to use mechanical means to cool the house, hence it surely incurs additional living cost to pay the electricity bill and maintenance cost. The overheating is a result from the hot air that trap in the house and the cause is due to poor of passive design; lack of ventilation provision in house design. It is important to remove the hot air from internal area to avoid any unforeseen event that could harm one's health; to avoid heat stroke from happening. To overcome this problem, the proposed ventilated roof is introduced and designed with more openings on the roof surface areas. This research was conducted and carried out to investigate the effect of openings on the roof surface towards the indoor temperature of a house in tropical climate areas. For this study, on-site experiment was conducted by building model houses with common roof and ventilated roof design under fully closed and fully opened condition. Air temperature and air velocity were recorded and the data was used as an input to the CFD Simulation. The CFD simulation was carried out for validation purposes. Once validated, the CFD simulation was proceeded with model house with different pitch of roof. The CFD simulation on Betong's house was conducted with ventilated roof tiles design. From the findings, it was concluded that model house with ventilated roof tiles design recorded lower indoor temperature as compared to common roof. In conclusion, the passive design of modern house is improved through the adoption of the ventilated roof tiles design, which it enhances the removal of the hot air and reduce air temperature inside the house.

Keywords: Passive design; ventilated roof; CFD simulation

Bumbung Pengudaraan untuk Rumah Kos Rendah Moden dalam Cuaca Lembab Panas

ABSTRAK

Suhu di dalam rumah yang terlampau panas mendatangkan kebimbangan kepada penduduk perumahan kos rendah. Kebanyakan penduduk merasa tidak selesa disebabkan suhu di dalam rumah melebihi paras suhu keselesaan terma. Penduduk akan mula bergantung kepada sistem pengudaraan mekanikal yang menggunakan tenaga elektrik, di mana kos bil elektrik dan penyelenggaraan akan meningkat. Kenaikan suhu di dalam rumah adalah disebabkan udara panas yang terperangkap disebabkan oleh rekabentuk pasif yang lemah; kekurangan sistem pengudaraan. Udara panas yang terperangkap di dalam rumah perlu dibebaskan kerana boleh menyebabkan strok haba. Untuk mengatasi masalah ini, kajian rekabentuk bumbung pengudaraan menyediakan lebih banyak bukaan di atas permukaan bumbung sebagai laluan untuk udara panas keluar dari dalam rumah. Ujikaji terhadap model-model rumah telah dijalankan ke atas rekabentuk bumbung biasa dan bumbung pengudaraan dengan keadaan pintu dan kesemua tingkap tertutup dan terbuka. Suhu udara dan kelajuan angin direkodkan dan data tersebut digunakan sebagai input kepada simulasi CFD. Simulasi CFD dijalankan untuk pengesahan kajian. Selepas pengesahan kajian dijalankan, simulasi CFD diteruskan dengan sudut bumbung rumah yang berbeza. Kajian simulasi CFD diteruskan kepada rumah kos rendah yang terletak di Betong, Sarawak dengan rekabentuk bumbung pengudaraan. Hasil kajian mendapati bahawa rumah yang menggunakan bumbung pengudaraan mencatatkan suhu yang lebih rendah berbanding rumah yang menggunakan bumbung yang biasa. Kesimpulannya, rekabentuk pasif rumah moden dapat ditambahbaik dengan penggunaan bumbung pengudaraan kerana ia dapat membantu untuk mengeluarkan udara panas dan menurunkan suhu udara dalam rumah.

Kata kunci: *Rekabentuk pasif; bumbung pengudaraan; simulasi CFD*

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LIST OF SYMBOLS AND ABBREVIATIONS

am	Ante Meridiem
°	Degree
°C	Degree Celsius
°N	Degree North
CFD	Computational Fluid Dynamic
kW	Kilo Watt
kWh/m ²	Kilo Watt Hour Per Meter Square
m/s	Meter Per Second
%	Percent
pm	Post Meridiem
PPR	Program Perumahan Rakyat
Unimas	Universiti Malaysia Sarawak

CHAPTER 1

INTRODUCTION

1.1 Introduction

Malaysia is located at 3 °N at the equatorial zone and experiencing tropical climate condition throughout the year. The country is considered as one of uncomfortable climate zones as compared to moderate and cold climate zone (Al-Obaidi et al., 2014a). The temperature all year round is ranging between 26 °C to 29 °C with average rainfall of 250 cm and average relative humidity between 70% to 80% (Suparta & Yatim, 2017). Malaysia is exposed to a very high amount of solar radiation ranging around 1400 to 1900 kWh/m² (Soonmin et al., 2019). It is known that the most crucial impact of the climate in Malaysia buildings are high solar radiation's intensity and high daily air temperature (Jamaludin et al., 2015; Soonmin et al., 2019). The driest months would be between June to August, where the temperature would be hot and dry during daytime and night time (Malaysia Meteorological Department, 2014).

It is known that the hottest time of the day is between 11.30 am to 4.30 pm (Roslan et al., 2015). The average daily sunshine duration was measured between the range of six to seven hours per day with an average of 26 °C of daily temperature and low wind velocity (Soonmin et al., 2019; Suparta & Yatim, 2017). The recommended comfortable indoor air temperature is ranging from 24 °C to 26 °C (Department of Standards Malaysia, 2017). The occupants would start to depend on the mechanical ventilation system for cooling purposes if the temperature is beyond the level of thermal comfort. Roslan et al. (2015) describe that

the concrete terrace house is thermally comfortable for only a few hours per day especially in the morning.

Sarawak is one of the states in Malaysia and the total population in Sarawak was increased from 2,071,506 to 2,471,140 in the year of 2000 and 2010 (Department of Statistics Malaysia, 2015). The rapid growth of populations in Sarawak has expanded the housing development industries, which has divided into three categories such as low-cost, medium-cost and high-cost housing. One of the Government's initiatives to help low-income family to own a house is through *Program Perumahan Rakyat* (PPR). During 10th Malaysia Plan, the PPR program has expanded to Sabah and Sarawak. As of the 11th Malaysia plan, the starting price of the house is around RM30,000 to RM35,000 per unit for Peninsular Malaysia while RM42,000.00 per unit for Sarawak and Sabah (Ministry of Housing and Local Government, 2018). Under the 11th Malaysia Plan, a total of 606,000 numbers of houses to be constructed for low and middle-income groups.

The low-cost house is designed based on the standard set by the Ministry of Housing and Local Government and local city council. The low-cost house typically designed with a smaller built-up area and cheaper building materials (Ajim et al., 2017; Arshard & Hassan, 2016). The low-cost house is considered unsuccessful in providing good thermal comfort towards the occupants due to its poor design (Ibrahim et al., 2014a). The authors also stressed that the low-cost house failed to provide acceptable thermal comfort to the occupants. Studies found that the urban and modern residential recorded indoor air temperature up to 32.6 °C, which is higher than recommended thermal comfort air temperature (Jamaludin et al., 2015).

The roofing system represents about 70% of the heat gain in building envelope element. The other studies carried out by researchers concluded that the heat transmitted into an indoor area through the roof and trapped was the one of the main factors of discomfort level in the non air-conditioned building (Azzmi & Jamaludin, 2014). In addition, according to Ibrahim et al. (2014b), the hot air cannot exit the house and become trapped due to lack of ventilation provision. The roof surface is affected by heat transmission, especially during clear sky condition when the amount of solar radiation can reach up to 1 kW/m^2 and the absorption is ranging from 20% to 90% of the amount of solar radiation in its fabric (Bakkush et al., 2015; Suehrcke et al., 2008). Roof is the building elements that contributes to the production of heat gains and is exposed to the direct sun (Lubis & Koerniawan, 2018).

According to Lau et al. (2008) and Roslan et al. (2015), about 85% of the house in Malaysia are using concrete tiles as their roofing material, followed by clay tiles and metal sheet with 10% and 5% respectively. The metal deck sheet is the typical roof material for low-income house. The roofing system of the low-cost house typically designed with a low roof angle between 10° to 15° (Ibrahim et al., 2014a). The roof material used are typically metal deck sheet. This material permits high transmission of solar radiation, hence creates a sauna effect and induces uncomfortable to the occupants (Al-Obaidi et al., 2014b). However, this material is cheap and easily available in the market.

Ibrahim et al. (2014a) identified that the low-income house suffered overheating during daytime due to its poor design constructed with no ceiling and very poor in roof insulation. The indoor air temperature of a modern low-cost house is higher than the occupant's thermal comfort range (Roslan et al., 2015). The authors stressed that the causes of overheating also known due to its roof pitch and poor ventilation provision on the house's wall. The overheating is usually happened due to the hot air trapped inside the house. The

source of the hot air mostly comes from the heat that has been transmitted roof surface and then transferred to the lower area. The roofing system is one of the building envelope components apart from the walls, floors, windows and doors. The orientation and location of these building envelopes play an important role in reducing the indoor temperature by maximizing the use of natural resources as cooling component. Previous studies showed that the building envelope to minimise the use of energy in a building by maximizing the natural ventilation (Apat, 2014).

Without a proper ventilation system, the house would suffer from the overheating. The overheating surely could cause discomfort state to the occupants; hence it would generate the needs for cooling system such as air-conditioning system, exhaust fans and so forth. The high transmission of solar radiation affecting occupant's level of comfort. Most of the occupants are well-versed with types of cooling system to cool down their residential and commercial building. Not to mention the energy used to generate the cooling system represent the biggest energy load. This matter arises due to the concern on modern comfort standards, social customs and design practices, which made the mechanical cooling is one of the necessary requirements (Rahman et al., 2013).

Based on report from Energy Commission (2014), commercial buildings use the electricity up to 38,645 GWh, while residential buildings consume about 24,709 GWh. The same report recorded the highest daily electricity demand amounting 345.25 GWh in 2013, which was increased by 5% from the previous year. In addition, the annual electricity demand increases by 3.6%, from 108,473 GWh in 2012 to 112,358 GWh in year of 2013 (Energy Commission, 2014). The increasing of energy demand is due to the increasing of number for commercial and residential buildings and rapid population growth as well as climatic changes (Rahman et al., 2015). The authors also addressed that most of electricity

use for ventilation system and cooling purpose. The cooling system is important to achieve occupant thermal comfort. Due to the increase in cost per rate of electricity, designer nowadays become more aware to use natural resources in daily lives (Roslan et al., 2015). The designer has started to look for application of natural resources for ventilation and cooling purposes inside a building to achieve occupant thermal comfort.

One of the good thermal comfort houses examples is the traditional Malay house. It was first introduced in Malaysia during the 1800s. The traditional Malay house is constructed with a lightweight material including minimum mass and voids, using high insulation materials and low thermal capacity, which are appropriate for thermal comfort in our climate (Ibrahim et al., 2015). Thermal capacity is defined as amount of heat on a body to raise temperature. Higher thermal capacity material would have greater amount of heat stored inside. Most of the traditional Malay house used timber as the main material, while the roof is made from the leaves of the *Arecaceae* or the common name is *Nypa fruticans*. Undoubtfully, both are considered good in insulation and providing natural ventilation. In addition, the traditional Malay house typically from the lightweight material (Ibrahim et al., 2015). The characteristic of the materials come with a low thermal capacity, which only allow a little amount of heat and easily cools at night time.

Apart from that, the traditional Malay house also has a higher ceiling, giving a larger space in the attic area and at the same time allows the hot air to rise and exit via the spaces between *Nipah* roof arrangement. The design such as higher ceiling and build higher from ground level also enhances the stack effect to occur effectively. It was found that the traditional Malay house is cooler than a modern house during daytime. Previous study concluded that the indoor air temperature in a traditional Malay house is cooler than outdoor climate up to 3.0 °C differences and maintaining average speed or air velocity of 0.10 m/s

(Prasetyo et al., 2014). It was found the idea of adapting the stack effect roof design in Malay house can help to minimise the hot air in a building (Ramli, 2012; Roslan et al., 2015). Many researchers agreed that the traditional Malay house is one of the best passive designs that enhance sustainable house (Ibrahim et al., 2015; Kamal et al., 2004; Ramli, 2012). The *Nipah* roof is good in maintaining good climatic condition inside the house. According to Roslan et al. (2015), the *Nipah* roof is having a lower thermal capacity, hence provide good insulation against heat. The *Nipah* roof provide a good climatic inside the house as the roof has the ability to cool the room during day time and warm the house at night (Ibrahim et al., 2015).

The modern concrete houses heat up during daytime and hardly to cool during night time (Ajeel & Yusof, 2016; Wahab & Ismail, 2012). Malaysian houses have problems with night ventilation because most residents usually open their house's windows during day time and close at night. This would lead to the high usage of electricity to achieve indoor thermal comfort at night time. Roslan et al. (2015) stressed that lack of ventilation provision and poor of passive design are the main causes of overheating. It is essential to investigate the passive design, especially at the top part of the house, such as the roofing system design that could allow or improve the natural ventilation. In this study, the roof was designed to investigate on the effect of the openings on the roof surface with the indoor air temperature.

1.2 Problem Statement

Building occupants especially for modern houses in tropical climate normally experienced higher indoor temperature during daytime. This is due to the poor passive design of the modern house these days. Nowadays, modern low-cost house is built with poor architectural specifications, lack of natural ventilation and unsuitable with prevailing

climatic condition which has result to the extreme indoor air temperature and comfort (Bhikhoo et al., 2017). The overheating inside modern house would lead to the increasing energy consumption to operate the air-conditioning unit (Elborombaly & Prieto, 2015). Natural ventilation system would help to reduce indoor air temperature naturally. From previous studies, attempts have been made to emphasis the reduction of indoor air temperature through opening of windows, doors and louvers (Ibrahim et al., 2014a; Roslan et al., 2015).

Roofing system plays an important part of the house that contribute to the thermal comfort of the indoor environment. The heat from solar radiance transmits into internal area through the roof surface. According to Zingre et al. (2015), roof could reduce up to 6% of the annual heat entry through roofing system during daytime but become an obstacle for heat loss at night time. Without proper ventilation, the trapped hot air inside the house escape via the smaller opening provided at the ridge vent, which located at the end and at the centre of the roof.

Roslan et al. (2015) addressed that modern house is built with lack of ventilation system especially at the roofing area. Roofing materials also play important part in allowing the amount of heat transferred into the house. The clay roof tiles also one of modern roof materials, but the cost per unit is expensive compared to the metal deck or zinc roof. Although metal deck and zinc roof are cost saving material for a modern house, but it has higher thermal conductivity than clay roof tiles. This is also one of the causes of the overheating inside the house when a large amount of energy from solar radiation is absorbed and transmitted into the lower area. The turbine ventilation in the other hand could help to remove the trapped hot air, but it is less preferable due to additional cost incur in operating and maintaining the unit. The traditional *Malay* house is one of the best examples providing

comfort to the occupants. Hosseini et al. (2016) concurred that traditional Malay house provides effective ventilation to control the indoor air temperature. The traditional Malay *Nipah* roof also one of the best roofing materials that could help to release the trapped hot air. As a developing country, modern house becomes the buyer's preference. While *Nipah* roof is not suitable for modern house due to the short lifespan and esthetical value.

The ventilated roof design for low-cost house could improve the reduction of overheating temperature internally. Apart from that, the roof openings in between roof material arrangement also play an important role to remove the hot air from the indoor area to the outside environment. However, little was known regarding performance of ventilated roof strategy to reduce overheating in modern low-cost house. There was little studies emphasis the ventilated roof strategy in modern house design, typically for hot humid region. Therefore, in this study, ventilated roof approach was studied and incorporated with roofing system to reduce the overheating issues inside modern low-cost house.

1.3 Aims and Objectives of the Research

The aims of the study are to design the ventilated roof tiles design that suitable for hot humid climate especially in Malaysia. To achieve the aim of the study, several objectives stated as follows:

- i. Validation of proposed ventilated roof tiles and common roof;
- ii. Investigate the thermal performance of the proposed ventilated roof tiles design with different roof angles through simulation;
- iii. Determine the thermal performance of proposed ventilated roof tiles on the modern low-cost house.

1.4 Research Background

The present work is an extension of the work reported earlier by Ibrahim et al. (2014b) with emphases on the openings on the roof surface. The background of the study is based on the problems of current passive design that lead to the overheating of indoor temperature. Nowadays, the designers are unaware with the importance of the roofing design for a building. Most practitioners prefer lower roof pitch of 10° due to cost saving and aesthetic value, hence ignoring the overheating on the occupants during day time. For this study, the ventilated roof design was improved and proposed based on information gathered from the current issues in modern low-cost house's passive design and traditional Malay house design. This study also covers thermal performance including modelling of the energy transfer between house and the surrounding through software. The result and outcome of this study will become an indicator of impact in temperature reduction as it is one of the main concerns apart from producing a good design of ventilated roof.

1.5 Hypothesis

Ventilated roof is able to reduce higher indoor air temperature inside the house as compared to common roof. The openings on ventilated roof allow the natural air movement circulation inside the house and provide area for hot air to escape.

1.6 Research Scope and Limitation

The scope of this study was restricted to the investigation on the issues regarding the roofing system in Malaysia, thermal performance study and air movement with helps from the building professional such as architect, civil engineers and academicians. The data obtained from this study (except the literature review) were mainly taken from the building

professionals, lecturers and the software related to the study. There was some limitation regarding the roofing system such as information on the roofing system and new roofing design system as well. Therefore, the scope of the study was limited to the available information and resources.

1.7 Thesis Organization

This thesis consists of five chapters and summary for individual chapter is given in the following section.

Chapter 1: Introduction

This chapter provides general introduction and overview of this study. The aims and objectives were briefly explained which covered on the issue arise due to current issues of overheating in modern low-cost house, current modern passive design, ventilated roof approach and investigation on the thermal performance of the proposed ventilated roof design.

Chapter 2: Literature Review

This chapter focuses on the literature review based on previous studies by various researchers. Most of the issues discussed in regards with the poor passive design in modern house and specifically focussing on the roofing system, which linked to the overheating. This research is focus on the upper part of the house, mainly on the roof opening. Inevitably the research on the ventilated roof is still lacking and become unpopular these days. Researcher more focus on developing technologies that can help to reduce overheating through mechanical system, which will surely incur cost for operation and maintenance.

Chapter 3: Methodology

This chapter describes the flow of the study and methodology on the experiments conducted. The design of the ventilated roof was proposed and constructed based on previous studies and research gap. The ventilated roof was designed to provide more openings on roof surfaces to allow undesirable hot air inside the house to exit. The on-site experiments were conducted on a small-scale model house. The ventilated roof was tested along with common roof to measure the differences and performance of both roofs. All recorded data were input to computational fluid dynamic software namely, ANSYS for validation purposes. After software has been validated and the data would show good agreement with the on-site experiment, simulation was conducted on different roof pitches and based on actual low-cost house scale in Betong, Sarawak.

Chapter 4: Results and Discussion

This chapter showed the results obtained from experiment works and simulation. The results were presented in graphical and table form. The results were compared and explained in detail for model house with 10°, 30° and 45° pitch of roof. The simulation was proceeded using actual low-cost house scale for proposed ventilated roof on 10° and 30° pitch of roof. The results were analysed and discussed.

Chapter 5: Conclusion and Recommendations

This chapter consists of a conclusion of this study and recommendations on the application of the ventilated roof. Suggestion on the application of the ventilated roof and improvement that can be considered in future study were discussed in this chapter.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Everyone needs buildings to perform their daily task or routine activities and also as a safety from nature's effect (Ahmed et al., 2014). Overheating is one of the concerns in modern low-cost house. Previous study shows that the low-cost house suffers overheating due to poor ventilation provision in the house design (Ibrahim et al., 2014a). Good passive design promotes natural ventilation and at the same time enhance the energy efficiency of the house. However, poor passive design would be affecting the occupants to suffer overheating and feeling uncomfortable inside their own house. This phenomenon occurs due to hot air inside the house rises upwards to the upper part of the house because of its lesser density with the cooler air.

Moreover, using cheap construction material and lack of ventilation provision in low-cost house design has caused the hot air to trap inside the house. Due to this, high temperatures would have an inimical affect towards human's health. When this scenario happens, it would create the needs for the occupants to install and use mechanical cooling system, which does not promote energy efficiency. Due to rapid development, urbanization, and climate change, it is important to promote appropriate passive design strategies to reduce the cooling load and lowering the indoor air temperature. Figure 2.1 shows typical electrical goods and its usage frequency for a house.

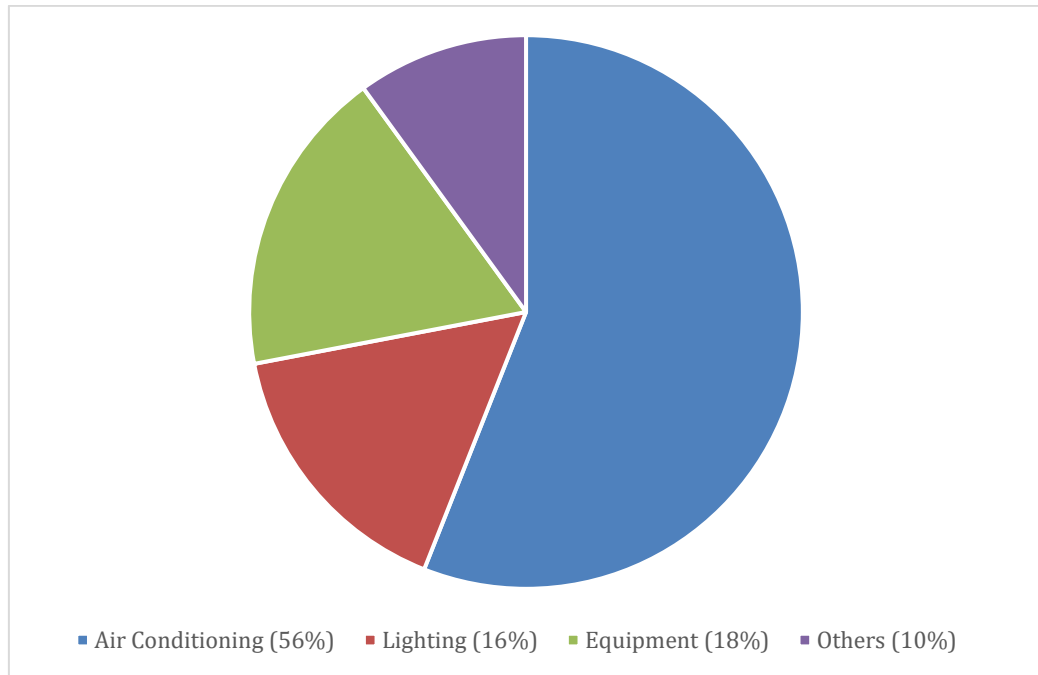


Figure 2.1: Energy consumption for typical building in tropical countries (Chen et al., 2021)

The data shows that most of the electrical usage in a house is for cooling purposes as with 56%, compared to usage of electricity for lighting with 16% and other house electrical appliances such as equipment with 18% and other with 10% respectively. Proper passive cooling strategies assists to minimize the heat gain into the building and helps to maximize the heat loss to the outside environment through air movement, cooling breeze and so forth. In the other hand, passive cooling system become an appealing solution to modify buildings and homes to achieve thermal comfort (Ahmed et al., 2014). The passive cooling system provide passive process for cooling purposes without the demands of mechanical cooling system such fans, air conditioning unit and compressor. In addition, energy consumption can be reduced or achieved through suitable passive design strategies.

In the other hand, the traditional Malay house has a thermal comfort fundamental that use the local materials, good house orientation, high pitch of roof for stack effect

function and so forth (Ramli, 2012). Various passive design strategies have been considered by researchers to reduce the cooling load in a building especially for hot humid climate countries (Chen et al., 2021). Thus, it is important to ensure modern low-cost house is built with proper and good passive design. This process is important to identify and understand the implementation of good passive design of modern low-cost house in hot and humid climate. It is also at the same time stressing the importance of ventilated roof strategy in defining the thermal performance of modern low-cost house. The thermal performance is referring to the process of energy transfer modelling between buildings and its surrounding. With this process, the energy efficiency of a building can be improved.

2.2 Passive Design

Passive design is a design that is taken into consideration of using natural resources such as wind and sunlight to keep the indoor climate within the thermal comfort zone. Passive design promotes natural ventilation to cool down the house. A good passive design of a house contributes to lower indoor temperature as compared to the surrounding temperature. Nowadays, most of the occupants in modern houses are suffered from overheating. A good passive design can be achieved by using free renewable sources of energy such as sun for lighting and heating, wind that provides cooling, ventilation towards the building and so forth. The traditional Malay house used ventilation and solar radiation control to provide climatic comfort for the occupants (Kamal et al., 2004). Previous study revealed that the passive design of a modern terrace house in Malaysia is not suitable for hot and humid climate (Ariffin, 2015).

It is important to consider proper passive design to minimise the need to use electricity for mechanical heating or cooling system. Heat transmits from the roof to the

ceiling, stores inside the concrete walls and floor slabs, and creates greater indoor temperature because of stagnant air (Wahab & Ismail, 2012). The poor passive design would result in overheating inside the house. Passive design can improve the quality of indoor air and reduce the high temperature inside the house during the hottest time of the day. Chen et al. (2021) stressed that the passive design strategies could be categorized based on various features including building environment design such as the building envelope, microclimate, ventilation, daylighting, orientation, thermal insulation, shading, construction materials and so forth. Thus, the important elements or parameters of passive design are building orientation, building envelope, shading, building material, insulation and ventilation, which were discussed further in this chapter.

2.2.1 Building Orientation and Layout

The modernist style has taken over the design, which less sustainability and would undermine the passive design in controlling climate in low-cost housing. The building orientation is one of the important parameters in determine good passive design. Previous researches have been frequently studied with the effect of building orientation towards minimising the indoor air temperature (Jovanović et al., 2014; Morrissey et al., 2011). Figure 2.2 shows the building orientation of a traditional Malay house in Malaysia.

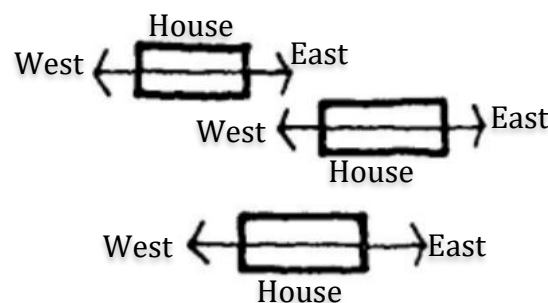


Figure 2.2: Traditional house's orientation facing east-west direction (Kamal et al., 2004)

Building orientation for traditional Malay house mostly following the religion factors that often facing Mecca, where the direction is at the east-west direction as shown in Figure 2.2 (Kamal et al., 2004; Ramli, 2012). The sun is rising from east direction while the sunset is at west direction. This direction will give more natural lighting in the evening time to reduce dependency of using artificial lighting (Ramli, 2012). Study by Sarkar (2013) revealed that to provide sufficient wind and amount of sunlight into a building, it is advised the building to be oriented in the east – west direction. However, this direction not suitable for modern low-cost house because more sunlight will be absorbed during the hottest time of the day especially in the afternoon time because of material used in construction such as metal roof, concrete wall and so forth. Previous studies concluded that the optimum for modern building orientation is facing to the south in hot and humid climate country (Mulyani et al., 2017; Omrany & Marsono, 2016).

Apart from the house's direction, another factor affecting the building orientation in traditional Malay house is that the houses are built scattered or randomly arranged. Figure 2.3 shows the layout of randomly arranged of the traditional Malay house.

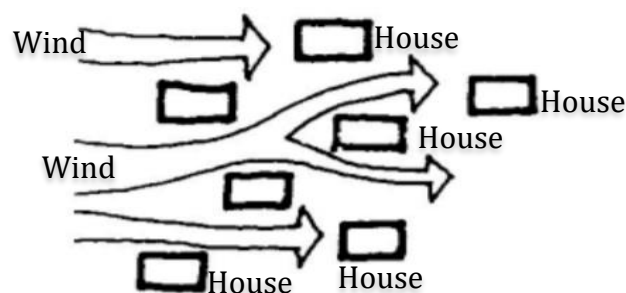


Figure 2.3: Randomly arranged layout for traditional Malay house (Kamal et al., 2004)

The traditional Malay houses is randomly arranged to allow the wind flowing and ensure the wind velocity is not substantially reduced when entering the houses. In hot and humid climate areas, selection of suitable building orientation towards wind direction could help to maximize the functionality of cross ventilation into the house (Nawayai et al., 2020). The importance of courtyard and patio with semi-open spaces in traditional house is functioned to enhance the indoor thermal comfort (Du et al., 2014). Moreover, different type of courtyard in traditional houses in hot humid climate create different functions in providing indoor thermal comfort (Kubota et al., 2017). The temperature difference between front yard and back yard area in traditional houses could provide comfortable indoor environment, which create mild air velocity in the house (Shaeri et al., 2018).

It is different from modern terrace house where the houses are built next to each other in one row without house gap in between and is properly arranged for uniformity. As modernization take place, randomly arranged detached or bungalow are rarely built, while landed terrace or semi-detached houses become well known development at present.

2.2.2 Building Envelope

The building envelope is known as the separator between the exterior and interior of a building. Traditional building in hot and humid climates usually adapt the spread-out plan and permeable internal organization. The components of the building envelope are mainly walls, roof, floors, partition, doors and windows. According to Al-Saadi (2006), building envelope contributes more than 70% of the thermal load in a house. In hot-humid climate, it is indeed that 70% to 80% of energy consumption is used for operating the air-conditioning unit to achieve thermal comfort (Khoukhi et al., 2020). Figure 2.4 shows the cross ventilation inside the house through the building envelope.

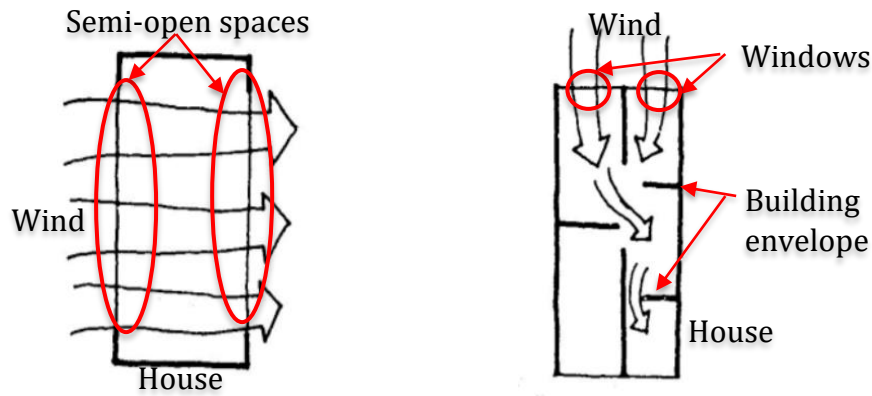


Figure 2.4: Plan view of cross ventilation inside the traditional Malay house (Kamal et al., 2004)

The traditional Malay house has a good building envelope arrangement, which enhance the natural cooling inside the house through cross ventilation as shown in Figure 2.4. According to Shaeri et al. (2018), the traditional Malay houses design in tropical climate provide a lower indoor temperature compared with the modern terrace house design. This is because of the building envelope for traditional Malay house is design with more open space or void area, which allows natural ventilation into the house and fill the rooms with the cooler air. Apart from that, courtyard or patio with semi-open space is one of the effective strategies to create suitable thermal condition in traditional house (Du et al., 2014).

The modern house is built with more closed area as compared to traditional house. The courtyard in modern house is replaced with small open area known as car porch while the building itself is enclosed. Cooling the house using cross ventilation may not be effective in modern house due to limitation of open spaces in the design. Veranda also one of the designed that still being apply in modern house. However, the design is not being use in low-cost house. Semi-open space design in modern house also not preferred by the developer or designer nowadays because of safety issue.

In the other hand, building envelope is influenced by the selection of material used (Al-Saadi, 2006). The author also stressed that exterior building envelope with high thermal mass material is affecting high capacity to store heat, thus determine the energy consumption of the building for cooling purposes. Traditional house is built with lower thermal capacity as compared to modern houses, which use brick wall of concrete wall with high capacity to store heat. The wall for traditional Malay house usually constructed from timber and one of the well-known wall installations is the *susun sirih*. Figure 2.5 shows the installation for the *susun sirih*.



Figure 2.5 The *susun sirih* wall arrangement (Zain, 2012).

The timbers are installed by stacking it with one another as shown in Figure 2.5. The stacking of the timbers will create small gaps in between, thus allowing the house especially the interior to cool down rapidly through natural ventilation. The wind can enter the house and the hot air can be easily remove from the house as well through these gaps in *susun sirih* wall. Modern house in the other hand is built with high thermal capacity such as concrete brick wall and metal roof as well as the house designed with more enclosed area. Thus, it is important to select suitable building material and allow some gaps in the installation or application to achieve thermal comfort inside the house.

2.2.3 Shading

The solar radiation through an opaque part of building envelope would raise the surface temperature and contribute to the increasing of indoor temperature. It is also has strong impact on thermal influence inside a building. Normally, the solar gain would directly enter the house through windows and doors, which are the major components of heat gains apart of roofing system in a house or building. Previous studies stressed the importance of providing shade for effective strategies to prevent overheating inside the house in hot-humid climate country (Laopanitchakul et al., 2007; Wang & Wong, 2007). According to Bellia et al. (2014), shading would be affecting the energy use in a building for lighting, heating and cooling as well as occupant's visual and thermal comfort.

Shading has provided positive effects on the thermal comfort (Chenvidyakarn, 2007; Sumanon, 2004). Solar shading can provide reduction on excessive daylight and as well as indoor temperature (Chen et al., 2021). Based on the Simons et al. (2014), the temperature becomes warmer due to lack of shading and orientation. The authors highlighted that the external shading must be used to enhance the thermal comfort conditions in naturally ventilated houses or buildings. Controlling intensive solar radiation through adaptation of shading covering the balconies and maximizing cross ventilation through the shaded windows provide an acceptable indoor thermal comfort in traditional houses (Teo & Kubota, 2015).

In South Korea, the application of horizontal shading device at windows and doors is part of law and regulation for the energy saving efforts of the existing buildings (Kim et al., 2017). The author also concluded that the application of horizontal shading device at windows reduced the indoor air temperature, which at the same time reduced the energy

consumption in the building. This strategy can be considered effective to reduce the energy consumption for cooling purposes since the heat gain from windows also one of the biggest contributions to higher indoor air temperature. Study by Bellia et al. (2014) showed that there are four types of shading such as overhang, blind system, light shelf and proposed experiment shading device. The author stressed that the proposed experiment shading device system has improved on the thermal comfort inside the building and protects from direct sunlight as well of 11% of energy saving. Based on these four types, proposed experiment shading device recorded higher energy saving, followed by light shelf type, overhang and lastly is blind system. Study by Alhuwayil et al. (2019) showed that shading could provide energy saving up to 20.5%. From these studies, it shows that shading help in energy saving, reducing higher amount of solar gain through windows, hence reduce indoor air temperature and so forth.

2.2.4 Building Material

In hot and humid climate, the factor of building material selection for building envelopes should take into consideration of minimising the heat gains into the buildings. Previous research found that many traditional buildings in hot and humid climate were built using lightweight materials such as timber walls with ventilation gaps and bamboo strip for flooring (Leaurungreong et al., 2005). A previous study has reported that most of the modern houses constructed are affected with high solar radiation transmission due to the use of non-reflective materials (Lau et al., 2008).

Many researchers agreed that the traditional Malay house is one of the best designs that enhance sustainable house (Hosseini et al., 2012, 2016; Ibrahim et al., 2015). The traditional Malay house is built with lower thermal capacity material, which means the

physical property of matter has lower amount of heat to be distributed to a given mass of a material to produce a unit change in its temperature. In addition, the main material used in the traditional Malay house usually the lightweight such as wood and other natural materials (Ibrahim et al., 2015). The characteristic of the materials come with a low thermal capacity which only allow a little amount of heat and easily cool down at night time (Ibrahim et al., 2015; Ramli et al., 2012). The main structure for traditional Malay house is from first class timber such as *belian*, while support structure is from secondary class timber such as *jelutung*, *rengas*, *selimpau* and so forth (Zain, 2012). The roofing system of traditional Malay house was made from palm leaves or known as *attap*, which offers best climate inside the house. However, these traditional building materials is hardly to be available in the market nowadays.

As industrial revolution takes place and rapid development in our country, modern materials such as bricks for the wall, metal sheet and roof tiles as the roof materials have become prevalent and easy to be found in our competitive market. These types of materials could speed up the construction duration as claimed by the manufacturer. These materials produce in a mass size and using the latest technologies. Effort has been made to study on their properties, thermal conductivities and water absorptions, which can be very useful in designing a low-energy building. In modern low-cost house, Spandex or metal roof is preferred by the developer due to lower material cost as compared to concrete or clay roof tiles (Roslan et al., 2016). Building standard in Malaysia is exist, however does not specify on the guidelines in view of human comfort (Ibrahim et al., 2015).

Nevertheless, the information on modern materials in regard of thermal capacities of these materials is still lacking. Adapting traditional materials in house construction provide

best solution in hot humid climate (Beccali et al., 2018). However, modern houses these days are not designed based on our local climate and pay no attention to basic requirement for occupant's thermal comfort (Ibrahim et al., 2015). The author further stressed that it is also not feasible to design entire house based on traditional Malay house in urban areas, but some features that can contribute towards thermal comfort can be accommodated in modern house concept.

2.2.5 Insulation

The function of building insulation is to reduce heat from the sunlight that radiates the building envelope, control noise from the rain, thermal expansion, contraction and so forth. There are many criteria need to be considered when selecting thermal insulation such as cost, durability, water vapour absorption, thermal conductivity, fire resistance, user friendly in view of installation and so on. Thermal insulation is known as materials made by fibrous, particulate film or sheet, block or monolithic, open or closed cell that chemically or mechanically supported the rate of heat transfer through conduction, convection or radiation process (Al-Homoud, 2004).

Insulation from external walls and roof is one of the effective strategies to save energy and offer more comfortable indoor thermal condition (Halim et al., 2012; Sisman et al., 2007). Radiant barrier foil is one of the roofing insulation examples and generally associate with the term of reducing the heat flux (Medina, 2012). The reflective insulation typically installed in enclosed spaces without no air moves in and out. The insulation only works to reflect the incoming thermal radiation, even though the space is ventilated (ASTM C1313, 2014; Malaysian Standard 2095, 2014). Previous study shows that the insulation at

roof pitch contribute up to 13.6% of cooling load and provide better attic thermal condition (Halim et al., 2011).

The modern type of insulation materials may help to reflect the thermal radiation but does not help to remove the trapped hot air inside the house or building because it made from high thermal capacity material. Modern house in Malaysia typically uses reflective material such as radiant barrier foil as roofing insulation (Allen et al., 2008). However, the dust may accumulate on the surface foil, and affect the radiant barrier performance by allowing the foil to absorb rather than reflect thermal radiation (Lee et al., 2016). Improving insulation into a building could save annual energy consumption up to 5% (Alhuwayil et al., 2019).

2.2.6 Ventilation

Ventilation provides cooling, especially in the indoor area and enhances the indoor area to achieve thermal comfort. It also enables convective heat transfer from a warmer interior zone to a cooler outdoor area. Higher indoor air velocity provides direct cooling to the occupants. Ventilation is divided into two types of system such as natural ventilation and mechanical ventilation system. In natural ventilation, the cooling system can be accomplished by wind, buoyancy or a combination of both wind and buoyancy. Cooling energy demand in a building can be reduced by 10% to 30% by allowing natural ventilation into a building (Yueer et al., 2017). However, occupants residing in modern low-cost house suffers overheating due to lack of natural ventilation in house design (Ibrahim et al., 2014a).

While mechanical ventilation such as fan and air conditioning are an alternative solution and the fastest way to cool or maintain air temperature within thermal comfort level. Mechanical ventilation is widely use all around the globe especially in hot humid climate

region and during summer season. However, the usage of mechanical ventilation will surely incur higher cost for daily operation and routine maintenance. The concern on the demand of energy for mechanical ventilation has arisen due to modern comfort standards, social customs and design practices, which has made it is important factors in daily life (Rahman et al., 2013).

Undeniable, natural ventilation is always a good choice to reduce overheating inside a house because it depends on natural air movement and also energy saving strategy in designing a house. In certainly, there is a need to discuss on the study gap of current ventilation provision and to generate recommendations to improve the design practices and at the same time promotes energy saving for modern low-cost house.

2.3 Natural Ventilation

Natural ventilation is the process of supplying and removing the air internally by natural means without using the mechanical system. The topic of natural ventilation is one of the most active areas in heat transfer research nowadays. Undoubtfully, natural ventilation is perceived to be the best initiatives in providing good comfort to occupants (Lechner, 2009; Nicol & Humphreys, 2002; Soebarto & Ribeiro, 2008; Su et al., 2009; Wong et al., 2002). The outdoor air flows inside and then flow outside the building, which caused by the differences of pressure between internal and external environment. The natural forces create the wind pressure and temperature differences between internal and external areas through radiation, convection or conduction (Al-Obaidi, 2015). The proper ventilation system is important to ensure the occupants feel comfortable inside the building. According to Roslan et al. (2015), the traditional Malay house design is one of the best examples that enhances the natural ventilation because it mostly depends on the natural cooling. Poor design of

ventilation system would make the occupants suffer due to overheating issue, which the indoor temperature exceeds the thermal comfort level.

The natural cross ventilation is preferred by the designers to generate air movement in the internal area and enhance the building thermal environment (Jamaludin et al., 2013). But nowadays, the concept of natural cross ventilation in modern houses does not always successfully apply in warmer climate area. To overcome this, the stack effect is one of the effective solutions for the outlet area at the top of the house to induce vertical air movement.

2.3.1 Stack Effect

The stack effect is the condition at which the hot air arises due to the temperature differences and it driven by buoyancy phenomenon. Buoyancy is known as an upward force that is proportional to the pressure differences. Different temperature would give different in pressure. Warmer indoor air temperature will rises due to buoyancy forces, which creating pressure difference that allow the air movement from bottom of the building and pushes the air out at the top level. It is one of the natural ventilations that relies on the buoyancy effect through the differences of temperature to promote air flow inside the building. The efficiency of the stack effect to cause natural air movement is depending on the ease of the air may arise within the house or the area. According to Balasbaneh and Marsono (2011), stack effect gives high impact on the air temperature inside the house. It was found the idea of adapting the stack effect roof design in Malay house can help to minimise the hot air in a building (Ramli, 2012). Jack roof is one of the examples to explain the concept of stack effect in the modern house. The jack roof is designed to release the heat from the house by providing opening in the upper part of the house. However, the jack roof is mostly

constructed on one side at the edge of the roof. Apart from its poor aesthetic value, the jack roof is least preferred by the designers.

The stack effect could occur during the calm wind condition where the air slowly moving up to the roof level due to pressure and density differences. The hot air travels from different density areas. In this principle, the hot air rises to the upper part of the house because of its lower density as compared to cool air with higher density. The stack effect is very useful, especially for houses with a limited side opening, like in a terrace house. Roslan et al. (2015) proposed that the stack effect should be adapted in passive design of the house. Figure 2.6 shows the movement of the air in a house without and with the stack effect occurrence.

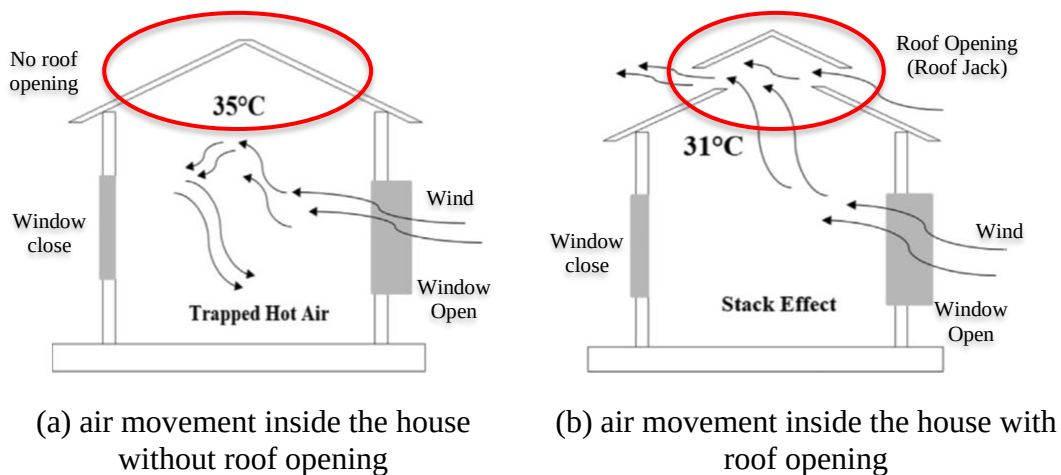


Figure 2.6: Condition of air movement inside a house

Figure 2.6 (a) shows the movement of wind entering the house and trapped due to one side of windows are closed and no opening at roof. Since the other available open source is not available, undesirable hot air trapped and circulated inside the house. While Figure 2.6 (b) shows the available opening at the roof able to release the trapped hot air through stack effect. The natural ventilation is one of the best choices because it is depending on the

natural air movement and a cost-effective approach in designing a house. The air gap on the roof surface should be adequate to allow natural air movement (Endriukaityte et al., 2005; Roslan et al., 2015). In addition, the air gap at a ventilated roof pitch on the roof surface could help in reducing heat transfer (Trinuruk, et al., 2007). Louvres are also one of the building envelopes retrofits and it is also known as a wall ventilation system. Retrofit is linked to modification of existing design that can help to improve energy efficiency. The louvers is designed to allow the air movement between outdoor and indoor through the wall. The traditional Malay house uses this concept to cool down the house and ease the air to flow within the house. This concept should be applied into the modern houses and help in minimising the dependency to the mechanical ventilation (Kamal et al., 2004; Ramli, 2012).

It has conclusively shown that high humidity can cause discomfort to the occupant. The mean relative humidity level at an optimum comfort temperature recorded is close to 73%, while air movement is needed continuously during a period of time for relative humidity level over than 73% (Djamila et al., 2014). The decreasing in temperature with a simultaneous increase of humidity by using a direct evaporative cooling in a confined space impairs the comfort level, especially in regions that have a hot and dry climate. High level of humidity can bring to the growth of unwanted microorganisms that can cause unhealthy environment for the occupants and as well as building materials, moisture damage and so forth.

2.3.2 Wind Pressure Effect

The wind pressure effect could help to remove the trapped hot air inside the house through the Bernoulli principle, which usually happens on the lower slope roof. The wind pressure effect typically contributes to enhance the effect of buoyancy forces that occurred

inside building (Cammelli & Mijorski, 2016). A lower slope is likely to experience higher local suction pressure along the roof (Baskaran, 2002). This phenomenon occurs due to the pressure difference on the roof surface. The wind flows over to the lower roof surface and exerts positive pressure on the windward area; while negative pressure or known as suction takes place on the leeward wall and the walls parallel to the flow direction. Figure 2.7 shows the windward and leeward region that occurs on the roof surface.

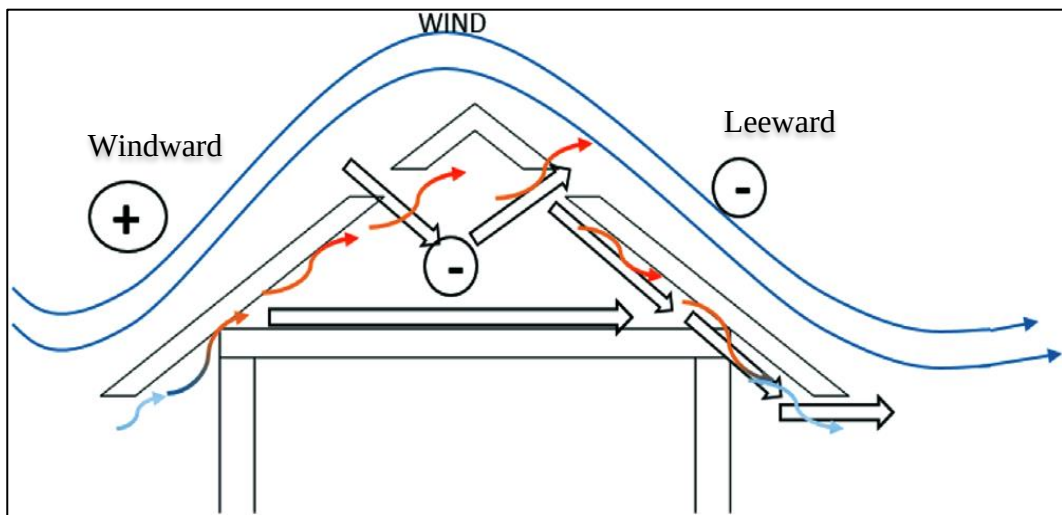


Figure 2.7: Windward and leeward area on roof surface (Roslan et al., 2015)

The negative pressure or known as suction usually occurs on the roof surface as shown in Figure 2.7. The suction pressure would be generated at any part on the roof surface and it depends on the wind speed, direction, turbulence, building topography and geometry, architectural features, and so forth. The suction pressure pulls out the hot air inside the house through the openings provided on the roof surface. The wind pressure effect should be considered in roofing design since it plays one of the important roles to remove the trapped hot air (Roslan et al., 2015).

Many researches agreed that by providing adequate openings on the roof surface provides ventilation that could help to minimise the heat transfer and reduce the indoor air temperature (Al-Obaidi et al., 2014a; Ibrahim et al., 2014b; Qasim et al., 2010; Trinuruk et al., 2007). A good ventilated roof design help in maintaining the indoor temperature within the thermal comfort zone, while minimising the electricity consumption. In the meantime, the dependence on the mechanical cooling system would become less necessary during daytime.

2.4 Mechanical Ventilation

Mechanical ventilation system is referred to fresh air that circulates using mechanical equipment or component such as ducts and fans in a house or building. There are various types of mechanical ventilation systems available in the market and is widely used such as electric fan and air conditioning unit. Many equipment has been invented to tackle this matter such as fans, air conditioning unit, turbine ventilator and so forth. However, it was found that the carbon emission in Malaysia from building sector have been doubled from the last four decades and now indicating 25% of total country's emissions (Lucon et al., 2014). The authors also highlighted that mechanical and cooling system unit is one of the greatest contributors to the emissions. Residents use electricity to generate the mechanical cooling system and cost for operation and maintenance are higher. Previous study has found that the mechanical cooling system in hot and humid climate area would consume up to double as much energy and compounding about up to 60% of total building energy consumption (Perez-Lombard et al., 2008).

2.4.1 Electric Fan

An electric fan is one of the cooling machines that becomes the first choice for comfort control during higher temperature due to low price compared to air conditioning unit. The fan is widely used in most tropical countries to create indoor breeze and enhances thermal comfort. The use of electric fan enhances the thermal comfort under various temperature (Mishra et al., 2016). The electricity usage to switch on the electric fan may be lower than an air-conditioning unit. But it still depends on the electricity to switch on and would not function during the power outage. The increasing of fan speed setting would enhance the cooling of the body, but it will increase the electricity used (Yang et al., 2015). According to Shah et al. (2015), ceiling fans contributes to electricity consumption of residential industry.

2.4.2 Air-Conditioning Unit

The air conditioning unit is a device that removes the heat and moisture from internal of an occupied area and to improve the occupant's level of comfort. It was found that the number of air-conditioning units installed in residential and office buildings was increase year by year. Previous study revealed that about 75% Malaysians depend on the air-conditioning system the indoor air temperature and good comfort (Al-Yacoubi et al., 2011a). The year of 2010 census revealed that the total number of households with air-conditioning unit in Malaysia has drastically increased from 13,000 in 1970 to 229,000 in 1990 and 775,000 in 2000 (Department of Statistic Malaysia, 2015). The dependency of air conditioning unit lead to higher expenses as the cost of operation and maintenance is more than the electric fan.

2.4.3 Turbine Ventilator

Turbine ventilator is designed to remove the internal heat and can be installed on the roof surface. Many factories use this ventilation system to remove the hot air from inside to the outside environment. Level of hot air is depending on the level of the turbine rotation. However, in the low-wind velocity condition, previous studies discovered that the fins of the turbine blocked the airflow in the connecting duct, resulting much lower rate of air remove from the ventilation duct (Ismail et al., 2012a; Roslan et al., 2015).

Due to concern on the energy use to generate the electrical appliances for cooling purposes, it is advised that several passive design strategies for natural ventilation approaches such as cross ventilation and stack ventilation to be focused on.

2.5 Types of Roofing

The roof is defined as the structure that forming the covering on the upper surface of a building or house. There are many types of roof available in the markets such as concrete roof tiles, metal deck roof, clay tiles and so forth. It is known that roof represents nearly 70% of the heat gain in building or house. It was found that the roof space in traditional Malay house is designed with proper ventilation provision through the joints and panels in the roofing system (Nawayai et al., 2020). Therefore, study in roofing system is important to identify the issues of modern roofing design that contributes to overheating inside a house. The colour of the roof surface should be one of the elements that need to be considered in passive design. Most roof tiles in Malaysia are a dark colour, which means that it absorbs more heat (Al-Yacoubi et al., 2011b). Table 2.1 shows the variety of roof tile colour used in Malaysia.

Table 2.1: Colour of roof tiles in Malaysia (Al-Yacouby et al., 2011b)

Roof colour	Percentage (%)
Red	38.0
Brown	25.9
White	9.5
Beige	7.8
Blue	7.8
Black	4.9
Grey	2.9
Yellow	2.0
Orange	0.5

Table 2.1 shows that red is the most preferred colour chosen by the house developer with 38.0%, followed by brown colour with 25.9%, white colour with 9.5%, beige and blue with 7.8%, black colour with 4.9%, grey colour with 2.9%, yellow colour with 2.0% and least favourite colour is orange with 0.5%. Several studies have found that the roof painted with a grey or dark colour recorded higher indoor temperature compared to the roof painted with a lighter colour (Al-Yacouby et al., 2011b). A black aluminium sheet for a flat roof or 10° roof pitch recorded the highest indoor temperature (Al-Obaidi et al., 2014b).

2.5.1 Roof Material

In olden days, the roof design is limited to traditional Malay house, *Minang Kabau* and so forth. The traditional Malay house is constructed using timber as the wall and partition, while *Nipah* leaves as the roof material. As our country is developing in decades, the design has changed from using timber to concrete wall while *Nipah* leaves to modern roof materials such as concrete roof tiles, metal deck sheet, etc. It was suggested that ceramic roof tiles would provide better performance in reduction of solar radiation transmission into the house. According to Miller et al. (2007) and Roslan et al. (2015), heat transmits through the ceramic

roof tiles decreases by up to 60% or less. The authors describe that the choice of using ceramic roof is not well understood due to modernization take place and vast development.

Nowadays, there are various types of roof material are being installed in Malaysia's residential industry, including concrete roof tiles, metal deck roof and so forth. Previous study revealed that types of roof materials used for residential as of today are mostly constructed with 85% of concrete roof tiles, clay tile and metal deck with 10% and 5% respectively (Allen et al., 2008; Roslan et al., 2015). Designers prefer to use roof tiles due to its characteristic that could prolong its life span and require minimal maintenance in the long run. However, the roof tile is considered expensive material as compared with a metal deck roof. Different from modern low-cost houses in Malaysia, where the designer, mostly uses a metal deck for the roof because of cheaper in the material and labour cost.

2.5.2 Roof Pitch and Colour

A previous study has primarily concentrated on the flat roof and found that the flat roof design in tropical climate could not be considered as good elemental design due to some factors that would lead to leakages, example stagnant water on the flat surface (Rahman et al., 2009; Roslan et al., 2015). Previous study revealed that higher pitch with darker colour recorder lowest indoor air temperature while lower roof pitch or flat roof with lighter colour recorded lowest indoor air temperature (Al-Obaidi et al., 2014b). Previous researches have shown that most of the roof is darker in colour (Al-Yacoubi et al., 2011b; Bludau et al., 2010).

In view of roof colour, the black colour of aluminium sheet recorded the highest indoor temperature compared to white colour (Al-Obaidi et al., 2014b). Table 2.2 shows the temperature recorded of three different roof pitches in black colour.

Table 2.2: Indoor air temperature inside black colours roof's house (Al-Obaidi et al., 2014b)

Roof Colour	Maximum Indoor Temperature (°C)			
	Roof Angle 0°	Roof Angle 30°	Roof Angle 45°	Roof Angle 60°
Black	41.66	41.13	40.81	40.76

As shown in Table 2.2, the black colour for 60° pitch of roof recorded the lowest indoor temperature with 40.76 °C, while flat roof or 0° for black colour recorded the highest indoor air temperature with 41.66 °C. Ramly and Hussain (2012) discovered that higher roof angle from 0° to 60° can reduce indoor climate up to 1.5 °C. According to Bludau et al. (2010), the dark-coloured roof shows the highest temperature and humidity variations, including comparatively high heat fluxes during summer due to conduction and latent heat effects. Moreover, the authors concluded that the bituminous roofing membrane (brownish colour) reaches the highest temperatures, about 70 °C while the white surface clearly shows lower temperatures on days with high solar radiation about 40 °C.

2.6 Common Roof

Roofs are considered as one of the most critical parts of houses, which generally would be facing solar radiation, climate and environmental change. Roofing system is important in providing shelter for the interior area of the houses (Talib & Sulieman, 2012). Roof design in Malaysia is typically flat roof and pitched roof. The most typical defects found on the roof are cracked for concrete flat roof and clay roof tiles move or cracked for pitched roof (Talib et al., 2014). According to Sarman et al. (2015), flat roof receives more direct sunlight throughout the day as compared to a pitched roof. The authors concluded that due to hot and humid climate condition in Malaysia, the issues related to flat roof are mouldy surface, cracks and water proofing-related issues. The cracked on concrete flat roof requires

extra cost for major restructuring. According to Al-Obaidi et al. (2014b), pitched roof is known as the common system for most tropical house design in Malaysia. The common roof slopes for house in Malaysia are typically built with 30° and 45° (Al-Yacouby et al., 2011a; Teh et al., 2017).

2.7 Ventilated Roof

Ventilated roof is referring to the name given to the proposed roof design. For this study, similar concept from traditional Malay house will be adapted to propose design and the detail will be discussed further in Chapter 2. The ventilated roof promotes ventilation on the roofing system. The ventilated roof is one of the approaches that can be considered in roof design for overheating reduction (Roslan et al., 2015) According to Wahab and Ismail (2014), proper size of attic ventilation openings would contribute to a good indoor air temperature provided with good wind speed. Ibrahim et al. (2014b) concluded that the indoor air temperature would reduce up to 8 °C by providing openings on the roof. The openings provide area for the hot air to exit.

Re-adaptation the stack effect roof design in traditional Malays house would minimise the hot air in the living area (Roslan et al., 2015). This is because the traditional Malay house's design provides more opening areas on the roof to the bottom part of the house. The openings promote natural ventilation at roofing area. The arrangement of *Nipah* roof is by stacking with one another, thus creating a very small gap that provide area that allow the hot air to be released. Nevertheless, it is known that traditional house design is very good in providing good thermal comfort (Suhendri & Koerniawan, 2017). The designs are developed based on consideration of the climate, lifestyles and availability of the materials (Jayasudha et al., 2014).

2.8 Thermodynamics

Thermodynamics is defined as science of energy, which involves in change of energy or energy transformation. Energy is changing from one state to another and can be concluded that the total amount of energy will remains constant. The changes of the energy content of a body are equal to the differences between the input and output of energy. Energy exists in various forms examples thermal, kinetic, magnetic, potential, mechanical, chemical and nuclear. The internal energy, U , represent a body with the sum of potential and kinetic energies between component atoms and molecule.

Heat in the other hand is a form of energy transferred between two systems with different temperature. The first law thermodynamics is defined as heat is equal to work and can be expressed as following Equation 2.1 and Equation 2.2.

For adiabatic system,

$$Q = 0 \quad \text{Equation 2.1}$$

$$\Delta U = W \quad \text{Equation 2.2}$$

Where, Q can be defined as heat energy (unit = watts). W , Work can be the fundamental physical property in thermodynamics and can be describes as motion against opposing force and measure in Joule.

For non-adiabatic system,

$$\Delta U = Q + W \quad \text{Equation 2.3}$$

2.9 Heat Transfer

Heat transfer is known as the energy that transport due to the temperature difference. The heat is transferred through three mechanisms namely conduction, convection and radiation. Thermal conduction is defined as energy transfer from one medium to another either in solids, liquid, gas or between two different materials in close contact with each other. The energy will transfer from higher temperature to a lower temperature. Thermal convection is described as heat exchange at a surface due to the air movement across the surface. The thermal radiation is an electromagnetic radiation that emitted by a body as result of its temperature.

In tropical climate countries, solar heat gained in the buildings enters through the envelope and glazing. This is one of the causes for the building to experience overheating during the day (Tatarestaghi et al., 2018). Building materials with higher thermal conductivity will result higher amount of heat transfer into the building environment. Based on Zingre et al. (2014), the metal roof has higher thermal conductivity as compared to concrete roof. Heat transfer can be expressed in Equation 2.4.

$$q = (k / s) A dT \quad \text{Equation 2.4}$$

2.10 Thermal Comfort

Thermal comfort is the condition of mind that satisfied with the temperature surrounding or thermal environment and is assessed by subjective evaluation (ASHRAE Standard 55, 2013). According to Department of Standards Malaysia (2017), the recommended comfortable indoor air temperature is between 24 °C to 26 °C. In compliance

with ASHRAE Standard 55 (2013), the recommended comfort temperature under the climatic condition for the dwellers is around 24 ± 1 °C. Factors affecting the thermal comfort are from environmental factors and human factors. Environmental factors affecting the thermal comfort are air temperature, radiant temperature, air velocity and humidity. While human factors affecting the thermal comfort are clothing insulation and metabolic heat.

Previous study conducted by Ibrahim et al. (2014a) described that indoor air temperature inside low-cost house does not achieve thermal comfort internally. This would lead occupants to suffer from overheating. When occupants were dissatisfied with their thermal environment, it will not only potential risk to human health but also impact on their ability to perform routine work. It is important to look into a good passive design that can contribute to further reduction of indoor air temperature within occupant's thermal comfort.

2.11 Computational Fluid Dynamic (CFD) Simulation

The CFD software is a high-performance software that has the capabilities with two-dimensional and three-dimensional model. It is a simulation program of fluids engineering system, which use modelling (mathematical physical problem formulation) and numerical methods (discretization methods, solvers, numerical parameters, grid generation etc.). The process can be summarized as shown in Figure 2.8.

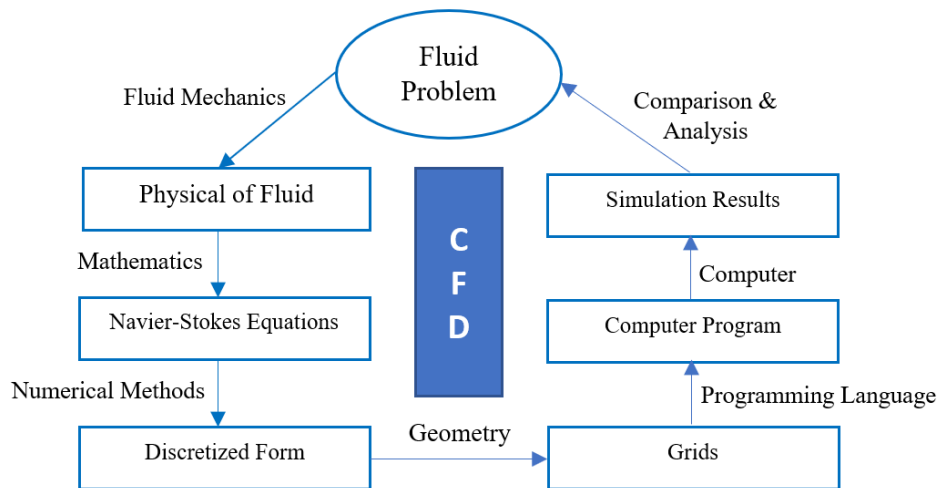


Figure 2.8 Computational Fluid Dynamic (CFD) process (Zuo, 2005).

All materials are come from fluid either it is solid, liquid or gas. To solve the fluid problem, the physical properties of the fluid to be identified using Fluid Mechanics. Mathematical equations can be used to describe the physical properties before entering to Navier-Stokes Equations through CFD. However, it needs to be translated to the discretized form via numerical discretization methods such as Finite Difference, Finite Element and Finite Volume methods. Then, the problem domain should be break or divide into smaller parts because the discretization needs to be based on it. To solve this matter, computer program will be run to get the simulation results for further analysis.

The CFD modelling techniques can be very useful during the design stage to investigate the thermal performance of the study including temperature distribution, ventilation flow rates and so on within the ventilated space (Malek et al., 2014; Ramly & Hussain, 2012). The CFD method has become widely utilized for predicting building airflows and heat transfer phenomena (Idriss et al., 2018). The authors also addressed that the energy efficiency of a building could be optimized with natural ventilation according to

the previous findings through CFD simulation. In this study, SolidWorks was used for the designing part, while ANSYS Fluent was chosen to run the thermal distribution analysis.

The two commons differential form for all the flow equations in finite volume CFD method are as following Equation 2.5 and Equation 2.6.

For steady state process:

$$\int_A \mathbf{n} \cdot (\rho \phi \mathbf{u}) dA = \int_A (\Gamma \text{grad } \phi) dA + \int_{CV} S_\phi dV \quad \text{Equation 2.5}$$

and for time-dependent processes

$$\begin{aligned} & \int_A \frac{\partial}{\partial t} \left(\int_{CV} (\rho \phi) dV \right) dt + \int_{\Delta t} \int_A \mathbf{n} \cdot (\rho \phi \mathbf{u}) dA dt \\ &= \int_{\Delta t} \int_A \mathbf{n} \cdot (\Gamma_\phi \text{grad } \phi) dA dt + \int_{\Delta t} \int_{CV} S_\phi dV dt \end{aligned} \quad \text{Equation 2.6}$$

2.12 Chapter Summary

Chapter two reviews on past studies conducted by various researchers to help on understanding the issues and study gap. Traditional Malay house is built with a good passive design such as building orientation, layout, building envelope, building material, shading and so forth, which promotes natural ventilation for better thermal comfort inside the house. Unlike modern low-cost house design nowadays which often experiences overheating inside the house, traditional Malay houses promote natural ventilation for better thermal comfort inside the house. Modern low-cost house design nowadays focused on terrace house instead of randomly arranged, material used for construction is highly thermal capacity due to

unsuitability or unavailability of traditional house materials such as attap roof as compared to availability of spandex or metal roof for modern low-cost house presently, more closed areas as compared to traditional house with semi-open space and so forth. There have been several studies on overheating inside modern low-cost house due to inadequate provision on ventilation and reported as a design issue. This overheating issue in modern low-cost house inevitably needs to be focused on this research. Previous studies also highlighted the contribution of ventilated roof in reduction of indoor air temperature inside a house. However, ventilated roof is not being explored often due to lack of research conducted on this area.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This research will be conducted to investigate on the effectiveness of the opening in providing area to allow hot air to exit. In this chapter, the proposed ventilated roof will be tested in a small-scale model to study on the performance of the ventilated roof towards the indoor temperature. The design and processes to test the ventilated roof will explained in this chapter. The on-site experiment will be conducted at Faculty of Civil Engineering, Universiti Malaysia Sarawak. The experiment was conducted in two conditions; (i) all windows and door were fully closed and (ii) all windows and door were fully opened. The data recorded were compared with the analysis from the Computational Fluid Dynamics (CFD) Simulation software namely ANSYS Fluent. This stage is important for software validation and the results will be discussed in Chapter 4. Apart from that, thermal imaging camera will be used to capture the thermal image of the model house. The images captured from thermal camera will be compared with the simulation generated from ANSYS. This research will be conducted in stages to meet the objectives of the study as shown in Figure 3.1.

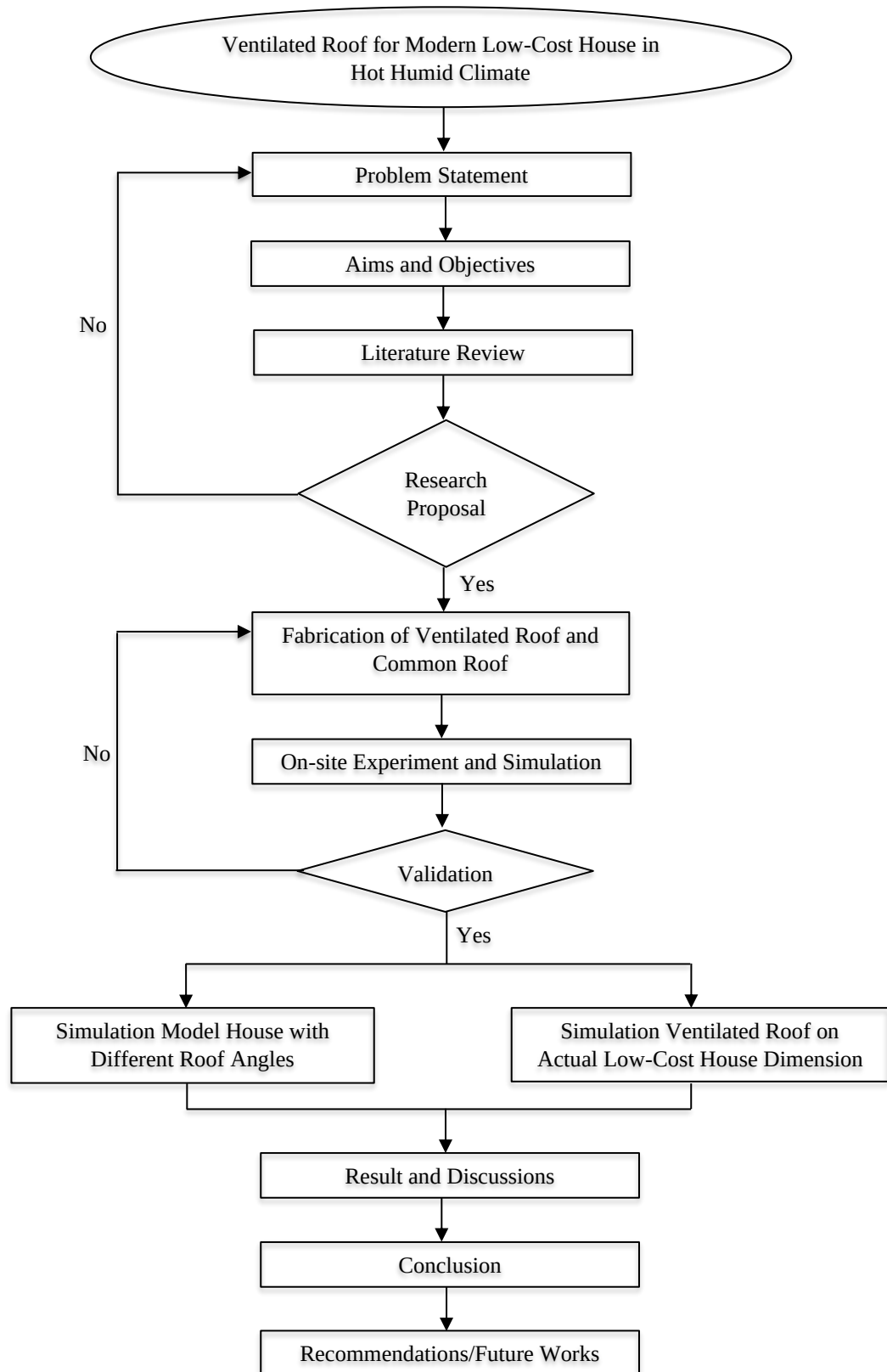


Figure 3.1: Overall research flowchart

This study commenced from the establishment of the aims and objectives based on the problem statements as explained in Chapter 1. This study commenced with the information gathered from previous study as presented in Chapter 2. The study proceeded with investigation in depth on the problem statement and issues arose as mentioned in literature review as well as other information related to the current passive design of modern house were gathered. The information based on these issues of the modern roofing system was discussed and a new design was proposed, known as the ventilated roof.

The ventilated roof was proposed and underwent the first on-site experiment, which was conducted to investigate the physical performance of the roof including smoke test and rain dripping test. Then, the on-site experiment on ventilated roof and common roof were conducted to investigate the performance of the roof in (i) all windows and door were fully closed and (ii) all windows and door were fully opened. With data gathered from on-site experiment, simulation using ANSYS Fluent was conducted to validate the roof with actual on-site conditions. All the data were recorded, and the results of ventilated roof were compared with the common roof design with the same pitch of the roof and condition, which was later discussed in Chapter 4.

3.2 Ventilated Roof Design

The ventilated roof design is the adaptation of traditional Malay *Nipah* roof concept. The proposed roof designed is based on the ventilated roof with recommended ventilated roof pitch. The recommended roof pitch is 30° because it recorded lower indoor temperature as compared to flat roof or lower roof angle, apart from it also provide easy maintenance purposes as compared to roof angle of 45° and 60° (Roslan et al., 2015). In the past years, the ventilated roof has attracted much attention as one of the strategies to improve the current

passive design. A ventilated roof or roof with openings is one of the best strategies or approaches to reduce the indoor air temperature and minimise the heat transfer (Al-Obaidi et al., 2014a; Ibrahim et al., 2014b; Qasim et al., 2010; Roslan et al., 2015; Trinuruk et al., 2007). It appears from the aforementioned investigations that most attention has been paid to the ventilated roof. No attempt was done to explore on the potential of the ventilated roof or roof with openings in hot humid climate region.

Meanwhile, the ventilated roof was designed with openings in between the roof stacking to provide more openings for trapped hot air to exit. For this roof, the openings were designed at the vertical section, which is known as flashing on the roof. Figure 3.2 shows the proposed design of ventilated roof.

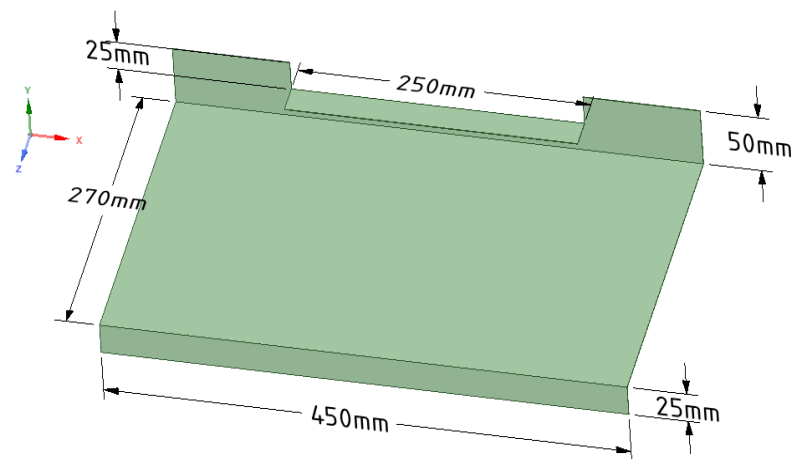


Figure 3.2: Ventilated roof design

The opening on the flashing side has 250 mm length and 25 mm height, which is half of the height of flashing as shown in Figure 3.2. The shape of the ventilated roof designed is with the roof flashing. The function of flashing is to prevent the rainwater to enter the internal space through the edge of the roof. The opening of the ventilated roof was designed with half of the flashing's height. Due to our hot, humid climate and highest rainfall

throughout the year, the 100% opening is not recommended as it easily allows the rainwater to enter the house. The material of the roof is spandex, which is considered inexpensive and easily available in the local market. Meanwhile, the arrangement of ventilated roof is stacked, which was based on the adaptation of traditional Malay's *Nipah* roofing system and *susun sirih* arrangement as shown in Figure 3.3.

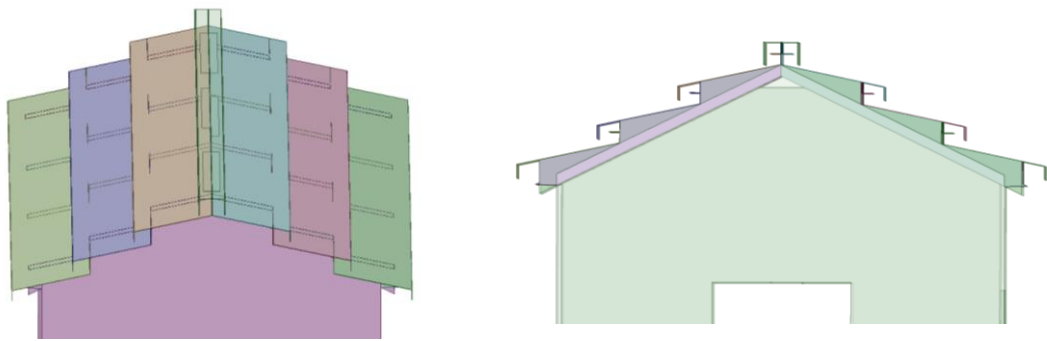


Figure 3.3: Arrangement of the roof

The ventilated roof provides area for hot air to exit and allow wind to enter as well as circulated inside the house. The openings promote natural ventilation for cooling purposes. The concept was driven by stack effect and wind driven effect. Hot air has lower density and lighter, therefore it rises towards the upper part of the house. If no opening provided is insufficient, the hot air would trap and the indoor air temperature would become higher. The occupants would feel discomfort due to overheating and would rely on mechanical ventilation for cooling, which surely will incur cost on electricity consumption. The concept of this ventilated roof was illustrated as shown in Figure 3.4.

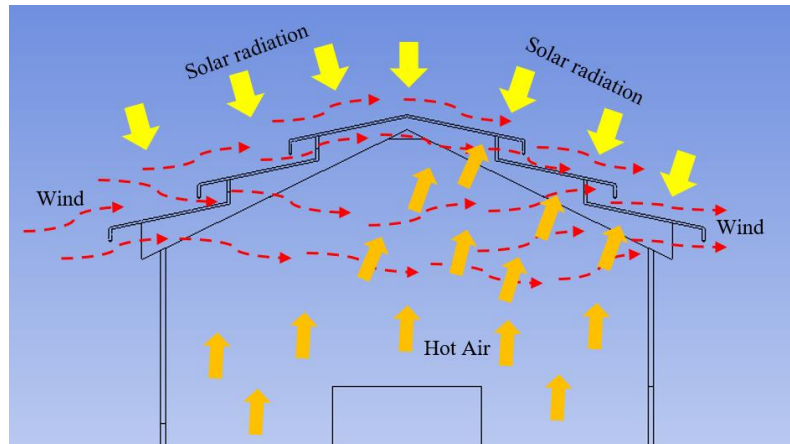


Figure 3.4: The design concept of the ventilated roof

During daytime, the hot air rises while the cooler air moves to the lower part of the house due to air density differences. The openings on ventilated roof are able to help in providing more area for the hot air to escape. This suggests that the openings would allow air circulation inside the house as well able to reduce the overheating inside the house, especially during the hottest time of the day. The design suggested that the heat transfer from the roof surface can be quickly removed into the nearest opening provided on ventilated roof. Before designing the ventilated roof, there were few requirements shall need to be considered, including the height of flashing and the area of roof opening.

3.2.1 Roof Flashing

The flashing of ventilated roof was set to two inches or approximately about 50 mm. It was the minimum requirement for roof flashing (Lysaght, 2014). This suggested that minimum height of roof flashing would able to prevent the rain dripping into the house. For this reason, the ventilated roof was designed with minimum height of roof flashing in vertical position to avoid the rain from entering through the openings.

3.2.2 Roof Opening

The roof opening was designed to half of the roof flashing height. Previous study was conducted to investigate and measure the effect of roof opening towards indoor air temperature. The full 100% opening recorded lower indoor temperature, followed by 50% of roof opening with only small differences from 100% opening (Ibrahim et al., 2014a). The authors also highlighted that the differences of indoor air temperature between fully opening and half opening are less than 1 °C (Ibrahim et al., 2014b). Despite of our country experiencing hot humid climate and high rainfall throughout the year, the 100% opening was not suitable to be used. Therefore, 50% roof opening was recommended to suit our climate.

3.3 Ventilated Roof On-site Experiment

A smoke test was conducted to determine the readiness of the proposed roof for further testing. The term was originally used in plumbing works, which referring to detection of cracks, leaks or breaks in closed systems. It is also one of the best methods for the testing any leakages. The ventilated roof's model house was fully closed and sealed, and the mosquito coil was light up. The openings on ventilated roof were used for observation of smoke movement. This testing was conducted to ensure that the smoke can escape through the openings provide on roof surface, which represented the leaks or breaks in enclosed system.

The model house with ventilated roof was placed at open space for heavy rain exposure. The rain test or specifically rain drip test was conducted to observe water penetration or dripping from the openings due to the exposure to drops of water fallings at a uniform rate. The ventilated roof needs to be exposed to rainwater in order to determine the

suitability of the proposed ventilated design under hot humid climate region with high rainfall.

These two tests were not the main focus of this study. These tests were mainly to ensure the openings on the ventilated roof can provide area for smoke to escape and to ensure the rainwater does not enter the house through the openings under heavy rain condition.

3.4 Thermal Performance of Ventilated Roof versus Common Roof

Thermal performance is referring to the process of energy transfer between and surrounding through modelling. The process is important to allow us to determine the effectiveness building design (Joseph et al., 2015). The on-site measurement was conducted between common roof and ventilated roof with 30° roof pitch. The ventilated roof and common roof design were tested under two different conditions, when windows and door were fully closed and fully opened. Term fully closed was referring to all door and windows were fully closed. This can be considered as enclosed area. While term fully opened was referring to all door and windows were fully opened. This study conducted in fully opened condition to investigate the contribution of door and windows to allow air movement into the house. The model house with common roof and ventilated roof were under the same ambient air temperature and air velocity. The data from the on-site experiment was recorded and compared with the data obtained from CFD simulation. The result was discussed further in Chapter 4 of this study.

3.5 On-site Experiment for House Model

On site measurement was conducted to investigate the performance of common roof and ventilated roof under the same conditions and parameters. Common roof design

represents the typical roof type of modern roofing system in Malaysia. Two unit model houses with ventilated roof design and common roof design with 30° roof pitch were built and the experiment was conducted in Universiti Malaysia Sarawak as shown in Figure 3.5. The roof angle of 30° represents the typical modern house roof pitch in Malaysia. The apparatus used for experiment were data logger, thermocouples, anemometer and thermometer. Thermocouple and data logger were used to measure the air temperature while anemometer was used to monitor air velocity. Thermal camera was used to capture the thermal image of the model house for validation purposes. Thermocouple is protected with foil to reflect the radiant heat during the experiment work.



Figure 3.5: On-site experiment for small-scale model house with ventilated roof (left) and common roof (right)

Each model houses came with ventilated roof design and common roof design with 30° roof pitch. The model houses were built with same dimension of the house body of 1000 mm x 1000 mm x 1000 mm as shown in Figure 3.6.

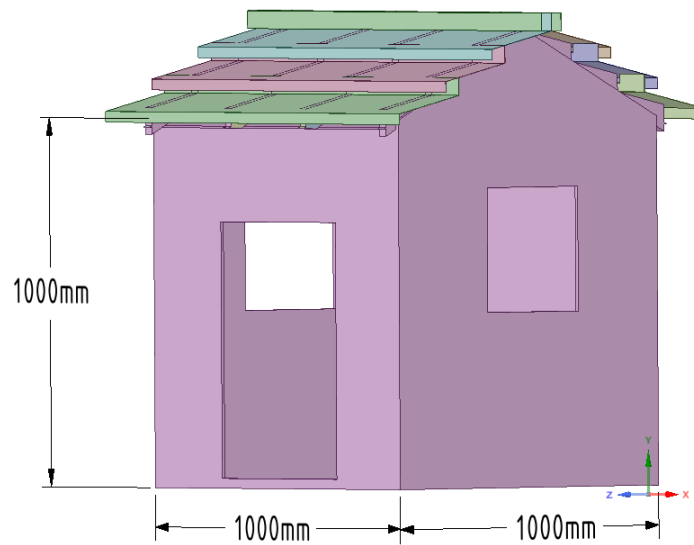


Figure 3.6: The dimension of the model house

The dimension of the model house scale of 1000 mm x 1000 mm x 1000 mm had been tested in previous studies of heat transfer (Mohamad & Mohamed, 2013; Qasim et al., 2010). For this study, dark grey colour was selected due to the availability of that roofing colour in the market and one of the common colours in modern house roof nowadays. The grey colour is cooler compared to the other darker colours and it was also darker than white colour. White colour was not recommended because it is easy to get dirty. Moreover, the grey colour also greater in aesthetical value. The model was placed under the direct sunlight from 8.00 am until 5.00 pm. The data collection or parameters for this experiment were as follows:

- i. Air temperature (ambient, outside and inside the model house)
- ii. Air velocity (inside and outside the model house)

The thermal imaging was used for thermal surface analysis that can provide information of temperature at every point and produce infrared digital images (Badida et al., 2015; Županić et al., 2015). In this study, thermal imaging capture from simulation was used

to determine the air temperature of model house. In the Chapter 4, the thermal images were presented and compared with different conditions. Figure 3.7 shows the location of 11 points of air temperature and air velocity for on-site measurement.

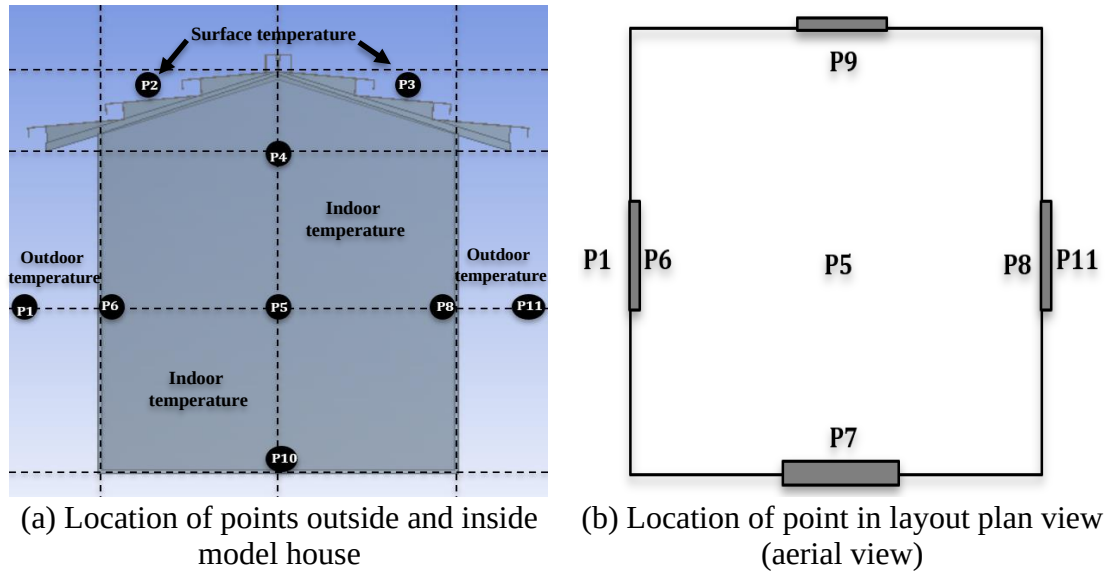


Figure 3.7: The location of points

There were four points at P1, P2, P3 and P11 to measure outside air temperature and air velocity, while seven points, specifically P4, P5, P6, P7, P8, P9 and P10 were placed inside the house as shown in Figure 3.7 (a) and (b). Point P4 was placed at the upper part in indoor areas, P5 was located at the centre, while P10 was at the bottom part of the model house. The three points, namely P4, P5 and P10 will be used for the CFD simulation comparison of three different roof pitches of 10° , 30° and 45° . The 30° and 45° roof pitches are commonly used for concrete or clay tiles roof in modern house design (Al-Obaidi et al., 2014b), while 10° is common roof pitch for low-cost house in Malaysia (Ibrahim et al., 2014a).

3.6 Thermal Performance of Model House with 30° Roof Pitch

Before validation was conducted, the model house was designed in SolidWorks before exporting the model to ANSYS for further investigation on thermal performance and modelling.

3.6.1 SolidWorks

The design of model house was developed by using SolidWorks software. According to Liao et al. (2010), SolidWorks software is easy to learn, use and widely applied in mechanical design. The study also demonstrated that SolidWorks can create or combine different entities, simple assembly module and meeting most of engineering design requirements, which is suitable for product development. Nowadays, SolidWorks has become one of the preferred mainstream software in mechanical design and modelling (Dashuai et al., 2006).

In this study, the material of the roof, truss, house body were selected and assembled. Three-dimensional of the model house was created with dimension of 1000 mm (width) x 1000 mm (height) x 1000 mm (length) for the house body with the 30° roof pitch. Figure 3.8 shows the assembled model house in SolidWorks.

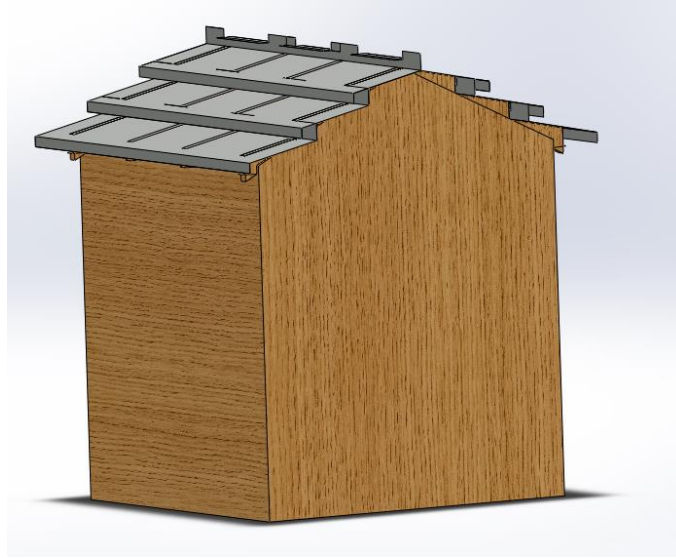


Figure 3.8: Assembled model house in SolidWorks

The material of the roof was spandex, which consist of 55% Zinc-Alloy roofing while the body of the house were 10 mm thick plywood as shown in Figure 3.8. The assembled model house from SolidWorks was imported into the Design Modeler via ANSYS Workbench.

3.6.2 ANSYS Fluent

ANSYS Fluent is a CFD software which allows the simulation of heat transfer, model flow, including internal and external flow, turbulence and reaction. The CFD approach has been widely used to measure and calculate the thermodynamics properties (Idriss et al., 2018). According to Basil et al. (2014), ANSYS Fluent is one of the CFD software that is powerful that could provide the most accurate result for heat transfer phenomena. Previous study of heat transfer concluded the value obtained from ANSYS is nearer to correlation and experiment, therefore it is validated (Karthikeyan et al., 2014). ANSYS Workbench consists of all stages required to generate the simulation. The Workbench contains the combination of various components such as Design Modeler, Meshing and Fluent. The analysis of the simulation will be further discussed in Chapter 4.

In this study, the fluid domain was created and represented as the environment. To get the analysis inside the house, Boolean was selected in Design Modeler. Boolean functions to combine define regions or subtract a region from one another. In this study, Boolean subtract was selected between the fluid domain and the model house. After the Boolean operation, the simulation model house was imported into Mesh for meshing purpose. Figure 3.9 shows the meshing of the model house.

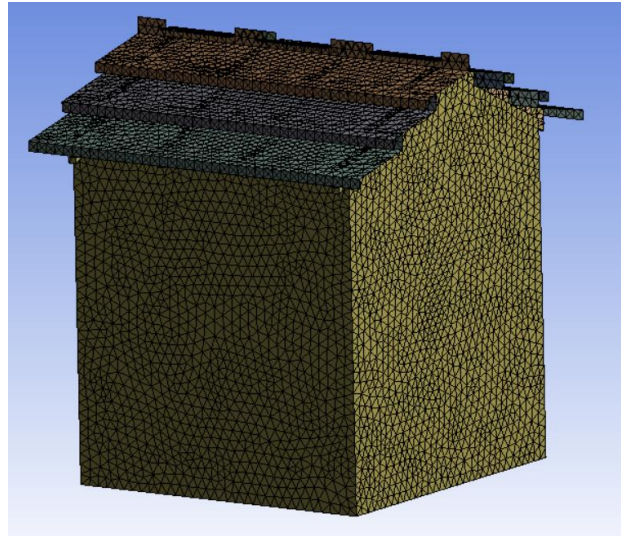


Figure 3.9: Model house meshing

For this study, the meshing's sizing was set to "Proximity and Curvature" for size function and "fine" for relevance centre. This setting was selected because the iteration was complex and would give the most accurate data or value as compared to other size function and relevance centre. After meshing, the data were exported into Fluent for further analysis. Fluent is one of the computational fluid dynamic software packages for model flow, heat transfer, turbulence and reaction for industrial use. In Fluent, there are several items need to be customized before running the analysis, such as the models, initial or cell zone conditions and boundary conditions.

The boundary condition was set up by referring to the ambient air temperature and velocity data obtained from the experiment. The boundary condition was applied to the inlet, outlet, the roof, the house body and fluid domain. A fluid domain is known as a bounding box of the object and serves as the boundary to the simulation. Fluid domain usually set as a fluid and all fluid objects must be in the domain. Fluid domain was set to the dimension as shown in Figure 3.10.

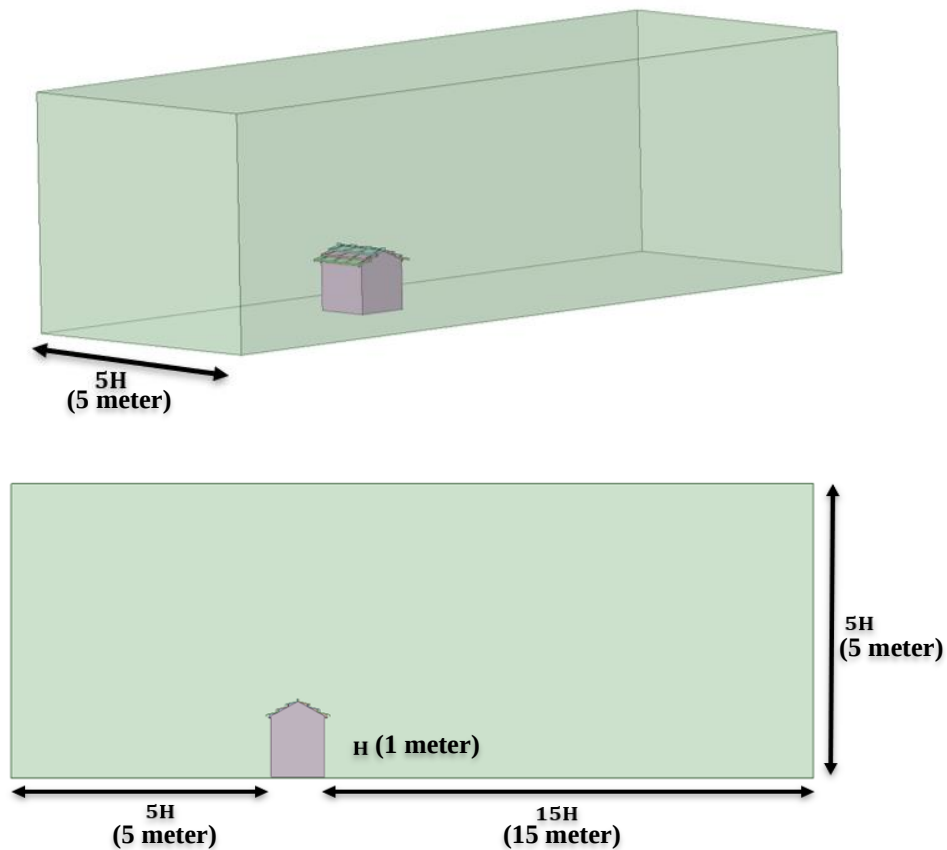


Figure 3.10: Dimension of fluid domain

For the simulation, the object must be enclosed with a domain. The inlet and top boundary shall be $5H$ (5 meter) away from the model house, while the outlet shall be placed a minimum of $15H$ (15 meter) away after the model house (Franke et al., 2004; Hargreaves

et al., 2010). In this study, since the height of model house is one meter, therefore the length of 5H before the model house and 15H after the model house were represent by five meters and 15 meters respectively.

3.7 Model Validation

For this study, the data from on-site experiment works on house model were compared with the simulation data for 30° roof angle for validation purposes before proceeding the simulation with other house model with different roof angles and actual low-cost house in Betong, Sarawak. The purpose of validation is to ensure that the data obtained from on-site experiment and data obtained from simulation is almost similar within acceptable tolerance, so that other parameters can be investigated through simulation without constructing actual model on-site. It is also cost and time saving for researcher to conduct the same modelling under different scenario, conditions or parameters. Table 3.1 shown the comparison on the importance of Computational Fluid Dynamics (CFD) and experiment for study purposes.

Table 3.1: Comparison between CFD and on-site experiment (Zuo, 2005)

	Simulation (CFD)	On-site Experiment
Cost	Cheap	Expensive
Time	Short period	Long period
Scale	Any	Small/Middle
Information	All	Measured Point
Repeatable	Yes	Depends
Safety	Yes	Depends, some dangerous

For this study, CFD simulation was chosen for further measurement and investigation with different conditions and information because of it consumed shorter time and cheaper cost. The on-site experiment on a small-scale model house still need to be

conducted for validation purposes before proceed with further roof thermal performance through CFD.

According to Ali et al. (2014), the acceptable tolerance between on-site measurement and the CFD software simulation shall be within 20%. Similarly, previous studies on heat transfer simulation using ANSYS agreed that the error in value obtained from the comparison of experimental and simulation, correlation and ANSYS simulation shall be less than 10% (Karthikeyan et al., 2014). Other studies stated that differences of air temperature and air velocity between on-site measurement and simulation are typically ranging 2% and 7%, respectively (Ibrahim et al., 2014a). The author also stressed that the acceptance percentage difference between data obtained from experimental and simulation should not more than 20%. The analysis of the model validation will be discussed further in Chapter 4.

3.8 Investigation of Ventilated Roof in Different Roof Angles and Low-Cost House

The on-site experiment was conducted and the data was used as an input into simulation for validation purposes. After the data had been validated, the ventilated roof and common roof were tested with different pitch of roof on the model house and actual low-cost house scale in Betong through CFD simulation.

3.8.1 Simulation on House Model with Different Roof Angles of 10° and 45°

The on-site experiment data was used and for simulation for validation purposes. Once the data were verified within the allowable variation percentage, simulation of ventilated roof was proceeded to different roof pitch of 10° and 45°. This simulation was conducted to further investigate the effect of roof pitch towards the performance of ventilated roof. This was because modern low-cost house was built with 10° or lower roof

pitch, while traditional Malay house with typically about 45° or higher roof pitch. For this simulation exercise, three different points were used for comparison and analysis specifically for points P4, P5 and P10, which were located inside the house as shown in Figure 3.11.

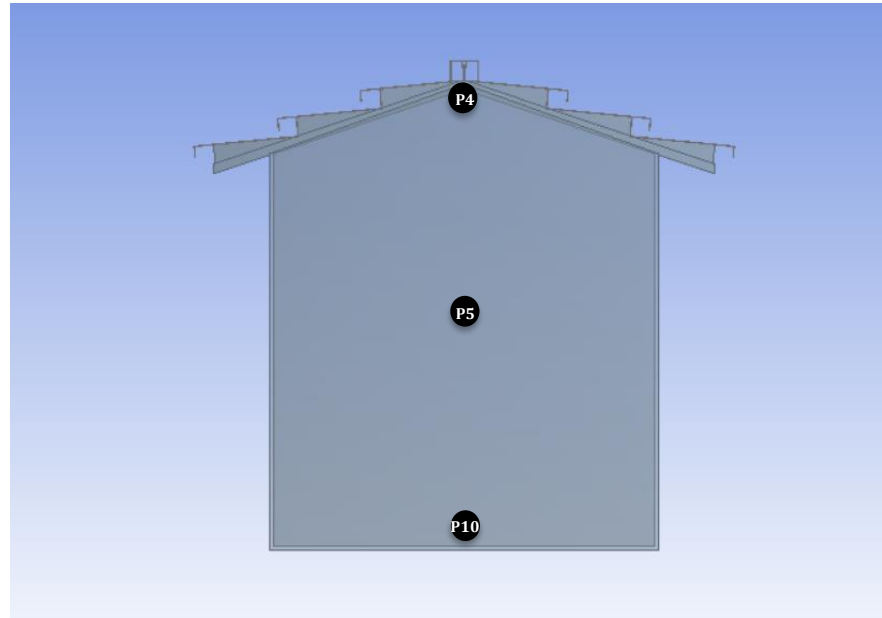


Figure 3.11: Location of the points for simulation

Point P4 was located at the upper part; underneath the roof, while point P5 at the centre of the model house and point P10 was placed at the bottom part. These points were used to indicate the indoor air temperature and air velocity of the model house. The reasons these three points were chosen because the heat transmitted from the roof surface and travelled downward due to gravity force. The indoor air temperature and air velocity were recorded to examine the differences at these three points.

3.8.2 Simulation of Ventilated Roof on Low-cost House in Betong, Sarawak

After conducting investigation of thermal performance on the model houses, the simulation was further proceeded on an actual low-cost house scale in Betong, Sarawak. This study was to investigate the impact of ventilated roof towards indoor air temperature of

modern low-cost house. Based on Ibrahim et al. (2014a), the low-cost house in Betong area suffers overheating during daytime. The simulation was conducted on the 10° roof pitch for low-cost house. The data from previous studies conducted by Ibrahim et al. (2014a) was used for the simulation purposes. Figure 3.12 shows the location of points for simulation purposes.

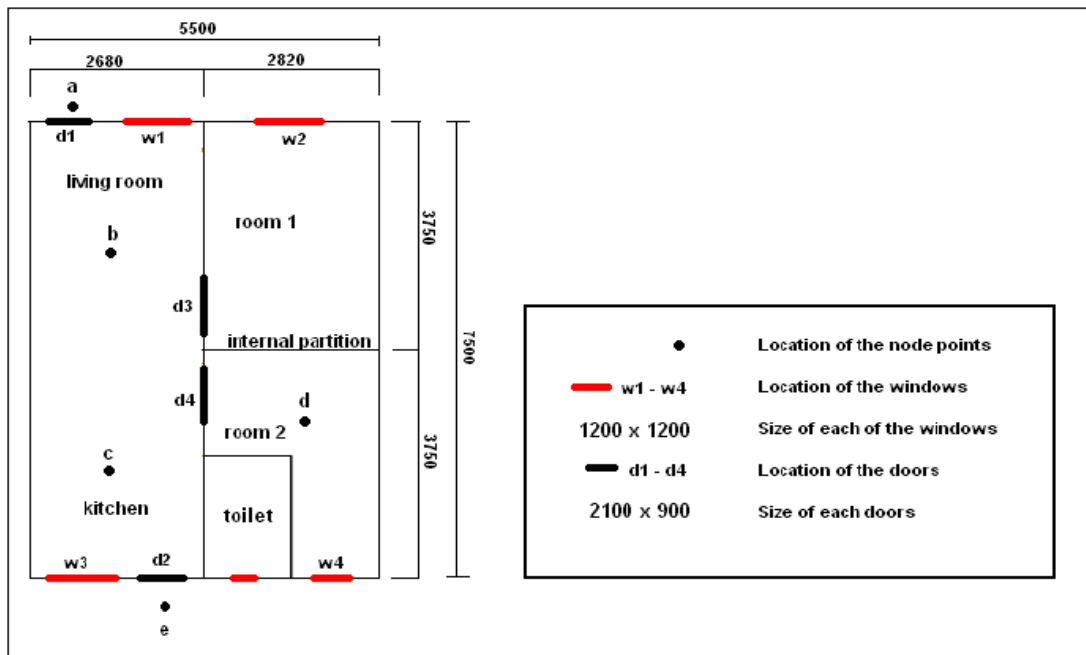


Figure 3.12: Location of points for the house in Betong (Ibrahim et al., 2014a)

There were five points measured in modern low-cost house at Betong. Point “a” was placed at the main door entrance, while point “b” at the centre of the living room, while point “c” at kitchen, point “d” at room 2 and point “e” at the back entrance. The results obtained from simulation were analysed and discussed in Chapter 4. To demonstrate further potential of ventilated roof, the low-cost house was adjusted to higher roof pitch of 30° through simulation.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter gives an overview on the results obtained from experimental works conducted as shown in Figure 3.1 (page 44). The ventilated roof underwent the smoke test and rain dripping test before starting to test the thermal performance of the roof. The smoke test was conducted to monitor the movement of air inside the model house. Meanwhile, the rain dripping test was conducted to test if the water could enter through the designated roof opening. For on-site experiment, common roof and ventilated roof were placed under the similar condition and data was recorded.

The data for on-site experiment and CFD simulation was compared and analysed to investigate the differences between the common roof and the ventilated roof. After validation was conducted, the ventilated roof and common roof were tested on 10° and 45° roof pitch through CFD simulation. The same data and condition for 30° model house was used in the simulation of 10° and 45° roof pitch. The results from the simulation were then analysed and explained. In addition, the analysis of the ventilated roof of actual low-cost house was discussed in this chapter.

4.2 Ventilated Roof On-site Testing

Before proceeding to investigate the thermal performance of the proposed roof, the model houses underwent smoke test and rain dripping test. After conducted smoke testing, it was observed that the smoke from mosquito foil was escaped from the roof openings, thus explained there are leaks or breaks in closed systems. The smoke was seen to escape through

the opening on the roof surface due to differences in air temperature occurred inside the model house. The hot air with lower density raises up, while the cooler air with higher density moves to the lower part of the model house.

On the other hand, the rain dripping test was conducted under the rain condition to determine any water penetration through the openings at ventilated roof. From this test, it was observed that there was no water entering the house from the roof openings. Hence, it showed the effectiveness of the proposed roof flashing height and its design for ventilated roof.

4.3 On-site Experiment for 30° Roof Pitch

After conducting the smoke and rain dripping test, the on-site experiment was carried out to investigate further on the performance of the roofs on model house with 30° roof pitch. The experiment was conducted in two different roof designs, which were the common roof and ventilated roof design. The highest ambient temperature and external air velocity of the day during this experiment were recorded at 1.00 pm with 34.6 °C and 0.37 m/s respectively.

In this study, 11 points were measured to determine the air temperature indoor and outdoor. Data logger with thermocouple was used to measure indoor air temperature at points P4, P5, P6, P7, P8, P9 and P10 as indicated in Figure 3.7 (page 53), whereas the outdoor air temperature at points P1, P2, P3 and P11 were measured using a thermometer. For measuring air velocity, anemometer was used.

4.3.1 Results for Air Temperature and Air Velocity for Common Roof and Ventiladed Roof Under Fully Closed Condition

Both common roof and ventilated roof model houses underwent experiment under fully closed condition, where door and all windows were fully closed and sealed. The

purpose of having the model houses in fully closed condition was to investigate the benefit of ventilation via roof openings in reducing the indoor air temperature. This was achieved by allowing internal air movement. Table 4.1 shows the recorded data for air temperature and air velocity at 1.00 pm for model houses with common roof and ventilated roof design under fully closed condition.

Table 4.1: Results for Measured Air Temperature and Air Velocity Under Fully Closed Condition

Points	Air Temperature (°C)		Difference (°C)	Air Velocity (m/s)		Difference (m/s)
	Common Roof	Ventilated Roof		Common Roof	Ventilated Roof	
P1	37.6	36.2	1.4	0.37	0.37	0.00
P2	53.0	52.3	0.7	0.32	0.33	0.01
P3	52.6	52.2	0.4	0.37	0.38	0.01
P4	46.2	36.2	10.0	-	-	-
P5	45.9	35.7	10.2	-	-	-
P6	46.1	35.5	10.6	-	-	-
P7	46.1	35.5	10.6	-	-	-
P8	45.9	35.5	10.4	-	-	-
P9	46.1	35.5	10.6	-	-	-
P10	46.1	35.5	10.6	-	-	-
P11	37.7	36.5	1.2	0.36	0.35	0.01

The difference of air temperature for common roof and ventilated roof was ranging from 0.4 °C to 10.6 °C. The indoor air temperature at points P4, P5, P6, P7, P8, P9 and P10, under ventilated roof model house, was highly reduced from 10.0 °C to 10.6 °C. The difference of air velocity outside the model house recorded at points P1, P2, P3 and P11 was insignificant. The data of air velocity were only recorded at the outside of the model house as the condition is stable with the windows and door fully closed and sealed for both common roof and ventilated roof design. Nevertheless, the air velocity readings were recorded for both model houses under fully opened condition which would be explained in Chapter 4.3.2. From the data recorded, it was observed that ventilated roof model house recorded lower

indoor air temperature readings as the openings on the roof surface allow the trapped hot air to escape from inside of the house. Hence, contributing to the reduction of indoor air temperature even though all door and windows were fully closed. Figure 4.1 showed a bar chart for clearer comparison of indoor air temperature between common roof and ventilated roof model house.

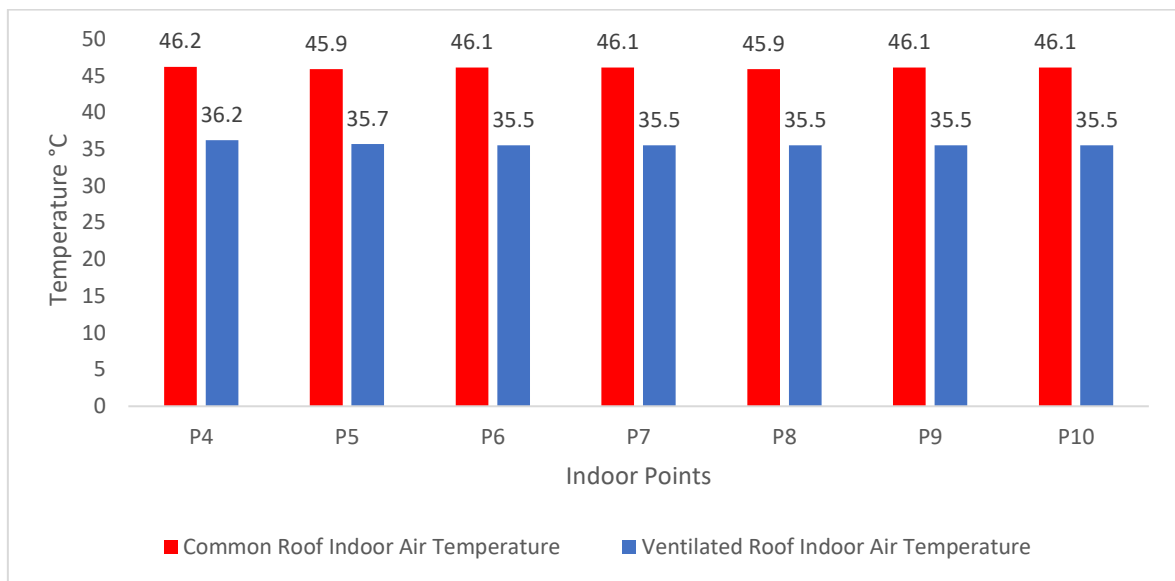


Figure 4.1: Comparison of indoor air temperature between common roof and ventilated roof under fully closed condition

Based on Figure 4.1, the highest indoor air temperature recorded for model house with common roof design under fully closed condition was at point P4 with 46.2 °C, which exceeded the ambient air temperature by 10.9 °C. For model house with ventilated roof, the highest indoor air temperature under same condition was recorded at point P4 with 36.2 °C, which was lower than the model house with common roof design. The indoor air temperature at point P4 for common roof's model house recorded the highest temperature as there was no opening provided on the roof surface. The indoor temperature recorded for model house with ventilated roof recorded at point P4 was slightly higher than the ambient air temperature by 0.9 °C.

From the observation, it was found that generally point P4, P5, P6, P7, P8, P9 and P10 for model house with common roof recorded higher indoor air temperature as compared to model house with ventilated roof design. This would affect the occupant's level of comfort and they also would suffer from overheating. Thus, leading to the increase of demand to use mechanical ventilation system to achieve the occupant's thermal comfort. Since the condition was fully closed, the heat energy was mostly transferred into the lower part of the model house and trapped underneath. However, this issue can be tackled by having the ventilated roof to improve the natural ventilation and minimise the heat trapped underneath of the roof. Hence, reducing the air temperature below (Ibrahim et al., 2014b).

4.3.2 Results for Air Temperature and Air Velocity for Common Roof and Ventiladed roof Under Fully Opened Condition

Both model houses for common roof and ventilated roof underwent fully opened condition, where door and all windows were fully opened. The purpose of having the model houses in fully opened condition was to investigate the contribution of natural ventilation to reduce the indoor air temperature. This was achieved by allowing internal air movement through roof openings, door and windows. With additional openings at door and windows, it could enhance the natural ventilation and air movement inside the house. Table 4.2 showed the recorded data for air temperature and air velocity at 1.00 pm for model houses with common roof and ventilated roof design under fully opened condition.

Table 4.2: Results for Measured Air Temperature and Air Velocity Under Fully Opened Condition

Points	Air Temperature (°C)		Difference (°C)	Air Velocity (m/s)		Difference (m/s)
	Common Roof	Ventilated Roof		Common Roof	Ventilated Roof	
P1	36.8	36.3	0.5	0.37	0.37	0.00
P2	51.8	51.8	0.0	0.25	0.12	0.13
P3	51.9	51.8	0.1	0.21	0.16	0.05
P4	36.1	35.3	0.8	0.05	0.29	0.24
P5	36.1	35.3	0.8	0.12	0.37	0.25
P6	36.1	35.3	0.8	0.33	0.37	0.04
P7	36.1	35.2	0.9	0.37	0.37	0.00
P8	36.1	35.2	0.9	0.36	0.36	0.00
P9	36.1	35.2	0.9	0.35	0.37	0.02
P10	36.0	35.0	1.0	0.14	0.18	0.04
P11	36.5	36.1	0.4	0.37	0.37	0.00

The difference of air temperature for common roof and ventilated roof was ranging from 0.0 °C to 1.0 °C. The indoor air temperature under model house with ventilated roof design was highly reduced at points P10 with 1.0 °C, while indoor area points of P4, P5, P6, P7, P8 and P9 were reduced between 0.8 °C and 0.9 °C. The difference of air velocity readings recorded for both model house with common roof and ventilated roof was ranging from 0.00 m/s to 0.25 m/s. Indoor area point at P5 recorded the biggest difference because of the openings on the roof surface contribute extra area for air movement inside the ventilated roof model house. While indoor area points of P6, P7 and P9 recorded smaller difference in air velocity as the point locations were at door and windows where the air from the outside environment entered and escaped. The wind only entered the common roof's model house through windows and door. While for model house with ventilated roof, the wind entered from openings on the roof as well as the windows and door. Figure 4.2 showed the comparison of recorded data for indoor air temperature for common roof and ventilated roof model house.

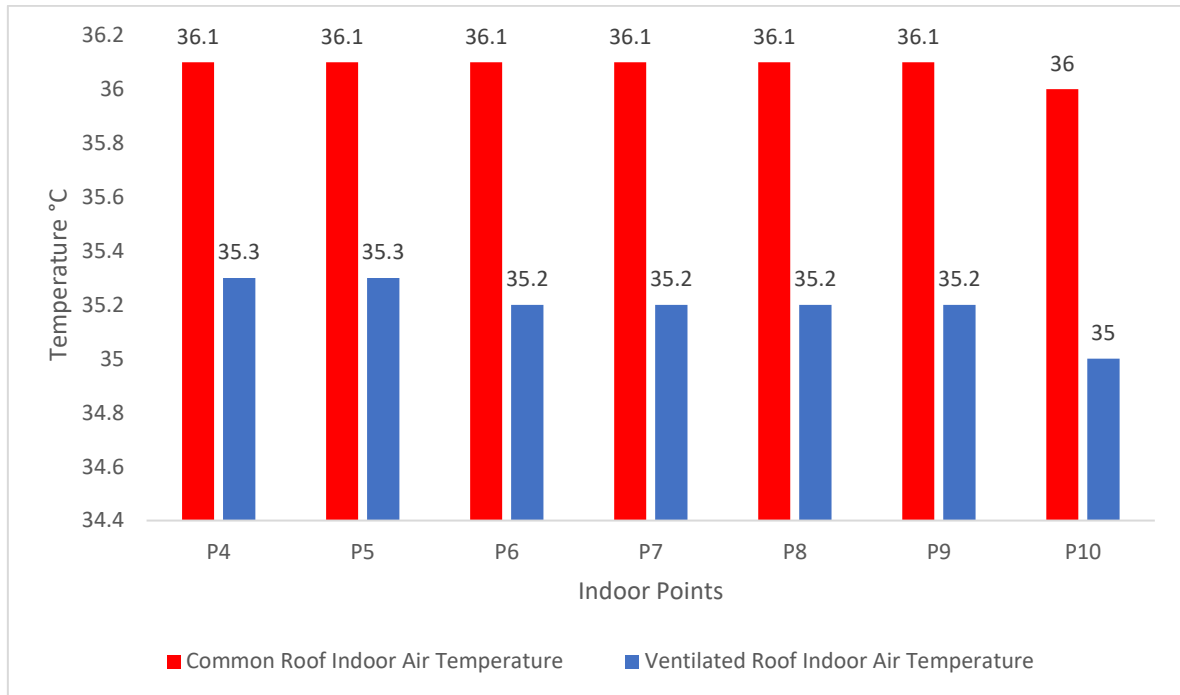


Figure 4.2: Comparison indoor air temperature for common roof and ventilated roof under fully opened condition

For model house with common roof, the highest indoor air temperature recorded at points P4, P5, P6, P7, P8 and P9 with 36.1 °C and P10 with 36.0 °C. The indoor temperature for model house with ventilated roof design recorded lower indoor temperature at points P4 and P5 with 35.3 °C, while points P6, P7, P8 and P9 with 35.2 °C and P10 with 35.0 °C. Overall, ventilated roof recorded lower indoor air temperature as compared to model house with common roof. The highest indoor temperature recorded for the common roof and ventilated roof with windows and door fully opened was at point P4 and P5 with 36.1 °C and 35.3 °C respectively. The indoor air temperature for model house with common roof were ranged between 0.7 °C to 0.8 °C higher than the ambient temperature. However, it was observed that the model house with ventilated roof recorded just 0.1 °C lower than the ambient air temperature.

This study revealed that openings on the roof surface provide extra area for air movement to enter the house. It also helps to enhance the air to enter the model house through door and windows, thus contribute further on reduction of indoor air temperature with door and all windows fully opened. The presence of extra air movement inside model house with ventilation affects the air temperature below the roof at point P4, P5, P6, P7, P8, P9 and P10 as recorded in Figure 4.2. As the air velocity recorded higher, it will highly help to reduce the indoor air temperature.

A model house with common roof under fully opened condition recorded much higher reduction in indoor temperature as compared to fully closed condition. Although the common roof under this condition showed a reduction of indoor air temperature, the data recorded shown that it was still higher than the model house with ventilated roof design. According to Ibrahim et al. (2014a), the house with windows and doors fully opened recorded lower indoor temperature than fully closed condition because it allowed the air movement to increase inside the house. The fully opened windows and door enhances the wind driven effect and stack effect to occur. For ventilated roof under fully opened condition, the hot air was removed from the house via the openings on the roof surface and from the door as well as the windows.

4.3.3 Heat Transfer for Common Roof and Ventilated roof Under Fully Closed Condition

Conduction as heat transfer took place at the roof surface and transmitted into lower part of the roof and internal area. The conductive of heat transfer were calculated for both roof design as shown in Figure 4.3.

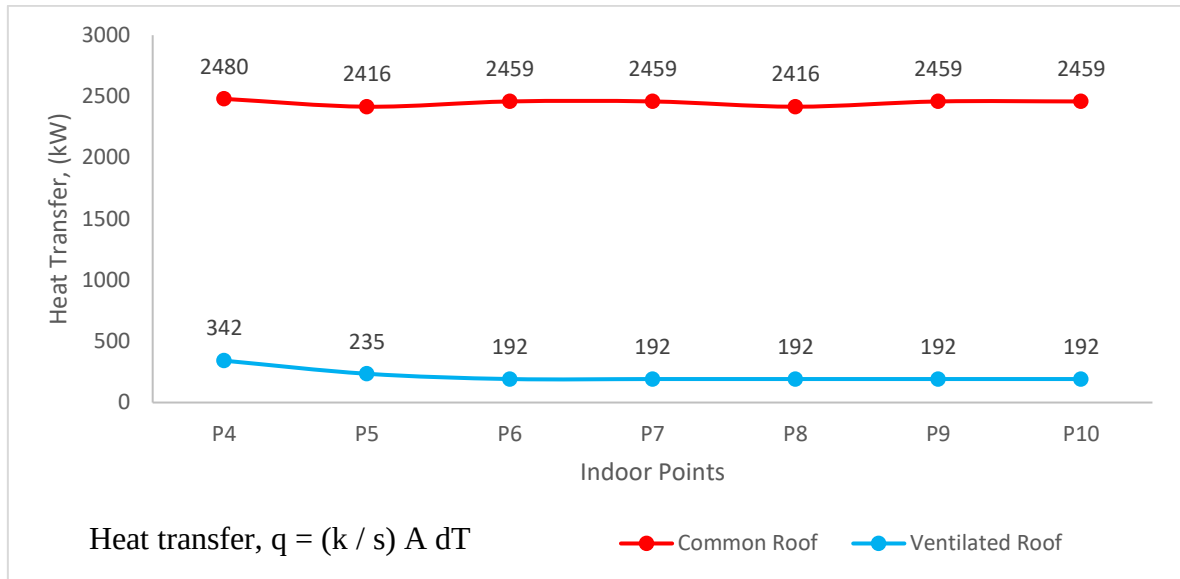


Figure 4.3: Heat transfer for common roof and ventilated roof under fully closed condition

From the result obtained from calculation, it shows that heat transfer was higher inside the common roof's model house. The conductive heat transfer inside the common roof's model house was more than 2000 kW, while heat transfer inside the ventilated roof's model house was less than 350 kW. Point P4 in common roof's model house recorded highest heat transfer with 2480 kW because the location was below the roof while points P5 and P8 recorded the lowest heat transfer with 2416 kW because the location of the points was at the middle of the model house. The common roof's model house measured higher heat transfer because the energy is transferred from roof surface and the heat is trapped inside the house due to all windows and door were fully sealed. Thus, no openings for the hot air to escape and had resulted on the overheating inside the house.

Meanwhile, ventilated roof's house model measured heat transfer between the lowest of 192 kW at points P6, P7, P8, P9 and P10, while the highest heat transfer occurred at point P4 with 342 kW. This shows that the openings on the ventilated roof surface helps to reduce the amount of heat transfer that transmitted to lower ground at point P4, P5, P6, P7, P8, P9

and P10 even though the door and windows for model house were fully closed. This was because of the openings on the roof allow the heat energy transferred from the roof surface into the model house to exit immediately before it reaches to lower part of the model house. Apart from that, the openings also allow the hot air from the bottom part of the model house to rise up and exit.

The hot air was then removed via wind driven effect and stack effect that occurred concurrently. The wind was flowing onto the roof surface, thus the suction occurred in the leeward region and pull out the hot air inside the house via the roof openings provided. The openings on the roof allowed the stack effect to occur. The hot air was carried and removed by the wind that enter the house. Thus, this explained on the reduction of the indoor temperature inside ventilated roof model house under fully closed condition. Ibrahim et al. (2014b) concluded that the higher indoor air temperature would reduce by providing the openings on roof surface even though the condition of the house is fully closed.

4.3.4 Heat Transfer for Common Roof and Ventilated roof Under Fully Opened Condition

While model houses under fully opened condition, an amount of heat transfer from roof surface to lower area was immediately exits from the model house via air movement through doors and all windows. The conductive of heat transfer were calculated for both roof design under fully opened condition as shown in Figure 4.4.

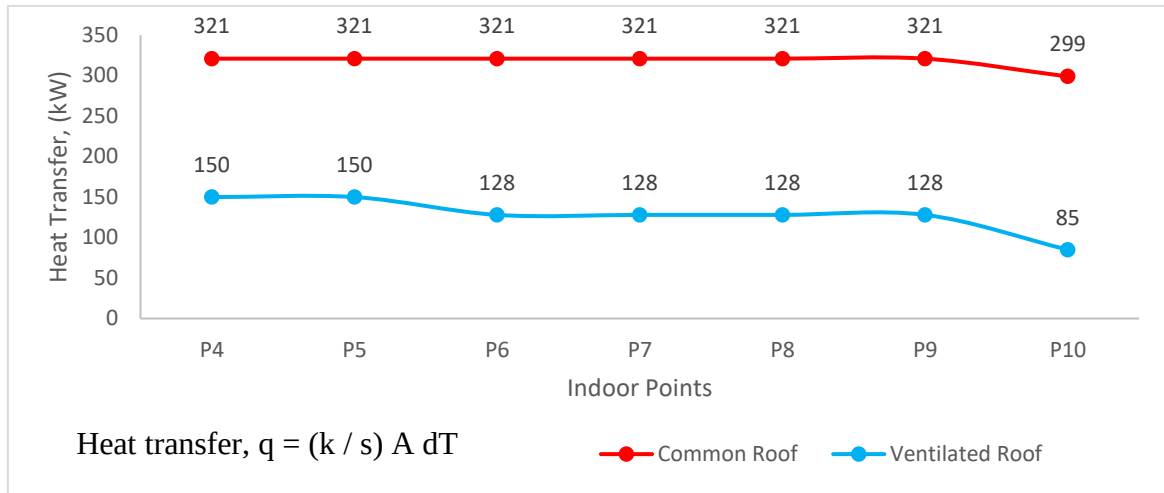


Figure 4.4: Heat transfer for common roof and ventilated roof under fully opened condition

Result from heat transfer calculation showed that heat transfer was higher inside the common roof's model house with ranged between 299 kW to 321 kW. In the meantime, ventilated roof's house model measured with lower heat transfer between 85 kW to 150 kW. It is undeniable that the openings of door and windows enhances the natural ventilation for cooling purposes and eliminate the overheating inside the model house. However, heat transfer inside ventilated roof model house recorded lower value as compared to common roof. This shows that the openings on the ventilated roof surface provide extra area for air movement to travel inside the model house for cooling purposes. The openings on ventilated roof surface enhances the stack effect to occurred effectively.

Heat transfer values for common roof's model house were higher than ventilated roof because of the removal of heat was only depends on the opening of door and windows. Unlike ventilated roof, the openings on the roof surface provide extra area for air movement to enter the model house for cooling purposes.

4.3.5 Analysis of Performance of the Model House with Ventilated Roof Design

It is undeniable that the roofing material plays an important role in their capability to transmit the heat into the house. The heat transmitted from the roof surface into the attic would be distributed in the lower part of the house due to the higher density of hot air. The roofing material also has a capability to minimise the amount of heat from entering the house. Since the material used for the experiment was a metal deck sheet, most of the heat gain amount was transferred from roof surface into the model house. Previous study has reported that the increase of indoor air temperature was due to the solar heat gain transmitted through the roof (Ibrahim et al., 2014a). The heat was trapped inside the house because it only depended on the air movement inside the house, which is too low and resulted in overheating internally.

Overall, ventilated roof's model house recorded higher reduction of indoor air temperature as compared to common roof's model house under fully closed condition based on data recorded from on-site experiment. This was further proved by heat transfer calculation, where the difference between common roof and ventilated roof's model houses was up 2,267 kW. While under fully opened condition, ventilated roof's model house recorded lower indoor air temperature as compared to common roof's model house. This reduction also further proved by heat transfer calculation, where the difference between common roof and ventilated roof's model houses was up 214 kW. This showed that the opening on roof surface provide extra area for hot air to escape. Apart from that, the opening of the windows and door help to enhance the natural ventilation into the house. Stack effect would take place because the opening increases the natural ventilation efficiency. The effectiveness of the stack effect would depend on the difference of outdoor and indoor air temperature as well as air velocity (Tatarestaghi et al., 2018). The authors highlighted that

the stack effect would occur effectively by providing more openings at the wall and roof area, following the vernacular house design. From these findings, it was concluded that the ventilated roof more contributing to minimise the overheating during the daytime as compared to common roof.

Since the roofing material used for this study was higher in thermal conductivity, therefore, the indoor air temperature for ventilated roof's model house under fully opened conditioned recorded slightly higher by 0.4 °C from recorded ambient temperature. Improvement was proposed in Chapter 5 for future study on the roofing material with low thermal conductivity to further reduce the indoor air temperature below ambient temperature.

4.4 Validation of Experimental Model House

Simulation was conducted to validate the on-site data before proceeding to further study on different pitch of roof with both fully closed and fully opened conditions. The model house was created and assembled using Solidwork software as indicated in Figure 3.8 (page 55) and imported in the ANSYS software. The data such as ambient air temperature and air velocity recorded from the on-site experiment was used to simulate the model house in the ANSYS software as shown in Figure 3.9 (page 56) and Figure 3.10 (page 57). The data were used to ensure the values obtained from the simulation for the model house can be used for validation purpose. The variation of data obtained from experimental work and simulation shall be between acceptable value of 20% for validation purpose, which was supported and explained in Chapter 3.

4.4.1 Validation of Air Temperature and Air Velocity

In simulation stage, 11 points were measured at the same location as points at the model house for experimental work as shown in Figure 3.7 (page 53). The data obtained

from experiment and simulation were compared to get the percentage difference. Table 4.3 shows the comparison of measure and simulate air temperature data for both common roof and ventilated roof.

Table 4.3: Comparison of measured and simulated air temperature on the small-scale model house

Points		Common roof			Ventilated roof		
		Measured (°C)	CFD Simulated (°C)	Percentage Difference (%)	Measured (°C)	CFD Simulated (°C)	Percentage Difference (%)
Fully Closed	P1	37.6	37.7	0.3	36.2	36.3	0.3
	P2	53.0	51.6	- 2.6	52.3	51.6	- 1.3
	P3	52.6	51.6	- 1.9	52.2	51.6	- 1.1
	P4	46.2	46.9	1.5	36.2	36.3	0.3
	P5	45.9	45.9	0.0	35.5	35.9	1.1
	P6	46.1	45.9	- 0.4	35.5	35.5	0.0
	P7	46.1	45.9	- 0.4	35.5	35.5	0.0
	P8	45.9	46.0	0.2	35.5	35.5	0.0
	P9	46.1	45.9	- 0.4	35.5	35.5	0.0
	P10	46.1	45.8	- 0.7	35.5	35.6	0.3
	P11	37.7	37.7	0.0	36.5	36.9	1.1
Fully Opened	P1	36.8	36.9	0.3	36.3	36.4	0.3
	P2	51.8	51.6	- 0.4	51.8	51.7	- 0.2
	P3	51.9	51.7	- 0.4	51.8	51.7	- 0.2
	P4	36.1	36.2	0.3	35.3	35.4	0.3
	P5	36.1	36.0	- 0.3	35.3	34.8	- 1.4
	P6	36.1	36.0	- 0.3	35.3	35.0	- 0.8
	P7	36.1	36.0	- 0.3	35.2	35.0	- 0.6
	P8	36.1	36.0	- 0.3	35.2	35.0	- 0.6
	P9	36.1	36.0	- 0.3	35.2	35.0	- 0.6
	P10	36.0	36.0	0.0	35.0	35.1	0.3
	P11	36.5	36.1	- 1.1	36.1	36.4	0.8
Mean Percentage Difference				- 7.2			- 2.1

The highest indoor air temperature for common roof under fully closed was at point P4 with 46.2 °C from experimental work, while 46.9 °C from the simulation data. The lowest measured and simulated indoor air temperature recorded for common roof under fully closed condition was at point P5 with 45.9 °C. For ventilated roof's model house under fully closed

condition, the highest indoor air temperature recorded at point P4 with 36.2 °C from experimental work, while 36.3 °C from the simulation data. The lowest measured and simulated indoor air temperature recorded for ventilated roof under fully closed condition was at point P6, P7, P8 and P9 with 35.5 °C respectively.

The lowest measured and simulated indoor air temperature for common roof under fully opened was recorded at point P10 with 36.0 °C respectively. For ventilated roof's model house under fully opened condition, the highest measured and simulated indoor air temperature recorded at point P4 with 35.3 °C and 36.4 °C respectively. The lowest measured and simulated indoor air temperature recorded for ventilated roof under fully closed condition was at point P10 with 35.0 °C and 35.1 °C respectively.

From the data comparison, it showed that the indoor temperature for ventilated roof for both fully closed and fully opened condition was lower than the indoor temperature recorded in common roof. The percentage difference comparison calculates the percentage difference between values from experiment and simulation in order to determine how close they are from each other. This method also used by previous study for validation purposes and the acceptable variation between experimental and simulation results shall be not more than 20%. The percentage difference of air temperature as shows in Table 4.1 was 7.2% for common roof and 2.1% for ventilated roof, which is within the allowable difference variation of 20%. Therefore, the data was validated and simulation for common roof and ventilated roof was proceeded with different pitches of roof with the same model house scale and also on the actual scale of low house.

4.4.2 Validation of Air Velocity

For air velocity validation, the air velocity at all points were recorded and compared between common roof and ventilated roof under fully closed and fully opened condition. Table 4.4 shows the recorded data for air velocity of both roof designs.

Table 4.4: Comparison of measured and simulated air velocity on small-scale model house

Points		Common roof			Ventilated roof		
		Measured (m/s)	CFD Simulated (m/s)	Percentage Difference (%)	Measured (m/s)	CFD Simulated (m/s)	Percentage Difference (%)
Fully Closed	P1	0.37	0.36	- 2.7	0.37	0.35	- 5.4
	P2	0.32	0.29	- 9.4	0.33	0.29	- 12.1
	P3	0.37	0.38	2.7	0.38	0.37	- 2.6
	P4	-	0	-	-	0.16	-
	P5	-	0	-	-	0.12	-
	P6	-	0	-	-	0.11	-
	P7	-	0	-	-	0.10	-
	P8	-	0	-	-	0.11	-
	P9	-	0	-	-	0.10	-
	P10	-	0	-	-	0.10	-
	P11	0.36	0.36	0.0	0.35	0.34	- 2.9
Fully Opened	P1	0.37	0.36	- 2.7	0.37	0.34	- 8.1
	P2	0.25	0.25	0.0	0.12	0.13	8.3
	P3	0.21	0.20	- 4.8	0.16	0.17	6.3
	P4	0.05	0.04	- 20.0	0.29	0.30	3.4
	P5	0.12	0.13	8.3	0.37	0.38	2.7
	P6	0.33	0.36	9.1	0.37	0.38	2.7
	P7	0.37	0.37	0.0	0.37	0.37	0.0
	P8	0.36	0.38	5.6	0.36	0.36	0.0
	P9	0.35	0.35	0.0	0.37	0.38	2.7
	P10	0.14	0.15	7.1	0.25	0.24	- 4.0
	P11	0.37	0.37	0.0	0.37	0.38	2.7
Mean Percentage Difference				- 6.7			- 6.3

Based on Table 4.4, the indoor air velocity was not recorded in the experimental of model house at points P4, P5, P6, P7, P8, P9 and P10 for both common roof and ventilated roof due to the condition of the door and all windows were fully closed and sealed. This was

explained in sub-topic 4.3.1 in this chapter. The simulated air velocity values inside common roof's model house recorded relatively too low up to three decimal places. This study only limited to two decimal places. Therefore, it explained the reading of zero at indoor points P4, P5, P6, P7, P8, P9 and P10 for common roof's house model with fully closed condition. However, there is values of simulated air velocity inside ventilated roof's model house under fully closed condition and the highest value was 0.30 m/s at point P4. In simulation, the air velocity was available inside the model house because the wind entered through the roof openings and reach point P4 first before it distributed to other areas or points. This described that point P4 indicated highest value of simulated air velocity inside the house compared to other indoor points of P5, P6, P7, P8, P9 and P10.

While the highest simulated indoor air velocity for common roof's model house under fully opened condition was 0.38 m/s at point P8, while for ventilated roof was about the similar value of air velocity with 0.38 m/s at P5, P6 and P9. The lowest simulated indoor air velocity under fully opened condition for both common roof and ventilated roof's model houses recorded at P5 with 0.13 m/s and P10 with 0.24 m/s respectively. Air entered through ventilated roof provide extra cooling in addition to air running through the opening of the windows and door. From this study, it showed that higher indoor air velocity contributes lower indoor air temperature.

The percentage difference of air velocity as shows in Table 4.4 was 6.7% for common roof and 6.3% for ventilated roof, which is within the allowable difference variation of 20%. Therefore, the air velocity also could be considered validated. Based on the data obtained from simulation, it was noticed that the air movement was present inside ventilated roof's model house under fully closed condition. Hence, it further clarified that the hot air was escaped through the openings on the roof surface and reduced the heat transfer to the

lower area. The openings on the roof allows extra natural ventilation into the house, hence created stack effect phenomenon. The difference density of air at lower area and upper area of house model contribute to the occurrence of the stack effect. This air density difference was resulted from difference in air temperature. Hotter air temperature would have lower density, while cooler air temperature comprises greater density. Buoyancy force was created due to density difference and pushing the hotter air upward to the roofing area. The openings on the roof enhance the removal of the hot air into outside area. Further to this, it explained that the stack effect enhances the efficiency of ventilated roof to remove the hot air through the openings. The ventilated roof could be more effective with the windows and door are widely open. The simulation was proceeded with other two different roof pitch of 10° and 45° under fully closed and fully opened condition respectively.

4.5 Thermal Modelling on Model House with 30° Pitch of Roof

Simulation on model house with 30° pitch of roof on both common roof and ventilated roof design was conducted to investigate on the thermal and air movement pattern formation inside the house. The images for both common roof and ventilated roof was compared and analysed. Further to this, three different points P4, P5 and P10 as indicated in Figure 3.11 (page 60) were measured and recorded. The simulation exercise was very important to visualise the patten of air temperature and air movement inside the model house, which we cannot be seen with human's eyes. Through simulation, researchers able to analyse the outcome and able to explain the differences in air temperature and air velocity.

ANSYS software was used to show air temperature pattern and air movement of the model house. Figure 4.5 shows the cross section of the simulated model house for 30° roof pitch with the fully closed condition.

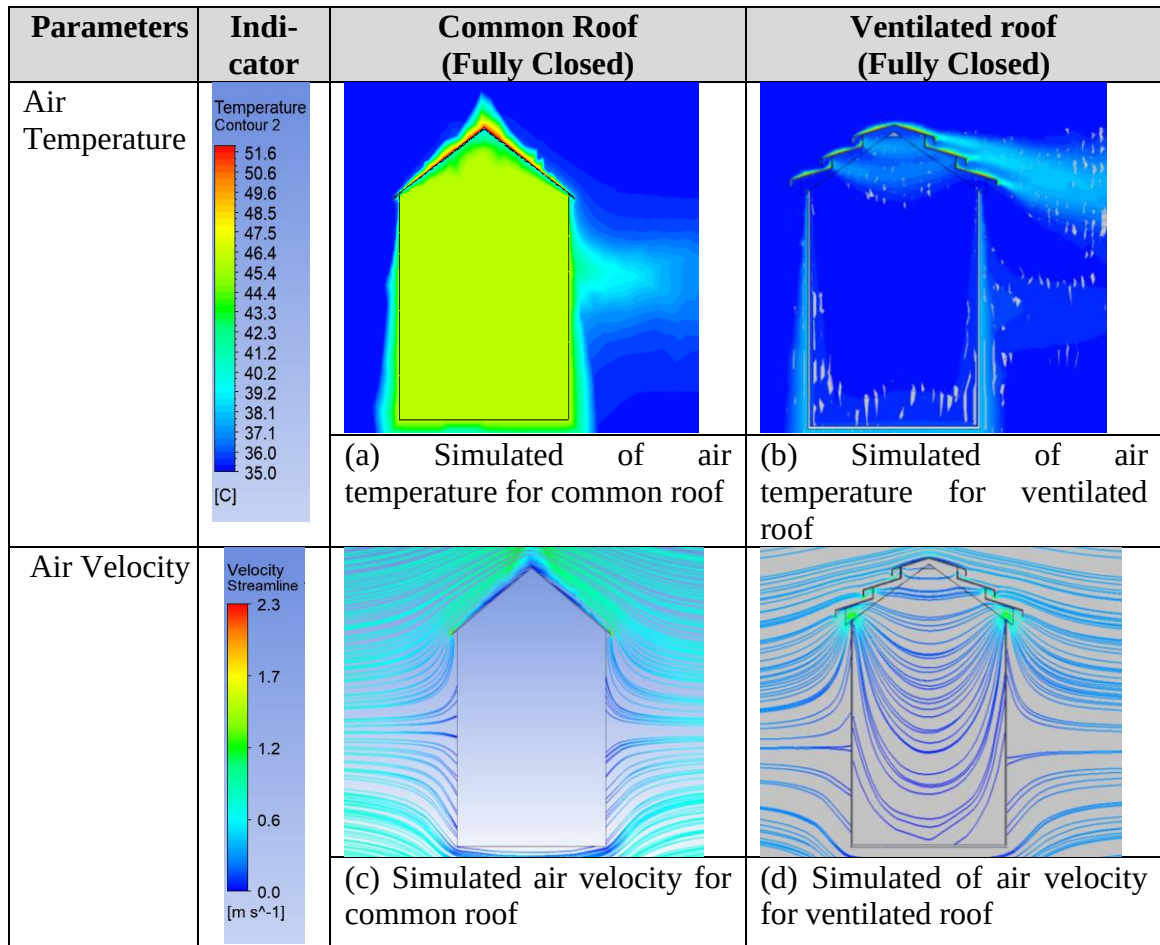


Figure 4.5: Cross section of simulated air temperature and air velocity for 30° pitch of roof with fully closed condition

Based on Figure 4.5, the indoor air temperature for common roof recorded higher indoor temperature than ventilated roof under fully closed condition. The green colour as shown in the model house in Figure 4.5 (a) indicated that the temperature is more than 45 °C, which exceeded the ambient air temperature. While the blue colour as shown in Figure 4.5 (b) indicated that the temperature is below 37 °C at the house indoor and outdoor area. The gradient of thermal pattern colour and air movement colour pattern can be referred at air temperature and air velocity's indicators as provided in Figure 4.5. Based on the simulation as shown in Figure 4.5 (b), it was found that the hot air escaped the model house at the upper area, which was through the openings provided on the roof surface. Further to this, it

explained the light blue colour at the upper right of the ventilated roof surface in Figure 4.5 (b).

Figure 4.5 (c) indicated that there was no presence of air velocity recorded inside the model house for common roof under fully closed condition. However, Figure 4.5 (d) showed air movement pattern inside the ventilated roof's model house under fully closed condition. The simulated air velocity recorded inside the model house with a ventilated roof ranged between 0.10 m/s to 0.16 m/s. Based on Rajapaksha et al. (2002), the indoor air temperature is depending on the air movement inside the house. The air movement through openings are likely caused by differences in air density due to air temperature differences between two areas (Blomqvist, 2009). Air movement caused by buoyancy forces or stack effect ventilation has made the air to travel from lesser to higher density as displayed through simulated air movement in Figure 4.5 (d). The lines that entered the model house represented the air movement to and from the model house. The air entered and exited from the roof openings on ventilated roof's model house.

After investigating the model house for 30° pitch of roof with the fully closed condition, the simulation of model house was continued with the other condition, which was all door and windows were fully opened. Figure 4.6 shows the cross section of the simulated model house for 30° pitch of roof with the fully opened condition for both common roof and ventilated roof.

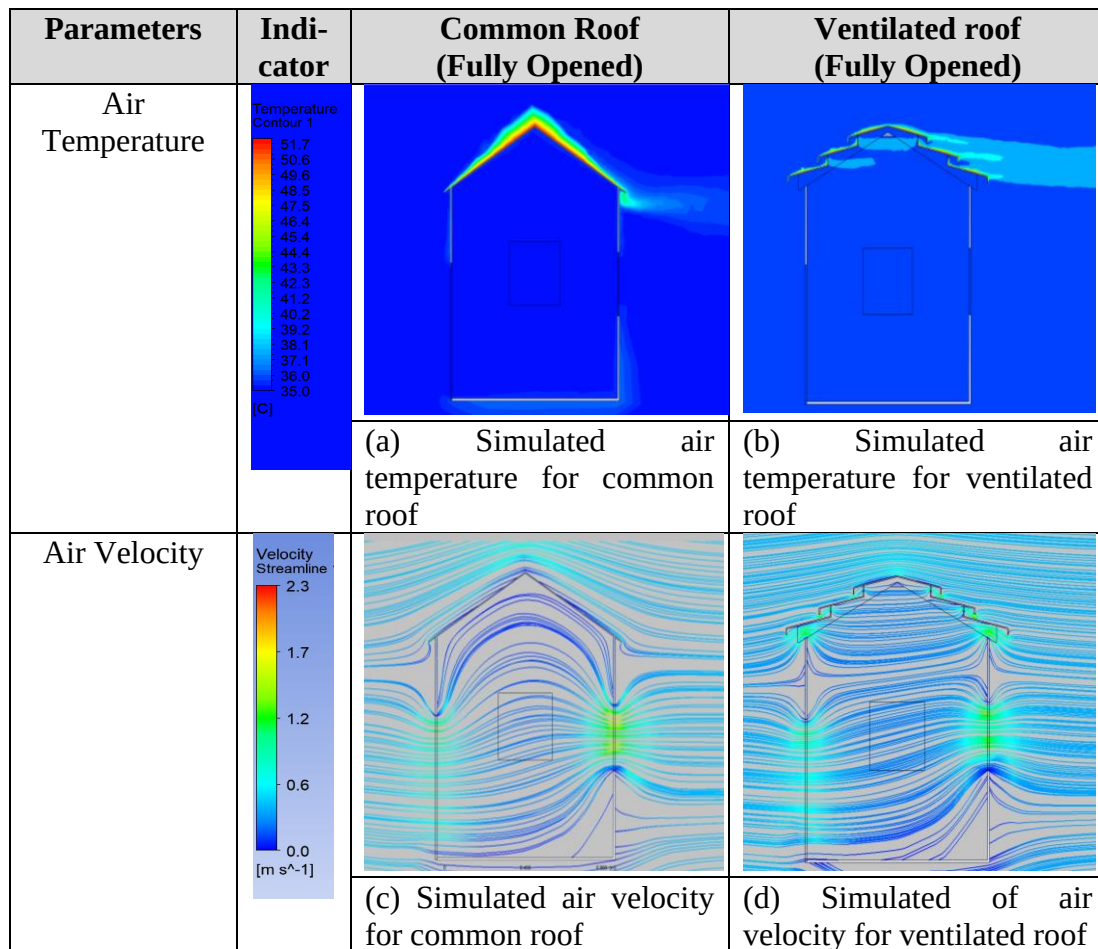


Figure 4.6: Cross section of simulated air temperature and air velocity for 30° roof pitch for fully opened condition

The gradient of thermal pattern colour and air movement colour pattern can be referred at air temperature and air velocity's indicators as provided in Figure 4.6. From Figure 4.6 (a) and (b), the colour at indoor area was a blue colour. It indicated that both model houses with common roof and ventilated roof recorded reduction in indoor air temperature under fully opened condition. The thermal pattern colour was different on the roof area for common roof and ventilated roof. Ventilating roof as indicated in Figure 4.6 (b) showed cooler air temperature on the surface as compared to common roof as displayed in Figure 4.6 (a).

It was also observed that the indoor air temperature for house model with common roof design recorded slightly higher than the ventilated roof by 1 °C. The indoor air temperature for ventilated roof recorded was lower than the common roof under fully opened condition. The simulated air temperature for common roof was still higher because of the air cannot leave the house through the roof and only depends on the opening of the door and windows to exit. In this condition, stack effect was occurred inside the house but however, wind driven effect on the roof area does not contribute to further enhancement of stack effect.

In the other hand, the stack effect and wind driven effect occurred on the model house with a ventilated roof as shown in Figure 4.6 (b) and Figure 4.6 (d). Wind driven effect that occurred on the roof surface area enhance the stack effect that occurred inside the house. The hot air rose due to differences in air temperature and air density. The positive pressure on roof surface of ventilated roof help to allow air to enter the house through roof openings while suction pressure on the roof surface of ventilated roof help to pull the hot air to the outside area. Based on Roslan et al. (2015), the ventilated roof strategy would enhance the natural ventilation into the house through wind driven ventilation and the stack effect.

The air velocity recorded in both model houses of common roof and ventilated roof were ranged from 0.18 m/s to 0.29 m/s and 0.28 m/s to 0.38 m/s respectively as shown in Figure 4.6 (c) and Figure 4.6 (d). The lines inside the model house represented the air movement. The wind enters and exits from the door and windows for common roof. While for model house with ventilated roof, the air exits via door, windows and roof opening.

4.6 Thermal Modelling on Different Pitch of Roof

This study proceeds with the CFD simulation on model house with 10° and 45° pitch of roof before further simulation on actual scale of low-cost house in Betong with 10° and

30° pitch of roof was conducted. The image of thermal modelling for model house with 10° and 45° pitch of roof were compared between common roof and ventilated roof. The importance of this simulation was to investigate the effectiveness of the ventilated roof to various roof pitches.

4.6.1 Thermal Modelling of Common Roof and Ventilating Roof on 10° Roof Pitch

Simulation was further conducted to both common roof and ventilated roof model house with different pitch of roof with 10°. The same condition as experimental on 30° pitch of roof were applied throughout the modelling process. The 10° was represented as typical roof pitch for low-cost housing in Malaysia. The data from simulation was used to extend the monitoring and coverage area. Table 4.5 indicated the simulated air temperature and air velocity data generated from CFD Simulation.

Table 4.5: Indoor air temperature and air velocity data simulated from CFD software for 10° roof pitch (common roof versus ventilated roof)

Experiment	Point	Common roof		Ventilated roof	
		CFD Simulated Air Temperature (°C)	CFD Simulated Air Velocity (m/s)	CFD Simulated Air Temperature (°C)	CFD Simulated Air Velocity (m/s)
Fully Closed	P4	47.5	0.00	37.8	0.16
	P5	46.9	0.00	36.8	0.10
	P10	46.7	0.00	36.6	0.10
Fully Opened	P4	36.5	0.05	35.8	0.23
	P5	36.3	0.17	35.6	0.23
	P10	35.9	0.07	35.4	0.22

Based on simulation and the data recorded in Table 4.5, model house with common roof under fully closed condition recorded higher indoor air temperature and no presence of air velocity inside the model house. However, for model house with ventilated roof under

the same condition recorded lower indoor air temperature. It was observed that the air velocity was also present inside the model house. While for fully opened condition, the model house with ventilated roof design recorded lower indoor temperature than the common roof design. It was observed the presence of air velocity inside both model house under fully opened condition. The air movement inside the house able to reduce the indoor air temperature further.

Overall, the indoor air temperature for fully closed and fully opened conditions for both model houses were compared. The comparison of indoor air temperature is shown in Figure 4.7.

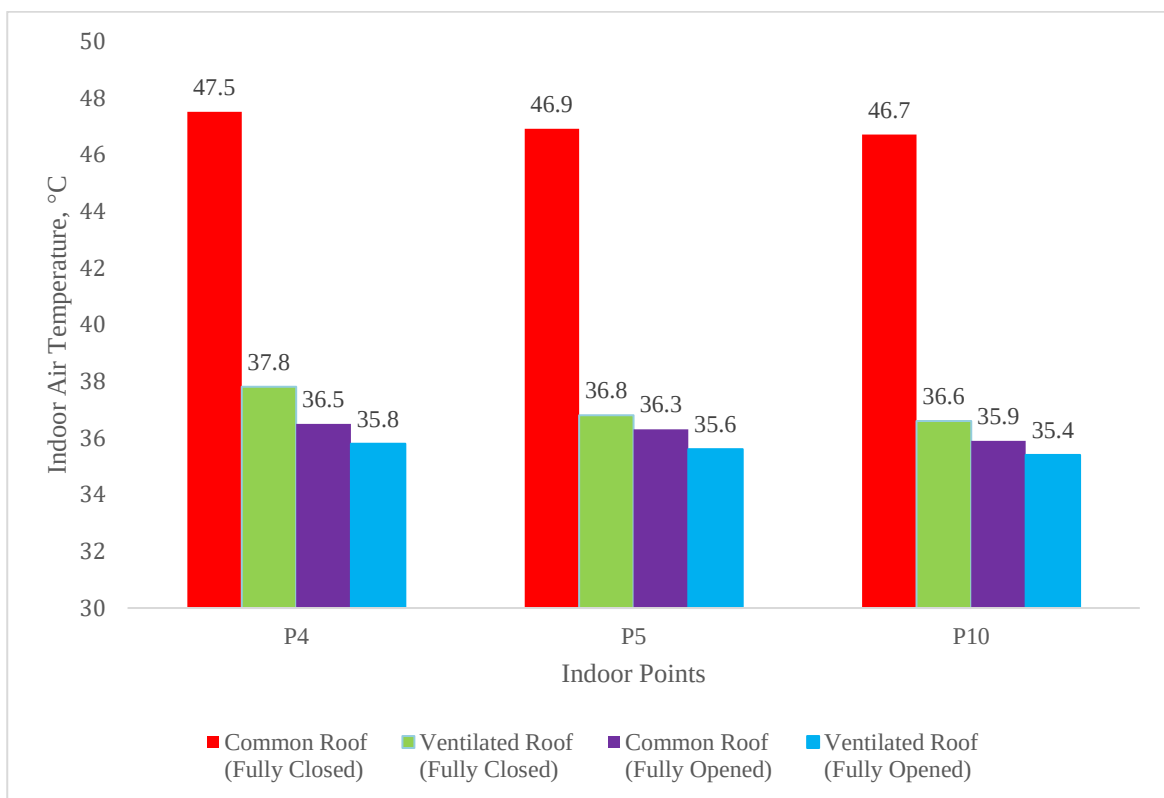


Figure 4.7: Comparison of indoor air temperature for common roof and ventilated roof under fully closed and fully opened condition for 10° roof pitch

The highest indoor air temperature recorded was the common roof under fully closed condition. The indoor air temperature for ventilated roof under fully closed condition showed higher reduction from common roof under the same condition. The reduction of air temperature between ventilated roof and common roof's model house reached up to 9.7 °C for point P4 and 10.1 °C for points P5 and P10 respectively. This shows that the opening on roof surface able to further reduce the indoor air temperature even the condition was fully closed. The openings on roof surface also provide area for hot air to escape and allow air movement into the model house.

While the indoor air temperature between common roof under fully opened condition shows slightly reduction as compared to the ventilated roof under fully closed condition. The lowest indoor air temperature was found at model house with ventilated roof house under fully opened condition. The reduction of indoor air temperature between ventilated roof and common roof's model house under this condition was 0.7 °C for point P4 and P5, while 0.5 °C for points P10. At this condition, the ventilated roof provide extra area for hot air exit via openings and at the same time allowing the wind to enter the house. This explained the indoor air temperature of ventilated roof's model house under fully opened condition much cooler than others.

Simulation was conducted and the thermal modelling image was capture for discussion and analysis. Figure 4.8 shows the cross section of simulated model house of 10° roof pitch under fully closed condition.

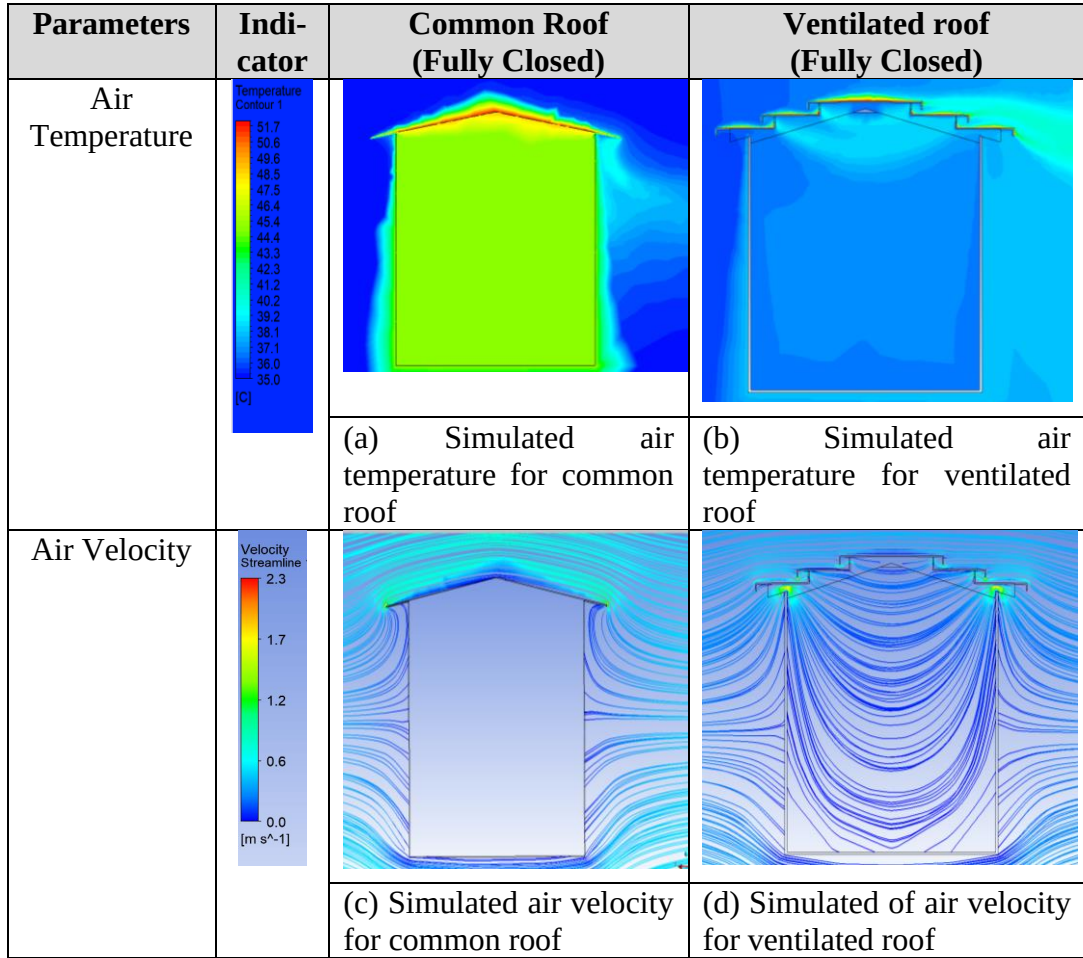


Figure 4.8: Cross section of simulated air temperature for 10° roof pitch for fully closed condition

Based on Figure 4.8 (a), the indoor air temperature for model house with common roof recorded higher indoor temperature than model house with ventilated roof under fully closed condition as shown in Figure 4.8 (b). The green colour as shown in the model house in Figure 4.8 (a) indicated that the temperature is more than 45 °C, which exceeded the ambient air temperature. While the blue colour as shown in Figure 4.8 (b) indicated that the temperature is below 37 °C. The gradient of thermal pattern colour and air movement colour pattern can be referred at air temperature and air velocity's indicators as provided in Figure 4.8. Based on the simulation as shown in Figure 4.8 (b), it was noticed that the hot air exited

the model house at the upper area, which was through the openings provided on the roof surface. Thus, it explained the light blue colour at the upper right of the ventilated roof surface in Figure 4.8 (b).

The image of thermal modelling in Figure 4.8 (c) indicated that there was no presence of air movement inside the model house for common roof. However, Figure 4.8 (d) revealed that there was air movement pattern captured inside the ventilated roof's model house under fully closed condition. The air velocity recorded in the ventilated roof's model house was ranging from 0.10 m/s to 0.16 m/s. The lines show the air movement occurred inside the house, which the wind enters and exits from the roof opening for model house with ventilated roof.

After investigating the model house for 10° pitch of roof with fully closed condition, the simulation of model house was continued to other condition of door and all windows were fully opened. Figure 4.9 shows the cross section of simulated model house for 10° pitch of roof with fully opened condition.

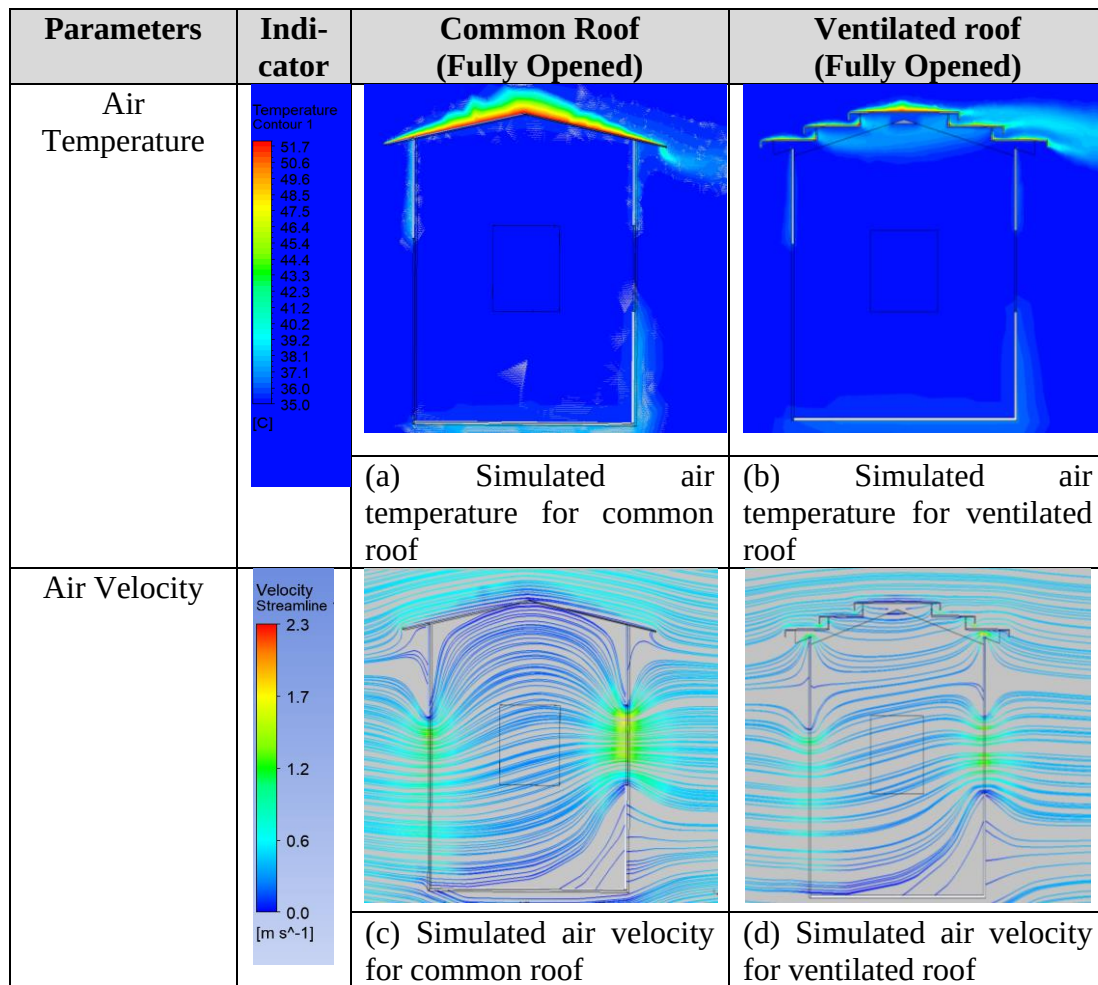


Figure 4.9: Cross section of simulated air temperature and air velocity for 10° roof pitch for fully opened condition

The gradient of thermal pattern colour and air movement colour pattern can be referred at air temperature and air velocity's indicators as provided in Figure 4.9. From Figure 4.9 (a) and (b), the colour at indoor area inside model houses was blue colour. Therefore, it showed that the model house with fully opened condition was cooler than model house under fully closed condition. The blue colour also explained that both model houses recorded further reduction in indoor air temperature. The thermal pattern colour was different on the roof area for common roof and ventilated roof. Ventilated roof as indicated

in Figure 4.9 (b) showed cooler air temperature on the surface as compared to common roof as displayed in Figure 4.9 (a).

It was noticed that the indoor air temperature for house model with common roof design recorded slightly higher than the ventilated roof by 0.7 °C. The was because of the air movement only circulated internally and only exit the house through openings of windows and door. In this condition, stack effect was occurred but however, wind driven effect on the roof area was not assisting to enhance the stack effect inside the model house. Meanwhile, the stack effect and wind driven effect occurred on the ventilated roof's model house as shown in Figure 4.9 (b) and Figure 4.9 (d). Wind driven effect that occurred on the roof surface area enhance the stack effect that occurred inside the house. Hence, it helps to further reduction of indoor air temperature and for cooling purposes through natural ventilation.

While the lines inside the model house represented the air movement inside the model house as shown in Figure 4.9 (c) and Figure 4.9 (d). The wind entered and escaped from the door and windows for common roof. While for model house with ventilated roof, the air exited via door, windows and roof opening. The hot air rose from lower part to the upper part of the model house due to differences in air temperature and air density. The positive pressure on the ventilated roof surface assists the air movement into the house through roof openings while suction or negative pressure on the roof surface of ventilated roof help to pull the hot air to the outside area. This explained the reading of air velocity recorded in ventilated roof's model house was higher than common roof.

4.6.2 Thermal Modelling of Common Roof and Ventilated Roof on 45° Roof Pitch

Considering the 45° roof pitch is second typical roof design for modern house in Malaysia apart from 30°, the simulation was conducted to investigate the performance of the roof on higher roof pitch. The simulation was conducted on both common roof and ventilated roof designs for the same model house scale but with different roof pitch of 45°. The data obtained was discussed and analysed to determine the effectiveness of the ventilated roof on higher roof pitch in reduction of indoor air temperature. The data from simulation was used to extend the monitoring and coverage area. Table 4.6 indicated the simulate indoor air temperature and air velocity data respectively, which was generated from CFD Simulation.

Table 4.6: Comparison of the simulated indoor air temperature and velocity data for 45° roof pitch (common roof versus ventilated roof)

Experiment	Point	Common roof		Ventilated roof	
		CFD Simulated Air Temperature (°C)	CFD Simulated Air Velocity (m/s)	CFD Simulated Air Temperature (°C)	CFD Simulated Air Velocity (m/s)
Fully Closed	P4	46.7	0.00	36.1	0.17
	P5	45.0	0.00	35.8	0.16
	P10	45.0	0.00	35.7	0.13
Fully Opened	P4	36.4	0.09	35.9	0.30
	P5	36.0	0.30	35.6	0.28
	P10	35.9	0.31	35.5	0.29

Based on simulation and the data in Table 4.6, model house with common roof under fully closed condition recorded higher indoor air temperature and no presence of air velocity was found inside the model house. While for model house with ventilated roof under the same condition recorded lower indoor air temperature than common roof design and the presence of air velocity was observed inside the model house. In the other hand, model house

with ventilated roof design under fully opened condition recorded lower indoor temperature as compared to the common roof design under same condition. It was observed the presence of air movement inside the house for both roof design. This air movement was allowed to enter the house through openings of door and windows for cooling purposes.

Overall, the indoor air temperature of model houses for fully closed and fully opened conditions were compared as shown in Figure 4.10.

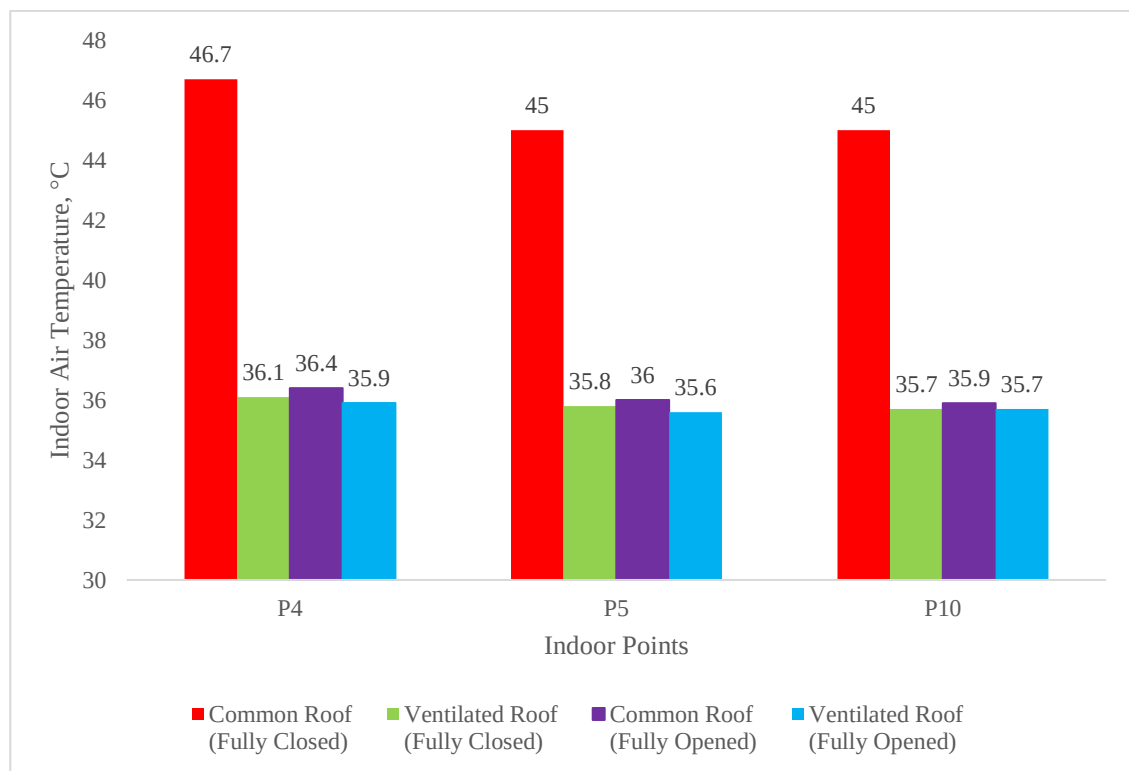


Figure 4.10: Comparison of indoor air temperature for common roof and ventilated roof under fully closed and fully opened condition for 45° roof pitch

Based on Figure 4.10, the model house with common roof under fully closed condition recorded the highest indoor air temperature as compared to ventilated roof under the same condition. The indoor air temperature for ventilated roof under fully closed condition showed higher reduction from common roof under the same condition. The

reduction of air temperature between ventilated roof and common roof's model house could reach up to 10.6 °C for point P4, 9.2 °C for point P5 and 9.3 °C for point P10. This shows that the opening provided on roof surface would help to further reduce the indoor air temperature. The openings on roof surface also provide area for hot air to escape and allow air movement into the model house under fully closed condition.

While the indoor air temperature for common roof under fully opened condition shows slightly reduced as compared to the ventilated roof under fully closed condition. The reduction of air temperature between ventilated roof and common roof's model house under fully opened condition was 0.5 °C for point P4, 0.4 °C for point P5 and 0.2 °C for point P10. The lowest indoor air temperature was recorded for ventilated roof's model house under fully opened condition. At this condition, the indoor air temperature inside the model house was cooler because the hot air escaped via few openings from door, windows as well as the openings provided on ventilated roof.

Common roof with fully closed condition were experienced overheating inside the house. Further to Figure 4.10, simulation on the model house under fully closed was conducted on the 45° pitch of roof to simulate the thermal modelling and air movement pattern. Figure 4.11 indicates the cross section of simulate model house for 45° pitch of roof.

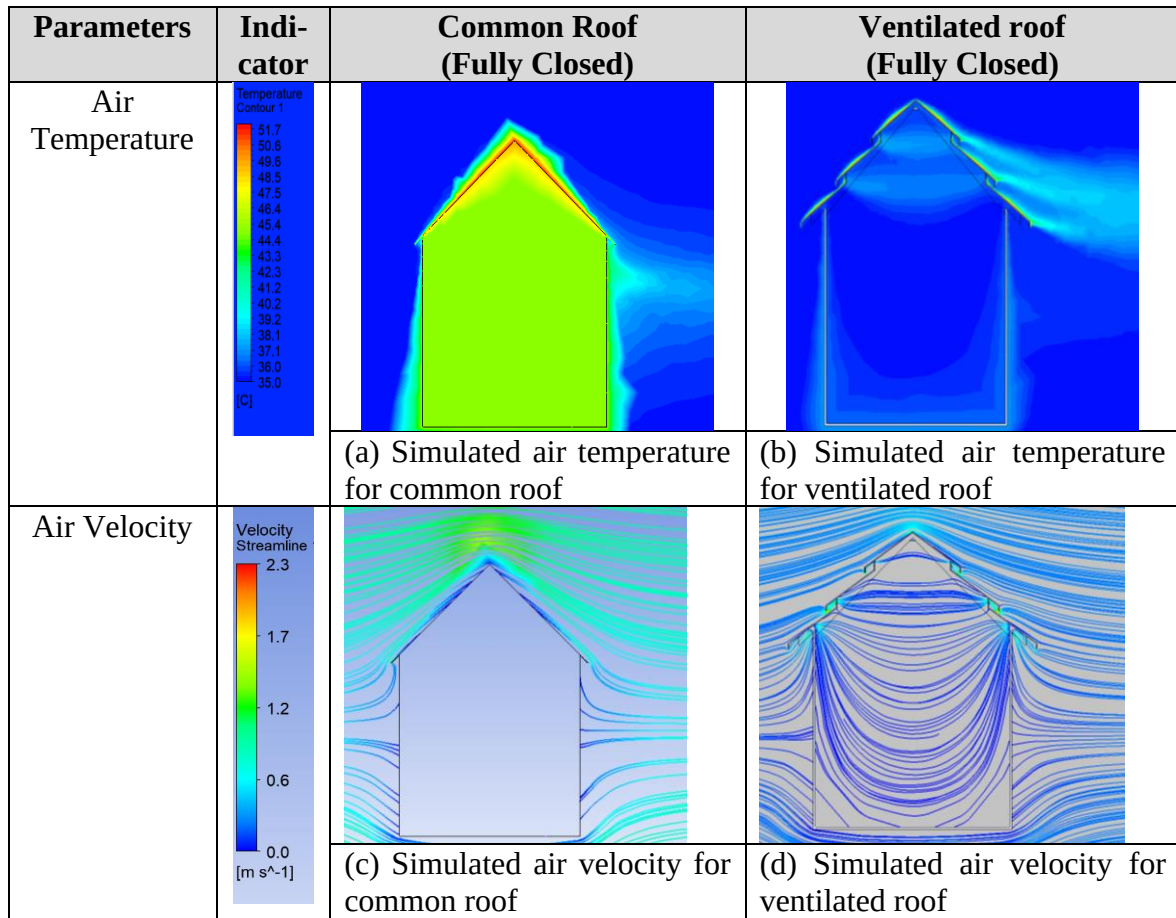


Figure 4.11: Cross section of simulated air temperature and air velocity for 45° roof pitch for fully closed condition

Based on Figure 4.11, the indoor air temperature for model house with common roof design recorded higher indoor temperature than ventilated roof under fully closed condition. The green colour as shown in the model house in Figure 4.11 (a) indicated that the temperature is more than 45 °C, which exceeded the ambient air temperature. While blue colour at model house with ventilated roof as shown in Figure 4.11 (b) indicated that the temperature is below 37 °C. The gradient of thermal pattern colour and air movement colour pattern can be referred at air temperature and air velocity's indicators as provided in Figure 4.11. Based on the simulation as shown in Figure 4.11 (b), it was observed that the hot air escaped the model house at the upper area, which was through the openings of the ventilated

roof. Hence, it explained the light blue colour at the upper right of the ventilated roof surface in Figure 4.11 (b).

The image of thermal modelling in Figure 4.11 (c) showed that there was no presence of air movement inside the common roof's model house. However, Figure 4.11 (d) showed that there was air movement pattern presented inside the ventilated roof's model house even the condition was fully closed. The air velocity recorded in the ventilated roof's model house was ranging from 0.13 m/s to 0.17 m/s. The lines indicated the air movement happened inside the house, which the wind enters and exits from ventilated roof's openings.

Common roof with fully closed condition were experienced overheating inside the house. The thermal modelling image from this simulation was almost similar with simulation conducted on model house with 10° and 30° pitch of roof under fully closed condition. The simulation was further conducted on 45° pitch of roof with all door and windows were fully opened. Figure 4.12 indicated that the simulation on the 45° pitch of roof for common roof and ventilated roof.

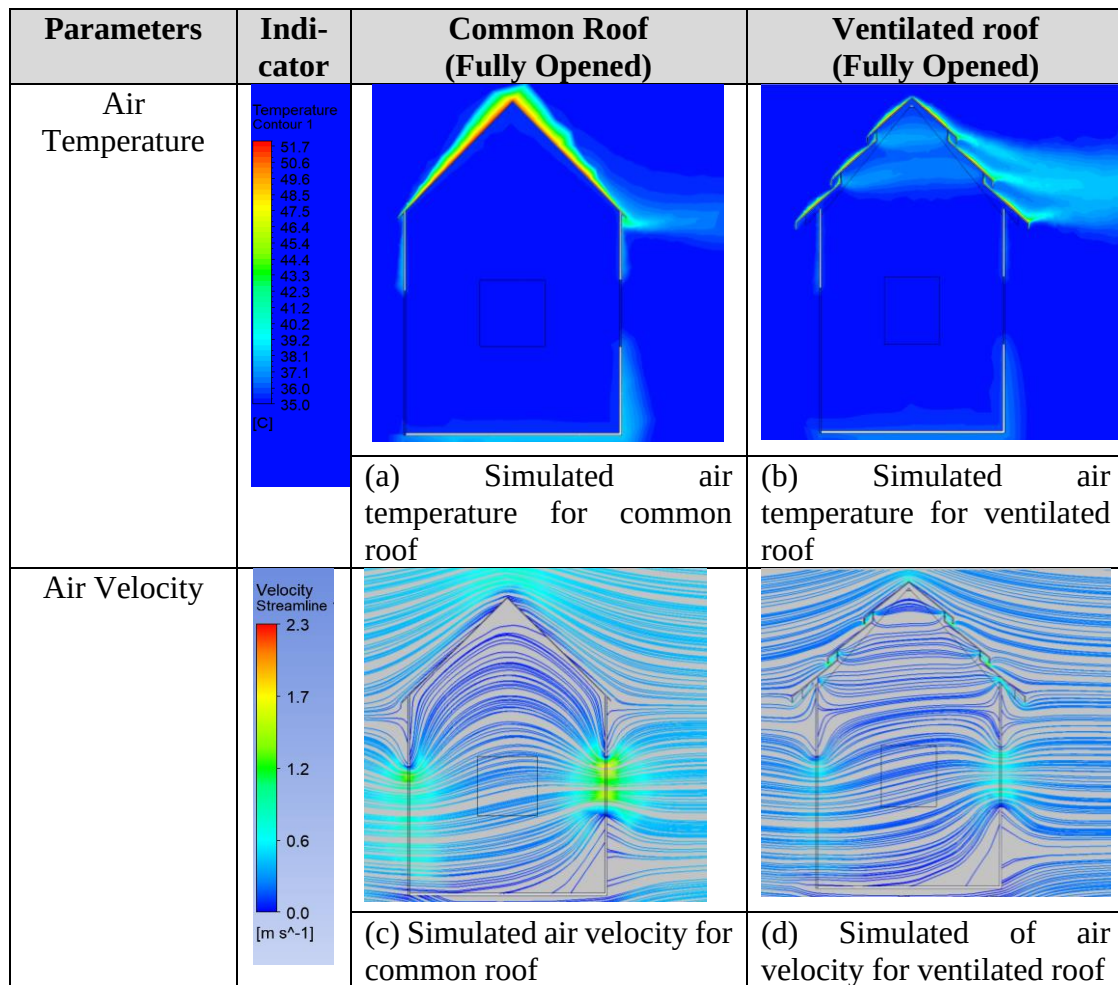


Figure 4.12: Cross section of simulated air temperature and air velocity for 45° roof pitch for fully opened condition

The gradient of thermal pattern colour and air movement colour pattern can be referred at air temperature and air velocity's indicators as provided in Figure 4.12. From Figure 4.12 (a) and (b), the colour at indoor area inside model houses was blue colour. Therefore, it showed that the model house with fully opened condition was cooler than model house under fully closed condition. The blue colour also described as further reduction on indoor air temperature for both model houses. Meanwhile, the thermal pattern colour was different on the roof area for common roof and ventilated roof. Ventilated roof as indicated in Figure 4.12 (b) showed light blue colour, which represent cooler air temperature on the surface as compared to colour on common roof as displayed in Figure 4.12 (a).

It was noticed that the indoor air temperature for house model with common roof design recorded slightly higher than the ventilated roof. The air movement only spread internally and only leave the house through openings of windows and door. In this condition, stack effect occurred but wind driven effect on the roof area was not assisting to enhance the stack effect inside the model house. While the stack effect and wind driven effect occurred on the ventilated roof's model house as shown in Figure 4.12 (b) and Figure 4.12 (d). Wind driven effect that occurred on the roof surface area improve the stack effect that occurred inside the house by helping to pull the hot air out from the model house. Hence, it supports the cooling and additional reduction of indoor air temperature.

4.6.3 Analysis on Thermal Modelling of 10°, 30° and 45° Roof Pitches

Further analysis was made to compare the results from the data obtained from CFD simulation. This comparison was made to determine the best roof pitch for ventilated roof. Table 4.7 shows the comparison of simulated data for indoor air temperature for common roof and ventilated roof with three different roof pitches.

Table 4.7: Comparison indoor air temperature common roof versus ventilated roof for 10°, 30° and 45° pitch of roof

Roof Pitch	Points	Common roof (°C)		Ventilated roof (°C)	
		Fully Closed	Fully Opened	Fully Closed	Fully Opened
10°	P4	47.5	36.5	37.8	35.9
	P5	46.9	36.3	36.8	35.6
	P10	46.7	35.9	36.6	35.5
30°	P4	46.9	36.2	36.2	35.4
	P5	45.9	36.0	36.0	34.8
	P10	45.8	36.0	36.0	35.0
45°	P4	46.7	36.4	36.1	35.9
	P5	45.0	36.0	35.8	35.6
	P10	45.0	35.9	35.7	35.5

From the Table 4.7, the 45° pitch of roof for common roof design recorded lower indoor temperature followed by 30° and 10° pitch of roof for both fully closed and fully opened condition. The roof area for 45° roof pitch perpendicular to the direct sunlight is lesser than the area of 30° and 10° pitch of the roof at morning or afternoon time, where only one sides that receive direct sunlight while the other side is considered as shading area. Therefore, the amount of heat gain through roof surface was lesser than others because only one sides receives the sunlight as compared to 10° and 30° roof pitch.

It was identified that the 45° was the coolest among two other common roof pitches, followed by 30° and 10°. Ramly and Hussain (2012) indicated that the indoor climate could reduce with the increase of pitch of roof. However, the indoor air temperature for 45° pitch of roof for common roof still higher than the ventilated roof design in general. This is because of the degree of inclination play important roles in reducing the heat gain into the house. According to Alshayji and Ebrahim (2020), it is suggested that the higher roof inclination angle help to reduce the heat gain. The study also revealed that the amount of heat reduction was increased up to 28.2% as the roof angle is higher up to 75%. Previous study showed that the amount of heat gain through roof is influence by degree of roof pitch (Roels & Duerinck, 2011).

While for ventilated roof's model house under fully closed and fully opened condition, the 30° pitch of roof recorded lower indoor air temperature and followed by 45° and 10° pitch of roof. It was observed that the 45° inclination is too steep as compared to 10° and 30°, thus creating obstacles or barrier for the suction pressure to pull the hot air rose because of buoyancy affect from the roof openings at leeward area. It was observed that air velocity at point P5 inside 45° roof pitch for ventilated roof's model house recorded lower readings than 30° roof pitch. It shows that the ventilated roof works very effectively on 30°

pitch of the roof because of the opening angle give adequate good distance for the air movement to flow into and exit due to suction pressure.

On the other hand, the 10° roof pitch for ventilated roof recorded highest indoor air temperature due to the said roof angle had biggest area that facing direct sunlight during noon time and more heat gain through roof surface during that time. Large amount of heat is absorbed on a lower roof pitch, thus creating higher indoor air temperature (Ibrahim et al., 2014a). It was also noticed that lower air velocity values inside the model house of 10° pitch roof. Lower roof inclination angle also influences higher friction between flow and the roof surface (Alshayji & Ebrahim, 2020). It was found that the indoor air temperature 10° was warmer than the 45° and 30° roof pitch because of the flat roof surface. The 45° pitch of roof recorded warmer indoor temperature as compared to 30° pitch of roof suction pressure less effective to pull the hot air out from the roof opening.

Ventilated roof approaches enhance natural ventilation with wind driven effect and stack effect (Roslan et al., 2015). Although the principle of the ventilated roof was based on the stack effect, with the wind driven pressure effect and density varies, the amount of wind hitting the roof surface and wind that entered the house also play an important role to create suction pressure and reduce the overheating inside the house. Even though the ventilated roof's model house for three different roof angles showed reduction of indoor air temperature, but none was recorded within thermal comfort temperature. Figure 4.13 indicated the comparison of indoor air temperature between the three pitches of roof to thermal comfort.

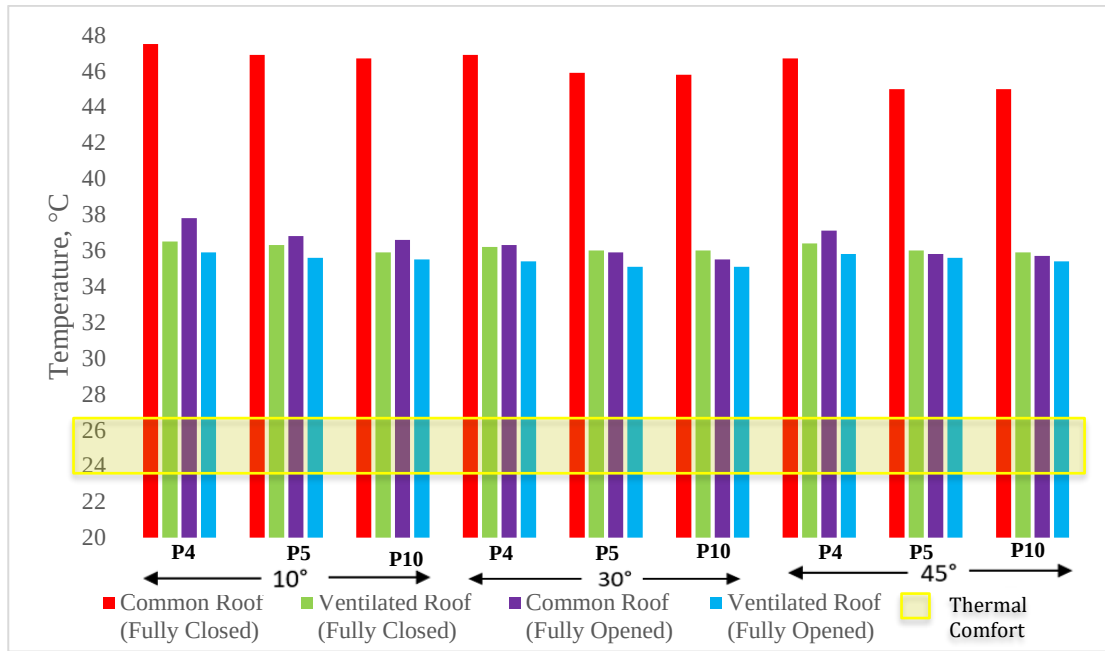


Figure 4.13: Comparison of points P4, P5 and P10 for 10°, 30° and 45° pitch of roof

The indoor air temperature for all points inside model houses under fully closed and fully opened condition recorded higher than thermal comfort because it only depends on natural ventilation for cooling purposes. The indoor air temperature was just 0.2 °C higher from ambient temperature at point P5 for ventilated roof's model house under fully opened condition. While the same point P5 for common roof recorded about 1.4 °C from ambient temperature.

From the results, the indoor air temperature exceeded the recommended thermal comfort temperature. However, the reduction of indoor air temperature inside model house was mainly contributed by natural ventilation and without using any mechanical ventilation system to cool the house. As such, it can be summarised that the ventilated roof can be adopted at all roof slopes. Nevertheless, it was effective on 30° or lower and less effective on higher roof pitch such as 45° and higher. Recommendations were discussed in Chapter 5 on the improvement of the design to achieve thermal comfort internally in future study.

4.7 Thermal Modelling for Betong Low-cost House

The on-site experiment was conducted and taken in 2014 in an actual low-cost house at Betong, Sarawak by Ibrahim et al. (2014a). The study was conducted previously to investigate the level of thermal comfort in typical low-cost house. The low-cost house was built with a common roof design and roof pitch around 10°. The house underwent two conditions of experimental work, which were all doors and windows were full opened and fully closed respectively. There were five points namely points a, b, c, d and e as shown on Figure 3.12 (page 61). The house was constructed with lightweight materials with limited ventilation provision on the walls. From previous study, it was discovered that the low-cost house experienced overheating inside the house. Even the condition of the low-cost house with all doors and windows were fully opened, the indoor air temperature still recorded higher than occupant's thermal comfort. This study is important to investigate the potential of ventilated roof to further reduce the indoor air temperature inside actual low-cost house.

4.7.1 Results and Thermal Modelling on Betong's Low-Cost House with 10° Pitch of Roof

The on-site data were recorded and simulation was conducted on the actual low-cost house scale. According to Ibrahim et al. (2014b), the differences between the on-site data and simulation should be below than acceptable variation value around 10%.

By using the previous on-site data as recorded in that study for common roof, the simulation on ventilated roof was applied using the same Betong's low-cost house scale. The same data were used for this study such as ambient air temperature with 33.5 °C and air velocity with 0.30 m/s. Table 4.8 stipulate the comparison of the simulated air temperature and air velocity for common roof and ventilated roof for Betong low-cost house.

Table 4.8: Comparison of the simulated indoor air temperature and air velocity data for Betong's low-cost house (common roof and ventilated roof)

Experiment	Point	Common roof		Ventilated roof	
		CFD Simulated Air Temperature (°C)	CFD Simulated Air Velocity (m/s)	CFD Simulated Air Temperature (°C)	CFD Simulated Air Velocity (m/s)
Fully Closed	a	33.7	0.26	33.6	0.22
	b	34.5	0.11	33.5	0.16
	c	34.6	0.12	33.5	0.16
	d	34.9	0.06	33.4	0.11
	e	35.7	0.26	33.5	0.22
Fully Opened	a	33.3	0.60	33.5	0.57
	b	33.5	0.48	32.7	0.50
	c	33.5	0.43	32.5	0.48
	d	33.4	0.35	32.5	0.39
	e	34.2	0.62	33.4	0.55

It was indicated that the common roof design for Betong low-cost house recorded higher indoor air temperature with ranged from 34.5 °C to 34.9 °C under fully closed condition for point b, point c and point d. While ventilated roof design with fully opened condition recorded the lowest indoor air temperature with ranged from 32.5 °C to 32.7 °C and even up to 1.0 °C reduction. It also noticed that the ventilated roof design under fully closed condition recorded almost similar as ambient temperature with 33.4 °C at point d, and 33.5 °C at point b and point c. While common roof under fully opened condition also recorded indoor air temperature almost similar with ambient temperature.

The air velocity values inside common roof's low-cost house under fully closed condition were very low with ranged of 0.06 m/s to 0.11 m/s. Meanwhile, air velocity inside ventilated roof under the same condition recorded higher value with 0.16 m/s at point b and c, while 0.11 m/s at point d. This showed that the openings on the roof area contributed to higher air velocity inside the low-cost house. For all doors and windows were fully opened

condition, ventilated roof recorded slightly higher air velocity as compared to common roof. Common roof recorded indoor air velocity with 0.48 m/s at point b, 0.43 m/s at point c and 0.35 m/s at point d. While ventilated roof recorded indoor air velocity with 0.50 m/s at point b, 0.48 m/s at point c and 0.39 m/s at point d.

The air temperature and air velocity data for both common roof and ventilated roof were compared. From the data, it was noticed that the ventilated roof provided lower indoor air temperature and higher indoor air velocity. Therefore, the analysis was focused on the ventilated roof and thermal modelling was further discussed. Table 4.6 still be referred for analysing the data and to make comparison of discussion.

The thermal modelling was conducted on ventilated roof under both fully closed and fully opened condition. This simulation was conducted to determine the performance of the ventilated roof towards indoor air temperature and the air movement inside the low-cost house. From this investigation, we can determine whether the design is suitable for low-cost house in order to minimise the overheating issues. The result of air temperature and air velocity was obtained from the simulation and the thermal modelling for ventilated roof was shown in Figure 4.14.

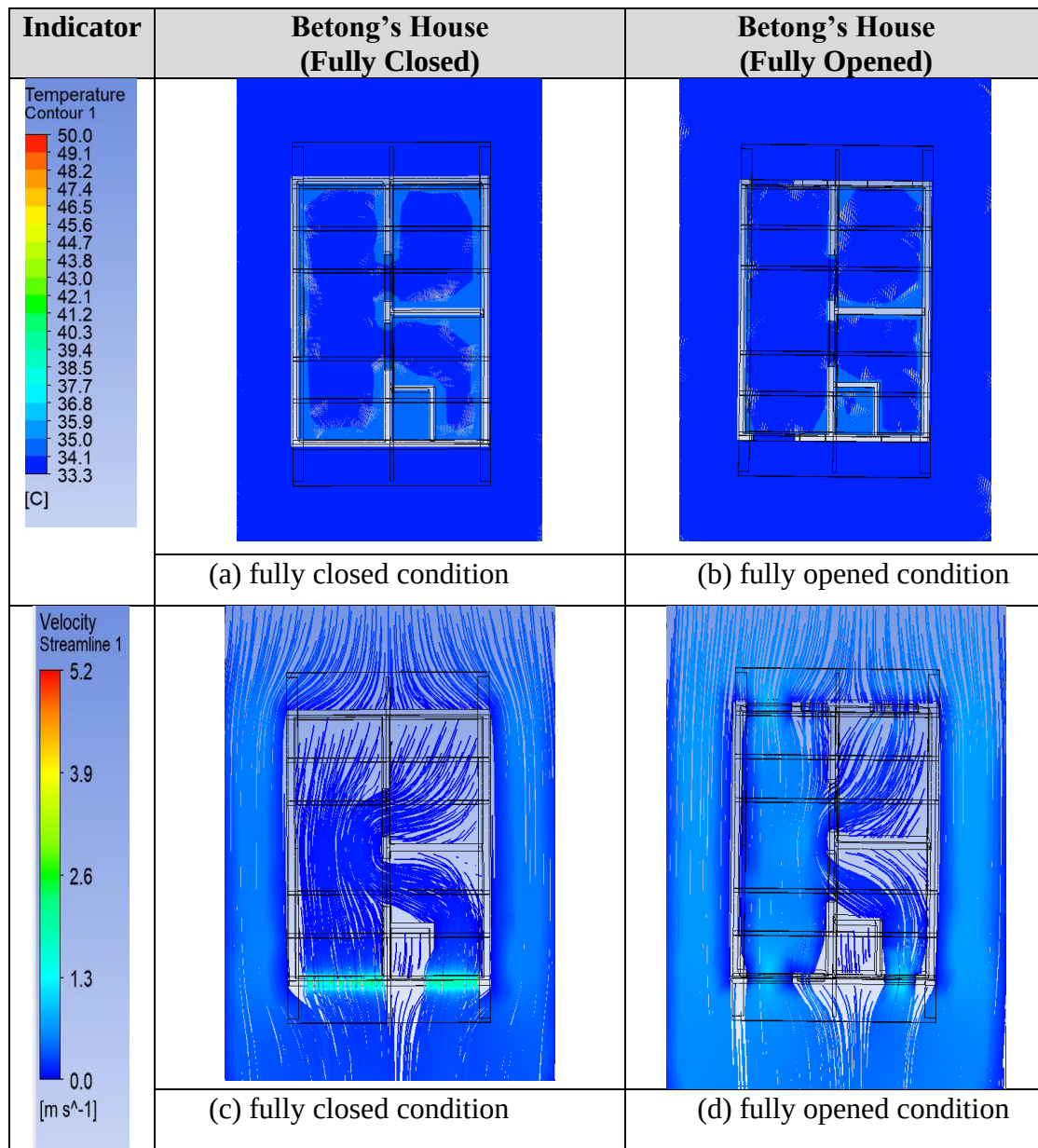


Figure 4.14: Simulated air temperature and air velocity inside ventilated roof low-cost house with 10° pitch of roof

The gradient of thermal pattern colour and air movement colour pattern can be referred at air temperature and air velocity's indicators as provided in Figure 4.14. Figure 4.14 (a) shows the indoor air temperature in Betong house under fully closed condition recorded highest than ventilated roof under the same condition. The building envelope area was observed to be light blue colour, which indicates higher temperature than darker blue

colour area as shown in Figure 4.14 (a). Figure 4.14 (b) shows that all area was in darker blue area, which indicates the area are cooler than Figure 4.14 (a). Figure 4.14 (c) and (d) shows the air movement inside Betong's low-cost house under fully closed and fully opened condition respectively. It was noticed that the lines, which indicated that air movement were observed inside the house.

For analysis and by referring to Table 4.8, the indoor air temperature for common roof at point b, c and d under fully closed condition recorded highest readings because of the house experienced overheating due to lack ventilation provision. At this point, occupants would suffer high temperature inside the house and the increase the energy consumption to use mechanical ventilation system for cooling purposes. The stack effect was occurred inside the house, however it become less effective for cooling purposes due to inadequate openings for the hot air to escape the house. The air movement was just circulated around the house and become slower as reaching point d because of the building envelope.

Since the condition was fully closed, the building envelope area became larger as it included the concrete brickwall, doors and windows. Therefore, the air movement hit the building envelope and some amount of kinetic energy from the air was transferred to the wall, doors and windows. It can be clearly explained the air velocity became slower when reach point d. When the air velocity become slower, it was less effective for the natural air movement inside the house to carry the hot air to escape the house. As a result, the hot air was trapped inside the house and cause higher temperature inside the house which is much higher than ambient temperature. While point a and point e showed higher air velocity as both were located at outside the house.

Nevertheless, the results of common roof under fully opened condition as per Table 4.6 shown reduction of the indoor air temperature at point b with 1.0 °C, while point c with 1.1 °C and point d with 1.4 °C. The reduction of indoor air temperature at point b, c, and d was mainly due to air movement into the house and the stack effect occurrence inside the house. With adequate openings of doors and windows help to reduce the higher indoor air temperature by allowing natural ventilation for cooling purposes. As the doors and windows were fully opened, this condition allowed more natural air to circulate inside the house and able to carry the hot air to outside environment even though some of the kinetic energy was transferred to the brickwall. We can summarise that the relationship of the openings will result in reduction of indoor air temperature and higher air velocity was allowed inside the house.

In the other hand, the Betong house with the ventilated roof under fully closed condition recorded lower indoor air temperature at point b, c and d than common roof under the same condition. The lowest indoor air temperature was 32.5 °C at point c and d, while the highest indoor air velocity at point b with 0.50 m/s. This was because of the opening on the roof surface allow the wind to enter the house through windward area on the roof surface and the hot air exit via openings on leeward area. The suction pressure at leeward area help to pull the hot air out from the house through the openings. The hot air from bottom of the house rose to the upper part of the house due to stack effect, which was driven by buoyancy forces. The difference in air temperature created difference in air density, which explained the buoyancy effect. The indoor air temperature at point b, point c and point d showed the readings similar with ambient air temperature. It showed that the indoor air temperature had reached equilibrium temperature.

Even though, the ventilated roof on low-cost house showed reduction of indoor air temperature or even equilibrium to the ambient air temperature, but it was still higher than thermal comfort temperature. Ventilated roof was applied on the same low-cost house scale with same conditions. Analysis and thermal modelling were discussed to determine whether ventilated roof on 30° would contribute to reduction of indoor air temperature close or within the thermal comfort temperature of 24 °C to 26 °C.

4.7.2 Results and Thermal Modelling on Betong's Low-cost House with 30° Pitch of Roof

After study was conducted on Betong's house with 10° pitch of roof, the ventilated roof was investigated under the same actual low-cost house dimension with different pitch of roof of 30°. The house underwent two conditions of experimental work, which were all doors and windows were full opened as well as fully closed. There were five points namely points a, b, c, d and e as shown on Figure 3.12 (page 61). From the earlier model house study, it was found that the 30° was the most effective and roof pitch, which provided more reduction towards the overheating inside the house. Therefore, the simulation was conducted on Betong's low-cost house design with 30° pitch of roof to investigate the effectiveness of the ventilated roof on different roof pitch. Table 4.9 stipulates the simulated indoor air temperature and air velocity of ventilated roof for a Betong house with adjustment of 30° roof pitch.

Table 4.9: Simulation data of ventilated roof on Betong's house with 30° roof pitch

Experiment	Point	Ventilated roof	
		CFD Simulated Air Temperature (°C)	CFD Simulated Air Velocity (m/s)
Fully Closed	a	33.5	0.22
	b	33.3	0.17
	c	33.4	0.16
	d	33.4	0.14
	e	33.5	0.22
Fully Opened	a	33.5	0.57
	b	32.4	0.51
	c	32.4	0.48
	d	32.3	0.41
	e	33.4	0.55

From the simulation data as shown in Table 4.9, it was observed that the Betong's house with ventilated roof recorded the lower temperature when the condition is fully opened. The fully closed condition showed that the indoor air temperature not much different from the ambient air temperature. In the other hand, the Betong's house with ventilated roof under fully opened condition shows reduction of indoor air temperature with 32.4 °C at point b and point c, while 32.3 °C at point d. The reduction of indoor air temperature between fully opened and ambient temperature can be up to 1.2 °C. Apart from that, the indoor air velocity inside the house at point b, point c and point d for the ventilated roof were varies from 0.14 m/s to 0.17 m/s under the fully closed condition while 0.41 m/s to 0.51 m/s for fully opened condition.

The CFD simulation for Betong's house for 30° pitch of roof was analysed and discussed. This simulation was conducted to determine the performance of the ventilated roof towards the indoor air temperature and the air movement inside the low-cost house with different roof angle. From this investigation, we can determine whether the design is suitable

for low-cost house with higher roof pitch of 30° in order to minimise the overheating issues. Figure 4.15 shows the analysis of air temperature and air velocity of Betong’s low-cost house with 30° pitch of roof.

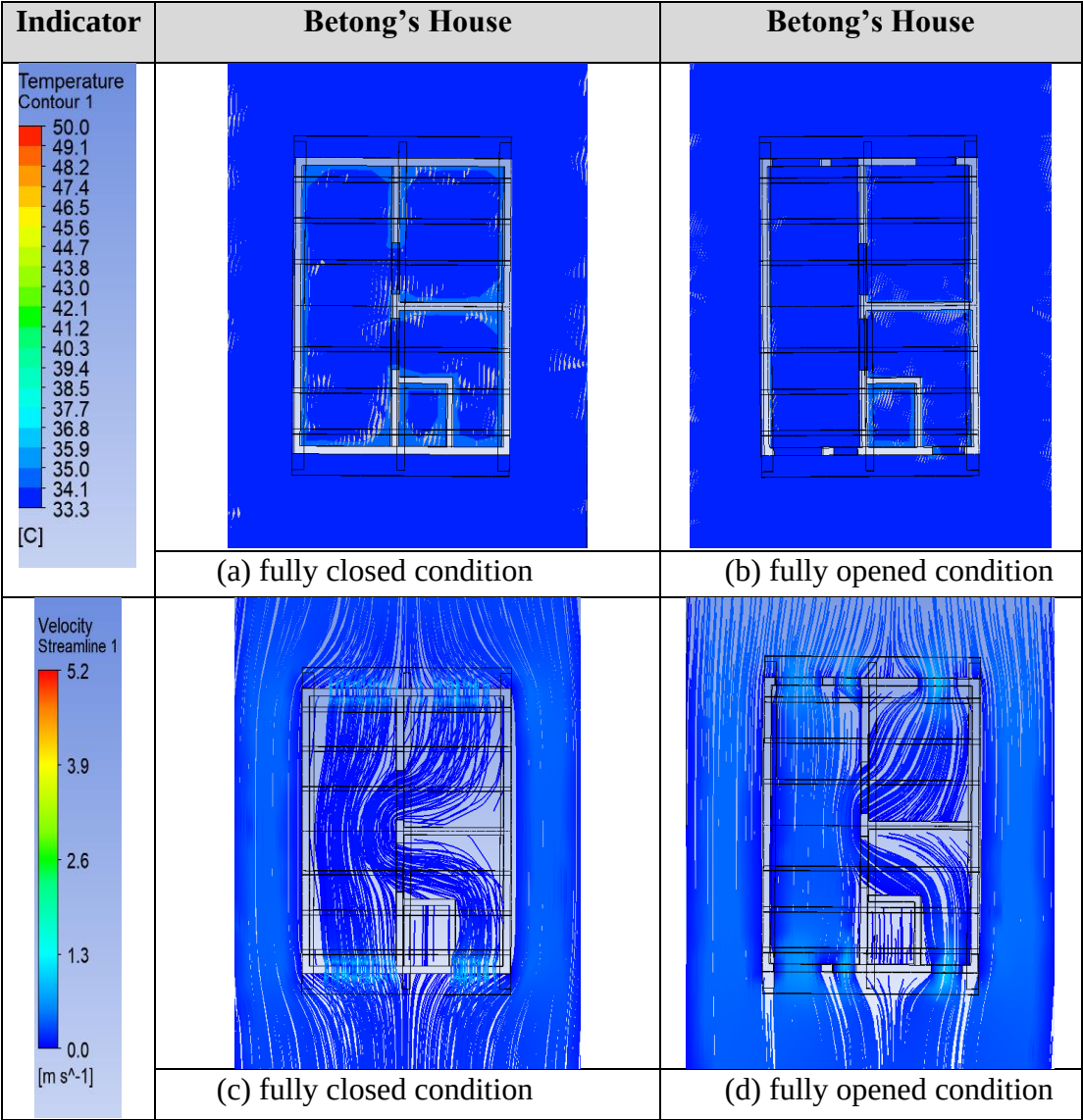


Figure 4.15: Simulated air temperature and air velocity inside ventilated roof low-cost house with 30° pitch of roof

The gradient of thermal pattern colour and air movement colour pattern can be referred at air temperature and air velocity’s indicators as provided in Figure 4.15. Based on the simulation, house with fully closed condition as shown in Figure 4.15 (a) recorded higher

indoor air temperature than house with fully opened condition in Figure 4.15 (b). The building envelope area was observed to be light blue colour, which indicates higher temperature than darker blue colour area as shown in Figure 4.15 (a). Most of the building enveloped area inside the house was darker blue colour in Figure 4.15 (b), which represent the indoor area was much cooler than colour as indicated in Figure 4.15 (a). Figure 4.15 (c) also showed that the indoor air velocity under fully closed condition was lower than the air velocity under fully opened condition. The indoor air velocity was seen in darker blue colour in Figure 4.15 (c) and light blue colour in Figure 4.15 (d). For air velocity, lighter blue colour indicated higher air velocity inside the house while darker blue colour showed lower air velocity. The higher the air velocity speed, the cooler air temperature in the indoor area.

The ventilated roof under fully closed condition was because of the opening on the roof surface allow the wind to enter the house through windward area on the roof surface and the hot air exit via openings on leeward area. The suction pressure at leeward area help to pull the hot air out from the house through the openings. The hot air from bottom of the house rose to the upper part of the house due to stack effect, which was influenced by buoyancy forces. The difference in air temperature created difference in air density, which explained the buoyancy effect. The indoor air temperature at point b, point c and point showed the readings similar with ambient air temperature. It showed that the indoor air temperature had reached equilibrium temperature.

The opening on the ventilated roof permitted the wind to enter the house through windward area on the roof surface and the hot air exit via openings on leeward area. The suction pressure that occurred on the leeward area assist to remove the hot air from the house through the openings. The hot air from bottom part rose to the upper part of the house due to stack effect, which was driven by buoyancy forces. This air temperature differences

created air density differences and explained the buoyancy effect. The indoor air temperature for fully closed condition recorded up to 0.2 °C lower than the ambient temperature. This showed that the 30° pitch of roof does contribute to further reduction of indoor air temperature as compared with 10° pitch of roof for ventilated roof on Betong's low-cost house under fully closed condition.

The ventilated roof on low-cost house showed reduction of indoor air temperature and it was lower than the ambient temperature for both fully closed and fully opened condition. However, it still higher than occupant's thermal comfort level. Therefore, future study shall be focussed on enhancement for further indoor air temperature reduction within thermal comfort by using ventilated roof and the recommendation was proposed in Chapter 5 of this study.

4.8 Reduction of Indoor Air Temperature by Using Ventilated Roof

Based on the result and data obtained from on-site experiment and simulation, the data was validated before can proceed with other simulation with different roof angles and house scale. This study showed that the highest percentage difference was 7.2%, which was still within the acceptable variations for validation purposes. From the simulation, it was known that the performance of ventilated roof was able to enhance the natural ventilation into the modern house. In additional, the ventilated roof also improves air circulation inside the house. This was proven by reduction of indoor air temperature and the air velocity inside the house model through on-site experiment and simulation.

From this study, the indoor air temperature in ventilated roof house was able to reduce indoor air temperature even though the condition was under fully closed condition. The air velocity inside ventilated roof house was higher than the common roof. Hence, the

ventilated roof promotes lower indoor air temperature and higher air velocity inside the house as compared to common roof. Thus, it also able reduce the overheating inside the house during the hottest time of the day without the mechanical ventilation system for cooling purposes. Ventilated roof also promotes energy consumption and cost saving because it only depends on natural means.

Study conducted by Ibrahim et al. (2014b) revealed that the indoor air temperature is substantially reduced due to the openings provided on the roof surface. The principle of removing the hot air from the house through the openings in ventilated roof was based on stack effect and wind driven effect. According to Roslan et al. (2015), ventilated roof approach promotes the natural ventilation through stack effect and wind driven effect. Previous studies by researchers agreed that the ventilated roof approach can reduce the indoor temperature and minimise the amount of heat transfer (Al-Obaidi et al., 2014a; Qasim et al., 2010; Trinuruk et al., 2007).

Colour of the roofing play essential role in heat transfer. This is because of the colour of the roof used in this study was dark grey colour and the roof pitches were 10°, 30° and 45°. Based on the findings, ventilated roof worked best at 30° pitch of roof. Darker colour absorbed more heat as compared to lighter colour (Al-Yacoubi et al., 2011b). Apart from that, pitch of roof also contributed to the amount heat gain into the house. According to the Al-Obdaidi et al. (2014b), the darker colour with 0° pitch of roof recorded higher indoor air temperature as compared to 30° pitch of roof. From this simulation exercise, it explained that the 30° roof pitch is the best roof angle for the ventilated roof design. Therefore, the performance of ventilated roof with 30° roof pitch would enhances the passive design to reduce the overheating especially for modern low-cost house.

The roofing materials also play important role in their ability to transmit amount of heat transfer into the house. This study investigated the heat transfer inside the house between common roof and ventilated roof by using the same material but different design and roof angles. It showed that ventilated roof was able to show reduction of indoor air temperature and improve air movement inside the house. Although indoor air temperature inside house with ventilated roof does not meet the occupant's thermal comfort level, the potential of ventilated roof to further reduce the indoor air temperature within 24 °C to 26 °C can be investigated and can be potentially achieved in future study.

Removal of hot air through stack effect and wind driven effect as the strategies were discussed. Both has potential as the best choices for cooling through natural ventilation. With this approach, the dependency on mechanical system can be reduced especially during daytime or night-time. A well-designed ventilated roof would enhance the reduction of overheating temperature inside a building (Ciampi et al., 2005; Roslan et al., 2015). This showed that the ventilated roof is one of the best approaches in good passive design of modern low-cost house.

4.8.1 Removing the Hot Air with Stack Effect

Stack effect is always one of the good options in enhancing the passive design of a house. The stack effect is driven by the temperature difference of internal and external environment (Mijorski & Cammelli, 2016). Further to this, Rahman et al. (2009) and Tatarestaghi et al. (2018) concluded that the stack effect would help to reduce the indoor air temperature. The ventilated roof approach is a great deal because of the design on the roof allow more openings for hot air to quickly exit. Based on the data obtained through on-site experiment and simulation, ventilated roof provides more openings area to allow the air to

enter the house and circulate naturally. When the wind that enter the house, it helps to increase the efficiency of natural ventilation into the house. Ventilated roof able to provide better air circulation inside the house.

Based on Choi et al. (2005), the efficiency of stack effect depends on the wind speed and wind direction. Figure 4.16 shows the occurrence of stack effect inside the model house for ventilated roof under fully opened condition.

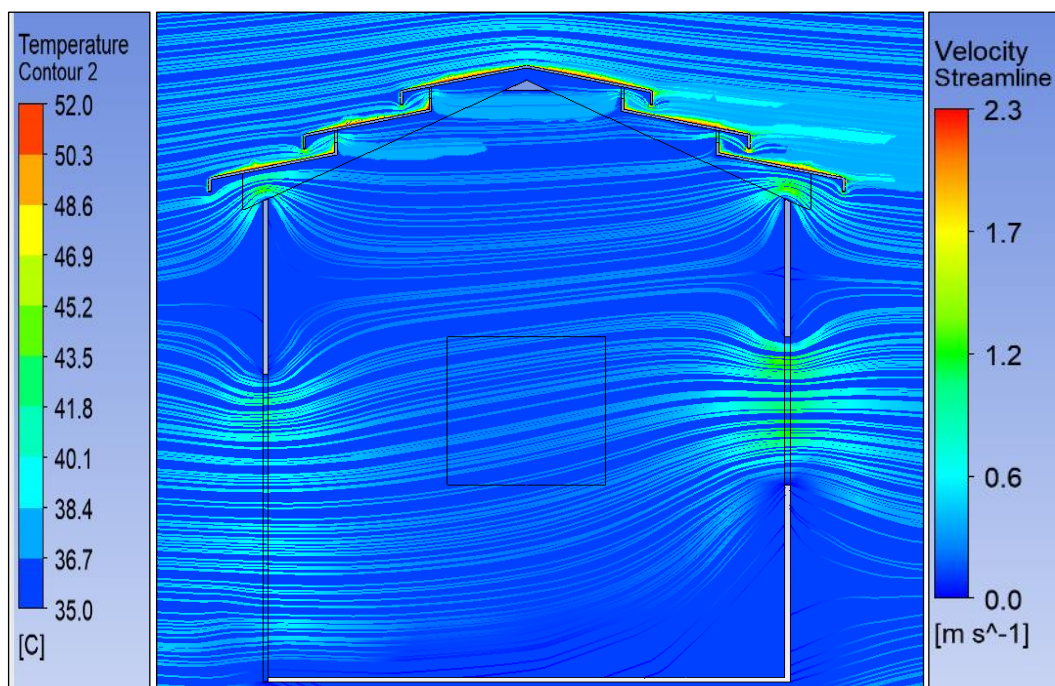


Figure 4.16: Stack effect simulation for model house with ventilated roofing system

Based on Figure 4.16, the openings on the roof surface enhances the stack effect. The wind enters and exits the model house through windows, door and roof openings. The upper right area as shown in Figure 4.16 shows that the temperature escaped through the openings on roof surface of the model house was higher than the indoor air temperature. Ismail et al. (2012b) discovered that roof surface temperature is depend on the roof ventilation provision.

The indoor air temperature remains lower, which explained the darker blue colour inside the model house.

Stack effect also occur on model house with ventilated roof under fully closed condition. Even though the condition of the windows and door for model house with ventilated roof was fully sealed, the openings on the roof surface allows the wind to enter the model house and permit the stack effect to occur. According to Neama (2016), the stack effect drives the air movement with the combination of the different densities of indoor and outdoor environment, which the higher temperature difference, the stronger the pressure differences. The findings of this study show that the model house for ventilated roof under fully closed condition recorded lower indoor temperature compared to common roof due to stack effect.

4.8.2 Removing Hot Air Through the Wind Driven Effect

In the simulation, it showed that the hot air was escaped from the internal area through the opening of ventilated roof. The hot air rises from bottom part to the roof area due to density differences. The openings on the roof ease the removal of the hot air. The cooler air has a higher density compared to hot air. The cooler air travel to the lower part of a house or building while the hot air rise to the upper part due to density differences. According to Chenvidyakarn (2007), ventilated cooling by wind approach provides the internal air movement and heat removal from the interior due to pressure differences between internal and external area. In the ventilated roof design, the openings provide the area for the hot air to exit. At such, the opening also allows the ambient air from outside environment with lower temperature or cooler air to travel into the house, while the hot air from the bottom part of the house travels into the outside environment.

The wind driven effect occurs when the wind flows to the roof and creates pressure on the roof surface. Thus, the positive and negative pressure which also known as windward and leeward respectively are formed on the roof surface. The negative pressure creates suction pressure, which play essential role to pull the hot air from the openings area into outside environment. Therefore, the wind driven effect enhances the removal of hot air via density differences. Figure 4.17 shows the effect of wind driven on the roof surface through simulation.

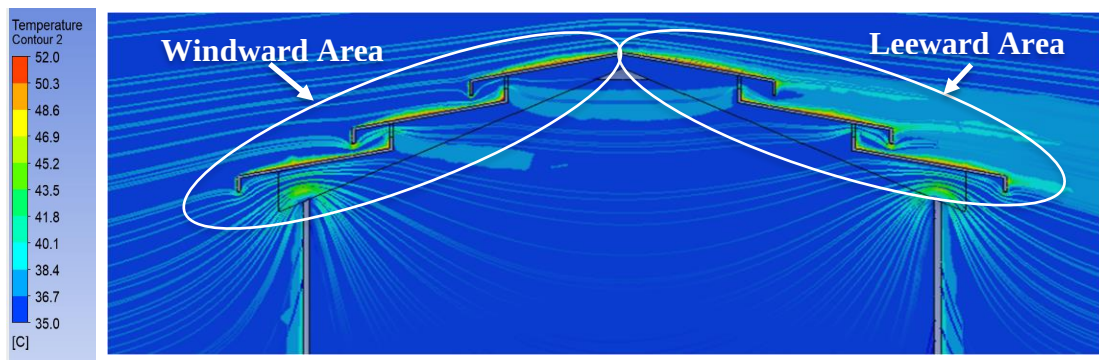


Figure 4.17: Windward and leeward area

Based on the Figure 4.17, the temperature at leeward area was higher and warmer than other area. The openings on the roof surface allow the wind to go through the house by positive pressure at windward area and exit through openings on leeward area by negative pressure called suction pressure. The suction pressure at leeward area also help to pull the hot air from the house through the openings. The hot air from bottom of the house rose to the upper part of the house due to stack effect, which was developed by buoyancy forces. This buoyancy effect happened because of the differences of air temperature, thus created difference in air density.

4.9 Chapter Summary

This chapter presented the result and discussion from on-site experiment including initial test and simulation for model house. Apart from this chapter explained the result from the simulation for modern low-cost house located at Betong, Sarawak. The results obtained from experiment and simulation were further discussed in detail and compared. From the findings, it is agreed that openings on the ventilated roof surface enhances the passive design by maximise the use of natural ventilation for cooling purpose. The ventilated roof also able to minimise the heat transfer from roof surface to lower area of the house. The ventilated roof design had applied the concept of stack effect and wind driven effect. Finally, it can be concluded that ventilated roof strategy able to reduce the indoor air temperature inside the house. However, the reduction of indoor air temperature was not able to reach thermal comfort level between. In the next chapter, the summary of the study and recommendations were further discussed in detail to enhance the ventilated roof in future study.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Introduction

This chapter explained the summary and conclusion of this study after findings both ventilated roof and common roof designed were discussed and evaluated. From this study, it is found that the indoor air temperature for ventilated roof recorded lower temperature than common roof design. The findings also found that difference of roof pitches provide different indoor air temperature readings. This study also revealed that fully opened condition will give high impact of indoor air temperature as compared to fully closed condition for both ventilated roof and common roof designed. This showed that the importance to have adequate openings in house design in order to maximize the natural ventilation and at the same time reducing the dependent on mechanical ventilation system for cooling purposes. The objectives were discussed further in detail to incorporate with the findings. In this chapter, few recommendations were suggested to improve the area of study for future work, which could improve the proposed ventilated roof design.

5.2 Summary

As stated in Chapter 1, there were three objectives to be achieved in this study. The first objective was to validate the proposed ventilated roof and common roof. The data for validation was obtained through on-site experiment and simulation process. The differences between these two data were expressed in percentage difference for air temperature and air velocity. The percentage difference of data between on-site experiment and simulation for air temperature were 7.2% for common roof and 2.1% for ventilated roof. While percentage

difference of data for air velocity between on-site experiment and simulation were 6.7% and 6.3% for common roof and ventilated roof respectively. Both percentage difference for air temperature and air velocity were within allowable difference variation of 20% limit. Therefore, the first objective to validate the proposed ventilated roof and common roof was achieved.

The second objective was to investigate thermal performance of proposed ventilated roof tiles design with different roof angles through simulation. After the validation was conducted, the thermal performance of proposed ventilated roof was conducted through simulation with different pitch of roof. The proposed ventilated roof was simulated on 10°, 30° and 45° under fully closed condition and fully opened condition. The data obtained from simulation was compared with simulation data of common roof under the same conditions. Throughout the analysis, it was found that ventilated roof on 30° pitch of roof under both fully opened and fully closed condition recorded the lowest indoor air temperature, followed by 45° and 10° pitch of roof under the same condition. Same goes with analysis of common roof design at which the 30° pitch of roof recorded lowest indoor air temperature, followed by 45° and 10° pitch of roof under fully closed and fully opened condition. The findings revealed that ventilated roof tiles at 30° pitch of roof provides better or cooler indoor temperature as compared to others and the roof angles was selected for further analysis on actual low-cost house scale design through simulation. Therefore, the second objective was achieved.

The third objective was to determine the thermal performance of proposed ventilated roof tiles on the modern low-cost house. The ventilated roof tiles were applied on actual low-cost house scale design through simulation to investigate the thermal performance on the actual house scale modelling. Previous study on thermal comfort inside low-cost house

in Betong, Sarawak was conducted and the data were used for simulation and comparison purposes. The findings showed that ventilated roof tiles provide lower indoor temperature as compared to common roof on 10° pitch of roof for this low-cost house. The ventilated roof was applied on 30° pitch of roof on the same actual house scale through simulation and the data showed that it recorded lower indoor air temperature than 10° pitch of roof. The application of ventilated roof tiles can be recommended on modern low-cost house with 30° pitch of roof. This showed that ventilated roof performs better on 30° pitch of roof. Thus, the third objective was achieved.

5.3 Conclusion

In conclusion, the design of low-cost house in Betong was lack with ventilation provision thus, the ventilated roof approaches help to reduce the indoor air temperature inside the house especially during the hottest time of the day without using any mechanical ventilation. The ventilated roof was tested and verified with its functionality and effectiveness of the roof to reduce the indoor temperature as compared to common roof design. The application of the ventilated roof provides more opening areas for the hot air to exit easily. The ventilated roof also enhances natural ventilation into the house, thus can help to reduce the electricity usage to cool internal area of the house especially in the early morning or night-time.

Even though the ventilated roof did not achieve the thermal comfort temperature inside the house during peak hour or hottest time, this study has shown that it successfully reduces the indoor air temperature as compared to common roof design. This study also shown that the application of the ventilated roof was based on the stack effect and wind driven effect. The openings on the roof surface provide area for stack effect to occur

effectively in modern low-cost house especially when all door and windows are opened. Moreover, the density differences enhance the movement of hot air to travel upwards and exit easily through the opening provided at roof surfaces. Thus, making the wind driven effect works efficiently. The ventilated roof works effectively on 30° or lower roof pitch. Therefore, this study suggested that the application of ventilated roof on the roofing system is recommended, especially for the modern low-cost house.

5.4 Recommendations

This research has opened to several new possibilities and further study to be conducted in the future. Even though some new knowledge and skills have been gained throughout this study, many issues still need to be addressed and acknowledged. It can be a value-added into high end applications. Future research should therefore concentrate on improvement of the current ventilated roof design in order to achieve the indoor thermal comfort the suggestions that should be addressed during the experimental work of this study as following:

- i. To improve the performance of ventilated roof, cool roof's coating namely Apex Ultima Acrylic Emulsion can be applied on the ventilated roof surface shall be investigated for further heat gain reduction.
- ii. The design can be improved by adding in the insulation material underneath the ventilated roof or on the surface to help reflecting solar radiation and only allow small amount of heat transmitted through into indoor areas.
- iii. More experiments on other parameters shall be examined through this study such as relative humidity, noise measurement, pressure measurement, indoor air quality and so forth.
- iv. To conduct experiment of ventilated roof on actual low-cost house.

- v. To consider adaptation of hybrid ventilated roof using small fans and solar panel.

The solar panel is functioned to generate electricity to power the small fans.

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APPENDIX

Publications

Journal

Ibrahim, S.H., Roslan, Q., Affandi, R., Razali, A.B. Samat, Y.S., & Nawi, M.N.M. (2018). Study on the Ventilated roof Type with 30° Roof Angle to Enhance Natural Ventilation and Air Circulation of a Passive Design. *International Journal of Technology*, 9(8), 1692–1701.

Roslan, Q., Ibrahim, S.H., Affandi, R., Mohd Nawi, M.N., & Baharun, A. (2016). A Literature Review on The Improvement Strategies of Passive Design for The Roofing System of The Modern House in A Hot and Humid Climate Region. *Frontiers of Architectural Research*, 1(5), 126–133.

Poster Presentation

Ibrahim, S.H., Roslan, Q., Baharun, A., Abidin, W.A.W.Z & Koesmeri, D.R.A. (2017). *Ventilated roof Design for Hot Humid Climate*. Innovation Technology Expo 2017, Sarawak, Malaysia.

Ibrahim, S.H., Roslan, Q., Baharun, A., Abidin, W.A.W.Z & Koesmeri, D.R.A. (2017). *Ventilated roof Design for Hot Humid Climate*. 5th Postgraduate Borneo Research Colloquium 2017, Sarawak, Malaysia.

Awards and Honours

Innovation Technology Expo (InTEX 2017), 17th – 18th May 2017, DeTAR PUTRA UNIMAS, Sarawak, Malaysia – Silver Medallist – Ventilated roof Design Concept for Hot Humid Climate.