INTEGRATION OF ACTIVE AND PASSIVE COOL ROOF SYSTEM FOR ATTIC TEMPERATURE REDUCTION IN GUARDHOUSE

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A project report submitted in partial fulfilment of the
Requirements for the award of Bachelor of Engineering
(Honours) Mechanical Engineering

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April 2020

DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

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APPROVAL FOR SUBMISSION

I certify that this project report entitled **"COOL ROOF SYSTEM FOR GUARDHOUSE"** was prepared by **LINGESWARAN A/L SUNDARAMORRTHY** has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of Engineering (Honours) Mechanical Engineering at University Tunku Abdul Rahman.

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ABSTRACT

This research project investigates the cooling effect of a roof system which is designed to enhance the comfort ability of guardhouse occupants with attic temperature reduction. Malaysia is considered as an equatorial climate country which having a hot-humid climate all the year. Therefore, an ideal cool roof system was developed with the implementation of thermal reflection coating (TRC), vacuumed rockwool insulation, polished aluminium sheet and solar powered fan for ventilation system as a space cooling device for houses in Malaysia. The selection of an efficiency cool roof system is carried out with a total of eight models fabricated and experimented for each aspect of heat transfer mechanisms (conduction, convection and radiation). The design that shows the best cooling efficiency is selected and implemented into the main design which is design X. The model simulation was carried out in a heating chamber by utilising the halogen lamp as the replacement for solar irradiation provided by the sun. Two passive cooling method were introduced in this research project which are vacuumed rockwool insulation and polished aluminium sheet. For vacuumed insulation, it was able to reduce 1.75 °C compared to normal insulation. For polished aluminium, sheet it was able to reduce 1.5 °C compared to unpolished aluminium sheet. Besides that, one active cooling method was introduced which is solar powered fan. The solar powered fan is consider as forced convection. Where it was compared to a ventilation hole which is consider natural convection. Hence from the results forced convection was able to reduce 1.25 °C more than natural convection. The result of this eco-friendly cool roof system (design X) has successfully reduced the attic temperature by 8.5 °C compared to the normal roof model (design A). As a result, this integrated cool roof design comprises the ability to enhance the comfort of guardhouse occupants with sustainable renewable energy.

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c_p	specific heat capacity, J/(kg·K)
h	height, m
K_d	discharge coefficient
M	mass flow rate, kg/s
P	pressure, kPa
P_b	back pressure, kPa
R	mass flow rate ratio
T	temperature, K
v	specific volume, m^3
α	homogeneous void fraction
η	pressure ratio
ρ	density, kg/m^3
ω	compressible flow parameter
ID	inner diameter, m
MAP	maximum allowable pressure, kPa
MAWP	maximum allowable working pressure, kPa
OD	outer diameter, m
RV	relief valve

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CHAPTER 1

INTRODUCTION

1.1 General Introduction

It is a common scenario in Malaysia where it is essential to have a guardhouse placed at housing areas. As per norm, guardhouse is found to be placed at the entrance. A certain criteria that makes a guardhouse is the area needed, number of floors which is usually one, roof and walls. The roof plays a major role in preventing the radiated heat from the sun entering the interior of guardhouse.

According to (Dehghannya, et al., 2019), the density of air is being altered with the change of temperature, pressure and humidity whereby the cool air becomes denser than warm air. Cool air is proven to be denser than warm air due to the closely packed molecules. This causes the bond to absorb less energy that leads to limited movement of the molecules. This causes the warm air to rise and cool air to sink (Figure 1:1). The main reason the warm air rises is because the cool air pushes the warm air up as it sinks. This process is called the convection current. The second law of thermodynamics states that the heat always flows from hot to cold. For example, ice cube melts (absorb heat) in the process of changing phase from solid to liquid. It is still possible to make a cool object remain cool in a warm environment such as refrigerator, but it requires electrical energy.

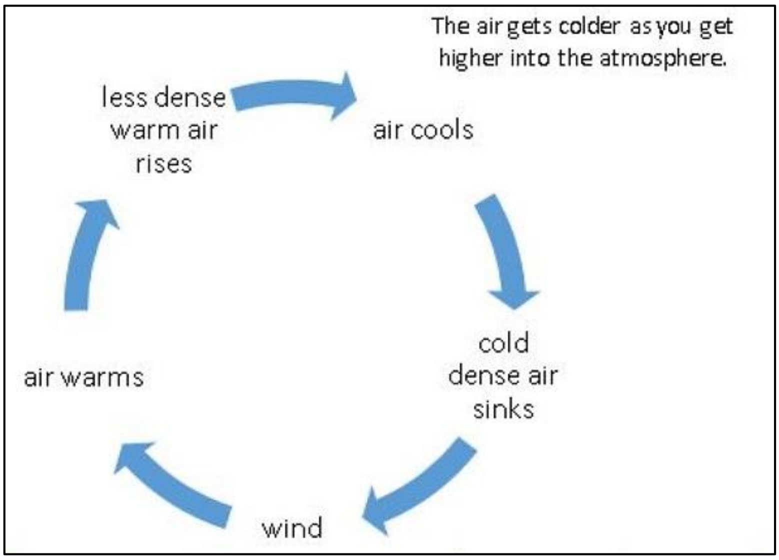

Figure 1:1: Shows convection of air (Dehghannya, et al., 2019).

There are four seasons in total which are summer, winter, spring and autumn but since Malaysia is located on the line of equator (garisan khatulistiwa). Therefore, Malaysia consists of only rainy and sunny days. The classification of monsoon seasons in Malaysia can be divided into two which are the Southeast monsoon and Northeast monsoon. As for the Southeast monsoon, they are more towards sunny days compared to rainy where its vice versa for the Northeast monsoon. According to the report in 2017 by Suruhanjaya Tenaga Energy Commission Malaysia (ST), the Southeast monsoon has an average temperature recorded which is 29 °C while the Northeast monsoon is 28 °C. For both monsoon season, the outdoor temperature is measured to be 27 °C to 28 °C and the attic temperature could reach up to 32 °C to 36 °C (Ahmed, Abdul Rahman and Zain-Ahmed, 2005). There are two main factor that affects the attic temperature which are Solar Reflectance and Thermal Emittance (Figure 1:2). According to (Abdul Rahman, Ahmed and Zain-Ahmed, 2004) the trapped hot air in attic during daytime becomes the major source of heat. With the help of the heat transfer mechanism, the hot air will be transferred into the building's interior.

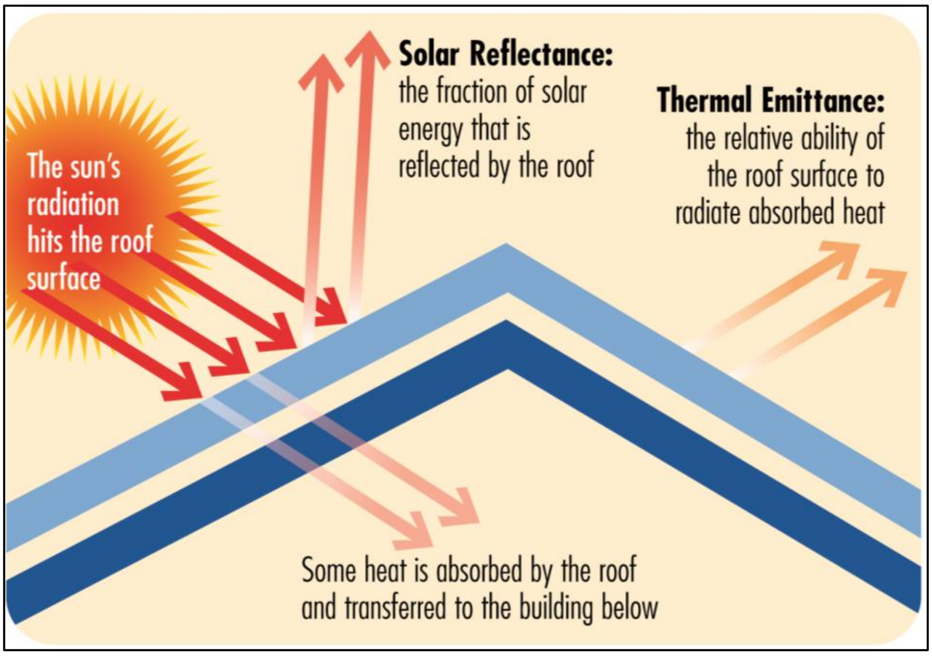

Figure 1:2: Explains how heat from the sun, radiates to the buildings (Levinson, 2019).

A roof is the main part of a building where its job is to protect the building against natural phenomenon such heavy winds, rain and heat from the sun. Heat to guardhouse by heat transfer mechanism. There are three types of heat transfer mechanism which are; conduction, convection and radiation. The surface of the roof receives radiated heat from the sun where conduction takes place at the roof itself. The heat will then undergo convection process and radiate into the interior of the guardhouse. The best way to cool down the guardhouse without air conditioner is to reduce the temperature in attic. It is because heat from the roof is transmitted via convection and radiation to the attic where the heat will be trapped. The temperature in attic will be higher than the surrounding temperature, if more heat is trapped in attic space. This will enhance the convection/ radiation of the heat into the guardhouse by ceiling. This cooling method is not only suitable for guardhouse but it is compatible with every building that has a roof top. This can be proved as 30 % to 35 % heat enter to building is from the roof, 21 % to 31 % heat through windows, 18 % to 25 % through walls and 12 % to 14 % through floor (Abdul Rahman, Ahmed and Zain-Ahmed, 2004). From this it can be conclude that, roof is the highest source of heat that is produced in a building. An ideal roof insulation could keep the attic space cooler in the summer and retain warmth in winter (Figure 1:3).

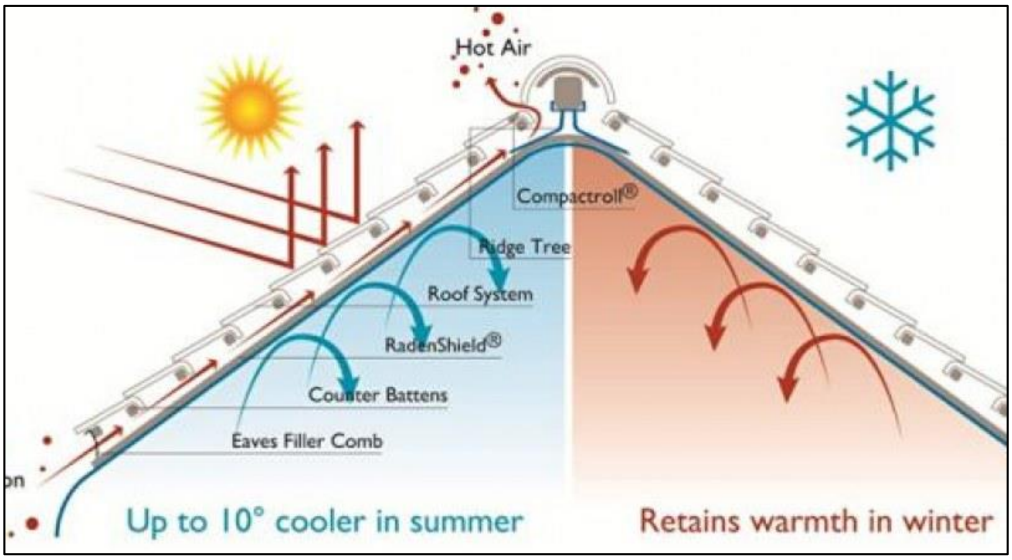

Figure 1:3: Analysis of cool roof system (Mishra, 2016).

1.2 Importance of the Study

The findings of this study contribute greatly to society and the future. A proper research is carried out to identify ways to reduce the temperature of a building by minimizing or using zero non-renewable resources that can preserve the environment. With the invention of cool roof system, the energy demand will be reduced drastically and also provide comfortable work space for the people in the building. As mention in the introduction, this cooling method is not only suitable for guardhouse but also compatible with every building that has a roof top.

The main aim of this research is to reduce each aspect of heat transfer mechanism, in terms of conduction, convection and radiation. As a results, thermal insulation, attic fan, and radiant heat barrier will be applied to reduce the temperature in the guardhouse. In addition, the thermal reflection coating will be applied on the surface to study the effect on the attic temperature.

1.3 Problem Statement

Global warming is becoming a serious issue in the world. The oceans and atmosphere getting warmer, the snow and ice volumes have decreased, sea levels has increased, and greenhouse gas concentrations has risen. Nearly the whole globe has undergone global warming based on the recent changes in surface temperature. Malaysia is no exception as the temperature over here has been increasing over the decade. To prove this statement, (Trading Economics, 2018) has recorded the average temperature of Malaysia since 2009 to 2018. Figure 1:4 shows the recorded average temperature from 2009 to 2018. Based on Figure 1:4, year 2009 has an average temperature of only 27.8 °C. After 5 years in year 2014, the temperature rises till 30.6 °C and in year 2018 the average temperature was 32.4 °C. According to data collected, the temperature is rising exponentially.

Figure 1:4: Average temperature recorded in Malaysia (Trading Economics, 2018).

Malaysia faces hot-humid weather all year round and in most towns the monthly mean air temperature and humidity is almost unchanged. As seen in Figure 1:5, cooling is the major consumption of electricity in Malaysia building in year 2015. The reason why cooling need high consumption of electricity is because the temperature of the building is high and causes discomfort to the people. In order to solve this issue, air-conditioner (cooling) is used to achieve their thermal comfort. High usage of air- conditioner leads to consequences where it causes an increase in global warming. According to ST (2017), stated that a standard air-conditioner is the largest contributor of electricity consumption with an average recording of 1,167 kWh of electricity.

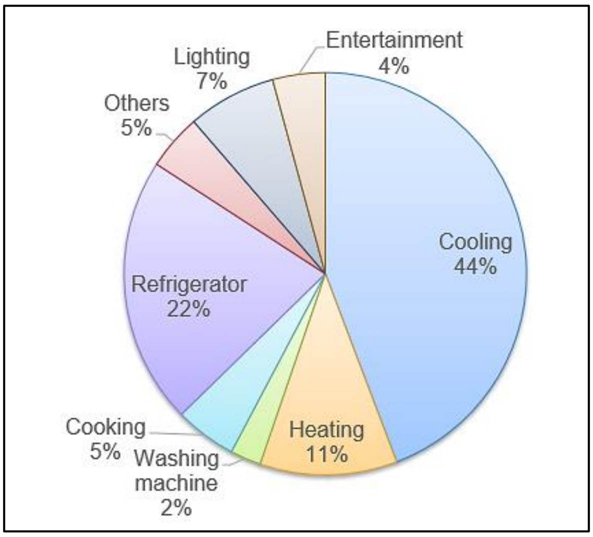

Figure 1:5: Average electricity consumption in buildings in Malaysia during 2015 (ST, 2017).

Furthermore, based on Figure 1:6, it is stated that energy consumption has been increasing since year 1990 as well as the consumers. According to (World Bank, 2018), over the past 50 years, the total population has increased from 18 million in 1990 to 30.2 million in year 2015. As mention earlier, air-conditioner consumes a lot of electricity hence, according to ST (2017), states that a standard air-conditioner need 296 ktoe per year to produce energy. That is a lot of gas emission to the atmosphere by burning crude oil to produce energy. According to (Kubota, Jeong and Dorris, 2009), in Malaysia one household will have at least one unit of air conditioner. Moreover, our three main source of electricity production is oil, coal and gas. These three are non- renewable source. The worst part of this scenario is three of these sources produce by-product when it is burnt, which leads to global warming. In Malaysia, Renewable and Nuclear energy is utilized less even though they do not produce greenhouse gases.

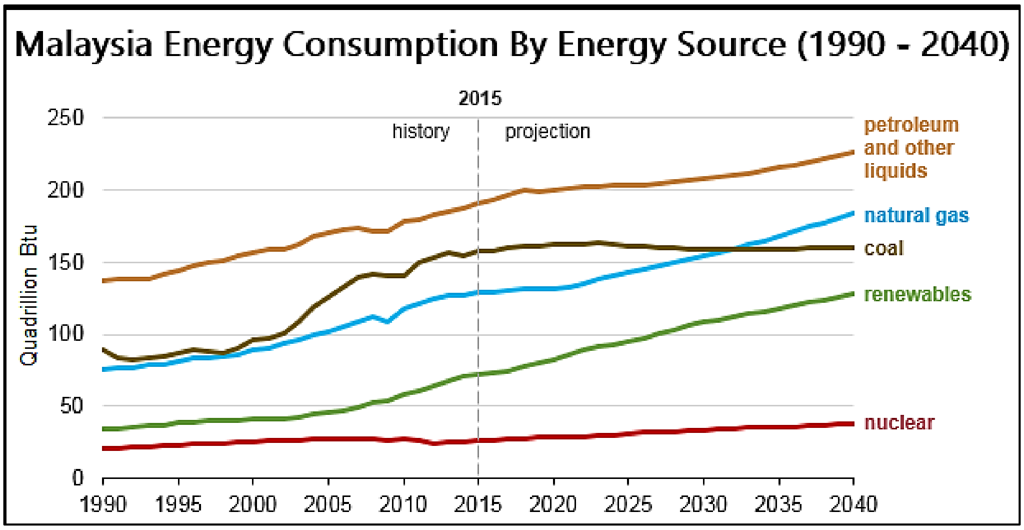

Figure 1:6: Energy consumption and prediction for each source in Malaysia (ST, 2017).

Achieving a thermal comfort without the use of active energy consumption measures is a major challenge for hot and humid environments. Studies have shown that these climatic circumstances area requires ventilation and dehumidification (Abdul Rahman, Ahmed and Zain-Ahmed, 2004). Humidity concentrations play an important part in the ability of evaporation of air. When the humidity is high, the increase of vapour pressure prevents evaporation and restricts the cooling impact unless there are greater air velocities. Moreover, according to (Trading Economics, 2018) has reported the average humidity in Malaysia is 87 %. Besides that, guardhouse also would have workers who is responsible for safety of its corresponding housing area. According to (Nidhi, 2018), the temperature of the workplace affects the productivity of the workers. High temperature distracts the workers from concentrating on their work. Therefore, this research identifies the right temperature to work in which is around 22 °C to 24 °C and it is a major challenge to achieve this temperature without using an air-conditioner.

1.4 Aim and Objectives

The aim of this research is to analyse the efficiency of reduction in temperature of the attic spaces in the guardhouse in order to improvise the interior factor of the building spaces in both hot and humid environment. The findings of this research can be used for further improvisation of cooling systems of similar functions that is currently being developed. In order to achieve the aim, the specific objectives of this study are defined:

1. To design and fabricate the cool roof system models for roof and attic temperatures measurement.
2. To evaluate the performance of the cool roof system that is implemented by the integration of thermal insulation coating, insulation material, radiant heat barrier material and heat removal using convection method.

1.5 Scope and Limitation of the Study

In this research, the scope covers the efficiency to cool the guardhouse and improvisation of the existing cooling system in order to remove heat more efficiently along with exploring plenty of new ways or technology to cool the guardhouse. It also includes the knowledge on how heat transfer mechanism works and how naturally heat travels in the environment. In this research there are some limitations;

1. There a lot of types of roof material. The data obtained from the research might differ for different roof material.

2. In Malaysia the weather is not constant throughout the year, considering the temperature, humidity and wind speed. Hence the data obtained from this research wouldn’t be very accurate when applied outdoor.
3. For roof building there are many types of structure and different types of inclination of roof. Moreover, in this research only 30° inclination and pitched type roof is studied. Hence, the date obtained in this research varies if applied to different types of roof and inclination.
4. The method in this research is more efficient for cooling system and will not be suitable for heating system (winter/cold countries).

1.6 Contribution of the Study

The contribution of this study will lead to the ways of cooling method and to reduce temperature in attic space. Besides that, with less consumption of energy, thermal comfort for people in the building could be achieved easily. Furthermore, this study explains how heat flow into the building and how heat mechanisms works. In addition, in this study only renewable energy powered cooling system is utilized for sustainable development approaches.

1.7 Outline of the Report

In this report, there are five chapters. Chapter 1 is mainly about introduction of this research. In chapter 2, literature review will be discussed based on active and passive cooling system. Chapter 3 shows how this study has been done and what cooling method is applied. In chapter 4 shows the results obtained from implementing cooling system and comparison of which cooling system works efficiently and selecting the best design. Chapter 5 is about how the attic model reduces the attic temperature when being implemented in the selected design. Chapter 6 is mainly about recommendation and conclusion of this study.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In this chapter, a brief explanation of the cooling mechanism system, working mechanism, different types and designs of cooling system will be discussed.

2.2 Active cooling systems

An active cooling system is a cooling system that depends on an external device such as electric fan to improve the transfer of heat. In other words, active cooling means forced convection (Figure 2:1). The rate of liquid flow rises during convection through active cooling systems, which significantly improves the rate of thermal removal. Forced air out or in through a fan or blower, and also forced liquid and thermoelectric coolers (TECs) are active cooling methods that can be used to enhance thermal management at all levels. Fans are utilized when there is inadequate natural convection to remove heat. Active cooling system's primary limitation is that it involves the use of electricity, resulting in greater expenses compared to passive cooling.

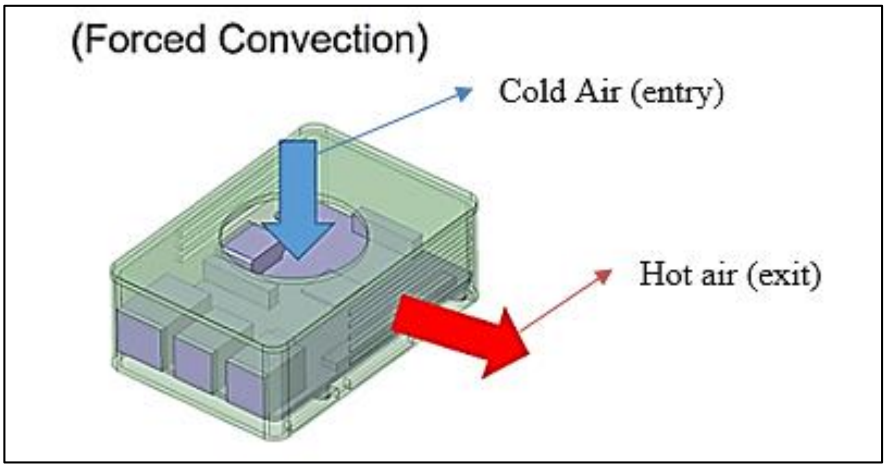

Figure 2:1: Flow of forced convection (Andrea, 2019).

2.2.1 Solar powered fan and open attic inlet

Solar powered fan would not use any electricity and an open attic inlet would be similar to the Figure 2:2. Solar powered fan would not need any electricity because it is dependent on sunlight. According to (Yew, et al., 2018), solar powered fans have been used to improve the airflow rate within the cavity by pulling out heat before being transferred to the attic. Solar powered fan only works when there is sunlight available. The disadvantage of solar powered fan is it does not function without sunlight. The roof needs to be cooled down when there is sunlight because sunlight is the main cause of increase in the temperature of attic. During night or cloudy/rainy days, the temperature of the attic would not be high compared to sunny days. Hence, the solar powered fan will turn on automatically where there is sunlight and it will extract hot air from inside to outside of the attic. This will reduce the temperature in the attic, as well as the energy usage of air conditioner. Even though the solar powered fan malfunctions, buoyancy in the air still remain whereby when the temperature rises, the hot air will eventually rise and escape through the open attic (Chong, et al., 2011). However, it would not be efficient without the solar powered fan as well as the open attic inlet. With solar fan and open attic inlet the cooling of the attic will be efficient.

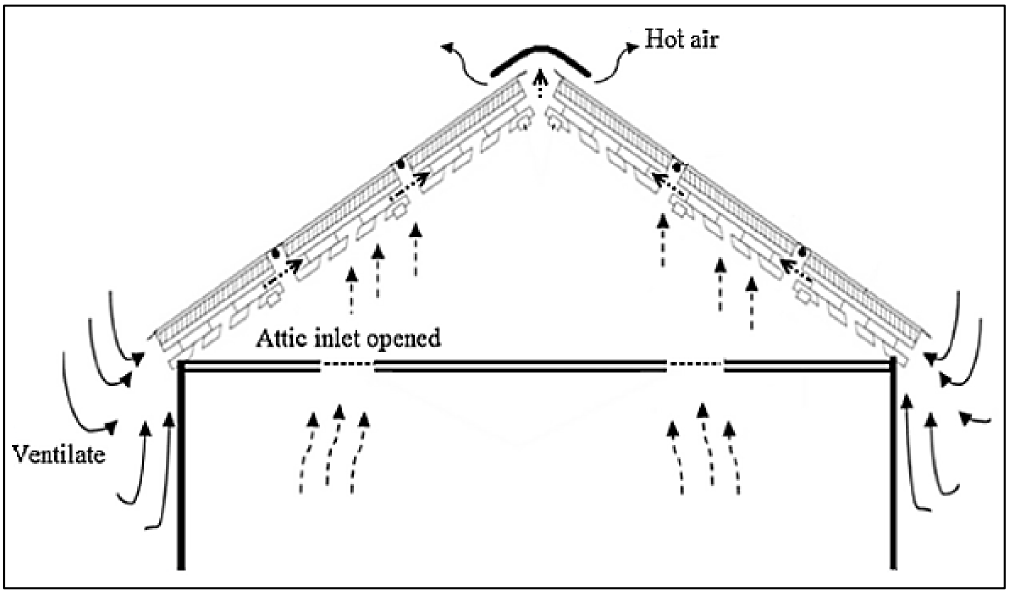

Figure 2:2: The flow of air and label in roofing system (Yew, et al., 2013).

2.3 Passive cooling system

Passive cooling is a building design strategy that emphasize on the controlling of heat gain and heat dissipation in a construction to enhance thermal comfort with reduced or no power consumption. In other words, passive cooling means natural convection (Figure 2:3). This strategy operates either by not allowing heat to enter the interior (prevention of heat gain) or by eliminating heat from the building (natural cooling). With the combination of the structural design of building part's natural cooling make use on-site energy from the atmosphere, rather than mechanical heat dissipation technologies. Therefore, natural cooling relies not only on the building's structural design, but also on how the natural resources of the site are used (i.e. all that absorbs or dissipates heat). Compared to active cooling methods, passive cooling methods have the benefits of energy efficiency and reduced economic costs.

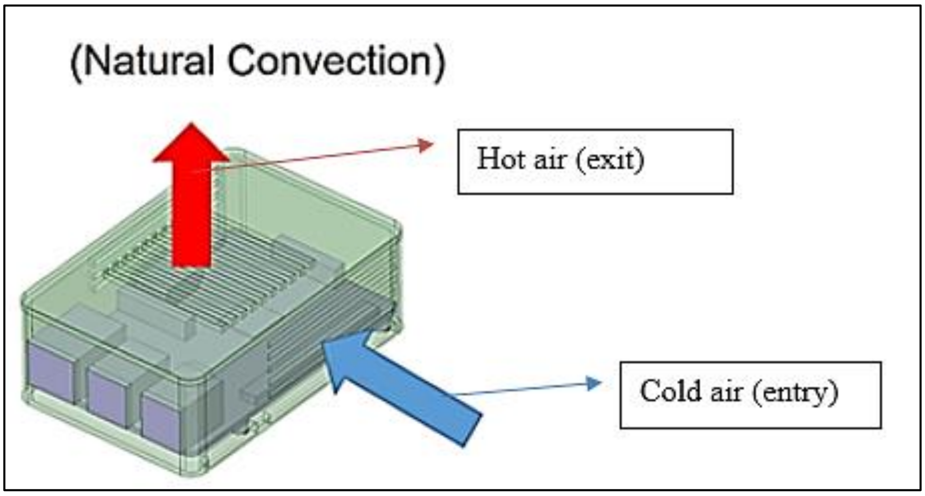

Figure 2:3: How air flow in natural convection system (Andrea, 2019).

2.3.1 Moving air-cavity (MAC)

The usage of cavities are equivalent to using an insulating material in the concept. If an air space in any building is left between two layers in making a ceiling or a roof, between the two layers the trapped air acts as a heat transfer boundary. Through a combination of convection, radiation and conduction heat is transmitted through an air room. Convection primarily relies on the height and depth of the air space. For radiation heat transfer is relatively independent of height and thickness but highly dependent on the reflectivity of the inner surface. Transfer of heat by conduction is inversely proportional to the depth of air space. If natural air flow is overlooked, the mathematical treatment of air cavity would be equivalent to that of the insulation. The thickness of an air cavity is a very important design parameter that regulates its efficiency by regulating the coefficient of heat transfer as in the event of insulation. In the research of (Yew, et al., 2013), a roof structure is designed where it can support the aluminium tubes (Figure 2:4) under the roof. Based on Figure 2:4 the aluminium tube is designed with diameter of 66 mm and 110 mm length for each aluminium tube. Each aluminium tube was attached using epoxy glue. The function of the aluminium tube is to act as moving air cavity where it forces the hot air flow through the cavity and let it exit through the base of the metal roof. This concept is similar to the studies of (Chong, et al., 2011). This study actually tells that the presence of the air buoyancy enables the rise of hot air. The moving air from the outside guides the air to the ridge in the room before it is released to the outside of the building. By this, the attic would be cooler, and the heat would not be transferred to living area. Hence, this will reduce the consumption of air conditioner where it also saves cost of electricity.

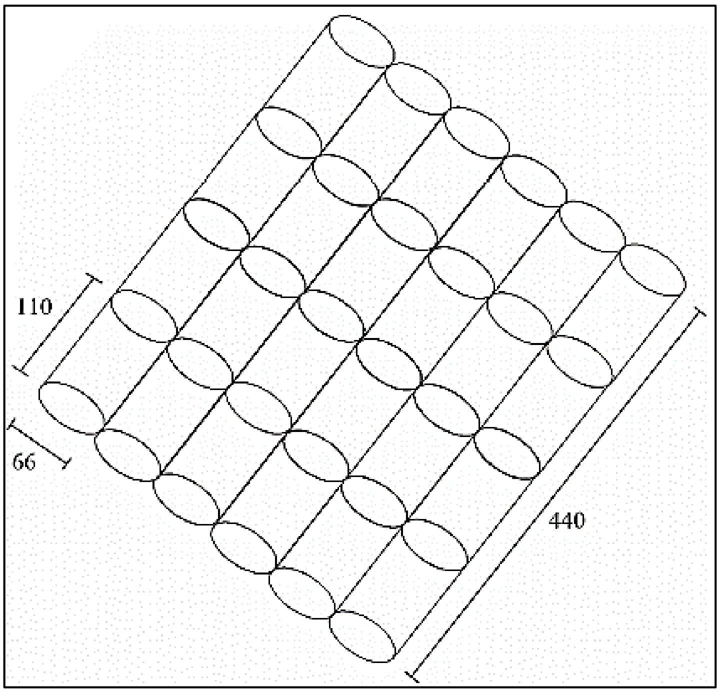

Figure 2:4: Moving air channel aluminium tubes measurements (Yew, et al., 2013).

2.3.2 Thermal Insulation

Insulation materials have countless microscopic dead air cells that block air from moving within the framework of the material. Air immobility inside the insulation material allows the transfer of heat to be delayed. Consequently, an insulation material's heat resistance is not obtained by the material itself, but by the air trapped within the framework of the material. Insulation materials also block the transfer of heat by splitting heat radiation routes into short distances. Long-wave infrared radiation is collected and dispersed by the insulation material's closed framework of microscopic cells. Hence, a material of high density with lower microscopic cells can be more efficiently prevent heat transfer by radiation. Contrary to this, lower cells leading to the elevated level of kinetic energy transfer between tiny cells in touch with each other, do not stop heat transfer by conduction. The thermal resistance of an insulating material is hence determined on the basis of its potential to prevent heat transfer by three types: convection, radiation and conduction (Aditya, et al., 2017).

Thermal insulation has several benefits, one of it is environment. Thermal insulation can bring advantage to environment by actually reducing the pollutants. This occurs by adding thermal insulation in the building where it will block the heat and reduce the air conditioner’s energy consumption. If air conditioner consumption is reduced hence electricity and pollutants that release to produce electricity also will be reduced. In addition, it also increases the comfort of people in the building. Besides that, thermal insulation also provide protection to the building. Rough climatic circumstances causes elevated temperature alterations that can harm the structure of the house. High insulation thermal resistance can reduce changes in temperature. As a result, building’s durability is maintained and building structures’ lifespan is improved. In addition, if the proper insulation material is chosen and mounted properly, insulation materials can stop fire immigration into the construction in the case of fire. In addition, insulation material can have extremely high melting point, which makes them an excellent fire barrier. There are few types of heat insulation that has relatively low thermal conductivity and frequently used are explain below and listed in Table 2:1.

Table 2:1 Thermal conductivity of material (Jelle, 2011).

Material	**Thermal conductivity**
PUR	0.02 to 0.03
XPS	0.03 to 0.04
EPS	0.03 to 0.04
Rockwool	0.03 to 0.04
Fibreglass	0.03 to 0.04

A chemical reaction between isocyanates and polyols, which are alcohols comprising various hydroxyl groups, which is to create polyurethane (PUR) (Figure 2:5). With an expansion gas such as HFC, CO_2 and C_6H_{12}, it is then extended the PUR.

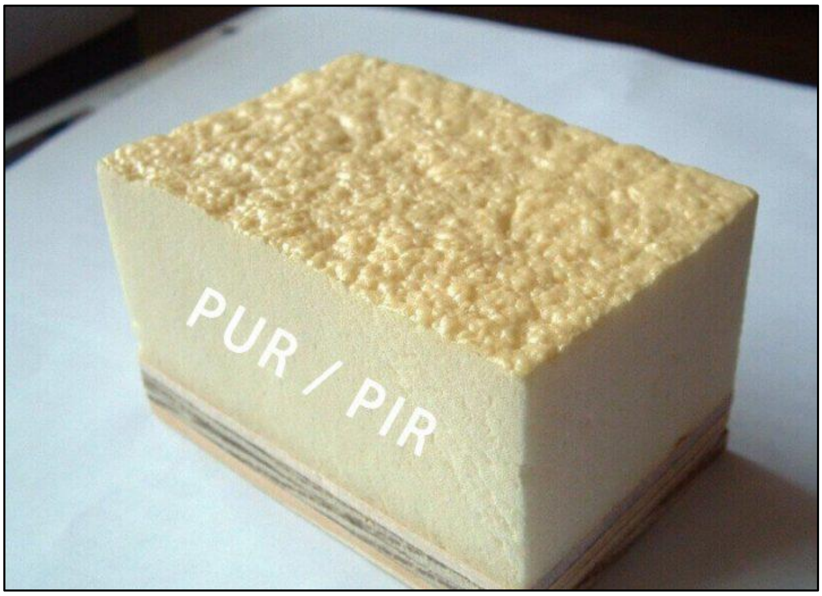

Figure 2:5: Image of polyurethane (Mahlia, et al., 2007).

Expanded polystyrene (EPS) and extruded polystyrene (XPS) is two common type of polystyrene (Figure 2:6). EPS consists of tiny polystyrene spheres made of crude oil comprising of an expansion agent such as pentane (C_6H_{12}) that expand if heated with water vapour. The expansion spheres are connected together and cast as boards with a partially open pore model. Next, XPS is produced of melted polystyrene by adding an expansion gas such as HFC, CO_2 and C_6H_{12}, where the mass of polystyrene that is extruded through a pressure release nozzle, causing the mass to expand. It is created and sliced after cooling in constant lengths. It has a pore structure that is closed.

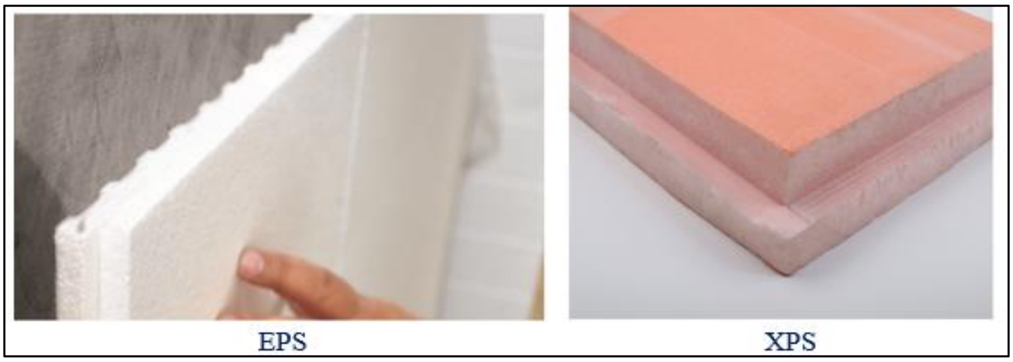

Figure 2:6: Image of EPS (left) and XPS (right) (Mahlia, et al., 2007).

Fibreglass and stone wool (Figure 2:7) are two kinds of mineral wool. Fibreglass is made of borosilicate glass heated at around 1400 °C and pulled to produce fibres by rotating nozzles. Rockwool is produced from stone like diabase or dolerite, which is heated at around 1500 °C until it melts where fibers were created hurling out of a wheel or disk. For both fibreglass and rockwool, fibers are bound together to improve their characteristics by adding dust depletion oil and phenolic resin.

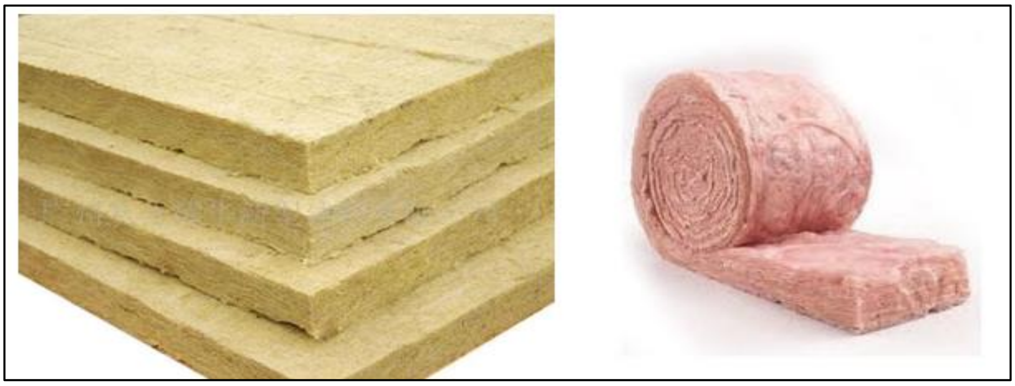

Figure 2:7: Image of Rockwool (left) and Fibreglass (right) (Mahlia, et al., 2007).

2.3.3 Thermal insulation coating (TIC)

Thermal insulation is a barrier for heat transfer. Its main function is to reduce heat transfer between object in contact (conduction) or in distance of radiate influence (radiation). More similar to thermal insulator, the only difference can be found is thermal insulation in solid state and in TIC is in coating state. Figure 2:8 shows the roof was coated with TIC about 0.2 ± 0.05 mm thickness by using gun spray. In the research of TIC, it has great advantage over the environment where it has potential to reduce heat island phenomena and the release of carbon dioxide (Yew, et al., 2013). The meaning of heat island is a phenomena where built-up region (city) is hotter than rural regions. Example a city with a lot of residence living can have an average annual air temperature 1 °C to 3 °C hotter than its surrounding.

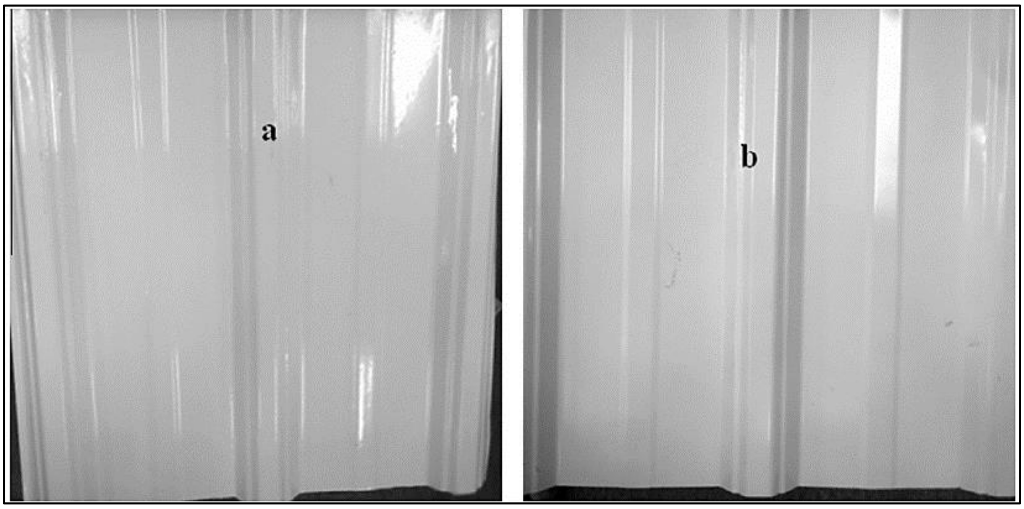

Figure 2:8: Roof coated with TIC (b) and uncoated roof (a) (Yew, et al., 2013).

According to (Yew, et al., 2013) , thermal insulation coating is not similar as other insulation such as expanded polystyrene (EPS), glass wool, extruded polystyrene (XPS) and rockwool. Those insulation required a thicker or denser insulation to achieve great thermal resistance. TIC is a coating where it is applied on top of the roof along with white solar reflective paint. TIC is developed through the use of titanium dioxide pigment and unwanted chicken eggshell as a bio-filler bounded by a low thermal conductivity polyurethane resin binder. There is also great impact on environment using this chicken eggshell where it could reduce wastage of eggshells. In the research of eggshell, it was found that several tons of eggshell has sent to landfill and landfill are costly to maintain (Hamideh and Akbar, 2018). From this recycling waste eggshell into bio-filler, from useless trash into useful coating. The addition of highly purify titanium dioxide would increase the solar reflective, by this it would reflect heat radiated from the sun, the result is a cooler attic would achieve.

2.3.4 Radiant heat barriers (RHB)

The term of Radiant heat barriers (RHB) is actually that an aluminium foil which will be attached to the insulation layer which functions to strengthen the insulation and to waterproof it. According to research by (Ong, 2011), it stated that RHB actually helps to reduce the attic temperature by 5.5 °C and this reduces the heat flow from the attic to the room below. To prove this statement, he did an experiment of two similar house which is more likely like in the Figure 2:9. Ong (2011) stated that the percentage of heat flow produced by RHB in the celling is conversely proportional to level of insulation in attic. Heat flows reduce in ceiling from 26 % to 41 %, based on the insulation thickness. (Winiarski and O’Neal, 1996) created an attic heat transfer proto-state model with various radiant barrier configurations and insulation thickness. The findings of their experiments showed that summer heat flux could be achieved to reduce from 29 % to 37 %.

Experiment conducted by (Soubdhan, Feuillard and Bade, 2005) shows that they bring up four similar scale downsize of horizontal roof of corrugated iron sheets. The reason is to contrast the effect of using various insulating materials such as RHB, fibreglass and polystyrene and also the impact of the roof colour (black and white). Besides that, they also investigate the results of ventilating the air space between both the bare roof top and the roof bottom. Their findings showed that 86 % of the roof's heat load was due to radiation. The white galvanized iron roof top achieves much better compared to black galvanized iron roof. Regardless of the roof heat absorption, the radiation barrier lowers the radiative heat flux significantly from 32 % to 36 %. As a result, however, the heat flux that the radiant barrier reflects, raises the temperature of the roof surface. In addition, the radiant barrier was more effective when the air space was ventilated compared polystyrene or fibreglass isolation. Although the air space was not ventilated, a decrease in heat flux was always given by the radiant barrier. Polystyrene offers better heat transfer resistance compared to fibreglass when the air space is not ventilated. Theoretical calculations submitted to demonstrate that a significant reduction in heat load can be accomplished in warm environments through the use of a bright or reflective roof colour (Suehrcke, Peterson and Selby, 2008). To prove the statement, (Amer, 2006) conducted an experiment with lab size cabinets with different colour (black and white) galvanized roof top. For the white cabinet, he found out that the inside temperature is reduced by 6.5 °C and reduced 7 °C for the aluminium foil which laminate the 5 cm thick fibreglass. Investigation of (Khedari, et al., 2000) and (Hirunlabh, et al., 2001) stated that the need for a solar roof collector to evoke natural ventilation in house similar to Figure 2:9 f section. Their investigation showed that even though the induced ventilation rate was adequate to provide sufficient fresh air for ventilation needs, it was inadequate to provide appropriate cooling for human comfort in the room. It showed that the roof solar collector could accomplish power savings of more than 30 % (Ciampi, Leccese and Tuoni, 2005).

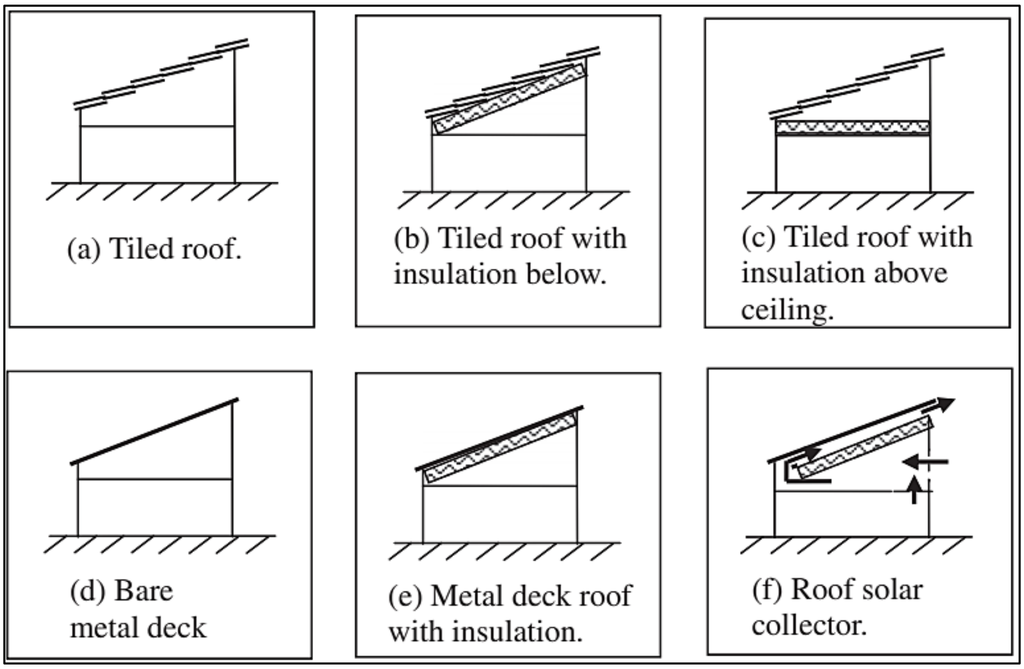

Figure 2:9: Passive solar roof designs (Ong, 2011).

2.4 Evaporative cooling

Evaporative cooling is indeed the earliest cooling method and can be used in both passive and active systems (Cuce and Riffat, 2016). Traditional mechanical cooling systems requiring large power costs and damages the environment which led experts to consider the best evaporative method and try to enhance its performance (Mujahid Rafique, et al., 2015). It was consequently heavily utilized in the air-conditioning model as an evaporative cooler or heat exchanger. However, a building evaporative cooling integration is only a limited number and yet to be developed. (Amer, Boukhanouf and Ibrahim, 2015) discovered that evaporative cooling had the greatest cooling impact among some passive cooling technologies, first would be solar chimney, which lowered indoor air temperatures respectively by 9.5 °C and 8.4 °C. For cooling an air stream, the evaporative cooling method utilizes water evaporation. Basically water absorbs heat from the environment to evaporate into vapour. This lowers the air or surrounding temperature. There two kind of evaporative cooling; Indirect and direct evaporating cooling.

2.4.1 Direct evaporating cooling (DEC)

The fundamental concept of direct evaporative cooling is transformation to latent heat from sensible heat. When water in the air vapour is evaporated, the air will be cooled. The water in the air stream is constantly supplied and recirculated so that the air removes the water and creates the impact of cooling. According to (Chan, Riffat and Zhu, 2010), the heated air will be transmitted to the water and became latent heat by evaporation of water and the latent heat follows the vapour of water and spreads into the atmosphere. After the process, the content of moisture of the supply air will increase. Figure 2:10 shows the illustration of this process.

Direct evaporative cooling can give possibilities for power preservation during advanced seasons in hot dry environments. The efficiency of the cooling system decreases as the humidity in the air stream rises during the process. Especially in very humid and hot environment , the cooling result may not be satisfactory (Chan, Riffat and Zhu, 2010). To enhance the cooling efficiency, the incoming air will be dehumidified by allowing it through a desiccant. A mixture of air-drying membrane and evaporative cooling systems was developed (Joudi and Mehdi, 2000). The membrane is made up of hollow fibers, such as acetate cellulose and polysulfone. The selective membrane enables the water vapour to be effectively separated from the air. Before entering the evaporative cooling unit, the air is pre-treated (dried) by crossing through both the membrane and operating in a drier air stream.

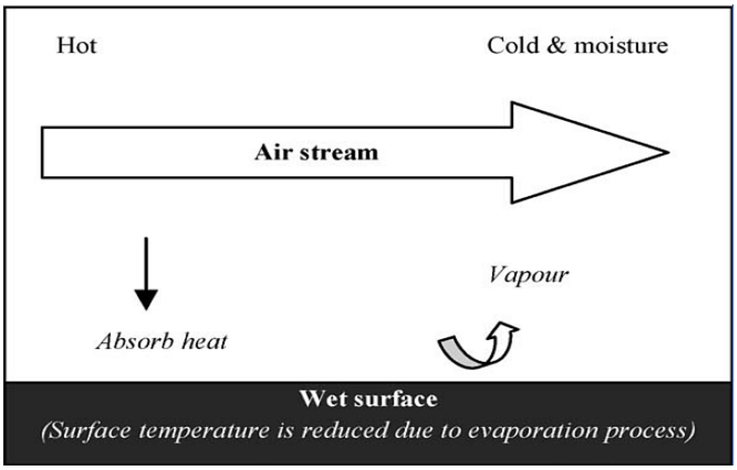

Figure 2:10: Evaporative process for DEC (Chan, Riffat and Zhu, 2010).

2.4.2 Indirect evaporating cooling (IEC)

Figure 2:11 illustrates the indirect evaporating cooling involves exchanging heat with another flow of air. A heat exchanging wall separates these two air flows, in which one side of the wall is moist and the other side is dry. According to (Chan, Riffat and Zhu, 2010), the working air will be passing through the moist side whereas the outcome air will be passing through the product parched section and through water evaporation, the moist side absorbs heat from the dry side as well as cools the dry side. The moist air flow includes latent heat while sensible heat is involved in the dry air flow. Hence, no extra moisture is therefore brought into the product air.

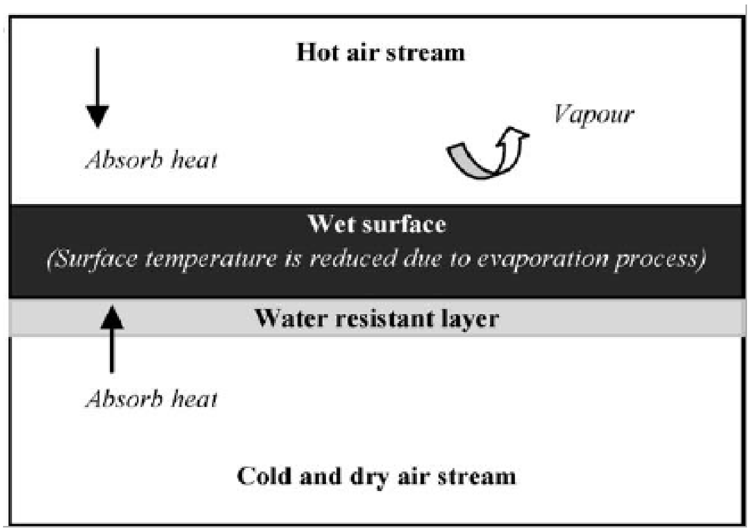

Figure 2:11: Evaporative process for IEC (Chan, Riffat and Zhu, 2010).

2.4.3 Building integration of evaporative cooling

Some of evaporative cooling's structure integration implementations is porous roof. During rainy season, through porous layer which the rainwater enters is kept/stored within the layer. During daytime the substantial quantity of rainwater that the porous layer maintains will evaporate to the atmosphere.

When evaporation occurs, the surface temperature of the porous layer reduces owing to the release of latent heat. This will reduce the building room temperature due to reduce of heat flux from the roof slab. The porous layer tends to adsorb moisture from the surrounding during the night or on rainy days and helps to reduce the temperature roof components.

(Wanphen and Nagano, 2009) studied about the efficiency of evaporative cooling roof materials and summarized the outcomes in Figure 2:12. Among the materials studied, it is discovered that siliceous shale, consisting of a large amount of mesopores, efficiently keeps surface moisture from vapour adsorption and also this material has the highest evaporation performance. This material can absorb more vapour during the night due to the elevated absorption rate. Within porous layers of siliceous shale, the stored water from those in the porous layer evaporates and produces more latent heat to the atmosphere during light hours, as volcanic ash, rocks and silica sand produce more sensible heat (smallest sensible heat / latent heat).

In addition, increased evaporation rate makes the surface cooler faster. As a matter of fact, siliceous shale can lower the temperature of the roof surface to 8.62 °C especially in comparison with mortar concrete.

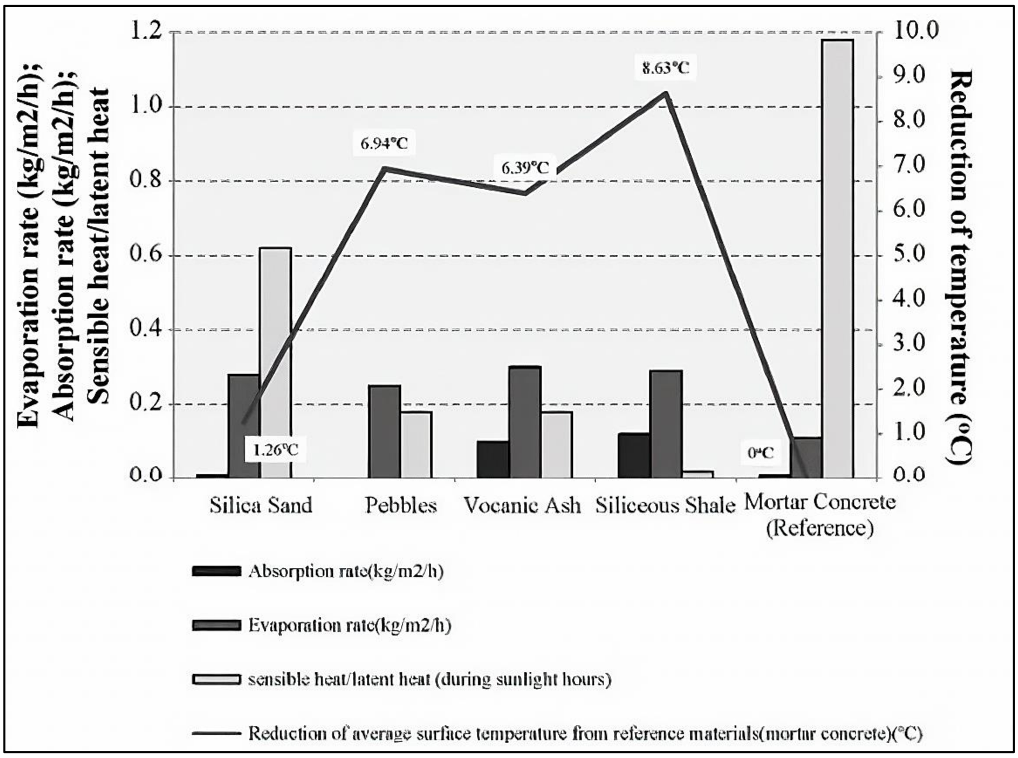

Figure 2:12: Evaporative cooling results on implementation of roof materials (Chan, Riffat and Zhu, 2010).

CHAPTER 3

METHODOLOGY AND WORK PLAN

3.1 Introduction

A small scale of roof (Figure 3:1) was setup using plywood, to investigate the heat transfer and the temperature difference on the surface of the roof and at the attic. The shape of the roof model is right angle trapezoid. In this project, there are two section which is the outer part (surface of roof) and inner part cooling system. For outer part, the cooling technique used is roof coating and for inner part there are three cooling techniques have been implemented: Conduction heat barrier, Convection heat barrier and Radiant heat barrier.

Figure 3:1: Small scale roof model.

3.2 Modal Dimension Analysis

Using plywood, a small scale of roof structure was built. The dimension of the structure is 360 mm long × 360 mm wide × 580 mm height. The thickness of plywood is 15 mm. For this model, the angle of inclination of the roof was set 30° which measured from the horizontal plane to the perpendicular height of the modal. Figure 3:2 shows the dimension of the small scale roof structure.

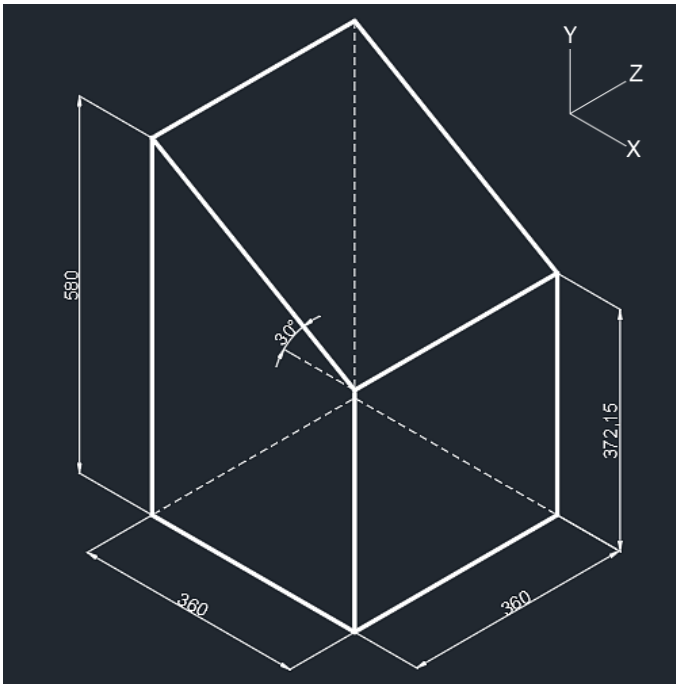

Figure 3:2: Dimension of attic model (all dimensions in the figure is in mm).

3.3 Outer part cooling technology implemented

In this section of methodology and work plan, explanation of cooling method implemented on the surface of roof deck.

3.3.1 Thermal reflection coating (TRC)

TRC was formalize using titanium dioxide pigment and chicken eggshell waste as a bio-filler. Then it was mixed polyurethane resin binder which has thermal conductivity of 0.65 W/m.K. Not only that, titanium oxide has low thermal conductivity (4.8 W/m.K) and it is white in colour, (Figure 3:3) which help increases the insulating properties. Besides, white colour reflects more sunlight compare to darker colour, so when most of the heat is reflected, the lesser heat is radiated into the attic space.

Figure 3:3: Image of titanium dioxide powder.

In this experiment two galvanized roof was used, one is coated with TRC and another is normal roof painted in red similar like in Figure 3:4. Each roof with 45 cm long × 36 cm wide and with 0.5 mm thickness. The roof is placed on top of the structure with the inclination of 30°. This is done in order to compare how much heat is block/reduced with TRC and non-TRC.

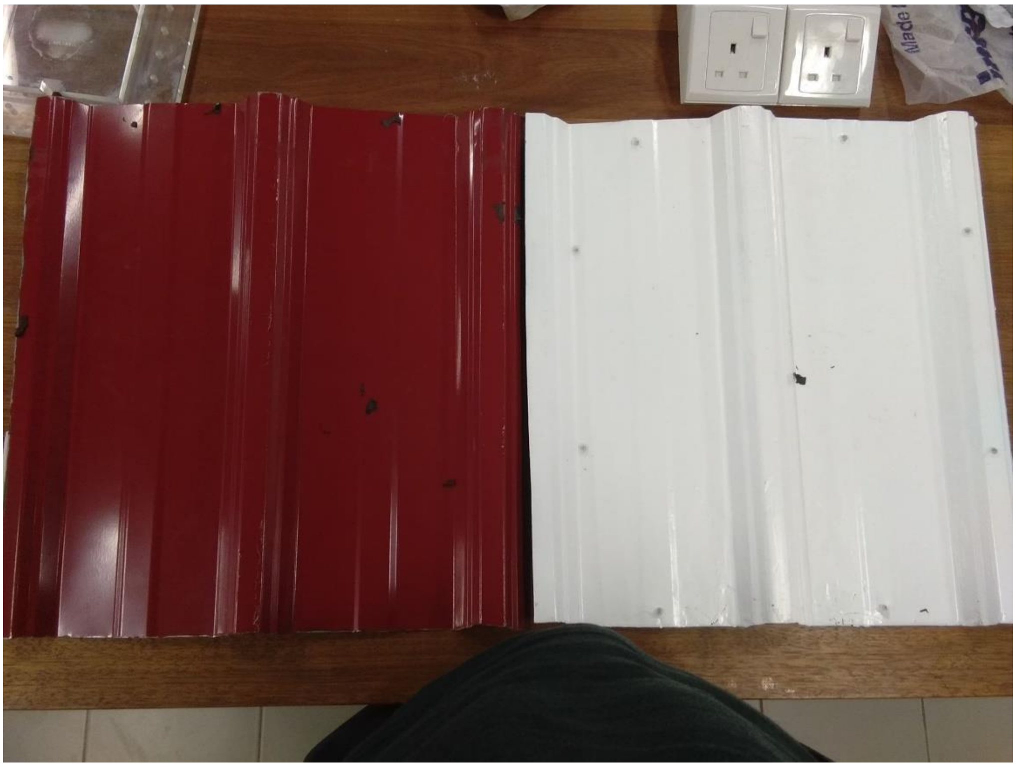

Figure 3:4: Uncoated galvanized roof (left) and Coated galvanized roof (right).

3.4 Inner part cooling technologies implemented

In this section of methodology and work plan, explanation of cooling method implemented in attic space.

3.4.1 Conduction heat barrier

The cooling techniques are emphasize on reducing conduction heat from entering the attic space. This barrier material will have high heat resistance which do not conduct heat, in other words it act as heat insulator. Conduction conducts heat by transferring heat via particles that collides with each other. This is why solids are better at conducting heat than liquid and gases. Liquid and gases do conduct heat but not as well solids. This is because for fluids the particles are wider way from each other for the collision to happen. Furthermore, metals are the best conductor of all solids. This is because inside the metal there is all these tiny electron whizzing around that are called the free delocalized electrons. They will collide into all the ions in the metal and they can absorb heat from the hot end and run straight down and collide into an atom at the cold end. They’re spreading the heat through metal much quicker than non-metal objects.

Normally the efficiency of this heat barrier will be in terms of R or U value. The R-value is a measure of the heat transfer resistance by the thickness of a given material. The higher the R-value, the higher the heat resistance the material has and the greater the insulating properties thereof. As for U-value, it is a measure of how much heat is lost by a given material's thickness which covers the three main ways in which heat loss occurs – conduction, convection and radiation. The lower the U-value the better the insulation properties of the material. Calculating R-value is the most common way, but U-value are far more accurate because it considering all the various ways in which heat loss happens, however its more harder to quantify.

In this experiment, rockwool insulation is used as conduction heat barrier. Rockwool is made of rock based mineral fiber insulation composed of recycled slag and basalt rock. Basalt is a volcanic rock (abundant on earth), and slag is a steel and copper by-product. The purpose of choosing this material is, it is easily available because there is two production company in Malaysia itself. In addition, rockwool theoretically has high R-value and low U-value. To increase the thermal resistance of the material, vacuum method is introduced. The purpose of this experiment is to see how conduction heat barrier affects the temperature in attic space and how the values of R and U-value affects the temperature in attic space. A comparison of this both materials will be done and the material which reduced the attic temperature the most will be selected and will be implemented on the main design.

3.4.1.1 Normal Rockwool insulation

The rockwool is cut into 41 cm by 31 cm and it was placed inside a plastic cover (not sealed) as in Figure 3:5. [More information about the plastic cover will be mention in 3.4.1.2 section.] The thickness of the insulation is 5 cm. Then it was placed into the attic space as in Figure 3:6.

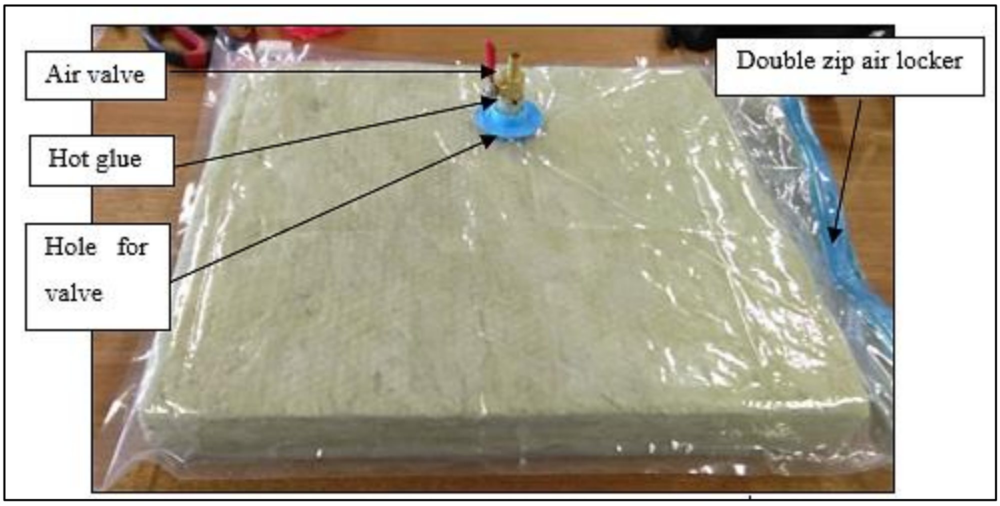

Figure 3:5: Rockwool inside plastic cover.

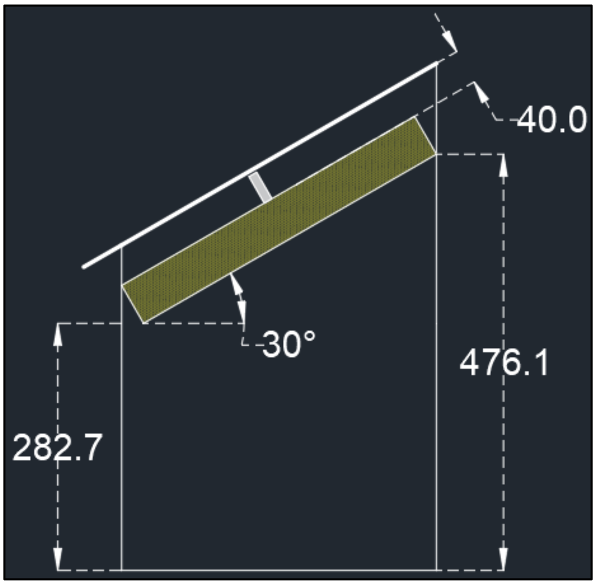

Figure 3:6: The location of Rockwool in attic model (all dimensions in the figure is in mm).

3.4.1.2 Vacuumed Rockwool insulation

To vacuum the insulation, a plastic cover is specially designed. The dimension of the plastic is 45 cm by 35 cm. The thickness is 60 mil and the material of the plastic cover is Polyethylene (PE). PE was the best thermoplastic choice among Polypropylene (PP), Polyethylene terephthalate (PET) and Polycarbonate (PC). The material was selected by the help of CES Edu pack 2005 software. To pass the 1st stage (Appendix D) the material should able to handle at least 70 °C and 0.10 MPa. 0.10 MPa is normal air pressure at sea level, when vacuum is created inside the container, the force acting outside the container will be approximately 0.10MPa of container surface area. In stage 1, PET material didn't pass through even though it would able to sustain the force created by vacuum, but the maximum service temperature is only 66.85 °C. In 2nd stage (Appendix D) of material selection emphasis on price and elastic limit. The left 3 material has passed the elastic limit; however, PC is way more expensive than PE and PP. Hence, PC is removed from the selection criteria. Comparing PE and PP, PE is more flexible, durable and tear resistance then PP. This is because PP has a rougher surface that might create scratches/holes and it is not flexible as PE. To create a good vacuum, hole must not present and it must flexible enough to adapt the shape of the rockwool in the vacuum process.

After choosing the material, designing the plastic cover will be next. The plastic cover is designed to be in 45 cm by 35 cm. As in Figure 3:5, in order to prevent the atmosphere air enter into the plastic bag, double air lock zipper was installed instead of one. The reason is to have double protection and to make sure there is no air enter in while vacuum process. A hole was also designated to install air valve to vacuum the product. Air valve was installed using hot glue gun, an excessive amount of hot glue is used to seal the air valve and the hole together. An excessive amount of hot glue is used to make sure there is no holes and it is perfectly sealed.

After completing the construction of vacuum plastic cover, the same rockwool is placed into the plastic bag which is sealed by the air lock zipper and start vacuuming the bag using the electrical vacuum pump (ROCKER 300) as in Figure 3:7. It took around 1 minute to complete the vacuum process (-0.8 Bar). Figure 3:7 shows the rockwool after vacuumed process. Then similar to normal rockwool it was place on the exact same location in attic model (Figure 3:8).

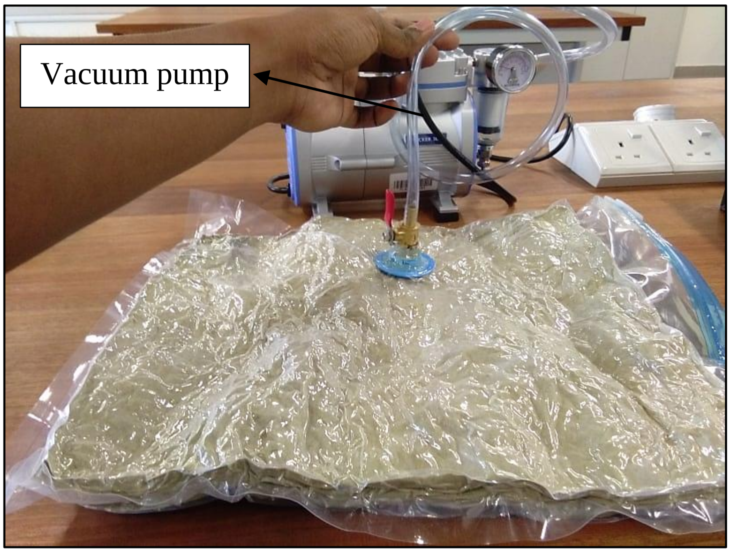

Figure 3:7: Process of vacuuming Rockwool insulation.

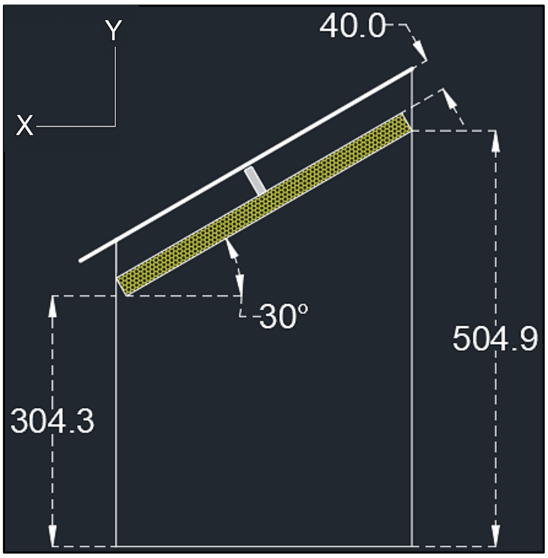

Figure 3:8: Location of vacuumed Rockwool in attic model (all dimensions in the figure is in mm).

3.4.2 Convection Heat barrier

In this section, cooling technologies are focused on removing heat using the convection method. Unlike conduction, convection only occurs in fluids (liquid and gases). A convection is a combination of advection (fluid motion) and diffusion (conduction) heat transfer. Advection heat transfer is transfer of heat through vertical or horizontal direction. For an example, advection commonly happen here in earth, where the wind blows horizontally which carries hot air towards cold air region and wind blows cold air towards hot air region. About diffusion, it is similar like conduction, but it happens in air particle where here it is a direct exchange of kinetic energy (heat) of particle through the boundary between two systems. According to the second law of thermodynamics, such spontaneous transfer of heat often occurs from a high temperature region to another lower temperature region. Based on the comparison of air and liquid, liquid has faster convection heat transfer due to particles are much closer in distance comparing to air. In this experiment, convection in air will be given more priority compared to liquid. In short, when there is a source of heat in a closed space, the air particle will gain energy (hot air) and move faster. This will make the air particles spacing wider which leads to the reduction of air density and the particle will rise. It is vice versa for the lower energy particle as it will start sinking due to the packed spaces and higher density. This process will continue till the temperature reach equilibrium.

In this experiment, natural convection (hole) and force convection (fan) is applied. To see how much natural and force convection affects the temperature in attic space. A comparison of this both techniques will be done and the method which reduced the attic temperature the most, will be selected and will be implemented on the main design.

3.4.2.1 Ventilation hole

A hole was created by hole-saw with a diameter of 4.4 cm. The location of the hole is 9.3 cm from the top as show as in Figure 3:9. The reason the hole is at high positioned is because using the knowledge of convection of air, where warm air will be at higher above the ground. The purpose of this experiment is to see how a ventilation hole will affect the temperature in attic space.

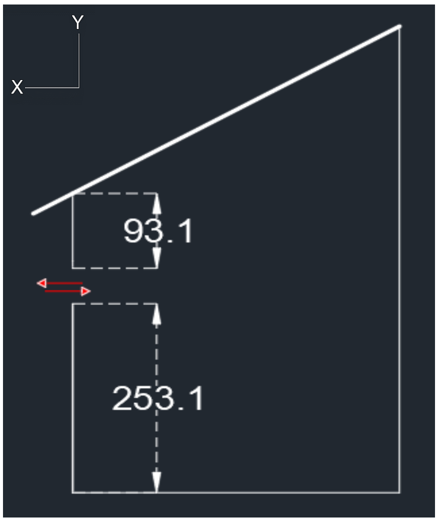

Figure 3:9: Location of ventilation hole in attic model (all dimensions in the figure is in mm).

3.4.2.2 Solar powered fan

Similar to the ventilation hole but this time a solar powered fan is placed in the hole. This fan has electrical rating of 12 V and 0.07 A, with a power of 0.84 W (P = I ×V). However, the solar power panel used at this experiment provides 11.5 V and 0.46 A, with the power of 4.9 W. Since in this experiment, only one piece of fan is used, 4.9 W is too much power for a fan which operate at 0.84 W. However, the fan will be operational at 4.9 W, it is just that the fan will spin in extreme speed more than it intended too. So, a current divider was construct as in Figure 3:10 using potentiometer (variable resistor, R1and R2). With the help of multimeter, each potentiometer was set in desired value as in Figure 3:10. After completing the circuit, the desire power has achieved that is 0.81 W (0.07 × 11.5). In Figure 3:10 shown the full calculation and current divider full circuit.

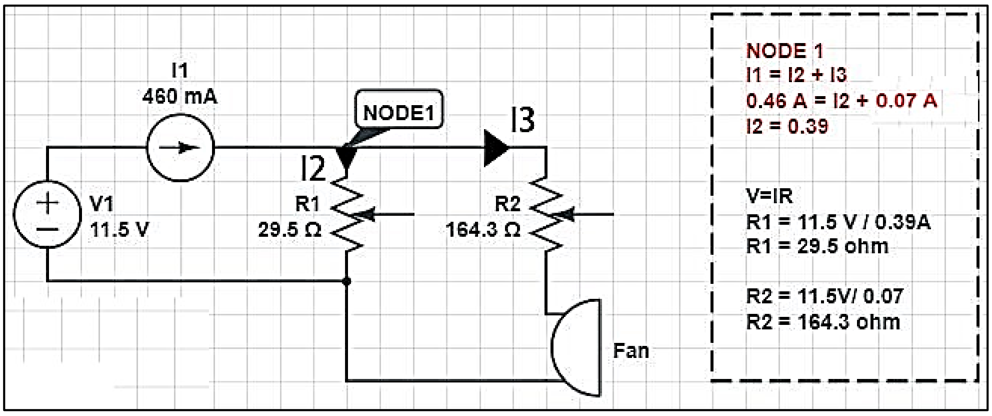

Figure 3:10: Current divider circuit and calculations.

Furthermore, having an ideal power supply makes the experiment to proceed to the next step is installation of solar powered fan, the attic fan is installed in the hole was created before for ventilation. The fan was attached with double side tape to make sure there is no hole beside the cavity of the fan as in Figure 3:11. The solar panel is placed outside the heating chamber, with a 500 W halogen lamp is set to face it at distance of 25 cm. The distance between halogen lamp and solar panel was set in a distance, where the light hits the entire solar panel. The purpose of this experiment is to see how a solar powered fan will affect the temperature in attic space.

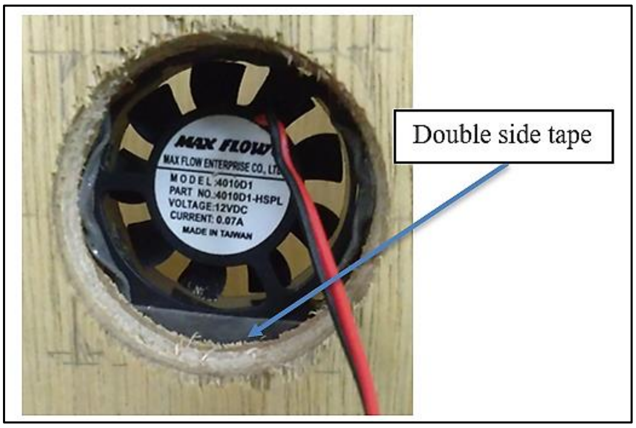

Figure 3:11: Attic fan installed in attic model with double side tape.

3.4.3 Radiant heat barrier. (RHB)

This cooling techniques focuses on reducing radiation heat from entering the attic space. Radiation is unlike conduction and convection; both of these methods need particle to transfer heat. Radiation transfers heat by radiation wave where it do not need particle to transfer heat. For an example, the heat from the sun travel through space to reach earth but in space there is no particle and it known as vacuum state.

The RHB are composed of a highly reflective material that reflects most of the radiant heat instead of absorbing it. In other words it is called ‘Albedo Effect’. Higher the albedo means, the ability to reflect more heat more and vice versa for lower albedo value. Emissivity also play an important role, where emissivity is the calculation of the capacity of an object to emit thermal radiation. Emissivity will have a value between 0 (shiny mirror) and 1.0 (black body).

In this experiment, aluminum alloy (6061) sheet is used. 6061 Aluminum alloy is a precipitation-hardened alloy that includes magnesium and silicon as its main alloy components. The reason this material is chosen because it is easy to be obtained from the market and the low cost of the material. In addition, aluminum alloy theoretically has lower emissivity and high albedo effect. The purpose of this experiment is to see how polishing affects the albedo and emissivity of the material along with how the radiant heat barrier will affect the temperature in the attic space. A comparison of this both materials will be done and the material which reduced the attic temperature the most will be selected and will be implemented on the main design.

3.4.3.1 Unpolished Aluminum sheet

The aluminum was cut into 43 cm by 32 cm and placed as in attic model. The thickness of the sheet is 0.3 mm. The location where the sheet was placed is 4 cm from the top as in Figure 3:12. Before it was tested, it was cleaned by ordinary dish washer shop to remove any dust or dirt particle.

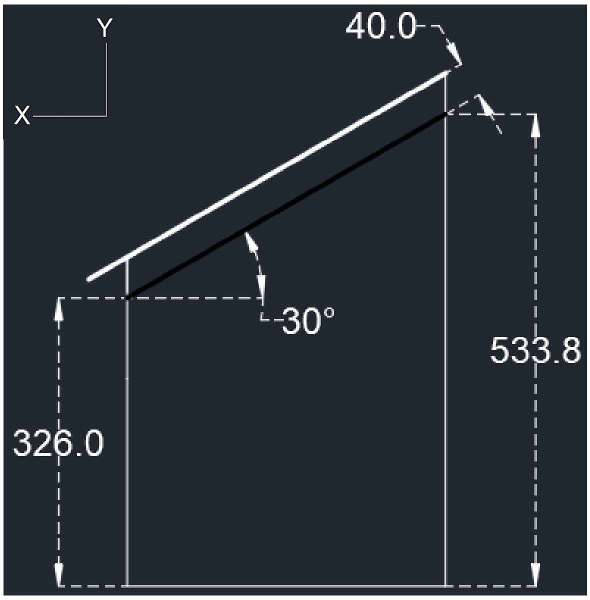

Figure 3:12: Location of aluminium sheet in attic model (all dimensions in the figure is in mm).

3.4.3.2 Polished Aluminium sheet

The dimension and the placement of the sheet is similar to unpolished aluminum sheet. There are several steps need to be done to have a good polished surface. Firstly, W-40 lubricant oil was sprayed on to the sheet evenly to act as lubricant for sanding. Secondly, using a 3000-grit sandpaper to sand the sheet uniformly (less pressure is applied). The purpose of sanding is to remove the small scratches and make the sheet smoother. Thirdly, the sheet was cleaned by ordinary dish washer to remove the lubricant, debris of aluminum and dust/dirt particle. The last step is polishing. Autosol metal polish was used as polishing agent. A decent amount of polish was applied until it was evenly distributed around the surface. After it was apply evenly, using microfiber cloth to wipe the surface in circular motion (moderate pressure is applied) until the surface was clear, smooth and shiny (Figure 3:13).

Figure 3:13: Polished (left) and unpolished (right) aluminium sheets.

3.5 Layouts of experiments

In this research, there are nine layouts of attic mockup (Figure 3:14), which are listed from design A to design H and design X. This designs was constructed and experimented to see the effect of temperature in the attic space.

3.5.1 Normal roof system (Design A)

In this design no cooling technologies is applied, the purpose of this design to see how hot the attic space gets under normal circumstances and how long does it take. The temperature is taken in interval of one minute until the temperature became constant for five consecutive minutes. This experiment is done in the same mock design as in Figure 3:14.

3.5.2 Roof coated with TRC (Design B)

In this design the roof is coated with TRC. The purpose of this to see how TRC affects the temperature in attic space. This experiment is considered passive cooling system. The duration of this experiment will be depending on design A, because then it will be easier to compare which designs will show better insulating properties. Design B will be compared with design A to see which type of roof will be better and it will be applied in the rest of the designs and main design.

3.5.3 Roof coated with TRC and Rockwool Insulation (Design C)

Similar to design B for the roof, however in this design there is a rockwool insulation was placed below the roof as in Figure 3:14. This experiment is considered passive cooling system. The purpose of this experiment is to see how rockwool affects the temperature in attic space. Duration is similar to design B where it depends on the design A**.**

3.5.4 Roof Coated with TRC and Vacuumed rockwool insulation (Design D)

Similar to design C but in this design the rockwool is vacuumed. This vacuumed rockwool is placed at the same location as design C. This experiment is considered passive cooling system. The purpose of this experiment is to see how vacuumed rockwool is going affect the temperature in attic space. Design D will be compared with design C to see which type of insulation will be better and it will be applied in the main design.

3.5.5 Roof coated with TRC and a ventilation hole (Design E)

In this design the roof is coated with TRC and a hole has been cut in the location is at the highest point of the attic model as in Figure 3:14. This experiment is considered passive cooling system. The purpose of this experiment is to see how a hole can affect the temperature in the attic space. The duration of this experiment is similar to design B where it depends on design A.

3.5.6 Roof coated with TRC and solar powered Fan (Design F)

Similarly, to design E but this time the hole is occupied with solar powered fan. This experiment is considered active cooling system. The purpose of it to see how the solar powered fan is going to affect the temperature in attic space. This design E will be compared with design F to see which type of cooling system will be more efficient and it will be implemented in the main design.

3.5.7 Roof Coated with TRC and aluminum sheet (Design G)

The roof is coated with TRC and a shiny aluminum sheet is place under the roof as in Figure 3:14. This experiment is considered passive cooling system. The purpose of this experiment is to see how this aluminum sheet is affecting the temperature of the attic space. The duration will be similar to design B where it will depend on the design A.

3.5.8 Roof coated with TRC and polished aluminum sheet (Design H)

Similarly to design G but instead, in this design the aluminum is polished. It is placed at the exact location as design G. This experiment is considered passive cooling system. The purpose of this experiment is to see how polished aluminum affect the temperature in attic space. Design H will be compared with design G to see which type of aluminum will show better cooling properties and it will be applied in the main design.

3.5.9 Roof coated with TRC, vacuumed rockwool insulation, polished aluminum sheet and solar powered fan (Design X)

This is the main design (Design X) for this research project. In this design the roof is coated with TRC as well. The vacuumed rockwool insulation was placed above the polished aluminium sheet. The distance between the insulation and the roof was set to 4 cm. Both the aluminium sheet and insulation was set in angle of 30° as in Figure 3:14 (Design X). A solar powered fan was installed, 25.3 cm above the ground. More detail will be further explain in section 4.5.1.

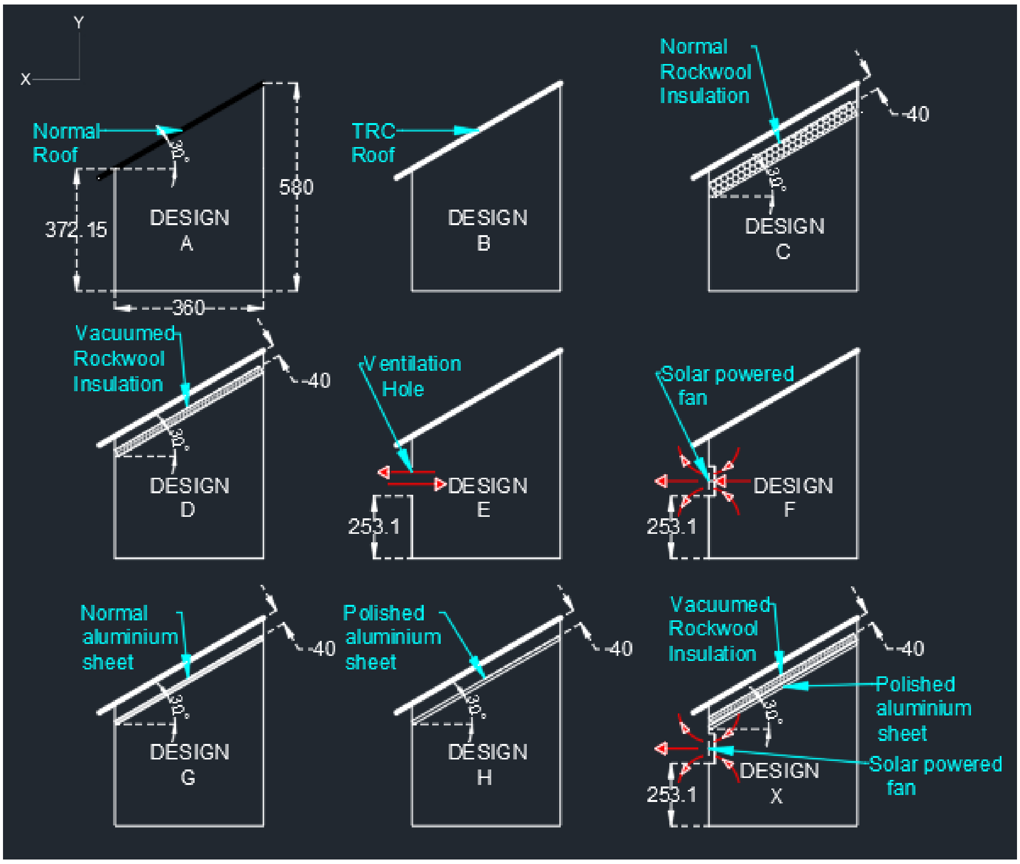

Figure 3:14: 9 layout of attic models (all dimensions in the figure is in mm).

3.6 Set up of experiment

In this section, it shows the equipment and apparatus to set up the experiment and how the experiment is done.

3.6.1 Heating chamber

The whole experiment was conducted inside the heating chamber. The purpose of this heating chamber is to create an environment with temperature ranging from 30 °C to 43 °C by using 200 watts halogen light. The reason is because highest temperature recorded in Malaysia was 40.1 °C and according to the (Trading Economics, 2018), in upcoming years there are high chances of temperature rise about 3 °C if global warming problem does not resolve.

The dimension of heating chamber as in Figure 3:15. The material used to build this heating chamber is 12 mm of plywood. It was designed as same shape as the attic model. This is because the height of the heat source (Halogen spotlight) is fixed 66.8 cm from the ground. If it was built as cuboid shape, it would be challenging to obtain the desired range of temperature as the trapped heat will be closer to the attic model. In order to save cost and to achieve a desired range of temperature, right-angled trapezium shape was chosen. Furthermore, in order prevent loss of heat and to maintain the range of temperature, the chamber was glue by aluminum foil on the plywood (bright side facing inwards), nevertheless the type of glue used was construction sealant (Vital nails), which design to work under high temperature. In addition, aluminum foil serves another purpose, which is protecting the wood from losing its strength and being damaged from the heat.

The whole chamber was cut into half as in Figure 3:15 (dotted green line) so it will be in two pieces (up and bottom), so that it will be easy to store and also it makes easier to do some changes of the attic model while the attic model stays in the half of the chamber. When there is cut, then they will be definitely gaps/holes. So to block the gaps/holes, polystyrene were used to cover the holes. The purpose of covering the holes is actually to reduce the heat loss to the atmosphere while maintaining a desire range of temperature inside. In addition, the lid’s opening will be manipulated until the desire temperature of the chamber is achieved. Once the desire range of temperature is achieved, opening of the lid will be fixed throughout the experiment.

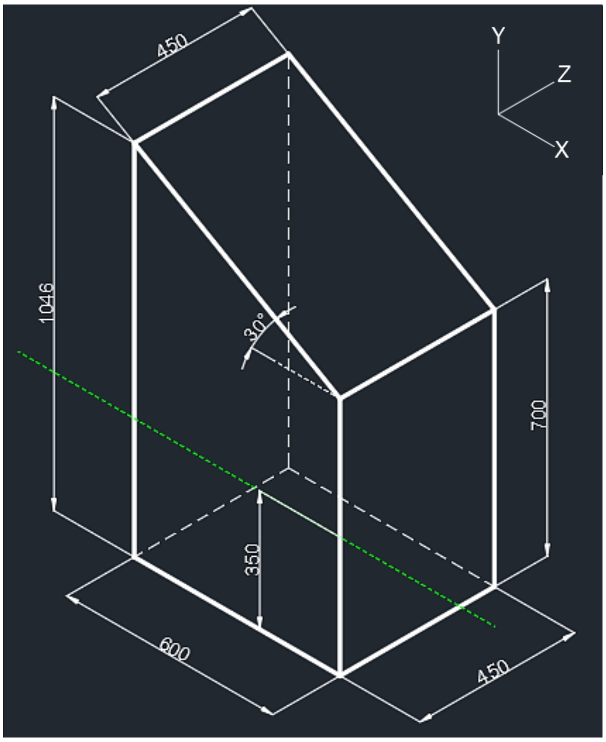

Figure 3:15: Dimension of heating chamber structure (all dimensions in the figure is in mm).

To choose a suitable design of mounting mild steel bar, slotted angle bar was chosen over flat slotted bar by using Solidworks simulation. Because under a load, the slotted angle bar has lesser resultant displacement (0.890 mm) compared to flat (9.450 mm) slotted bar in Y- direction (Appendix C). The slotted angle bar was mounted on the heating chamber for the purpose of hanging the halogen light as a heat source. The location of halogen light is fixed throughout the experiments which located center along the Z-direction. The location of the halogen light in X and Y- direction is label in Figure 3:16 and the halogen light is positioned at 30° (parallel to roof inclination). In addition, the halogen light produces enormous amount of heat and to protect it, a rockwool insulation which is wrapped with aluminum foil was placed on top of the halogen light to protect the plywood. A hinge was installed on upper part of the plywood so the upper part could be opened and will be easily accessible to the halogen light.

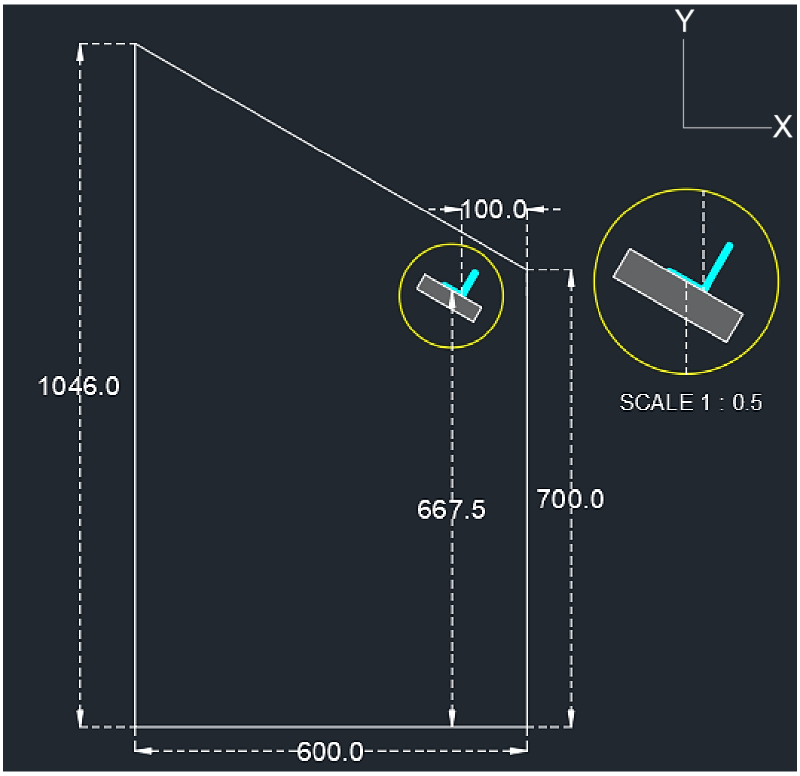

Figure 3:16: Location of halogen light and angle bar in X and Y- direction (all dimensions in the figure is in mm).

The halogen lamp light is generated by heating a filament with color temperature 2700 Kelvin to 2800 Kelvin (similar to outdoor weather). The halogen lamp emits of its diverse energy in the form of infrared radiation or heat. In this experiment, 200 Watt halogen light is used and the temperature recorded from the halogen light was emitting from 53 °C to 65 °C (outside the safety glass). This is because only roughly 3.5 % of the energy consumed by halogen lamp is converted to visible radiation or light and the 96.5 % is in term of heat. Thermodynamics first law states that energy cannot be created or be destroyed and it only transfers into another form of energy. For usage as light source it not efficient but as heating agent it is a great source.

3.6.2 Sensor Location and data logger

An arduino data logger was built to monitor the temperature in this experiment in every 1-minute interval up to 50 minutes. To build an arduino data logger there are several material and equipment needed. Firstly, Arduino Uno Compatible, where it act as a motherboard of the system which can receive data from sensor and send to computer/memory card and also it acts as a programmable device which can be program to a desire function. Secondly is thermocouple amplifier MAX6675, the purpose of this material is a sensor and a connector to type- K thermocouple which able to convert the signal from K-type thermocouple to a digital input. Thirdly, will breadboards and jumper wire to connect and have a complete circuit. In addition, having arduino software to code the program and execute the command. Finally, PLX-DAQ is a Microsoft excel extension is needed, which it is able to tabulate the data recorded in arduino data logger.

Four type-K thermocouples were used in this experiment. It was connected to thermocouple amplifier to read the temperature. The first thermocouple (T1) was attached to surface of the roof with aluminum tape. The aluminum tape was cut in a square (2 cm × 2 cm) so that the heat will be evenly distributed and more accurate data could be obtained. The position of it attached was 14 cm from bottom and 5.5 cm from the right as in Figure 3:17 and Figure 3:18. The position was fixed for the entire experiment so that the result will be comparable. For the second thermocouple (T2) it was placed inside the attic space. It was located in the attic space as in Figure 3:18. As this sensor as well, it was fixed throughout the experiment. The third thermocouple (T3) was place inside the chamber, where it is located 357 mm above the ground as in Figure 3:19 (cyan). Before choosing T3, a small experiment was conducted to find which point was the ideal position for T3, four sensors (A1, A2, A3, and A4) was located at various location as in Figure 3:19 in magenta color. It was particular placed near the attic model so to know the surround temperature around the attic model. The temperature recorded for A1 is 45.5 °C, A2 is 41.5 °C, A3 is 44.0 °C and A4 is 42.0 °C. Calculating the average temperature and distance, position of T3 was selected. Then the opening of the chamber’s lid is manipulated until T3 reach 43 °C. The fourth thermocouple (T4) was placed outside the chamber to get the ambient temperature.

Figure 3:17: Roof sensor location in real image (Top view).

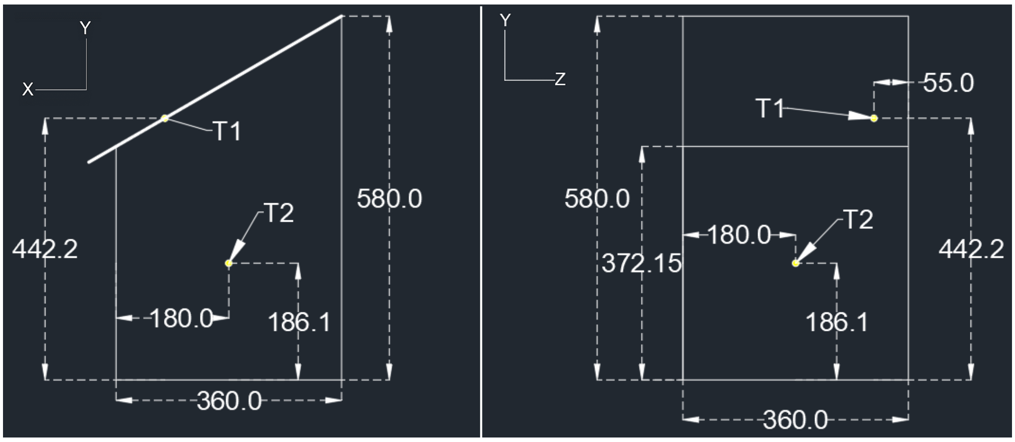

Figure 3:18: Location of T1 and T2 sensor in drawings, Side view (left) and front view (right) (all dimensions in the figure is in mm).

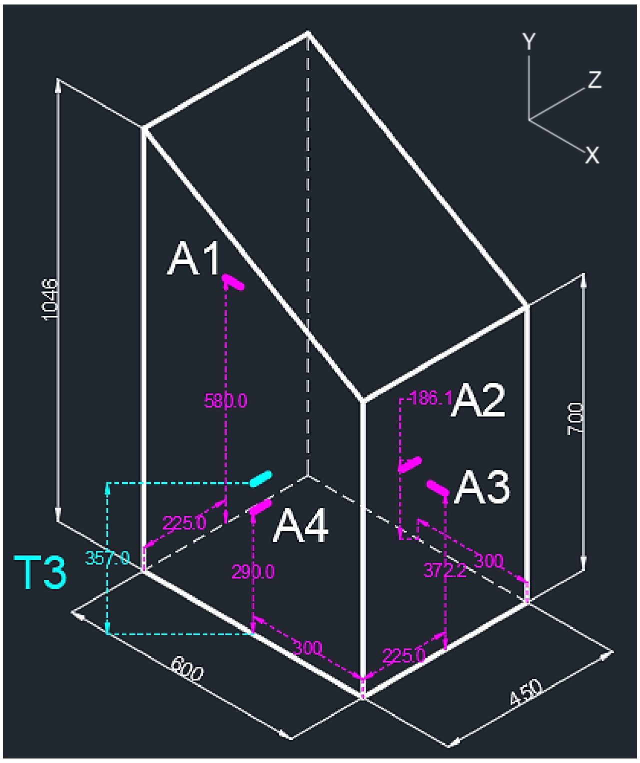

Figure 3:19: Location and experiment for heating chamber sensor (all dimensions in the figure is in mm).

3.7 Procedure (Setup of experiment)

The attic model is placed in heating chamber as in Figure 3:20. The attic model will be modified with different design/cooling technologies and placed back into the chamber. The roof is attached with cloth tape (black colour) to the attic model as in Figure 3:17. If there is any visible hole present, polystyrene will be used to block the holes. Sensor and data logger will attached to attic model and heating chamber as mention earlier. The data will recorded by PLX-DAQ software. The experiment will run under operational halogen light for few minutes. Once one experiment is over, to continue with another experiment, the process will have to wait until the attic model and heating chamber to cold down. The experiment can be proceed when the initial temperature is close to the ambient temperature. Figure 3:21shows that how this experiment is carry out (Lid of the chamber is open).

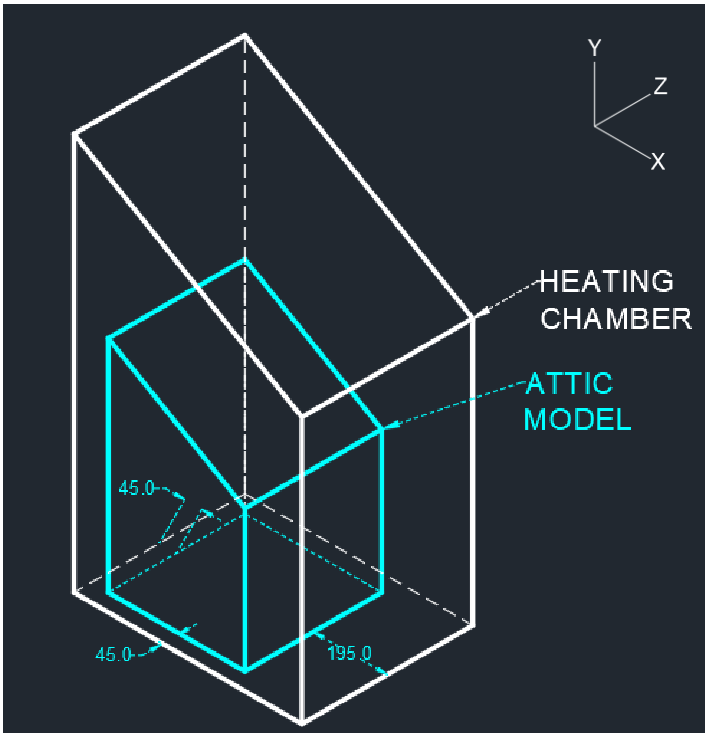

Figure 3:20: Placement of attic model into heating chamber (all dimensions in the figure is in mm).

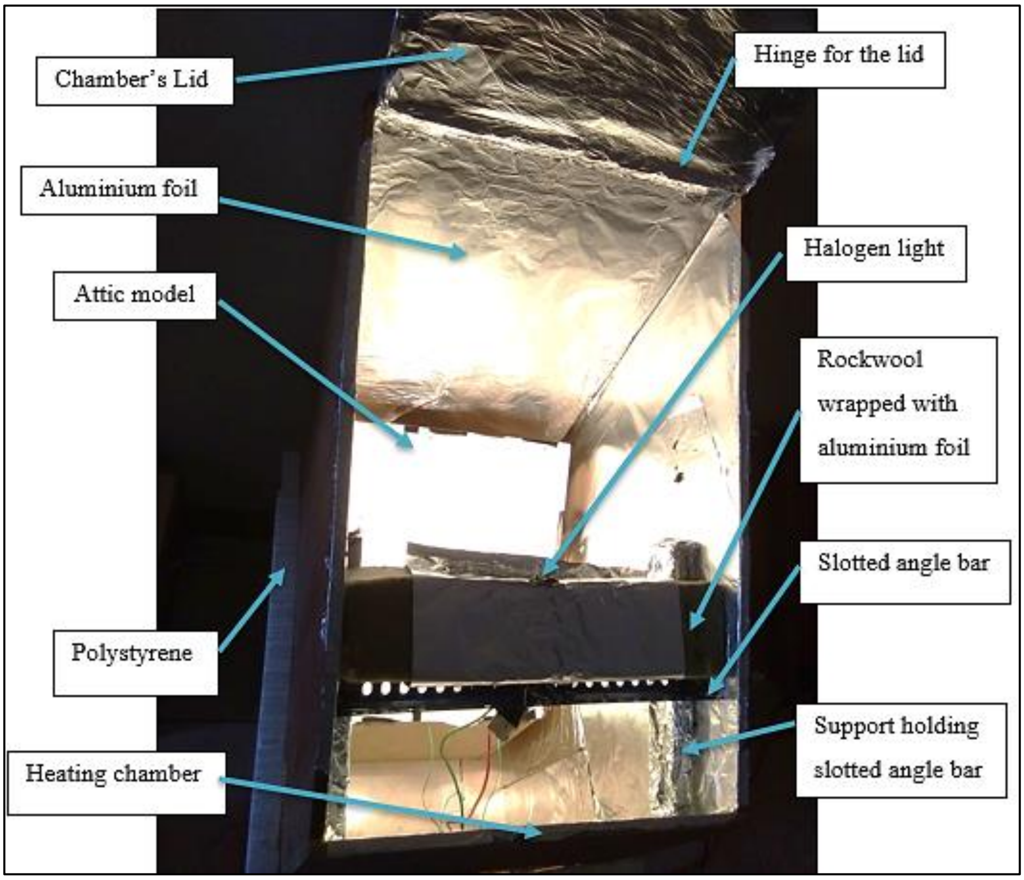

Figure 3:21: Real time experiment set up.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter will be discussing more on the outline of the selection process to determine the best cooling system for each section. There are two section to be discussed which are the outer part (surface of roof) and inner part cooling system. For the outer part, cooling techniques was implemented on the roof surface and for inner part there are three cooling techniques have been implemented in the attic model: conduction heat barrier, convection heat barrier and radiant heat barrier.

4.2 Outer part cooling techniques

In this section, cooling techniques will be implemented on the surface of the roof and the type of cooling techniques that shows greater cooling efficiency will be selected.

4.2.1 Normal Roof surface (Design A)

In this design no cooling techniques were used or applied, the purpose was to observe how much heat it is capable of absorbing or reflecting under normal condition. The recorded results were plotted in Figure 4:1. The ambient temperature throughout this experiment was 28.75 °C to 30 °C. The initial temperature of the roof was 29 °C and for the attic was 28.75 °C. This experiment stopped when the attic temperature was undergoing slight fluctuation of 0.25 °C every minute for five consecutive minutes, which lasted for 47 minutes. The final surface temperature increased by 33.5 °C (73.75 °C – 40.25 °C). For the attic final temperature, it was recorded to be 42.25 °C. There was an increase of 12.75 °C (42.25 °C – 29.5 °C) in the 47 minutes time interval. For the chamber temperature, the lowest temperature recorded was 32.75 °C and the highest temperature recorded was 41.25 °C. Based on the Figure 4:1, after 21 minutes, the attic temperature was higher than the chamber temperature and the attic temperature increases over time. At 47 minutes, the temperature difference between the attic and surrounding (chamber) temperature was 1 °C. This is similar to our real life scenario where the attic temperature was observed to be almost similar to the surrounding temperature followed by equal and then higher than the surrounding temperature. In this roof design, it only protects other hazards such as rain but does not block heat out of the attic temperature.

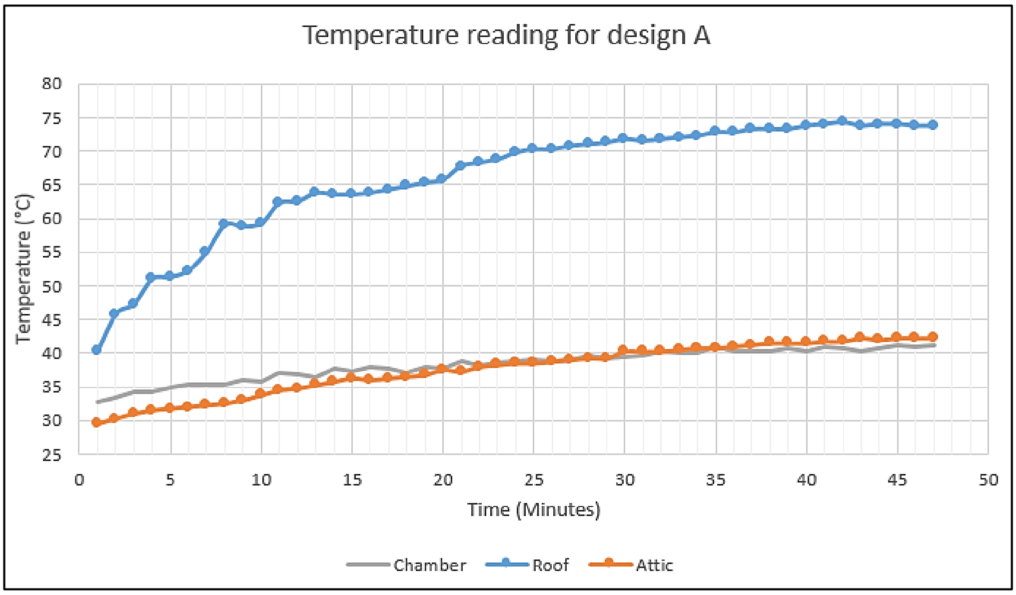

Figure 4:1: Temperature reading for design A.

4.2.2 Roof Coated with TRC (Design B)

In this design, TRC was applied on the surface of the roof. The purpose of this experiment is to investigate how good TRC is against the heat. The recorded results were plotted in Figure 4:2. During the time when this experiment was conducted, the ambient temperature was 29 °C to 30.25 °C. The initial temperature for the roof was 28.75 °C and for the attic was 28.50 °C. Based on design A, this experiment ended in 47 minutes. In the end of the experiment, the temperature increased for the surface of the roof was 31 °C (65.5 °C – 34.5 °C). The final temperature for attic was 39.75 °C and that shows an increase of 11 °C (39.75 °C – 28.75 °C). For the chamber with the lowest temperature, it was recorded to be 33 °C and the highest temperature recorded was 41.5 °C. As per graph, the attic temperature was equal to the chamber temperature after 42 minutes of experiment. Based on Figure 4:2, the temperature difference between the chamber and attic was decreasing over time. In this design of roof, heat was reflected, and it delayed the heat transfer to the attic.

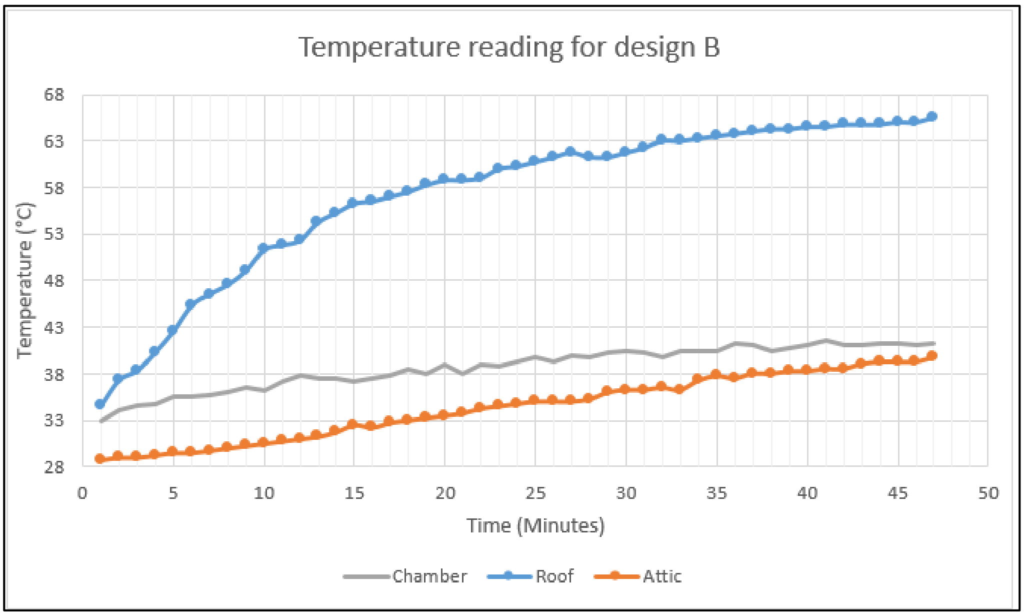

Figure 4:2: Temperature reading for design B.

4.2.3 Comparison of attic temperature for Design A and B

Figure 4:3 shows the comparison of attic temperature in design A and B. The temperature increased for design A is 12.75 °C and for design B is 11 °C. From this data, design B shows reduction of 1.75 °C compared to design A. It is proven that TRC is able to decrease the attic space temperature by 1.75 °C compared to the conventional roof.

TRC is a coating applied on the surface of the metal roof. In short, TRC is a coating made of titanium dioxide pigment and egg shell (chicken) is used as a bio-filler whereby it is merged together with polyurethane resin binder which has low thermal conductivity. The addition of mixture with titanium dioxide gives the coating a shiny white appearance.

TRC has reduced the attic space by reflecting more radiant heat due to the white appearance of the coating as it has a higher albedo value compared to red appearance (design A). According to (Jandaghian and Berardi, 2020), white colour has albedo value of 0.65 and red colour has value of 0.30 [0 - perfect absorber, 1 - perfect reflector]. Since the white have higher albedo, more heat is being reflected than being absorbed hence gives out less emissivity of heat from the roof to the attic space. Besides that, adding TRC coating has decrease the thermal conductivity and increase the thermal resistance of the roof. This results in delay of heat transfer to the attic space.

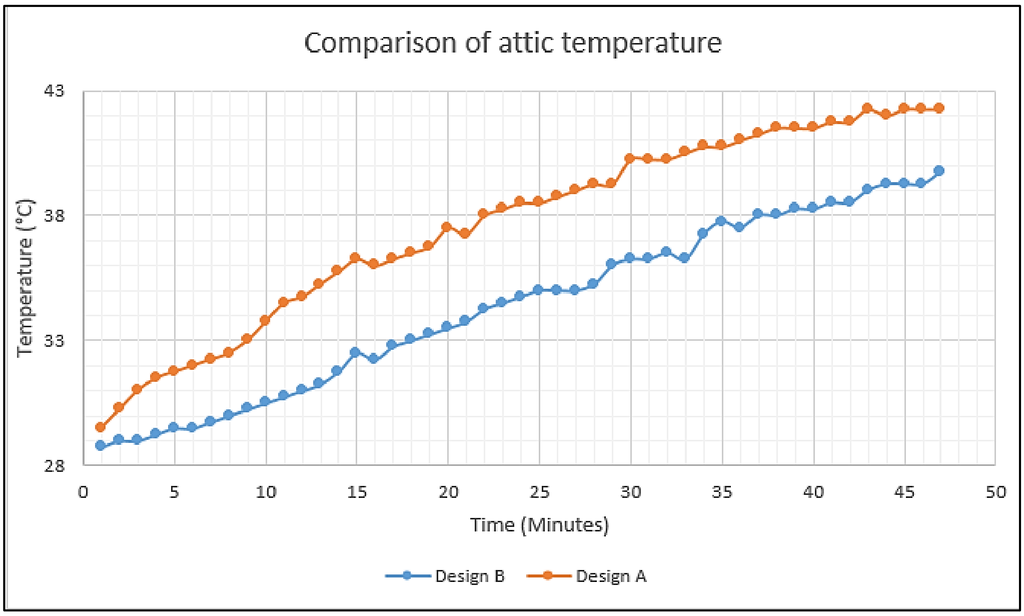

Figure 4:3 : Comparison of attic temperature for design A and B.

4.2.4 Comparison of roof surface temperature for Design A and B

Figure 4:4 shows the comparison of roof surface temperature of design A and design B. Temperature increased for design A is 33.5 °C and for design B is 31 °C. Similarly, comparison between the attic temperature, design B shows lower roof surface temperature about 2.5 °C compared to design A. Application of TRC to the roof surface shows that it can reduce the temperature of the roof surface as well.

TRC will reflect more radiant heat compared to roof surface without TRC. By reflecting radiant heat, there were less heat transfer to the metal deck (conduction) and also with the presence of TRC coating, it also acts as heat thermal resistance. The layer of coating will form resistance layer for heat, which will be harder to conduct the roof compared to the one without coating. Since it has reflected the radiant heat, the attic temperature reduces which also leads to the increase of heat loss at the roof. This is similar to Newton’s cooling law, where it stated that the heat loss of a material is dependent on the surrounding temperature.

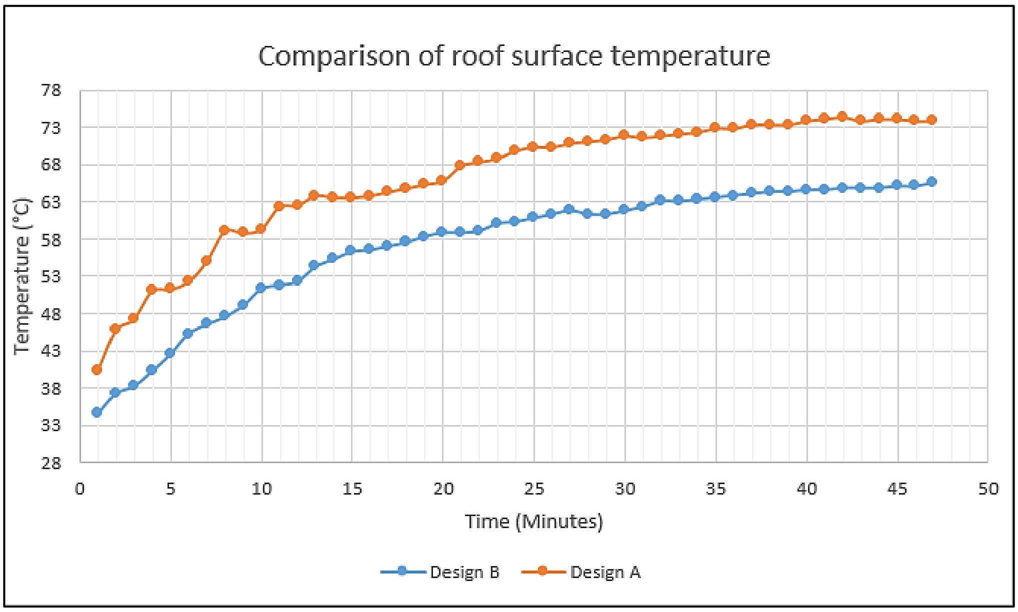

Figure 4:4: Comparison of roof surface temperature for design A and B.

4.3 Inner part cooling techniques

In this section, cooling techniques will be implemented inside the attic model. The techniques are divided into three sections; conduction heat barrier, convection heat barrier and radiant heat barrier. A comparison in each section and the type of cooling techniques which shows greater cooling efficiency will be selected.

4.3.1 Conduction heat barrier

For this section, a comparison between rockwool and vacuumed rockwool will be evaluated. Among these two materials, the material that shows the best cooling efficiency will be selected.

4.3.1.1 Roof coated with TRC and fixed Rockwool insulation (Design C)

In this design TRC and rockwool insulation was used whereby the purpose is to observe how much heat it was able to delay/block with rockwool insulation. The recorded results was plotted in Figure 4:5. The ambient temperature throughout this experiment was at 29 °C to 30 °C. The initial temperature for the roof was 29.50 °C and for the attic was 29.25 °C. Based on design A, this experiment ended in 47 minutes. Within 47 minutes, the final surface temperature increased by 40.25 °C (77 °C – 36.75 °C). For the attic final temperature, it was recorded to be 37.25 °C. There was an increase of 8 °C (37.25 °C – 29.25 °C) in 47 minutes. For the chamber temperature, the lowest temperature recorded was 33.75 °C and the highest temperature recorded was 41.5 °C. Based on Figure 4:5, the temperature difference between the chamber and attic was decreasing over time. In this design of roof, heat was reflected, and it delayed the heat transfer to the attic.

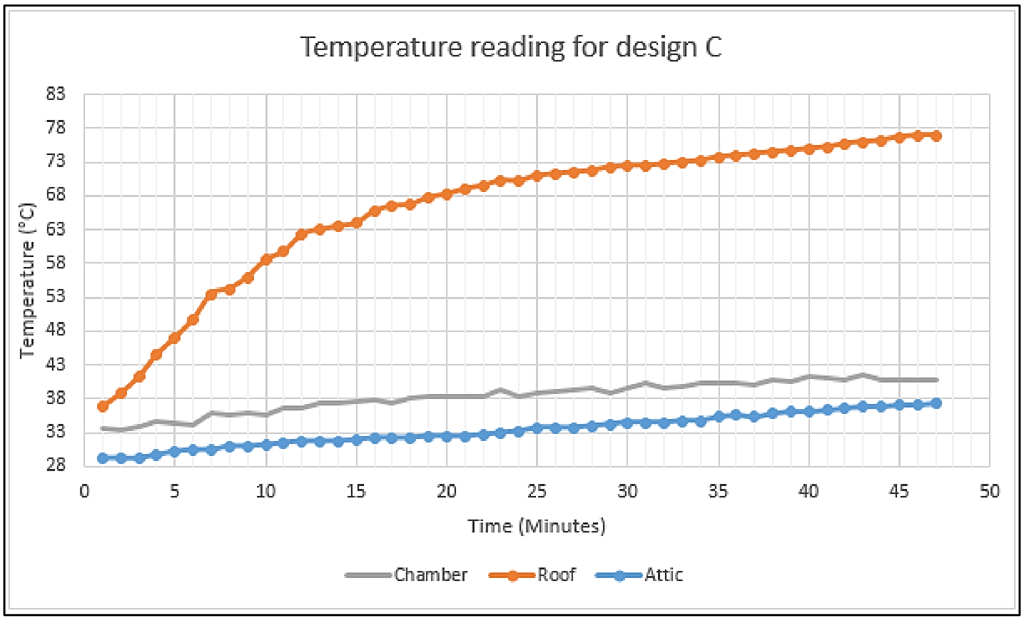

Figure 4:5: Temperature reading for design C.

4.3.1.2 Roof coated with TRC and fixed vacuumed rockwool (Design D)

Similar to design C, but instead in this design the rockwool is vacuumed. The purpose is to investigate how much heat it can delay from reaching the attic space. The recorded results was plotted in Figure 4:6. The ambient temperature throughout this experiment was 28.75 °C to 29.5 °C. The initial temperature for the roof was 29 °C and for the attic was 28.75 °C. Based on design A, this experiment was completed in 47 minutes. Within 47 minutes, the final surface temperature of roof increased by 41.5 °C (74.25 °C – 32.75° C). For the attic final temperature, it was recorded to be 35 °C. There was an increase of 6.25 °C (35 °C – 28.75 °C) in 47 minutes. For the chamber temperature, the lowest temperature recorded was 32.75 °C and the highest temperature recorded was 42.25 °C. Based on Figure 4:6, the temperature difference between the chamber and attic was decreasing over time. In this design, heat was reflected and it delayed the heat transfer to the attic.

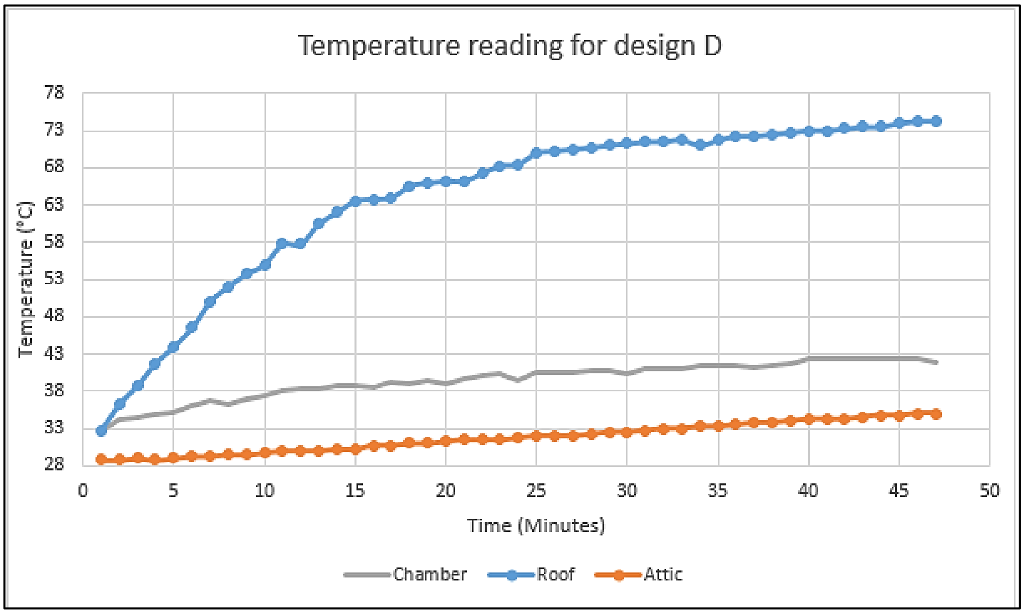

Figure 4:6: Temperature reading for design D.

4.3.1.3 Comparison of attic temperature for Design C and D

Figure 4:7 shows the comparison of attic temperature for design C and D. The temperature increase of design C and D are 8 °C and 6.25 °C respectively. From this it can be concluded that design D is far more efficient in cooling attic space compared to design C. It was able to reduce 1.75 °C more than design D.

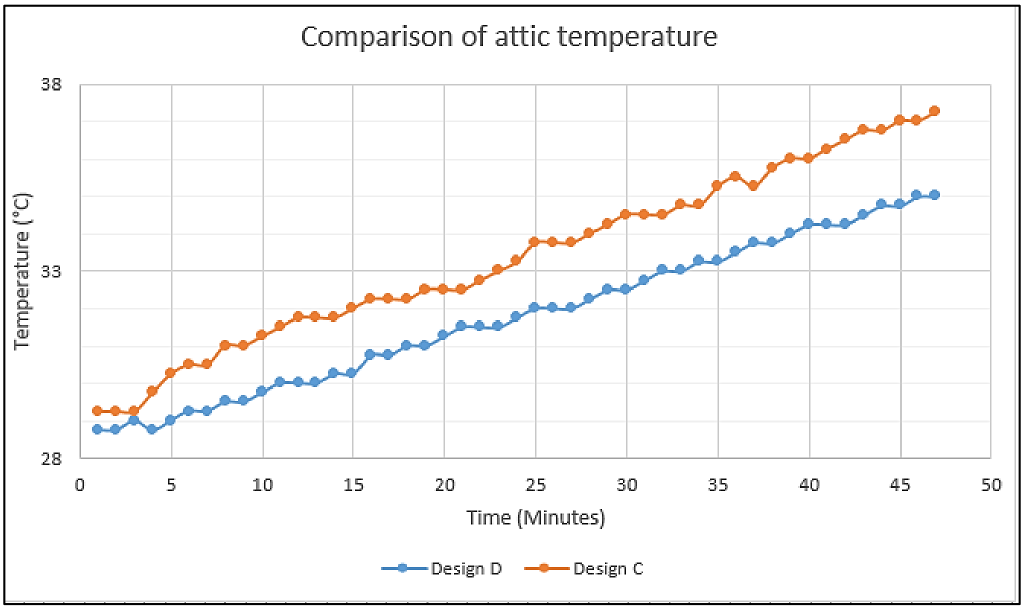

Figure 4:7: Comparison of attic temperature for design C and D.

Naturally, normal rockwool is a good heat insulator. Rockwool has R value of 1.42 and thermal conductivity (k) of 0.035 W/m.K. Rockwool insulation is packed with small air pocket (R = 1, k = 0.02624). Air is good thermal insulator and has a low thermal conductivity in room temperature (25 °C). Hence, having small air pocket in the insulation makes it a better thermal insulator. The insulation actually slows down the transfer of heat to the attic space, Figure 4:8 illustrates the heat flow. As mention earlier, this method focuses on heat transfer via conduction. Hence, most of radiation heat will pass through the insulation.

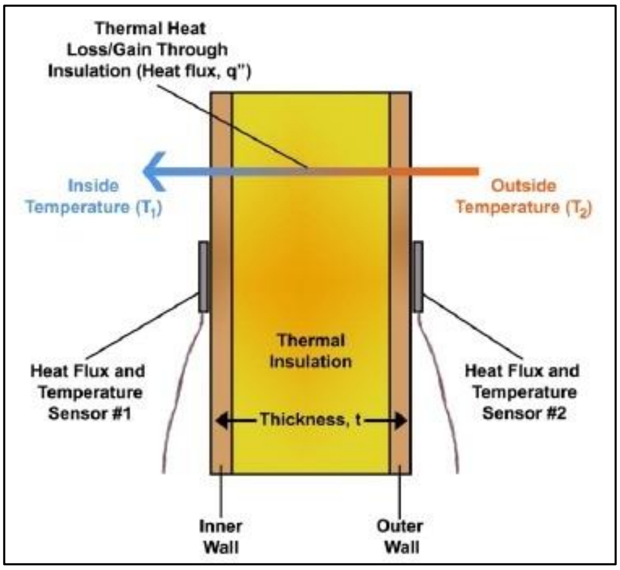

Figure 4:8: Heat flow through insulation (FluxTeq, 2019).

According to (Engineering ToolBox, 2019), it is stated that the thermal conductivity of air will increase along with temperature and pressure. In other words, thermal conductivity of air will decrease in lower air pressure and temperature and vice versa for higher temperature and pressure. The scientific explanation on how thermal conductivity of air changes in pressure is when the air pressure is lower, the distance between air particles gets larger so the collision and transfer of energy between particles will become less frequent. Also, as the distance between particles increases, the R-value for air will increase too. For temperature, as the temperature of air increases, the molecular diffusion also increases. Thermal conductivity of air is directly proportional to the lattice vibration and molecular diffusion. Hence, thermal conductivity of air increase as the temperature increases.

By acquiring knowledge about the behaviour of thermal conductivity of air, normal rockwool has been vacuumed up to -0.8 bar compared to atmospheric pressure. By using this technique, it was able to reduce more temperature compared to the normal rockwool. However, the difference in temperature between the two designs was only 1.75 °C. Based on the theory of thermal conductivity of air, this vacuum technique should be able to reduce heat transfer more than the obtained result. The reason is because in normal rockwool the insulation is loosely pack and after vacuum the insulation is more closely pack compared to the normal rockwool. Hence, heat transfer increases in rockwool insulation and yet decreases through air particle.

4.3.1.4 Comparison of roof surface temperature for Design C and D

Figure 4:9 shows the comparison of roof surface temperature of design C and design D. For design C the temperature increased is 40.25 °C and for design D the temperature increased was 41.5 °C. Unlike for attic temperature comparison, the roof surface temperature for design C is more efficient in cooling roof surface compared to design D. The temperature difference between two designs is 1.25 °C.

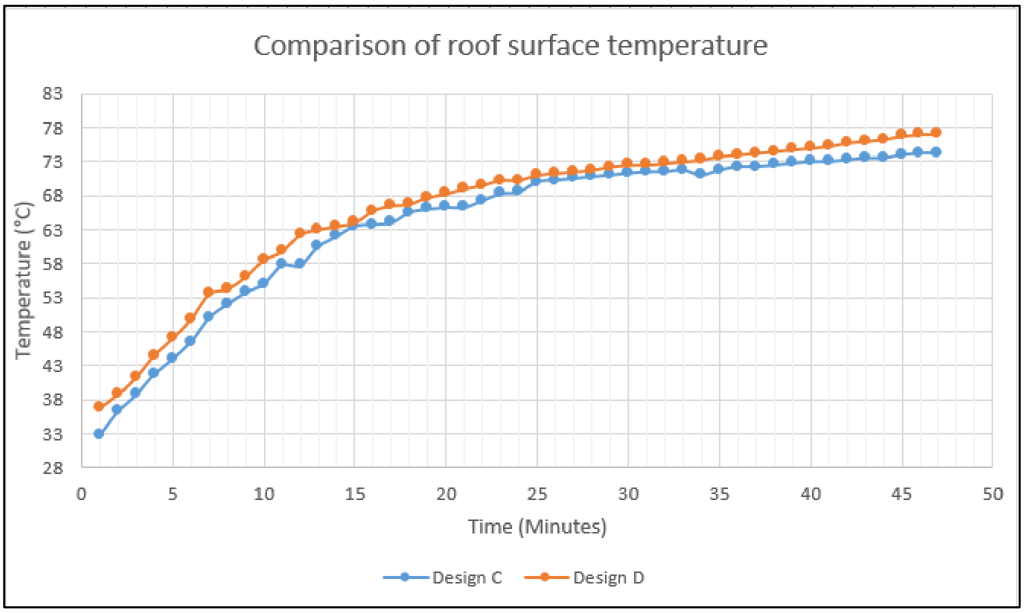

Figure 4:9: Comparison of roof surface temperature for design C and D.

The reason is because when insulation is placed below the roof it creates two different region of air as in Figure 4:10. Region 1 gets hotter faster because the heat transferred to region 2 is reduced. This causes more heat to accumulate at region 1, where it gets hotter in a short period of time due to the small area. According to Newton’s law of cooling, it is stated that the rate of the body's heat loss is directly proportional to the difference in temperatures between the body and its environment. As the temperature of the surrounding increases, the heat loss of the body decreases. In addition, this also proves that cooling system for design D reduces the heat transfer more compared to design C.

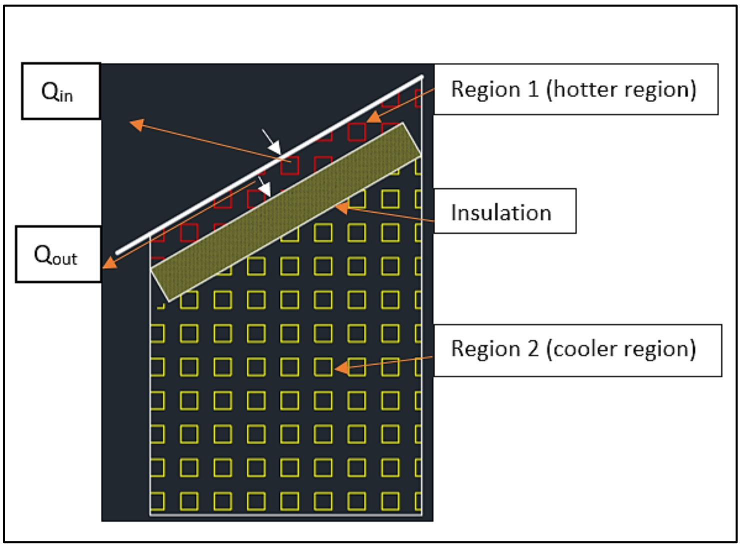

Figure 4:10: Heat loss explanation of for roof deck.

4.3.2 Convection heat barrier

For this section, a comparison between ventilation hole and attic fan will be evaluated. Among these two methods, the method that shows the best cooling efficiency will be selected.

4.3.2.1 Roof coated with TRC and with ventilation hole (Design E)

In this design of experiment, TRC and a ventilation hole were created on the attic model. The purpose of this experiment is to see how a ventilation hole can affect the temperature in attic space. The recorded results was plotted in the Figure 4:11. The ambient temperature throughout this experiment was 28.5 °C to 29.75 °C. The initial temperature for the roof and attic was 28.5 °C. Based on design A, this experiment concluded in 47 minutes. Within 47 minutes, the final surface temperature increased by 30.5 °C (62.25 °C – 31.75 °C). For the attic final temperature, it was recorded to be 38.75 °C. There was an increase of

9.75 °C (38.75 °C – 29 °C) in 47 minutes. For the chamber temperature, the lowest temperature recorded was 31.5 °C and the highest temperature recorded was 40.25 °C. Based on Figure 4:11, the temperature difference between the chamber and attic was decreasing over time. In this design, heat was reflected and air flow in attic space was improved.

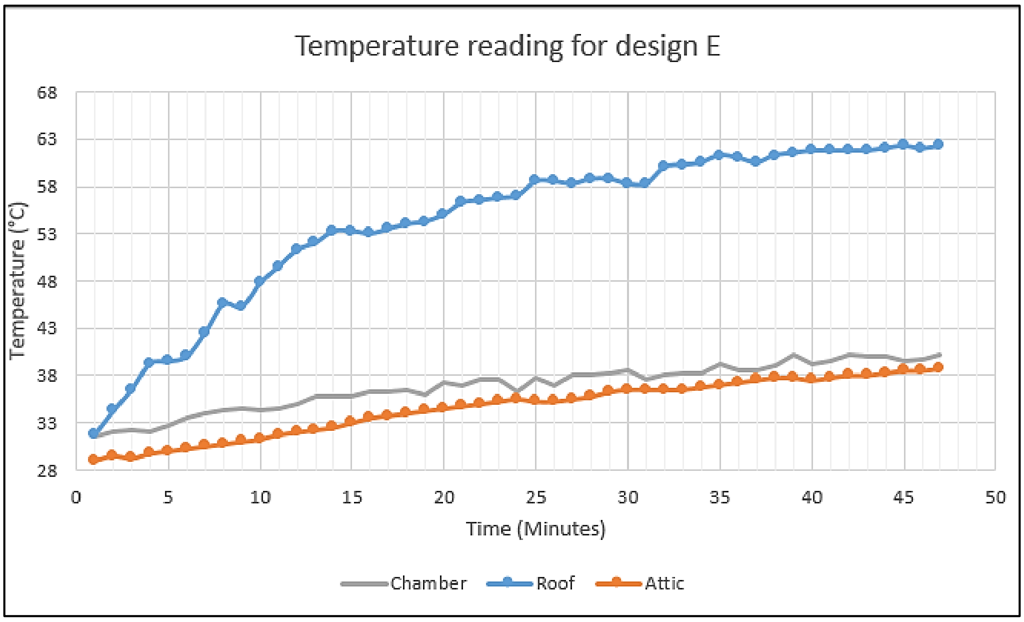

Figure 4:11: Temperature reading for design E.

4.3.2.2 Roof coated with TRC and solar powered fan (Design F)

Similar to design E but instead of ventilation hole now it has a solar powered fan. This experiment is to investigate how heat could be extracted out using solar powered fan. The recorded results was plotted in Figure 4:12. The ambient temperature during this experiment was 28.25 °C to 29 °C. The initial temperature for the roof was 28.5 °C and for the attic was 28.25 °C. Based on design A, this experiment concluded in 47 minutes. Within 47 minutes, the final surface temperature increased by 29.5 °C (60.5 °C – 31 °C). For the attic final temperature, it was recorded to be 36.75 °C. There was an increase of 8.5 °C (36.75 °C – 28.25 °C) in 47 minutes. For the chamber temperature, the lowest temperature recorded was 31.5 °C and the highest temperature recorded was 43.75 °C. Based on Figure 4:12, the temperature difference between the chamber and attic was decreasing over time. In this design, heat was reflected by TIC and extracted using force convection from the attic space.

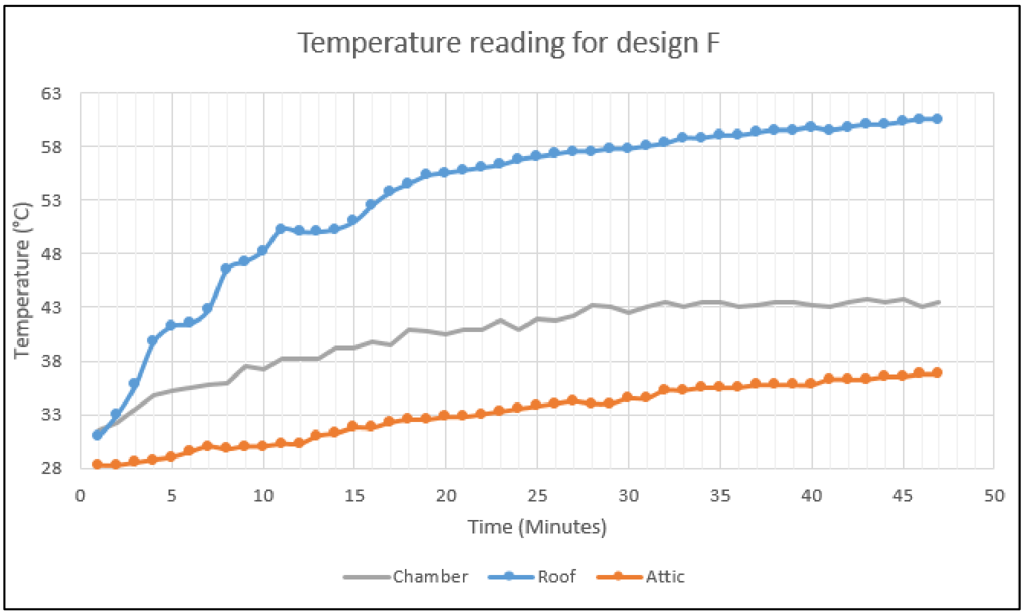

Figure 4:12: Temperature reading for design F.

4.3.2.3 Comparison of attic temperature for Design E and F

Based on Figure 4:13, it shows the comparison of attic temperature for design E and design F. For design E the temperature increased was 9.75 °C and for design F was 8.5 °C. From this, design F has greater cooling efficiency, where it able to reduce 1.25 °C more than design E.

As mentioned earlier, warm air is less dense than cooler air which makes the warm air to rise at higher location. That was the reason why the ventilation and hole is located at higher position so it will be suitable to remove the hot air and reduce the attic temperature.

By adding a ventilation hole, it creates a pressure difference between the attic space and the surrounding. The heat will transfer between these two medium until the pressure equalizes. According to (Everts and Meyer, 2018) when two different temperatures of medium is there, it creates two different pressures, the heat transfer will occur till both temperature and pressure is equal.

However, by adding an attic fan (suction) it creates a negative pressure ventilation system where it will extract hot air that accumulates in the attic space. Hence, it has reduced the pressure and temperature in the attic space. When the pressure of the medium is low, the distance between particles increases. The increased distance cause the conduction between air particles to reduce.

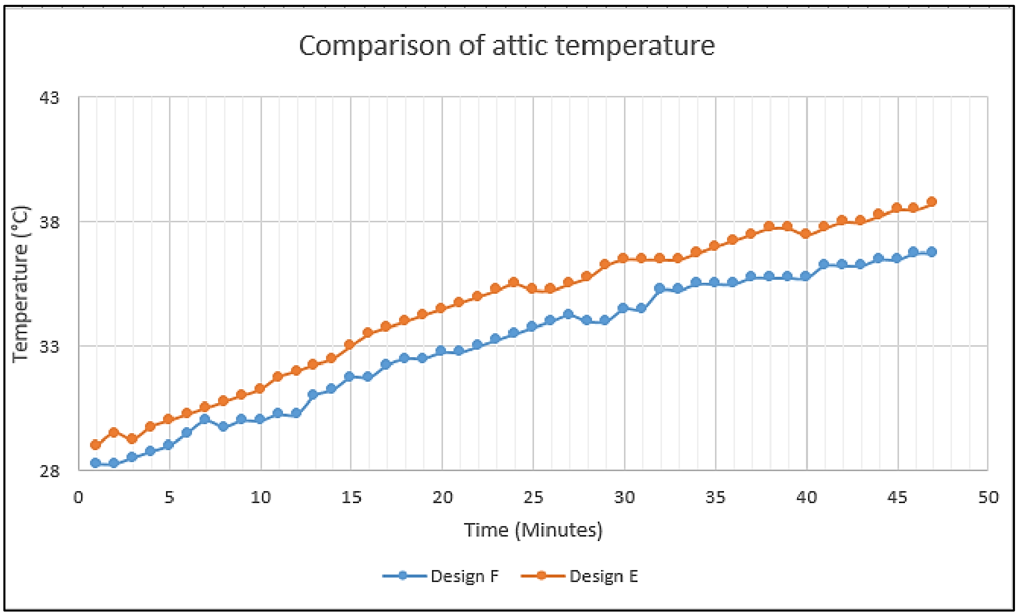

Figure 4:13: Comparison of attic temperature for design E and F.

4.3.2.4 Comparison of roof surface temperature for Design E and F

Figure 4:14 shows the comparison of roof surface temperature for design E and F. For design E the temperature increased was 30.5 °C and for design F was 29.5 °C. Similarly for attic temperature, design F shows more cooling efficiency for surface of roof. Design F is able to reduce 1 °C more compared to design E.

Similarly like Newton’s law of cooling, since the attic temperature was reduced by attic fan and ventilation hole, the heat loss for the roof increases, hence for attic fan it was placed near the roof deck so when the roof deck emits radiated heat it will be removed by the attic fan, this makes the heat loss of the roof higher compared to ventilation hole.

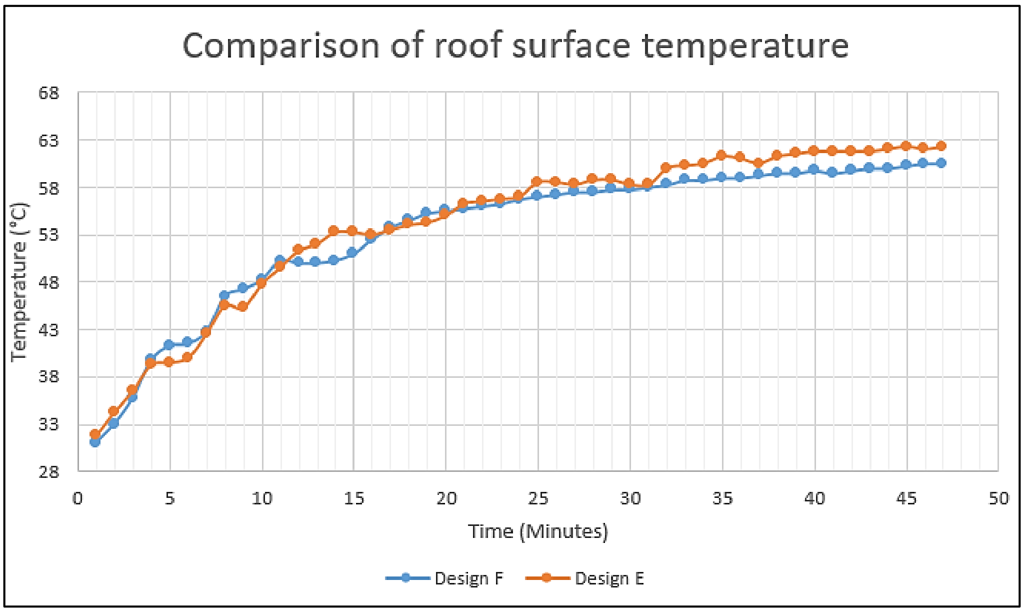

Figure 4:14: Comparison of roof surface temperature for design E and F.

4.3.3 Radiant heat barrier

For this section, a comparison between polished and unpolished aluminium will be evaluated. Between these two materials, the material shows the best cooling efficiency will be selected.

4.3.3.1 Roof coated with TRC with unpolished aluminium (Design G)

In this design TRC and aluminium sheet has been used as cooling method. The purpose of this experiment is to find out how much heat can be reflected using aluminium sheet. The recorded results was plotted in Figure 4:15. The ambient temperature throughout this experiment was 28.75 °C to 29.25 °C. The initial temperature for the roof was 28.5 °C and for the attic was 28.75 °C. Based on design A, this experiment concluded in 47 minutes. Within 47 minutes, the final surface temperature increased by 39.75 °C (72 °C – 32.25 °C). For the attic final temperature recorded was 35.5 °C. There was an increase of 6.75 °C (35.5 °C – 28.75 °C) in 47 minutes. For the chamber temperature the lowest temperature recorded was 31 °C and the highest temperature recorded was 42 °C. Based on Figure 4:15, the temperature difference between the chamber and attic was decreasing over time. In this design, heat was reflected and it delayed the heat transfer to the attic.

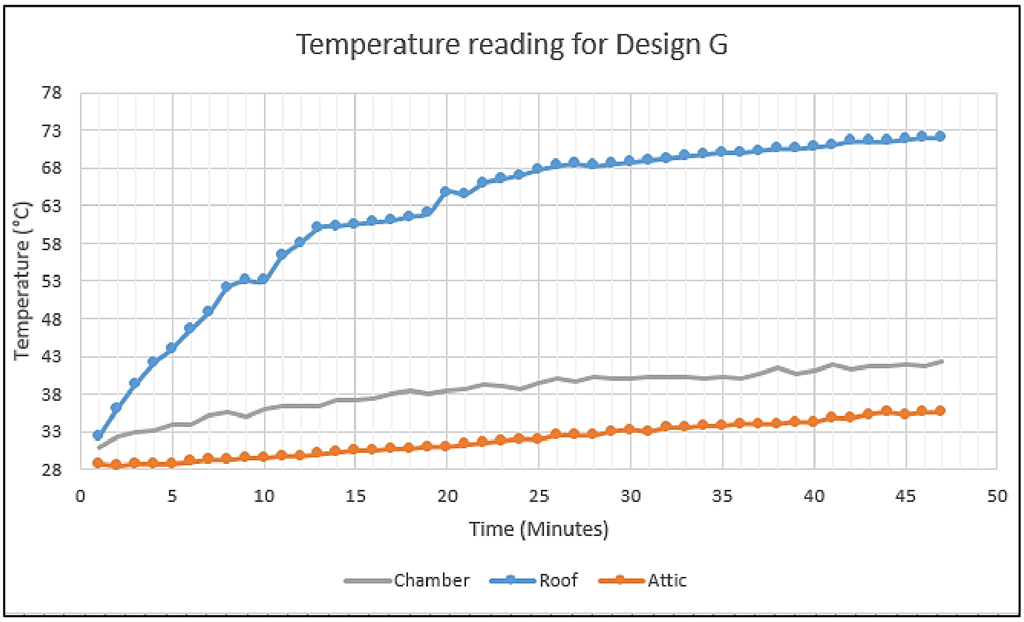

Figure 4:15: Temperature reading for design G.

4.3.3.2 Roof coated with TRC and polished aluminium (Design H)

Similar to design G except in this design aluminium sheet is polished. This experiment shows how polishing a surface affect the reflection of heat. The recorded results was plotted in Figure 4:16. The ambient temperature throughout this experiment was 30 °C to 31 °C. The initial temperature for the roof was 29.5 °C and for the attic was 29.75 °C. Based on design A, this experiment concluded in 47 minutes. Within 47 minutes, the final surface temperature increased by 42.75 °C (73.5 °C – 30.75 °C). For the attic final temperature, it was recorded to be 35 °C. There was an increase of 5.25 °C (35 °C – 29.75 °C) in 47 minutes. For the chamber temperature, the lowest temperature recorded was 33.5 °C and the highest temperature recorded was 41.75 °C. Based on the Figure 4:16, the temperature difference between the chamber and attic was decreasing over time. In this design, heat was reflected and it delayed the heat transfer to the attic.

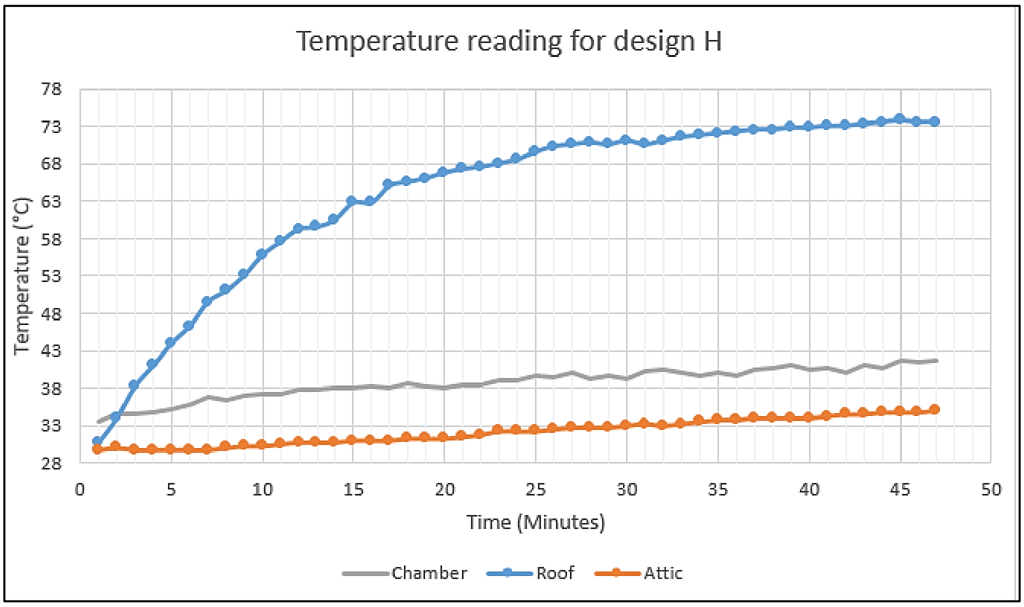

Figure 4:16: Temperature reading for design H.

4.3.3.3 Comparison of attic temperature for Design G and H

Figure 4:17 shows the comparison of attic temperature for design G and H. For design G the temperature increased was 6.75 °C and for design H is 5.25 °C. From this, it shows that design H has better cooling properties compared to design G. Design H is able to reduce 1.5 °C more than design G.

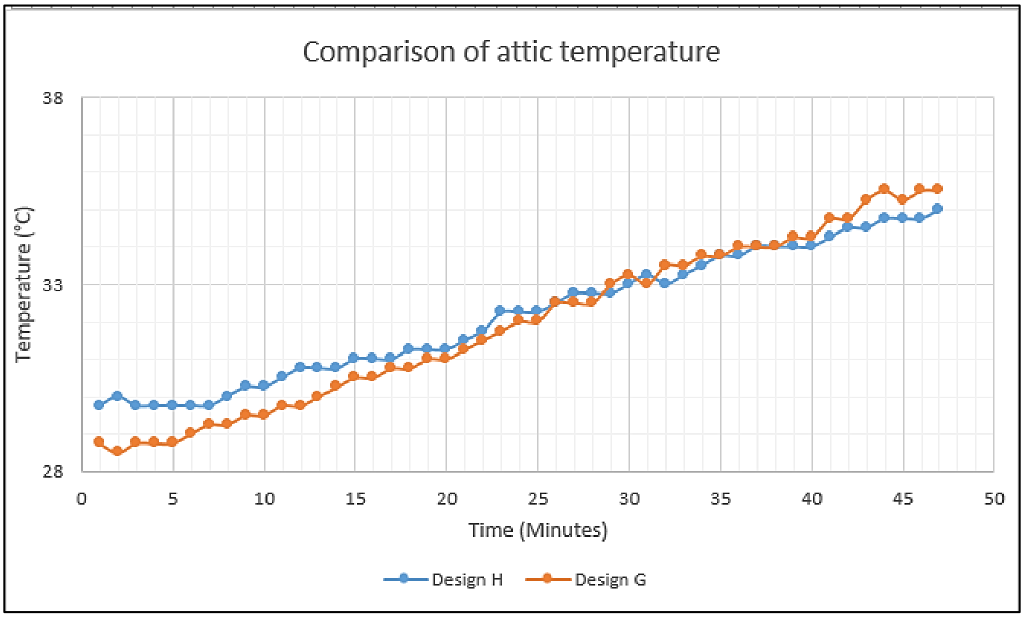

Figure 4:17: Comparison of attic temperature for design G and H.

Aluminium is a good conductor of heat as it has thermal conductivity of 205 W/m.K. Aluminium is a good heat conductor but in terms of radiant heat it has high albedo and low emissivity. Theoretically, according to (Engineering ToolBox, 2003), aluminium has emissivity of 0.09.

Normally, metals have lower emissivity and non-metals has higher emissivity. According to (Manfred, 2019), surface of the material is one of the main factor that affect the emissivity of the material. He stated that smooth and shiny surface will have low emissivity compared to rough and dull surface. Method of polishing also affect the emissivity as heavily polished material will have significantly lower emissivity compared to lightly polished material.

The aluminium was sanded and lightly polished (design H). The results was satisfying where it was able to 1.5 °C more compared to unpolished aluminium. This proves that the emissivity of aluminium is reduced more than 0.09. For albedo effect, it mainly depend on the colour and surface of the material, in other words whiteness of material. Much similarly to emissivity, but instead albedo measure how much radiation is absorbed and reflected. According to (Engineering ToolBox, 2012), for aluminium, the albedo is 0.70 it means 70 % of heat is reflected and only 30 % is absorbed. From this it can be concluded that polishing can reduce the emissivity of the material and increase the albedo effect of the material.

4.3.3.4 Comparison of roof surface temperature for Design G and H

Figure 4:18 shows the comparison of roof surface temperature for design G and H. For design G the temperature increase was 39.75 °C and for design H was 42.75 °C. Unlike in attic temperature, temperature surface of the roof design H shows 3 °C more than design G.

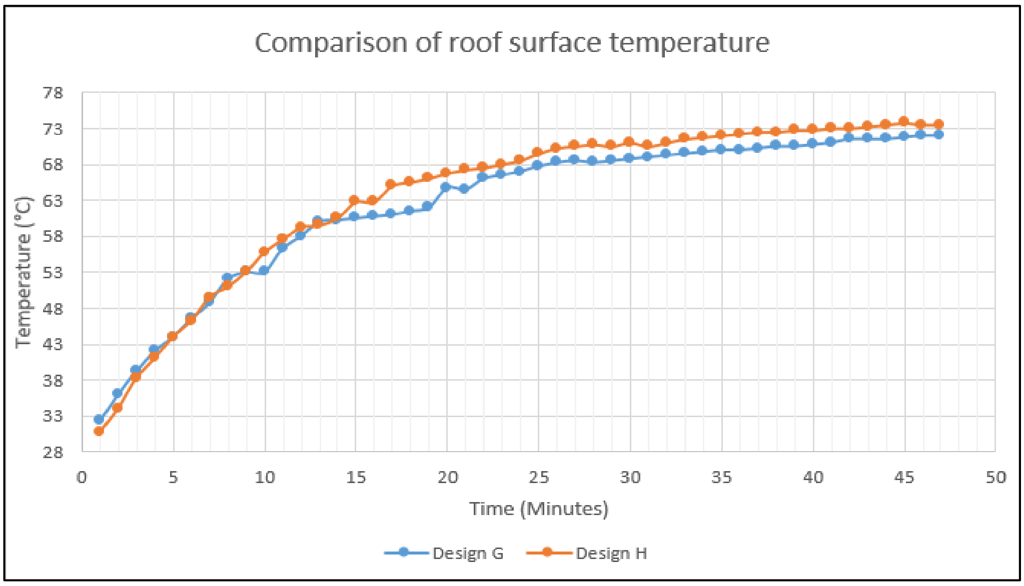

Figure 4:18: Comparison of roof surface temperature for design G and H.

Unlike in rockwool insulation, in here it is because of the reflected heat radiation and not because of reduced heat transfer. According to (Meola, Boccasrdi and Carlomagno, 2017), there are two types of heat reflection which are specular and diffuse (Figure 4:19). The type of reflection is highly dependent on surface of material. If the surface is highly polished and smooth, (mirror like surface) the reflection would be specular but if the surface is rough and dull the reflection would be diffuse type. For aluminium polished or unpolished, it will be the combination of diffuse and specular (Figure 4:20). Besides that, for polished aluminium, it will have more heat ray reflected compared to unpolished aluminium. This proves the reason why attic space was much cooler for design C, due to more heat radiation been reflected.

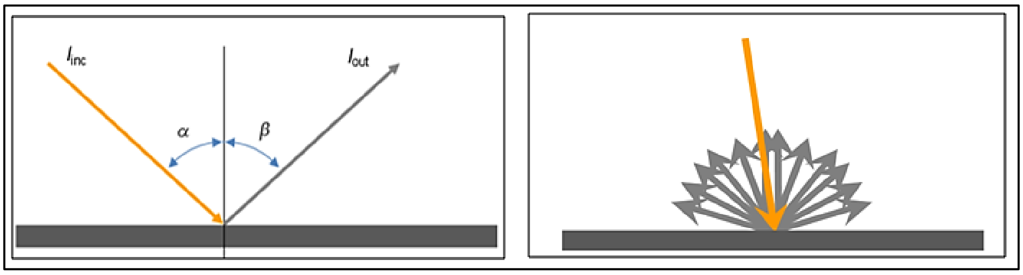

Figure 4:19: Specular (left) and diffuse (right) heat reflection (Meola, Boccasrdi and Carlomagno, 2017).

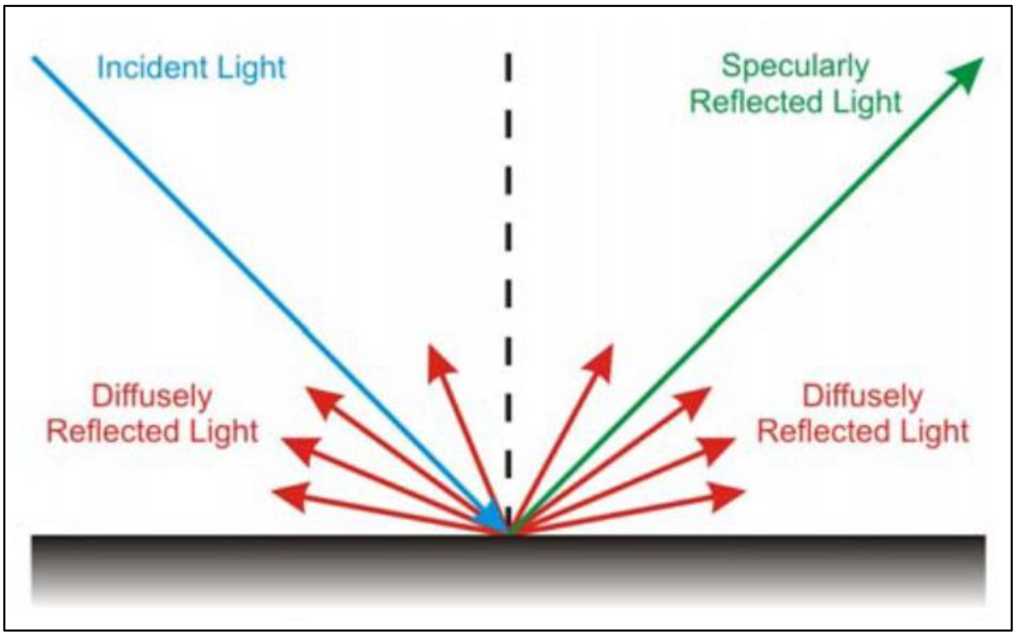

Figure 4:20: Combination of specular and diffuse heat reflection (Oleg, 2010).

4.4 Summary

From this process selection analysis, Design B, D, F and H is selected. This selected design will be implemented on the main design and analyse the cooling efficiency. In Table 4:1 show the selected design in each category and comparing the attic temperature of each selected design to design A.

Table 4:1: Summary of selected design and temperature rise in attic space.

Category	**Selected Design**	**Temperature rise in attic space (°C)**
Roof surface (outer)	Design B	11
Conduction (inner)	Design D	6.25
Convection (inner)	Design F	8.5
Radiation (inner)	Design H	5.25

4.5 Main Design Configuration

In this section, the final design has been constructed based on selection made in previous section. The selected cooling designs have been implemented and the temperature in attic space and roof surface were observed and analysed. The data has been plotted in the following sections.

As mentioned earlier, the main design is built to manage heat from conduction, convection and radiation. So in each section, a best material/method is chosen and implemented on the model. For this design the same model is used but with few modification in the design. In short, this design has combination of all selected cooling system fixed in.

4.5.1 Main design layout (Design X)

Figure 4:21 shows the layout for design X. TRC was applied on the surface of the roof as outer part of heat barrier. As for conduction heat barrier, vacuumed rockwool was installed as per Figure 4:21. For radiant heat barrier, polished aluminium was placed below the vacuumed rockwool. Finally, for convection, attic fan was installed 23.5 cm above the ground.

There is a reason why the cooling system is arranged in these manner (conduction, radiation and convection). According to (Williamson, 2018) the emissivity of metal material will be affected with increasing temperature. Even though aluminium is a good radiant heat barrier, it is also a good heat conductor. In order to make sure the aluminium does not get heated, rockwool insulation is placed above the aluminium instead of below. The attic fan is placed below the insulations because when the transfer of heat is reduced, it will be easier to extract heat more efficiently than placing the attic fan above the insulation. By using trigonometry knowledge, the hypotenuse will always be the longest in right angle triangle. Hence placing in inclined will cover more surface. If cover more surface area it means can reduce more heat transfer to the attic.

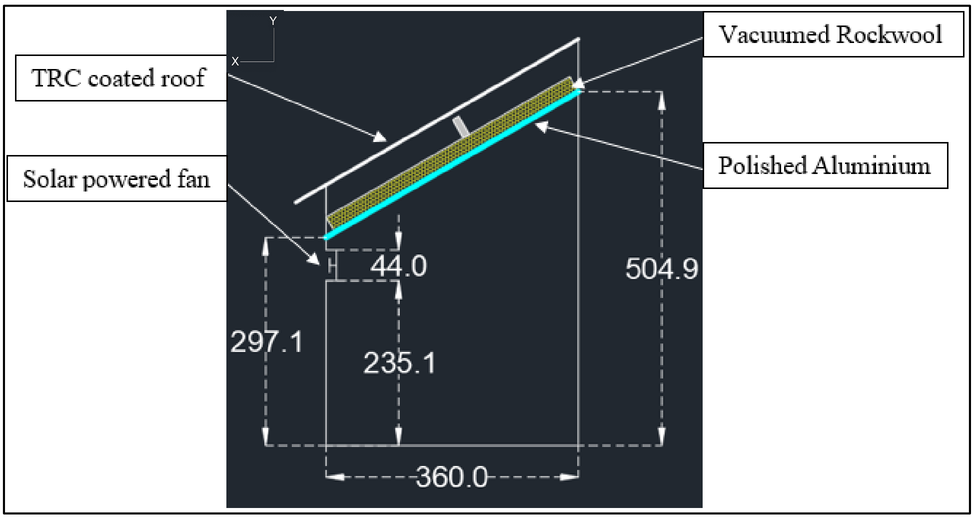

Figure 4:21: Design X layout (all dimensions in the figure is in mm).

4.6 Results for design X

After comparing all cooling method, the best is chosen and applied in this design. The purpose is to see how efficient does it remove heat when the best cooling technique in each heat transfer mechanisms is applied. The recorded results was plotted in Figure 4:22. The ambient temperature throughout this experiment was 29.75 °C to 30.25 °C. The initial temperature for the roof and the attic was 29.75 °C. Based on design A, this experiment concluded in 47 minutes. Within 47 minutes, the final surface temperature increased by 40.5 °C (72.75 °C – 32.25 °C). For the attic final temperature, it was recorded to be 34 °C. There was an increase of 4.25 °C (34 °C – 29.75 °C) in 47 minutes. For the chamber temperature, the lowest temperature recorded was 31.5 °C and the highest temperature recorded was 41.75°C. With combination of active and passive cooling system, the temperature in attic space was able to control the temperature of attic about 34 °C from 42 minute till end of experiment. There is a slight reduction of 0.25 °C at 44th minute.

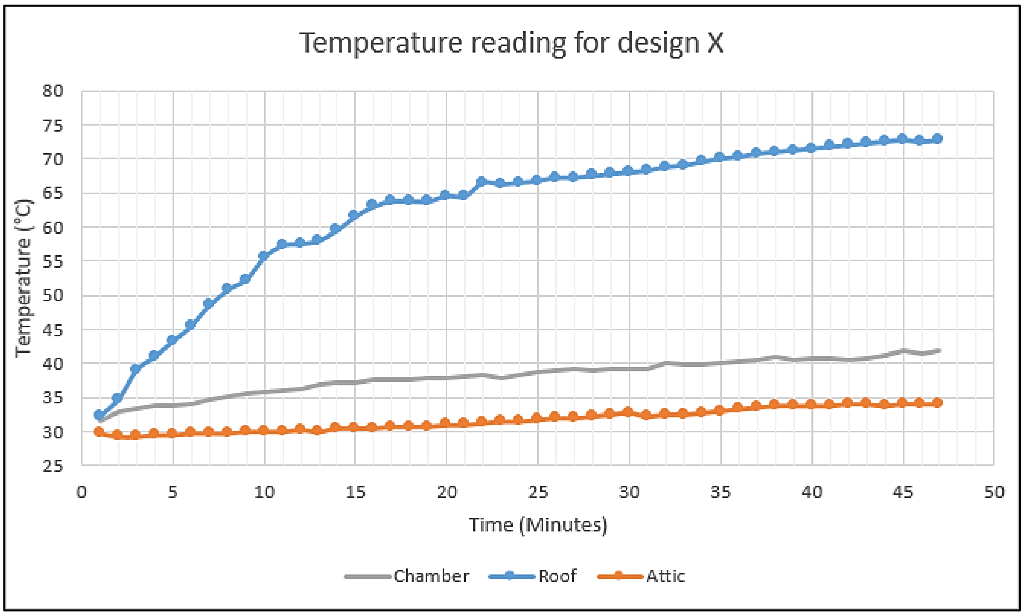

Figure 4:22: Temperature reading for design X.

4.7 Comparison of attic temperature for all design

Figure 4:23 shows the comparison of attic temperature of all designs. By comparing design X and A. For design A the temperature increased was 12.75 °C and for design X it was 4.25 °C. Clearly design X has better cooling efficiency where it can reduce 8.5 °C more than design A. Not only that, design

X shows the lowest increase of temperature compared to the rest of the design. This is because, each cooling method has been selected to reduce each type of heat transfer mechanisms (conduction, convection, radiation). However, any type of insulation applied is better than no insulation. Even by applying TRC, it was able to reduce 1.75 °C more compared to design A. Figure 4:24 show the flow of the worst to best cooling method for attic temperature. Besides that, when conducting experiment based on radiant heat barrier, it shows that significant amount of temperature is reduced. This prove that most type of heat transmitted through attic space is radiation heat.

However design X only reduced 1 °C more compared to design H, this is because some of the heat reflected by aluminium is reflected by the rockwool and the roof surface, hence allowing more heat to enter the attic space. According to (Whitwam, 2014) says that the lowest albedo material on earth is vantablack, it has 0.00035 albedo. Even the lowest albedo material does not absorb all the radiation light so definitely rockwool and roof surface also will not absorb all the radiation heat. But taken that rockwool has lower albedo compared to aluminium, not much heat were reflected. The aluminium will reflect back some of the reflected heat and some will be absorbed. The process goes on loop.

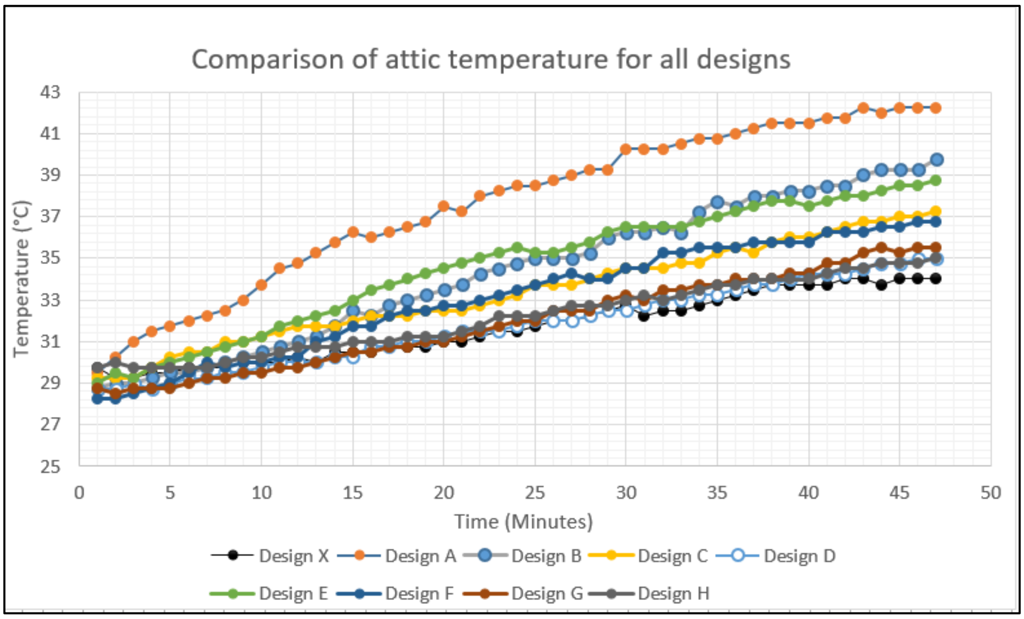

Figure 4:23: Comparison of attic temperature for all designs.

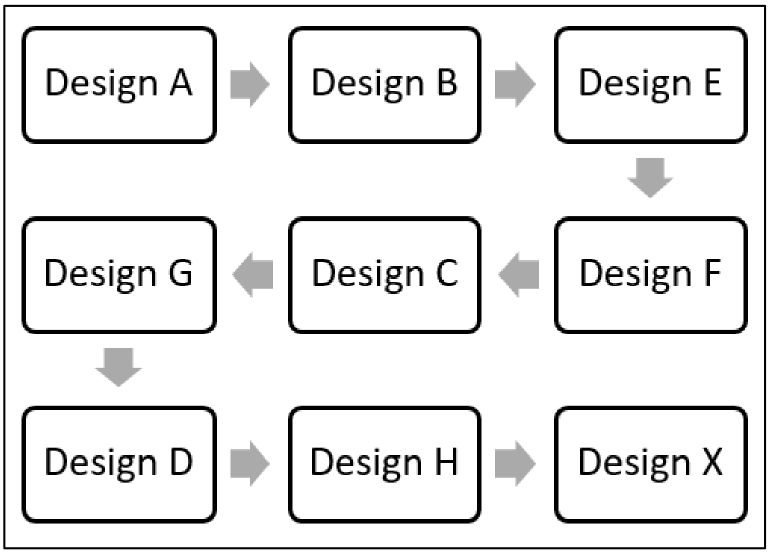

Figure 4:24: Designs arranged in worst to best cooling order.

4.8 Heat transfer mechanism

The heat transfer mechanism is split into two parts, active and passive cooling system. The following diagram in Figure 4:25 show how the passive heat mechanism travels to attic space. From Equation 4.1, the heat source supplied by halogen lamp in terms of radiation, convection and conduction heat produced by halogen lamp. Equation 4.2 shows when the radiation heat is exposed to the coating of the roof. Some of the radiation heat were reflected due to TRC. Q'^{in}_{rad} is the remaining radiant heat transfer towards insulation. Equation 4.3 shows the heat transfer between the coating and to the roof deck (Q_{cond1}). Equation 4.5 shows the heat transfer between the insulation and aluminium (Q_{cond2}). In Equation 4.4 Q'''^{in}_{rad} is the remaining heat after been reflected by the insulation (Q'^{out}_{rad}) and aluminium (Q''^{out}_{rad}). For active heat transfer mechanism is shown in Figure 4:26 and Equation 4.6. Q_{ve} will extract the hot air from the attic space. The Equation 4.6 shows how to calculate convection air extracted.

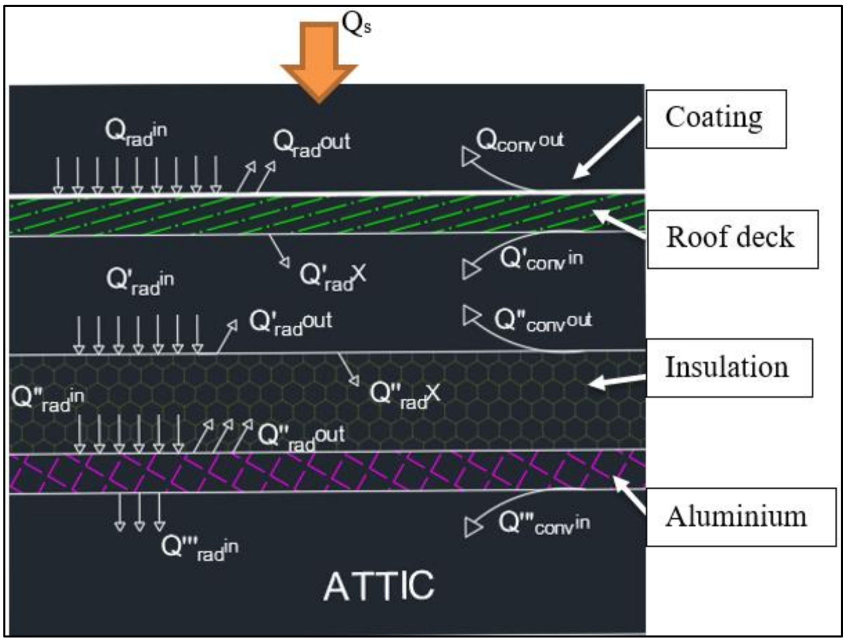

Figure 4:25: Heat transfer mechanisms for Passive cooling system.

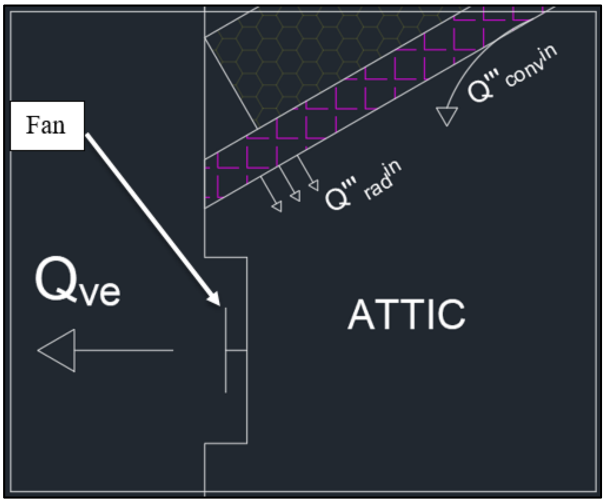

Figure 4:26: Heat transfer mechanisms for Active cooling system.

$$Q_S = Q_{rad}^{in} + Q_{conv}^{out} + Q_{cond} \tag{4.1}$$

$$Q'_{rad}{}^{in} = Q_{rad}^{in} - Q_{rad}^{out} \tag{4.2}$$

$$Q_{cond1} = Q'_{rad}{}^{in} + Q'_{conv}{}^{in} \tag{4.3}$$

$$Q'''_{rad}{}^{in} = Q'_{rad}{}^{in} - (Q'_{rad}{}^{out} + Q''_{rad}{}^{out}) \tag{4.4}$$

$$Q_{cond2} = Q'''_{rad}{}^{in} + Q'''_{conv}{}^{in} \tag{4.5}$$

$$Q_{ve} = M\,c_p\,(T_{out} - T_{in}) \tag{4.6}$$

Where;

Q_S = Main heat source from halogen light (W)

Q_{rad}^{in} = Radiation heat transfer exposed to roof surface (W)

Q_{conv}^{out} = Convection heat transfer from the roof (W)

Q_{cond} = Conduction heat transfer from halogen lamp (W)

Q'_{rad}^{in} = Radiation heat transfer exposed to insulation (W)

Q_{rad}^{out} = Reflected radiation heat from TRC (W)

Q_{cond1} = Conduction heat transfer between coating and roof deck (W)

Q'_{conv}^{in} = Convection heat transfer into the roof deck (W)

Q'''_{rad}^{in} = Radiation heat transfer exposed to attic (W)

Q'_{rad}^{out} = Reflected radiation heat from insulation (W)

Q''_{rad}^{out} = Reflected radiation heat from aluminium (W)

Q_{cond2} = Conduction heat transfer between insulation and aluminium (W)

Q'''_{conv}^{in} = Convection heat transfer into insulation and aluminium (W)

Q_{ve} = Extracted heat out through ventilation (W)

M = Mass flow rate of the removed air (kg/s)

c_p = Specific heat capacity of air at atmospheric pressure (J/kg.K)

T_{out} = Environmental temperature in the chamber (K)

T_{in} = Attic temperature (K)

Q''_{rad}^{in} = Radiation heat transfer exposed to aluminium (W)

Q'_{rad}^{X} = Reflected radiation heat from insulation reflected heat (W)

Q''_{rad}^{X} = Reflected radiation heat from aluminium reflected heat (W)

4.9 Comparison of roof surface temperature for all designs

Unlike attic temperature, for roof surface temperature, design X is not the lowest temperature rise, design F show the lowest rise of roof surface temperature. Not only that, design X roof temperature exceeds design A by 7 °C. Based on Figure 4:27, it shows that the roof temperature increased when rockwool and aluminium cooling method was implemented. Figure 4:28 shows the flow of the lowest to highest temperature increased for roof surface temperature.

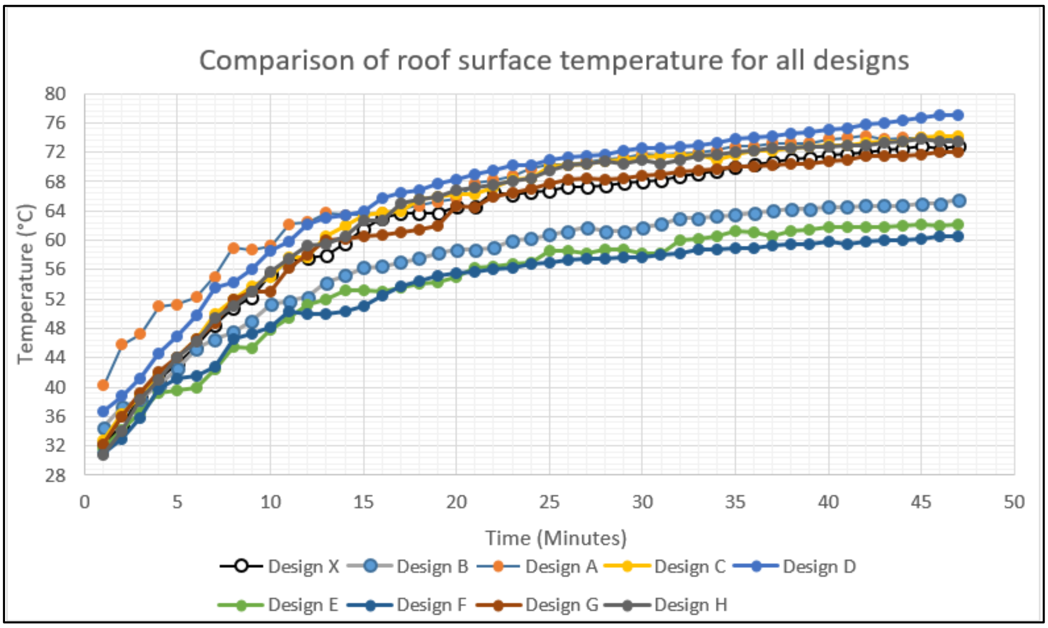

Figure 4:27: Comparison of roof surface temperature for all designs.

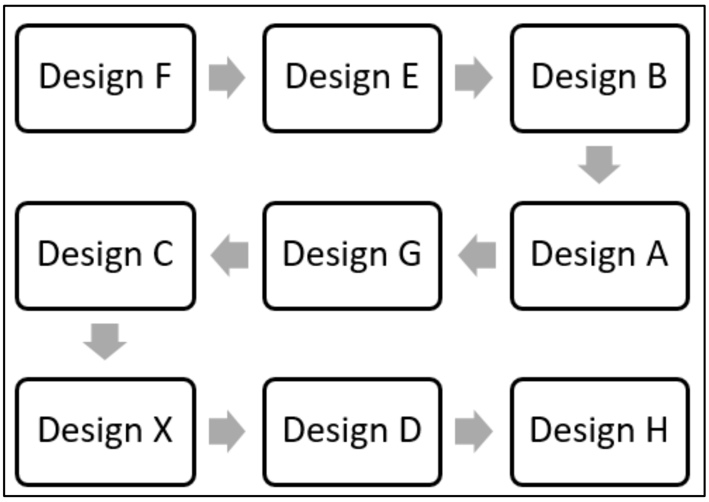

Figure 4:28: Designs arranged in lowest to largest temperature rise.

Design X shows higher temperature than design A is because of the reflected heat by insulators and radiant heat barrier. Based on Figure 4:25, the reflected heat travels towards the roof became a source of heat. As mentioned earlier, when having an insulation, it divides attic space into two regions. Due to surrounding temperature increase, the heat loss of the roof decreases. However, the roof surface is lower compared to design H and design D. This is because when attic fan is installed, the surrounding temperature reduced hence increases the heat loss of the roof surface.

4.10 Comparison of chamber temperature for all designs

Figure 4:29 shows the comparison of chamber temperature for all designs. From the Figure 4:29, it can be seen that the average lowest temperature was 32.36 °C and the average highest temperature was 41.61 °C. Hence, the average temperature increased for the chamber is 9.25 °C. However for design F, the chamber temperature was slightly higher compared to the rest of the design due to the installation of attic fan. When the hot air was extracted out from the attic space, it increases the chamber temperature but for design X, even though it has attic fan installed, the chamber temperature which was in average temperature. The reason is because due to insulation and radiant heat barrier is installed. It reduces the heat transfer to the attic space. This makes less heat air extracted compared to design F. Besides that, for design E, the temperature fluctuates and it is the lowest temperature compared to all other designs. This is because heat flow into attic space back and front makes the chamber temperature reduce and fluctuate.

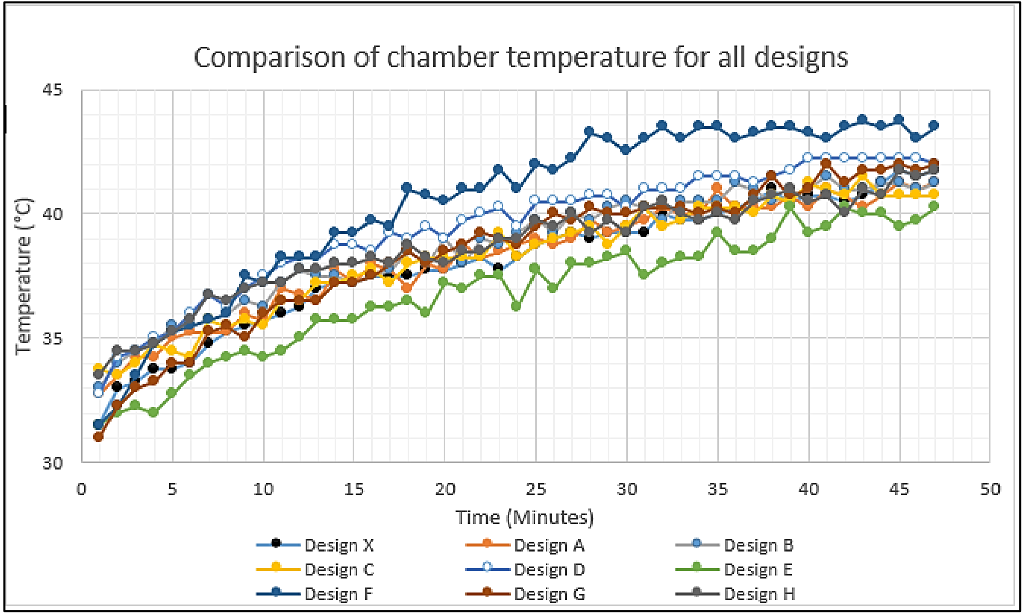

Figure 4:29: Comparison of chamber temperature of all designs.

4.11 Comparison for Active and Passive cooling system

Figure 4:30 shows the temperature of attic space was collected to compare active and passive system. For active and passive system, the duration of each experiment is extended to 50 minutes. For this research, only designs X and F have active cooling system, the rest of the designs are passive cooling system.

As per Figure 4:30, it can be observed that design F (Active) has a constant temperature over 5 minutes and for other designs (Passive) the temperature is rising, and for designs G and H the temperature is rising but in slower state. From this situation, it can be seen that passive cooling system only could reduce the transfer heat into the attic space but not stop/block the heat from entering. However, for active cooling system when the heat in and heat out became equal, there is no further increase of temperature in the attic space.

Besides that, active and passive cooling system has their own advantages and disadvantages. Advantages for passive cooling system are that they do not require any power to operate, product life is longer and they do not require any maintenance. The disadvantage is that they only can reduce the transfer of heat but not block it, so the heat might increase over a long period. Advantage for active cooling system is, as mentioned earlier when the heat in and heat out became equal, there were no further increase of temperature in attic space. However, the disadvantage is it requires an external power and since fan involves moving part it might need servicing and maintenance.

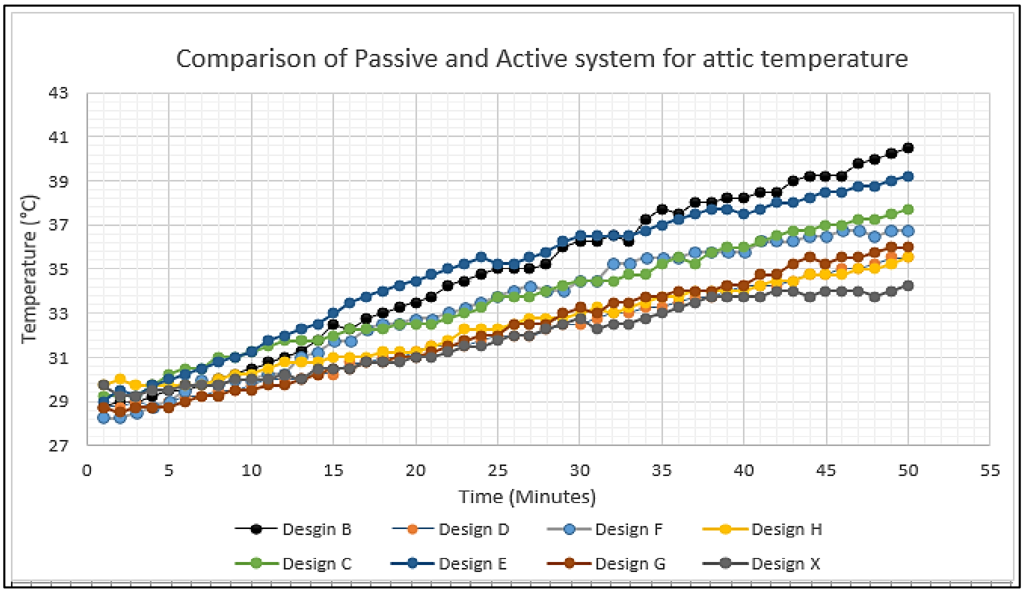

Figure 4:30: Comparison between Active and Passive cooling system for all designs.

4.12 Summary

Based on the results, design X shows the best cooling efficiency as it shows the lowest temperature increased compared to all designs. This shows that by reducing heat transfer in each category (conduction, convection and radiation) plays an important role to cool a particular medium. Table 4:2 shows the summary of all designs. For attic temperature comparison to design A is the calculation for how much the particular design can reduce the temperature in attic compared to design A. Example calculation for design B shows that, the temperature rise in attic space is 11 °C and for design A is 12.75 °C. So by comparison, design B is able to reduce 1.75 °C (12.75 °C – 11 °C) more than design A.

Table 4:2: Summary of designs.

Layout of attic model.	**Temperature rise for attic (°C).**	**Temperature rise for roof surface (°C).**	**Attic temperature Comparison to design A (°C).**
Design A	12.75	33.5	-
Design B	11	31	1.75
Design C	8	40.25	4.75
Design D	6.25	41.5	6.5
Design E	9.75	30.5	3
Design F	8.5	29.5	4.25
Design G	6.75	39.75	6
Design H	5.25	42.75	7.5
Design X	4.25	40.5	8.5

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The objective of this research report has been successfully achieved. A small scale attic model and a heating chamber was able to fabricate using plywood. Heating chamber is used as a solar radiation/ heat supply to the attic model to run the experiment. The chamber was designed in a way to simulate a severe condition of weather in Malaysia. Design A was fabricated in a way where it simulates normal housing roof (no cooling method is implemented). It was analysed to see how hot the attic temperature could get in the environment.

There are total of 8 layouts of attic model. Each attic model is experimented for each category of heat transfer mechanism where the best cooling efficient was selected and implanted on design X. Design A and B is compared to select which type of roof shows the best cooling efficiency. Design B was chosen because it was able to reduce 1.75 °C more compared to design A. Design C and D was compared to see which design shows the best conduction heat barrier. Design D was chosen because it was able to reduce 1.75 °C. Design E and F was compared to see which technique demonstrates more efficiency to extract hot air using convection method. Design F shows better cooling effect, it was able to reduce 1.25 °C more than design E. Finally, for radiant heat barrier, design G and H were compared. Design H shows better cooling of attic space where it was able to reduce 1.5 °C more than design E.

When all the best design is selected, it was implemented on Design X. Design X consist of TRC on the surface of roof, a vacuumed rockwool, polished aluminium and an attic fan was installed. Each of this material is selected to reduce each heat transfer mechanism (conduction, convection and radiation). Design X was analysed and it was able to reduce 8.5 °C compared to the normal roof design (Design A). Combination of active and passive cooling system is able to remove and reduce the heat transfer to attic space more efficient then individual cooling system is applied.

In conclusion, eco-friendly roof cool roof system was able to reduce the attic temperature by 8.5 °C and successfully improve the comfort of the people/guard in the building without or less effect on environment. In addition, the attic temperature is reduced without any use of non-renewable energy which also benefits the environment.

5.2 Recommendation for future work

One of the recommendations for future work is using T-type of thermocouple. It has sensitivity of 43 µV/°C which is more than K-type thermocouple which is only 41 µV/°C. T-type thermocouple is more accurate compared to K-type thermocouple in which T-type has an accuracy of ± 1.0 °C and K-type has an accuracy of ± 2.2 °C. T-type thermocouple is suitable for the use of this research because T-type thermocouple is designed to handle -270 °C to 300 °C. Besides that, using a button magnet type thermocouple to measure the roof surface temperature will give more accurate results. The current thermocouple is in spherical junction shape. With this shape, not all the surface is in contact with the roof surface, hence using button type (flat surface) will be accurate to measure surface temperature (Figure 5:1). In addition, the button magnet is made of neodymium magnet (SH), which can withstand up to 150 °C and low as -130 °C.

Besides that, fabricating a building model instead of just attic can identify how much heat is transferred to a building space. It also can identify how cooling effect of attic space affects the interior of the building (below attic). Furthermore, doing experiment based on after heating effect on attic. It means how fast the attic space cools down after the heating process. With this, it can identify whether the heat is contained or loss to the environment.

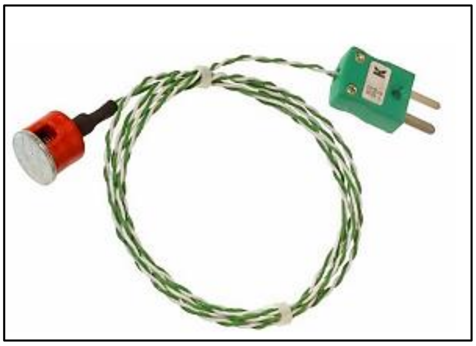

Figure 5:1: Button magnet thermocouple.

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APPENDICES

Appendix A : Temperature tabulated for all designs

Table A-1: Results for design A.

Minutes	Roof (°C)	Attic (°C)	Chamber (°C)
1	40.25	29.5	32.75
2	45.75	30.25	33.5
3	47.25	31	34.25
4	51	31.5	34.25
5	51.25	31.75	35
6	52.25	32	35.25
7	55	32.25	35.25
8	59	32.5	35.25
9	58.75	33	36
10	59.25	33.75	35.75
11	62.25	34.5	37
12	62.5	34.75	36.75
13	63.75	35.25	36.5
14	63.5	35.75	37.75
15	63.5	36.25	37.25
16	63.75	36	38
17	64.25	36.25	37.75
18	64.75	36.5	37
19	65.25	36.75	38
20	65.75	37.5	37.75
21	67.75	37.25	38.75
22	68.25	38	38.25
23	68.75	38.25	38.5
24	69.75	38.5	38.75
25	70.25	38.5	39
26	70.25	38.75	38.75
27	70.75	39	39

28	71	39.25	39.75
29	71.25	39.25	39.25
30	71.75	40.25	39.5
31	71.5	40.25	39.75
32	71.75	40.25	40.25
33	72	40.5	40
34	72.25	40.75	40
35	72.75	40.75	41
36	72.75	41	40.25
37	73.25	41.25	40.25
38	73.25	41.5	40.25
39	73.25	41.5	40.75
40	73.75	41.5	40.25
41	74	41.75	41
42	74.25	41.75	40.75
43	73.75	42.25	40.25
44	74	42	40.75
45	74	42.25	41.25
46	73.75	42.25	41
47	73.75	42.25	41.25
48	74	42.25	41.25
49	74	42.5	41
50	74.25	42.5	41.25

Table A-2: Results for design B.

Minutes	**Roof (°C)**	**Attic (°C)**	**Chamber (°C)**
1	34.5	28.75	33
2	37.25	29	34
3	38.25	29	34.5
4	40.25	29.25	34.75
5	42.5	29.5	35.5
6	45.25	29.5	35.5

7	46.5	29.75	35.75
8	47.5	30	36
9	49	30.25	36.5
10	51.25	30.5	36.25
11	51.75	30.75	37.25
12	52.25	31	37.75
13	54.25	31.25	37.5
14	55.25	31.75	37.5
15	56.25	32.5	37.25
16	56.5	32.25	37.5
17	57	32.75	37.75
18	57.5	33	38.5
19	58.25	33.25	38
20	58.75	33.5	39
21	58.75	33.75	38
22	59	34.25	39
23	60	34.5	38.75
24	60.25	34.75	39.25
25	60.75	35	39.75
26	61.25	35	39.25
27	61.75	35	40
28	61.25	35.25	39.75
29	61.25	36	40.25
30	61.75	36.25	40.5
31	62.25	36.25	40.25
32	63	36.5	39.75
33	63	36.25	40.5
34	63.25	37.25	40.5
35	63.5	37.75	40.5
36	63.75	37.5	41.25
37	64	38	41
38	64.25	38	40.5

39	64.25	38.25	40.75
40	64.5	38.25	41
41	64.5	38.5	41.5
42	64.75	38.5	41
43	64.75	39	41
44	64.75	39.25	41.25
45	65	39.25	41.25
46	65	39.25	41
47	65.5	39.75	41.25
48	65.5	40	41.5
49	65.75	40.25	41.25
50	65.75	40.5	41.5

Table A-3: Results for design C.

Minutes	**Roof (°C)**	**Attic (°C)**	**Chamber (°C)**
1	36.75	29.25	33.75
2	38.75	29.25	33.5
3	41.25	29.25	34
4	44.5	29.75	34.75
5	47	30.25	34.5
6	49.75	30.5	34.25
7	53.5	30.5	35.75
8	54.25	31	35.5
9	56	31	35.75
10	58.5	31.25	35.5
11	59.75	31.5	36.5
12	62.25	31.75	36.5
13	63	31.75	37.25
14	63.5	31.75	37.25
15	64	32	37.5
16	65.75	32.25	37.75
17	66.5	32.25	37.25

18	66.75	32.25	38
19	67.75	32.5	38.25
20	68.25	32.5	38.25
21	69	32.5	38.25
22	69.5	32.75	38.25
23	70.25	33	39.25
24	70.25	33.25	38.25
25	71	33.75	38.75
26	71.25	33.75	39
27	71.5	33.75	39.25
28	71.75	34	39.5
29	72.25	34.25	38.75
30	72.5	34.5	39.5
31	72.5	34.5	40.25
32	72.75	34.5	39.5
33	73	34.75	39.75
34	73.25	34.75	40.25
35	73.75	35.25	40.25
36	74	35.5	40.25
37	74.25	35.25	40
38	74.5	35.75	40.75
39	74.75	36	40.5
40	75	36	41.25
41	75.25	36.25	41
42	75.75	36.5	40.75
43	76	36.75	41.5
44	76.25	36.75	40.75
45	76.75	37	40.75
46	77	37	40.75
47	77	37.25	40.75
48	77.25	37.25	41
49	77.25	37.5	41.25

50	77.25	37.75	41.5

Table A-4: Results for design D.

Minutes	Roof (°C)	Attic (°C)	Chamber (°C)
1	32.75	28.75	32.75
2	36.25	28.75	34.25
3	38.75	29	34.5
4	41.75	28.75	35
5	44	29	35.25
6	46.5	29.25	36
7	50	29.25	36.75
8	52	29.5	36.25
9	53.75	29.5	37
10	55	29.75	37.5
11	57.75	30	38
12	57.75	30	38.25
13	60.5	30	38.25
14	62	30.25	38.75
15	63.5	30.25	38.75
16	63.75	30.75	38.5
17	64	30.75	39.25
18	65.5	31	39
19	66	31	39.5
20	66.25	31.25	39
21	66.25	31.5	39.75
22	67.25	31.5	40
23	68.25	31.5	40.25
24	68.5	31.75	39.5
25	70	32	40.5
26	70.25	32	40.5
27	70.5	32	40.5
28	70.75	32.25	40.75

29	71	32.5	40.75
30	71.25	32.5	40.25
31	71.5	32.75	41
32	71.5	33	41
33	71.75	33	41
34	71	33.25	41.5
35	71.75	33.25	41.5
36	72.25	33.5	41.5
37	72.25	33.75	41.25
38	72.5	33.75	41.5
39	72.75	34	41.75
40	73	34.25	42.25
41	73	34.25	42.25
42	73.25	34.25	42.25
43	73.5	34.5	42.25
44	73.5	34.75	42.25
45	74	34.75	42.25
46	74.25	35	42.25
47	74.25	35	42
48	74.5	35.25	41.75
49	74.75	35.5	42
50	74.75	35.5	42.25

Table A-5: Results for design E.

Minutes	**Roof (°C)**	**Attic (°C)**	**Chamber (°C)**
1	31.75	29	31.5
2	34.25	29.5	32
3	36.5	29.25	32.25
4	39.25	29.75	32
5	39.5	30	32.75
6	40	30.25	33.5
7	42.5	30.5	34

8	45.5	30.75	34.25
9	45.25	31	34.5
10	47.75	31.25	34.25
11	49.5	31.75	34.5
12	51.25	32	35
13	52	32.25	35.75
14	53.25	32.5	35.75
15	53.25	33	35.75
16	53	33.5	36.25
17	53.5	33.75	36.25
18	54	34	36.5
19	54.25	34.25	36
20	55	34.5	37.25
21	56.25	34.75	37
22	56.5	35	37.5
23	56.75	35.25	37.5
24	57	35.5	36.25
25	58.5	35.25	37.75
26	58.5	35.25	37
27	58.25	35.5	38
28	58.75	35.75	38
29	58.75	36.25	38.25
30	58.25	36.5	38.5
31	58.25	36.5	37.5
32	60	36.5	38
33	60.25	36.5	38.25
34	60.5	36.75	38.25
35	61.25	37	39.25
36	61	37.25	38.5
37	60.5	37.5	38.5
38	61.25	37.75	39
39	61.5	37.75	40.25

40	61.75	37.5	39.25
41	61.75	37.75	39.5
42	61.75	38	40.25
43	61.75	38	40
44	62	38.25	40
45	62.25	38.5	39.5
46	62	38.5	39.75
47	62.25	38.75	40.25
48	62.5	38.75	40
49	62.5	39	40
50	62.5	39.25	40.25

Table A-6: Results for design F.

Minutes	**Roof (°C)**	**Attic (°C)**	**Chamber (°C)**
1	31	28.25	31.5
2	33	28.25	32.25
3	35.75	28.5	33.5
4	39.75	28.75	34.75
5	41.25	29	35.25
6	41.5	29.5	35.5
7	42.75	30	35.75
8	46.5	29.75	36
9	47.25	30	37.5
10	48.25	30	37.25
11	50.25	30.25	38.25
12	50	30.25	38.25
13	50	31	38.25
14	50.25	31.25	39.25
15	51	31.75	39.25
16	52.5	31.75	39.75
17	53.75	32.25	39.5
18	54.5	32.5	41

19	55.25	32.5	40.75
20	55.5	32.75	40.5
21	55.75	32.75	41
22	56	33	41
23	56.25	33.25	41.75
24	56.75	33.5	41
25	57	33.75	42
26	57.25	34	41.75
27	57.5	34.25	42.25
28	57.5	34	43.25
29	57.75	34	43
30	57.75	34.5	42.5
31	58	34.5	43
32	58.25	35.25	43.5
33	58.75	35.25	43
34	58.75	35.5	43.5
35	59	35.5	43.5
36	59	35.5	43
37	59.25	35.75	43.25
38	59.5	35.75	43.5
39	59.5	35.75	43.5
40	59.75	35.75	43.25
41	59.5	36.25	43
42	59.75	36.25	43.5
43	60	36.25	43.75
44	60	36.5	43.5
45	60.25	36.5	43.75
46	60.5	36.75	43
47	60.5	36.75	43.5
48	60.5	36.5	43.5
49	60.75	36.75	43.75
50	60.5	36.75	43.75

Table A-7: Results for design G.

Minutes	**Roof (°C)**	**Attic (°C)**	**Chamber (°C)**
1	32.25	28.75	31
2	36	28.5	32.25
3	39.25	28.75	33
4	42	28.75	33.25
5	44	28.75	34
6	46.5	29	34
7	48.75	29.25	35.25
8	52	29.25	35.5
9	53	29.5	35
10	53	29.5	36
11	56.25	29.75	36.5
12	58	29.75	36.5
13	60	30	36.5
14	60.25	30.25	37.25
15	60.5	30.5	37.25
16	60.75	30.5	37.5
17	61	30.75	38
18	61.5	30.75	38.5
19	62	31	38
20	64.75	31	38.5
21	64.5	31.25	38.75
22	66	31.5	39.25
23	66.5	31.75	39
24	67	32	38.75
25	67.75	32	39.5
26	68.25	32.5	40
27	68.5	32.5	39.75
28	68.25	32.5	40.25
29	68.5	33	40
30	68.75	33.25	40

31	69	33	40.25
32	69.25	33.5	40.25
33	69.5	33.5	40.25
34	69.75	33.75	40
35	70	33.75	40.25
36	70	34	40
37	70.25	34	40.75
38	70.5	34	41.5
39	70.5	34.25	40.75
40	70.75	34.25	41
41	71	34.75	42
42	71.5	34.75	41.25
43	71.5	35.25	41.75
44	71.5	35.5	41.75
45	71.75	35.25	42
46	72	35.5	41.75
47	72	35.5	42.25
48	72	35.75	42
49	72.25	36	42
50	72.5	36	42.25

Table A-8: Results for design H.

Minutes	**Roof (°C)**	**Attic (°C)**	**Chamber (°C)**
1	30.75	29.75	33.5
2	34	30	34.5
3	38.25	29.75	34.5
4	41	29.75	34.75
5	44	29.75	35.25
6	46.25	29.75	35.75
7	49.5	29.75	36.75
8	51	30	36.5
9	53	30.25	37

10	55.75	30.25	37.25
11	57.5	30.5	37.25
12	59.25	30.75	37.75
13	59.5	30.75	37.75
14	60.5	30.75	38
15	62.75	31	38
16	62.75	31	38.25
17	65	31	38
18	65.5	31.25	38.75
19	66	31.25	38.25
20	66.75	31.25	38
21	67.25	31.5	38.5
22	67.5	31.75	38.5
23	68	32.25	39
24	68.5	32.25	39
25	69.5	32.25	39.75
26	70.25	32.5	39.5
27	70.5	32.75	40
28	70.75	32.75	39.25
29	70.5	32.75	39.75
30	71	33	39.25
31	70.5	33.25	40.25
32	71	33	40.5
33	71.5	33.25	40
34	71.75	33.5	39.75
35	72	33.75	40
36	72.25	33.75	39.75
37	72.5	34	40.5
38	72.5	34	40.75
39	72.75	34	41
40	72.75	34	40.5
41	73	34.25	40.75

42	73	34.5	40
43	73.25	34.5	41
44	73.5	34.75	40.75
45	73.75	34.75	41.75
46	73.5	34.75	41.5
47	73.5	35	41.75
48	73.75	35	41.5
49	74	35.25	42
50	74	35.5	41.75

Table A-9: Results for design X.

Minutes	**Roof (°C)**	**Attic (°C)**	**Chamber (°C)**
1	32.25	29.75	31.5
2	34.75	29.25	33
3	39	29.25	33.25
4	41	29.5	33.75
5	43.25	29.5	33.75
6	45.5	29.75	34
7	48.5	29.75	34.75
8	50.75	29.75	35.25
9	52.25	30	35.5
10	55.5	30	35.75
11	57.25	30	36
12	57.5	30.25	36.25
13	58	30	37
14	59.5	30.5	37.25
15	61.5	30.5	37.25
16	63	30.5	37.5
17	63.75	30.75	37.5
18	63.75	30.75	37.5
19	63.75	30.75	37.75
20	64.5	31	37.75

21	64.5	31	38
22	66.5	31.25	38.25
23	66.25	31.5	37.75
24	66.5	31.5	38.25
25	66.75	31.75	38.75
26	67.25	32	39
27	67.25	32	39.25
28	67.5	32.25	39
29	67.75	32.5	39.25
30	68	32.75	39.25
31	68.25	32.25	39.25
32	68.75	32.5	40
33	69	32.5	39.75
34	69.5	32.75	39.75
35	70	33	40
36	70.25	33.25	40.25
37	70.75	33.5	40.5
38	71	33.75	41
39	71.25	33.75	40.5
40	71.5	33.75	40.75
41	71.75	33.75	40.75
42	72	34	40.5
43	72.25	34	40.75
44	72.5	33.75	41.25
45	72.75	34	41.75
46	72.5	34	41.5
47	72.75	34	41.75
48	72.75	33.75	42
49	73	34	41.75
50	73	34.25	42

Appendix B : Arduino Data Logging’s Coding

```
#include "max6675.h"
unsigned long previousTime = millis();
long timeInterval = 60000;
int roofCS = 2;
int roofDO = 3;
int roofCLK = 4;
int atticCS = 5;
int atticDO = 6;
int atticCLK = 7;
int chamberCS = 11;
int chamberDO = 12;
int chamberCLK =13;
int ambientCS = 14;
int ambientDO = 15;
int ambientCLK = 16;

MAX6675 roof(roofCLK, roofCS, roofDO);
MAX6675 attic(atticCLK, atticCS, atticDO);
MAX6675 chamber(chamberCLK, chamberCS, chamberDO);
MAX6675 ambient(ambientCLK, ambientCS, ambientDO);

void setup() {
  Serial.begin(9600);
  Serial.println("CLEARSHEET");

Serial.println("LABEL,Date,Time,Roof(°C),Attic(°C),Chamber(°C),Ambient(°C");

  Serial.println("MAX6675 test");
  // wait for MAX chip to stabilize
  delay(500);
```

```
}

void loop() {
//  basic readout test, just print the current temp
  unsigned long currentTime = millis();
  if (currentTime - previousTime > timeInterval) {
    //do action
    previousTime = currentTime;
    Serial.println((String) "DATA,DATE,TIME," + roof.readCelsius()+ ","
+attic.readCelsius()+"," +chamber.readCelsius() +"," + ambient.readCelsius());
    /*Serial.print("roof = ");
    Serial.println(roof.readCelsius());
    Serial.print("attic = ");
    Serial.println(attic.readCelsius());
    Serial.print("chamber = ");
    Serial.println(chamber.readCelsius());
    Serial.print("ambient = ");
    Serial.println(ambient.readCelsius());*/

  }

   delay(1000);
}
```

Appendix C : Solidworks Displacement Simulation

Based on Figure C-1, Solidworks simulation has done to test the maximum deflection of flat bar. The bar was tested under 100 N of force and 80 °C. The end of the bar was set as fixed point (green arrow). The maximum displacement/ deflection of flat bar is 9.450 mm.

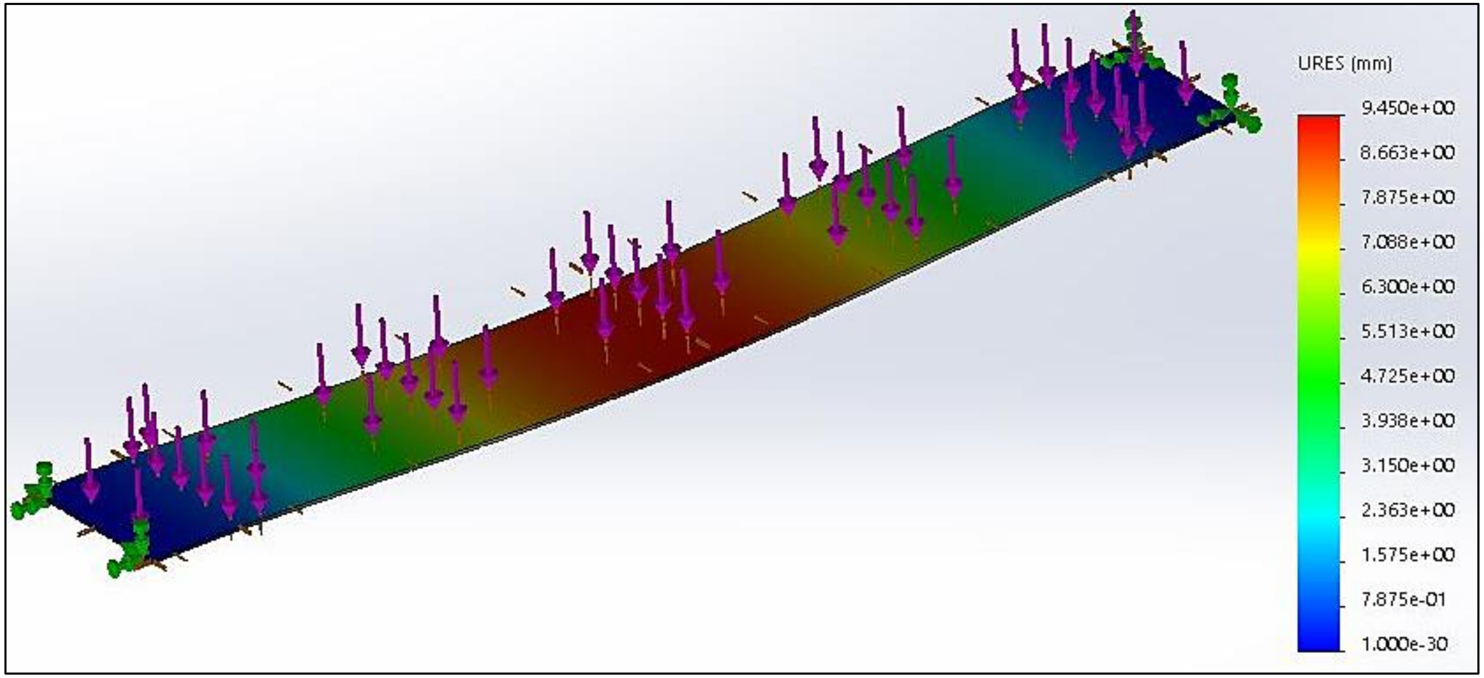

Figure C-1: Flat bar displacement simulation.

Based on Figure C-2, Solidworks simulation has done to test the maximum deflection of angle bar. The bar was tested under 100 N of force and 80 °C. The end of the bar was set as fixed point (green arrow). The maximum displacement/ deflection of flat bar is 1.038 mm. Compared to flat bar, angle bar has lesser deflection, hence angle bar has been chosen to support the halogen lamp.

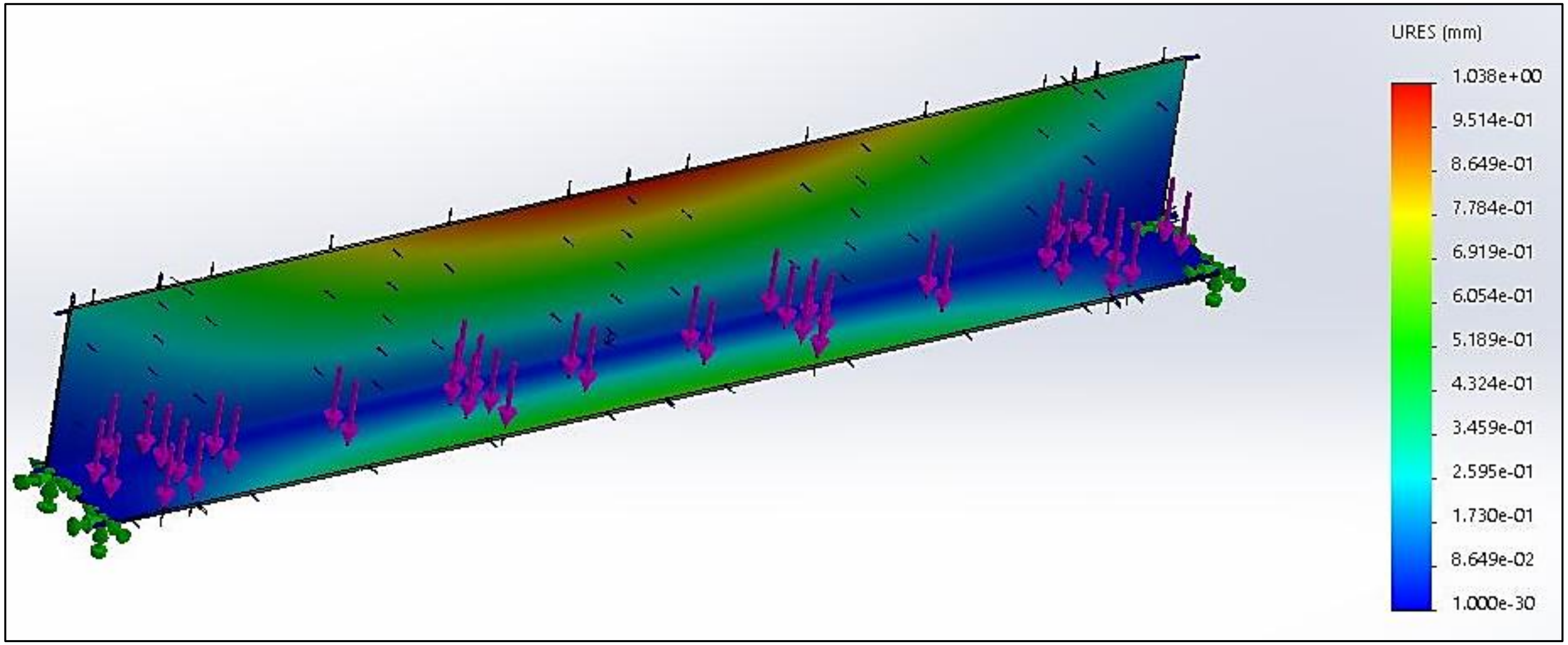

Figure C-2: Angle bar displacement simulation.

Appendix D : Material Selection Criteria

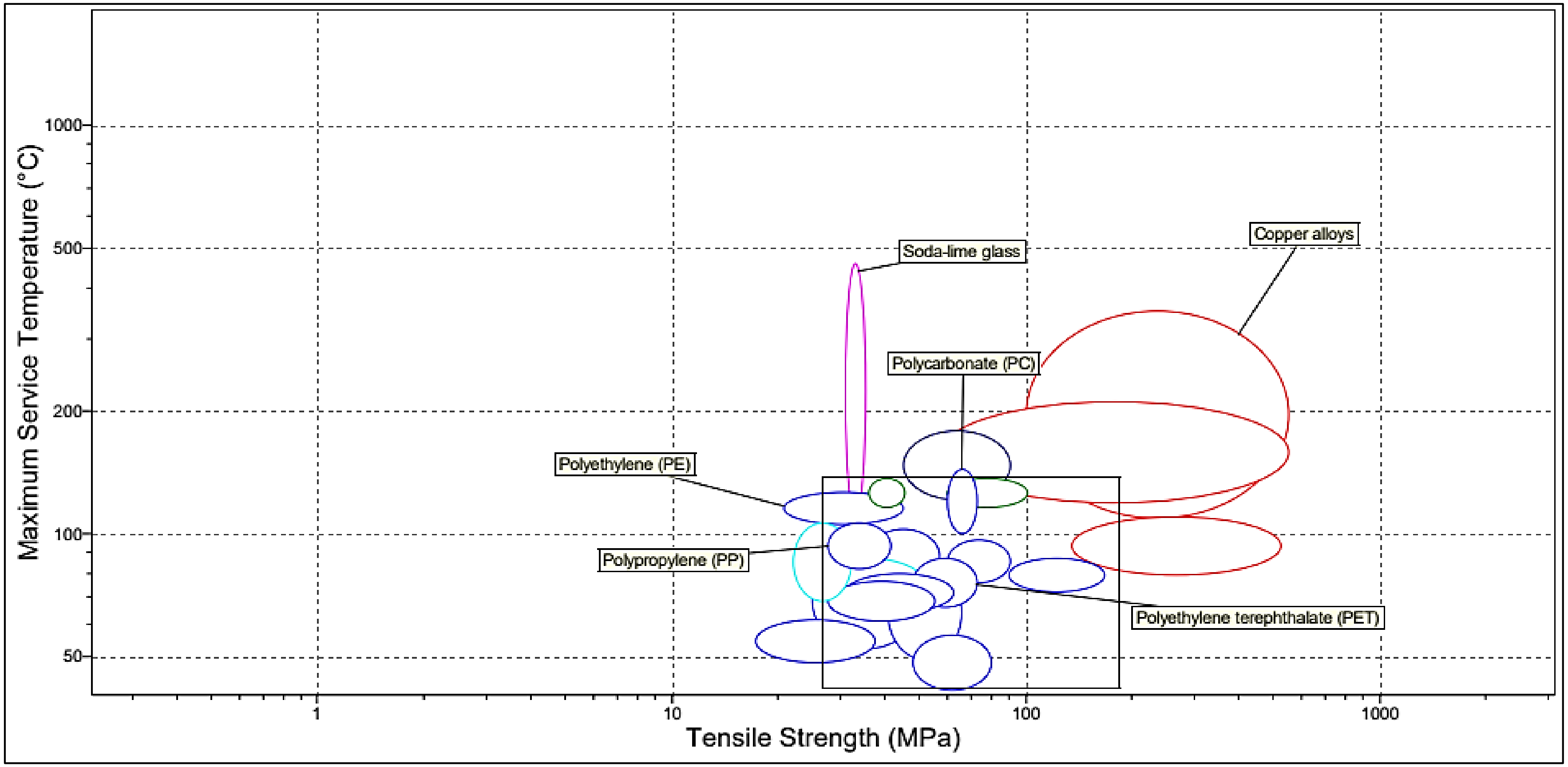

Figure D-1: Stage one material selection.

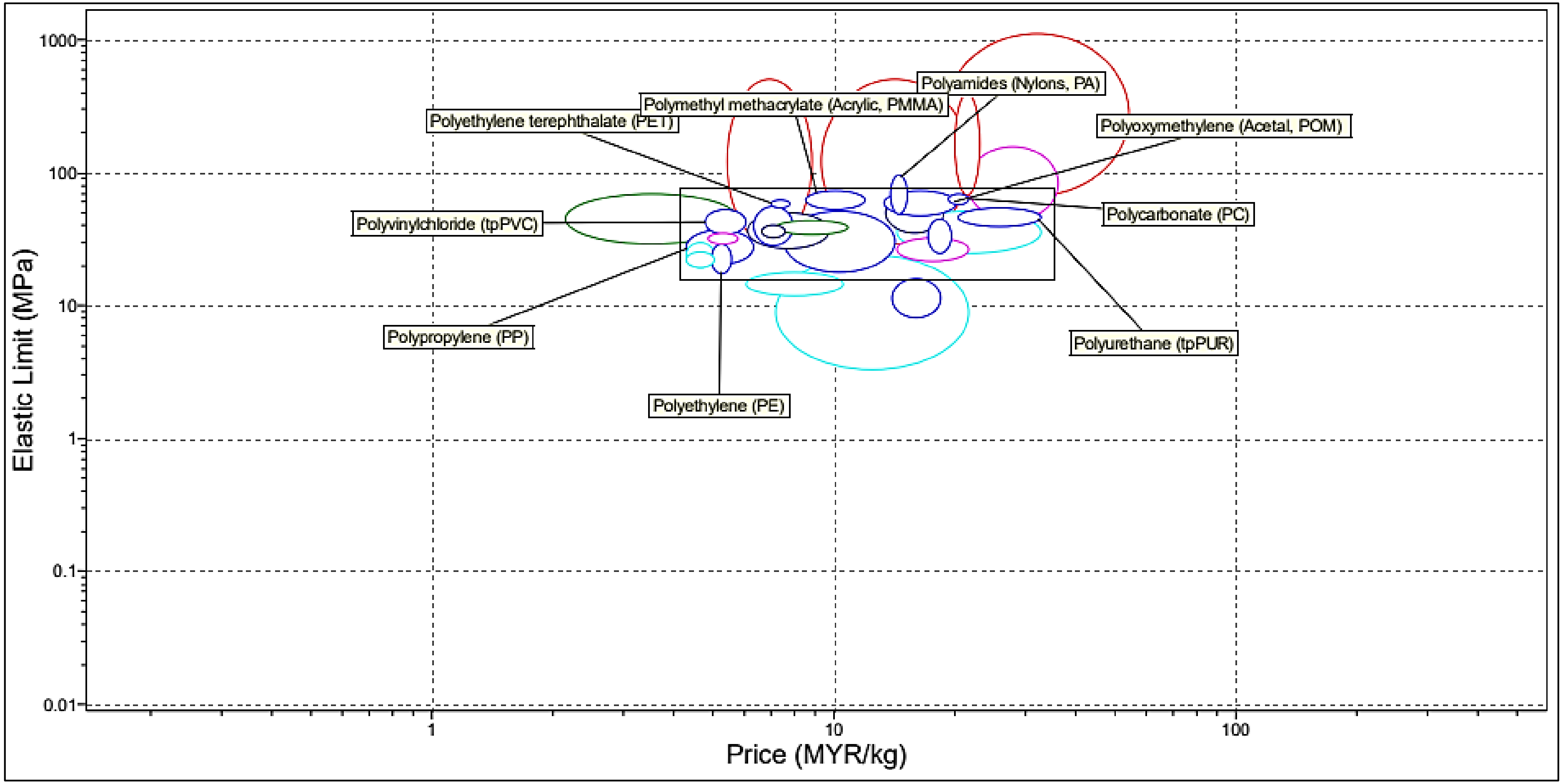

Figure D-2: Stage two material selection.

Appendix E : Alternative Cooling System Design

The initial design, is to create a vacuum air cavity. In the first design, an aluminium box was welded together and vacuum pump is being used to suck the air out. However, during the vacuum process, the aluminium box tends to bend inwards and the welded joints starts to break. This is because 0.4 mm aluminium sheet was too thin for this process. To save cost, in the second design plywood and oak wood was fabricated as in figure E-1. However, in this design there was air leak in the air valve. The air valve was not designed to withstand vacuum pressure. As result, this design was replaced by the new design which is proposed and fabricated in this prototype.

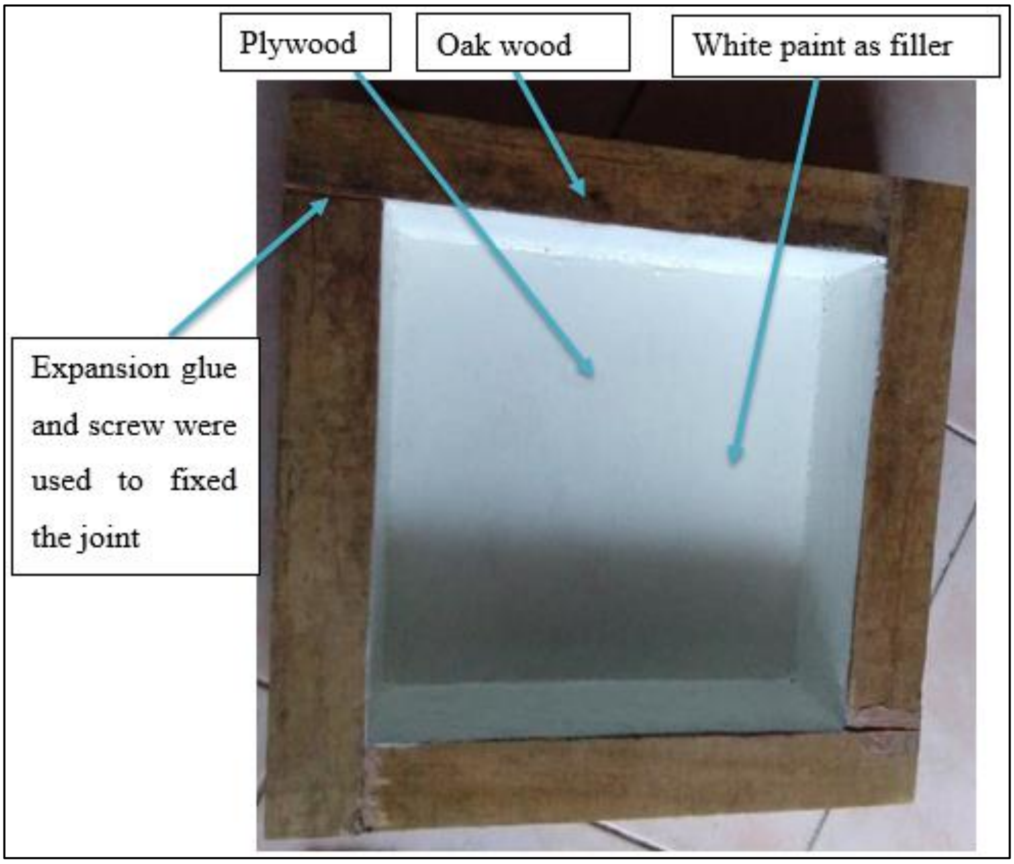

Figure E-1: Fabrication of vacuum cavity box using wood (cover of the box not installed).

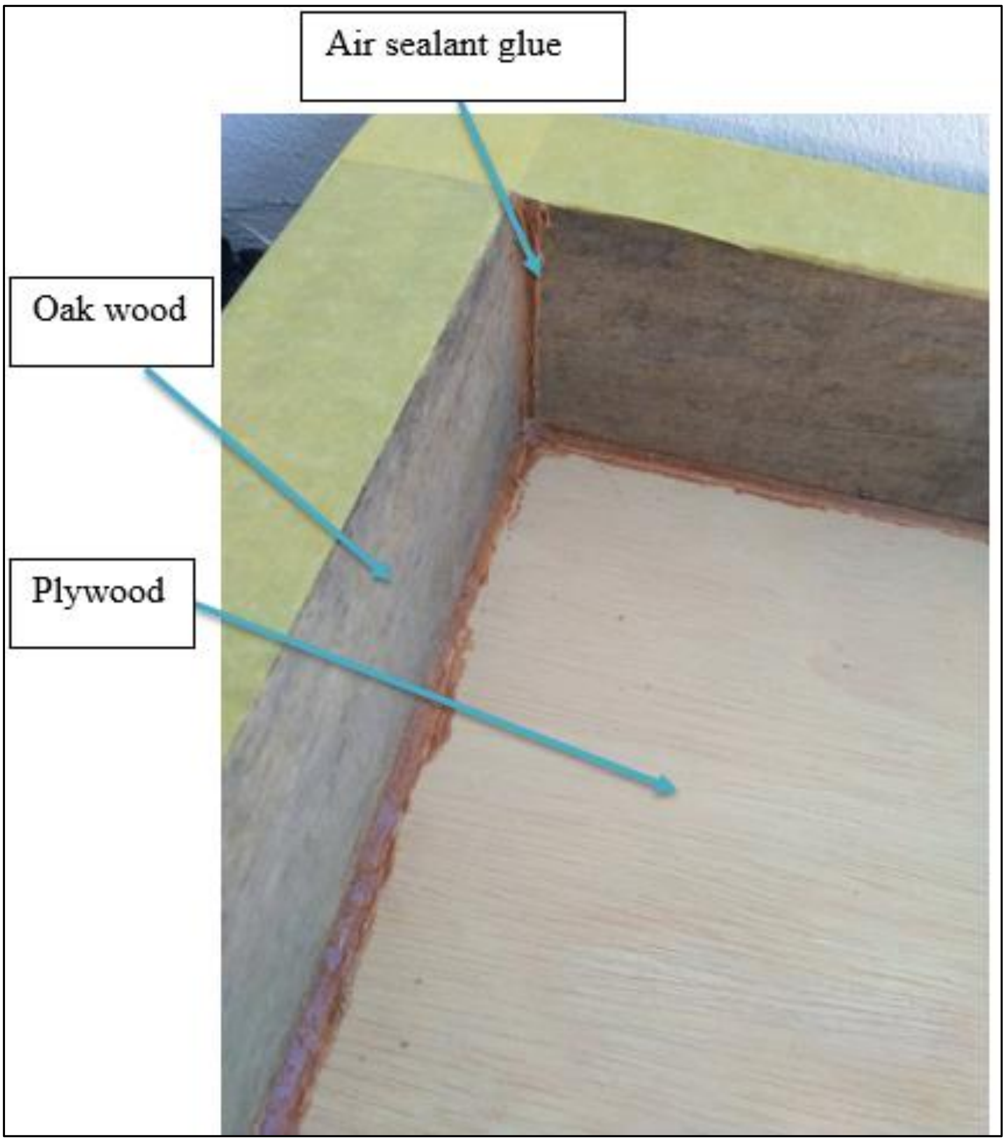

Figure E-2: Fabrication of vacuum cavity box using wood (before paint).