INTEGRATION OF SOLAR POWERED FANS AND MOVING-AIR-CAVITY FOR ATTIC TEMPERATURE REDUCTION

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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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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 **"INTEGRATION OF SOLAR POWERED FANS AND MOVING-AIR-CAVITY FOR ATTIC TEMPERATURE REDUCTION"** was prepared by **HO MUN LING** has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of Engineering (Honours) Mechanical Engineering at Universiti Tunku Abdul Rahman.

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ABSTRACT

With an increasing demand of building's cooling load, the cool roofing technology system is important in modern roof design to reduce the building's electricity consumption by keeping buildings cool. Cool roof system is the substantial building approach. The focus of this study is to design a cool roof system that promotes both the passive and active cooling methods. The cool roof system in this research project integrated solar powered fans as the active cooling element and radiative surface on moving air cavity as the passive cooling element. In addition, the cool roof was fabricated with lightweight foam concrete tile of density 1250 kg/m^3 and water cement ratio of 0.6. The main purpose of this project is to reduce the attic temperature by rejecting the heat from entering the structure. Six small scale roof prototypes were built to evaluate the performance of each cool roof designs in reducing attic temperature. The performance of cool roof was compared with the conventional metal deck roof. The roof prototypes experienced 30 minutes of heat exposure from two spotlight halogen lamps of power 500 W each. The experiment was carried out indoor. The temperature variation was measured by the temperature sensor, K-type thermocouple. Four thermocouples were used and assigned at roof surface, ambient, moving air channel and attic. In this cool roof system, the moving air cavity, solar powered fans and rockwool were implemented in stages to determine the efficiency of each element in enhancing the cooling performance. The maximum attic temperature decreased from 38.7 ℃ (Roof Design I) to 32.5 ℃ (Roof Design VI) after the integration of cool roofing technology. This eco-friendly cool roof system which was built by the combination of lightweight foam concrete roof, moving air cavity, solar powered fans and rockwool successfully reduce the attic temperature by 6.2 ℃ as compared to the normal roof design.

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LIST OF SYMBOLS / ABBREVIATIONS

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

Malaysia is a developing Southeast Asia country which located just the north of the Equator. Malaysia's economic growth had greatly increased the country's energy consumption. The highest daily electricity demand for Malaysia hits 17 788 MW on 19 April 2016 after the record of 17 175 MW on 9 March 2016 (Hasan, 2017). The rise of population in Malaysia had led to the increasing demand for residential housing and industrial building. Malaysia averagely will have 27 ℃ in most of the cities. However, for East Malaysia, the temperature ranges between 23 ℃ to a maximum temperature of 32 ℃ (Ooi et al., 2020).

The buildings in Malaysia were constructed closely to each other especially in cities area, which causes a poor ventilation between the buildings. Moreover, the hot climate weather results in a high indoor temperature when the sun radiation hits the buildings which increases the demand for air conditioner. The main component of a building receives the most amount of sun radiation is the roof. Roof located at the most high-up of a building and is covered by a gypsum celling board before the inner place of a house. In Malaysia, most general roof materials in houses and factories are concrete roof tiles (85 %), clay roof files (10 %) and metal deck (5 %) (Yew et al., 2013).

For a building, the highest temperature takes place at the attic region. The attic region is the space below the roof and above the building's ceiling board. When the roof absorbed the sun radiation during daytime, the heat is transferred into the attic region through conduction. The heat then trapped inside the attic region due to the airtight design of the conventional roof. The prohibition of entering air of a conventional roof design is the main cause of high temperature recorded at attic region. The heat then transferred to the inner building which resulted a hot indoor atmosphere. The attic will always have higher temperature compared to the living space (Zhao et al., 2019).

A few cool roof systems were designed and developed by researchers in order to reduce the building's energy consumption on keeping the building cool (Romeo and Zinzi, 2013). A cool roof system is one of the modern substantial energy reduction approaches. When the overall temperature of the attic region is reduced, the temperature inside the building would be directly reduced, which causes the lowering of cooling load. A cool roof system promotes attic ventilation, the cool ambient air is being drawn in, and the hot trapped air is being drawn out. When the cool ambient air reaches attic region and mix with the air inside, the air temperature can be effectively reduced at day time, which resulted in the lower transfer of heat from attic region to the living space (Zhao et al., 2019).

Figure 1.1 shows the schematic diagram of an integrated cool roof system. The cool roof system had a radiative surface which facilitates the solar reflection. Moreover, the cool roof system composed of few radiative air coolers linked in parallel manner to promote heat transmission (Zhao et al., 2019). In overall, a cool roof is an upgraded roof design which composed of passive and active cool roof systems. In this study, the designed cool roof makes use of radiative surface, solar powered fan with improved moving air cavity and insulation on a model with lightweight foam concrete roofing to reduce the attic temperature.

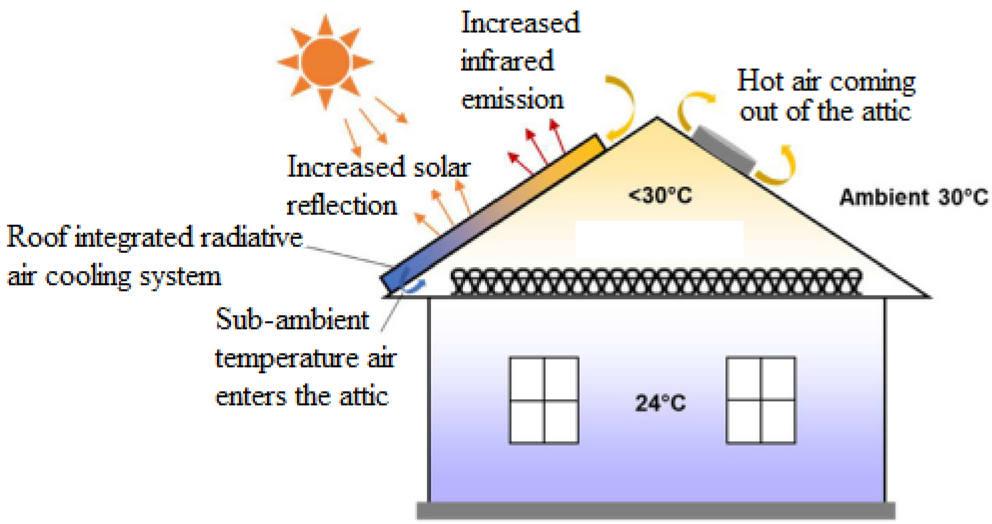


Figure 1.1: Integrated Radiative Cool Roof System (Zhao et al., 2019).

In this project, the cool roofing technology system is a eco-friendly and substainable roof design. Renewable solar energy is the source of energy to promote the attic ventilation with the using of solar powered fans. Radiative surface on moving air cavity automically increases the heat dissipation rate. The mixture of waste chicken eggshell (CES) and polyurethane binder is used to construct the thermal reflective coating (Yew et al., 2018). Both the active and passive cool roofing technology systems were implemented. Radiative cooling and thermal insulation material act as the passive systems. For active system, solar powered fans are used at the inlet of moving air cavity under the roof.

1.2 Importance of the Study

The temperature at attic region is always higher than the surrounding temperature due to the lack of ventilation in a conventional roof. When the temperature at attic region is high, the heat which trapped at the attic can moved to the living space when the attic is not well insulated. This had badly affected the indoor comfortableness which results in the increase of air conditioner usage. Hence, in order to lower the energy consumption and improve the efficiency of an air conditioner, a well-designed roof which also known as the cool roof system is an important study.

The result of this study is important in terms of the evaluation of cool roof system performance. The cool roof system involved both the active and passive characteristics. The temperature of attic region may be reduced by the implementation of thermal reflective coating, improved moving air cavity and thermal radiative material. By utilizing these methods into the roof design, ventilation is promoted in the attic, hence the air trapped in the attic region which then convert into hot air when the sun radiation is continually absorbed can be prevented.

The major focus in this study is to apply the radiative and insulation layer on air channel with solar powered fans as the improvement of moving air cavity design and cast a lightweight foam concrete tile model. The performance of concrete roof will be compared with the conventional metal deck. The metal deck will be applied with reflective coating to reflect the sun radiation away before being absorbed by the roof. By utilizing this roof design, the air conditioner usage may be reduced, air conditioner can work more efficiently with the resulting cooler indoor temperature.

1.3 Problem Statement

The burning of fossil fuels which act as the main energy source in Malaysia releases carbon dioxide, which is one of the greenhouse gases. Moreover, the usage of air conditioner emited chlorofluorocarbons which will react with the ozone in the atmosphere. This led to the thinning of ozone layer. When the ozone layer gets thinner, the sun radiation gets stronger which increases the roof temperature and lead to the higher living space's temperature. This trend had led to the unstoppable demand for air conditioner. 65 % of the building energy's consumed for keeping the indoor environment a more comfortable place (Lam et al., 2010).

The average temperature rise at peninsular Malaysia was 0.25 ℃ per decade, while for Sabah and Sarawak were 0.20 ℃ and 0.14 ℃ respectively (Ho and Tang, 2019). This serious climate change is due to human activities especially the greenhouse gases emission. The scientist had concluded that the increase of average global surface temperature is overtaken by the carbon dioxide and greenhouse gases emission due to human activities. Figure 1.2 shows the annual average earth temperature from year 1880 to 2019 (Schmunk, 2020).

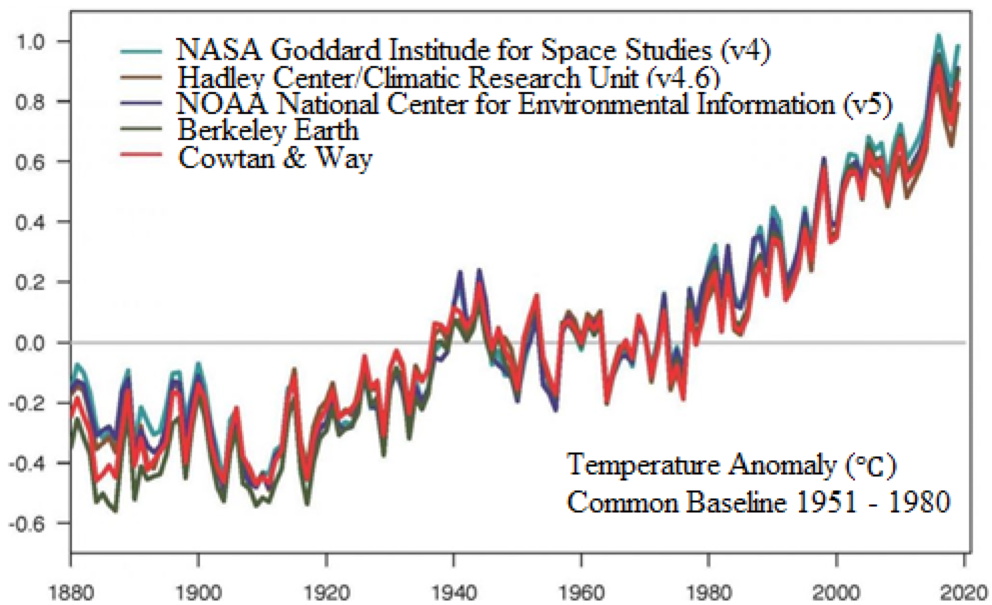


Figure 1.2: The Average Earth Temperature (Schmunk, 2020).

The rise of earth average temperature directly increases the thermal load received by the building. This is more obvious in tropical countries like Malaysia that is experiencing summer throughout the year. The rise of surrounding temperature increases the building's cooling load in order to maintain the indoor comfortableness. In the future, maintaining the cool indoor temperature becomes a great challenge with the rising of thermal load on earth. The main problem is how to keep the indoor cozy yet ensuring the sustainability.

On a hot sunny day, heat radiated from the sun strikes the roof, produces a hot roof. The heat then moved to the attic. When heat is accumulated at the attic, it radiates to the attic floor which then radiates to the living space. When outdoor temperature is 32 ℃ (90 °F), the temperature on roof can hits 77 ℃ (170 °F), the temperature at the floor of attic can hits 60 ℃ (140 °F). Figure 1.3 demonstrates the outdoor, roof and attic temperature with the temperature shown in Fahrenheit (INC, 2018).

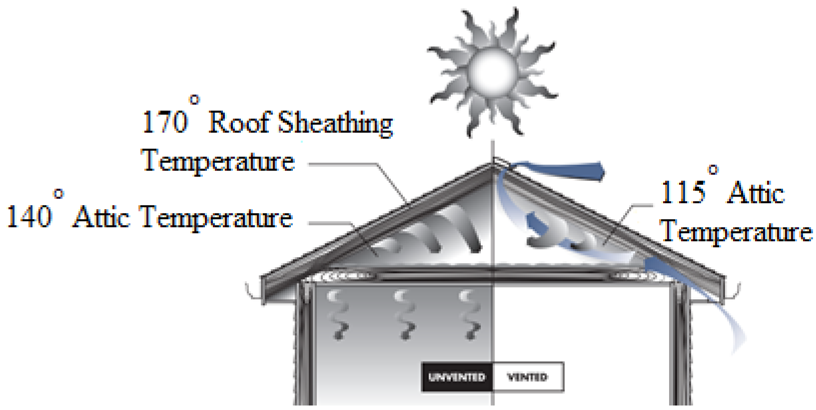


Figure 1.3: The Outdoor, Roof and Attic Temperature (INC, 2018).

Most of the buildings in Malaysia utilize traditional roof with air-tightness design. Promoting ventilation in attic region is not a trend in Malaysia's roof design yet. However, most of the buildings in Malaysia equipped with air conditioner. The buildings in Malaysia do not integrate both the active and passive cool roofing technology systems which lead to the high consumption of electricity in operating the cooling devices.

Malaysia has started to create the awareness on substantial energies development, one of it is a substantial building design. A green building is the solution for all the problems stated. A green building is an energy saving design, which can produce the maximum building's thermal comfortableness with minimum energy usage. Cool roofing system can be implemented into Malaysia's building as one of the green building designs. Cool roofing system can reduce the thermal load received on building from the sunlight thus increasing the thermal comfort. Then, it helps in the reduction of air conditioner usage and country's electricity consumption.

Cool roof utilizes the natural approach method in reducing the thermal load in attic and prevent the heat from transferring into the building. In this study, the cool roofing system firstly utilizes the high heat emissivity properties of radiative surface on moving air cavity . Then, the rotating fans powered by solar energy can remove the heat in the moving air cavity. Insulation approach is applied at moving air cavity to block the heat from transferring to attic then the indoor space. The designed cool roofing system focuses on the radiative and insulation layer (passive cooling system) as well as solar powered fan (active cooling system) to improve the moving air cavity ventilation.

1.4 Aim and Objectives

The aim of this project is the attic temperature reduction. To achieve the aim of attic temperature reduction, the objectives of this project are as defined:

1. To develop a moving air cavity for cool roofing model.
2. To examine the capability of cool roof system that implemented (i) solar powered fan with improved moving air cavity, (ii) thermal reflective coating, and (iii) lightweight foam concrete roofing tile, respectively.
3. To evaluate the performance of cool roofing model by integrating both active and passive systems.

1.5 Scope and Limitation of the Study

The main scope of this project is the building of the designed cool roof system to cut down the attic temperature. The cool roof system requires the casting of lightweight foam concrete roof. Seven channels with insulation layer for the improved moving air cavity is built with steel rod, Aluminium sheet and Aluminium foil and placed underneath the roof. The thermal reflective coating is applied at the metal deck. Lastly, the performance of roof cooling for the metal deck with thermal reflective coating and lightweight form concrete with improved moving air cavity is compared. The limitations of this study are:

- The difference in types and properties of concrete roof materials in Malaysia and global might lead to the impracticality of the cool roof system.
- The difference in roof inclination angles in Malaysia and global might lead to the impracticality of the cool roof system.
- The non-uniformity of Malaysia's weather at different states might lead to different results. For example, the variation of solar intensity, air humidity and raining volume at different states.

1.6 Contribution of the Study

The contribution of this study is the design of cool roofing system for good attic temperature reduction. By utilizing the cool roofing design to the conventional roof, the indoor temperature will remain at a comfortable level despite the hot outdoor temperature. At the same time, the air conditioner demand and the country's energy demand are reduced because the energy source of cool roofing system is the green renewable energy. Cool roofing system uses both the passive and active systems to keep the attic cool.

1.7 Outline of the Report

The Chapter 2 of this report emphasizes the literature review for few cool roof systems. Then, the Chapter 3 of this report outlines the Methodology, experimental set up and six different cool roof configurations. Next, the Chapter 4 of this project is the results of six cool roof configurations' cooling effects and the discussion of the result recorded. Finally, the Chapter 5 of this project emphasizes the conclusion and recommendation of this report.

CHAPTER 2

LITERATURE REVIEW

2.1 Energy Consumption in Malaysia

The ambient temperature of Malaysia fluctuates between 26 ℃ to 40 ℃ with relative humidity fluctuates between 60 % to 90 % (Ong, 2011). The high ambient temperature with high humidity causes an unfavorable living condition for The Malaysians. Such unfavorable condition lead to the increasing demand for air conditioner and the required cooling load.

In order to maintain the indoor comfortableness in a tropical country like Malaysia, an air-conditioner is an important indoor element. The unstoppable demand for air conditioner and cooling load hence increased the country's energy demand. The main energy source of Malaysia is fossil fuels. According to World Data, the carbon dioxide emissions for Malaysia achieved 240 million tons at the year of 2015. While the renewable energies merely occupied 5.2 % of the total energy consumption. One third of world energy consumed go to the exercise of temperature keeping of building and lighting appliances (Hepbasli, 2012).

The increasing of energy demand thus increases the carbon dioxide footprints on earth. The electricity generated in Malaysia is 94 % by fossil fuels. The buildings energy usage occupied 40 % of the world energy. One third of the world greenhouse gases emission comes from the burning of fossil fuels to meet the energy demand of buildings (Mohammad et al., 2014). The energy demand for sector residential and commercial in Malaysia increases from 3868 ktoe at year 2000 to 7796 ktoe at year 2017 as shown in Figure 2.1 (Tenaga, 2017). At year 2017, transportation is the most energy demand sector followed by industrial. While for commercial, the 64 % of energy consumption go to air conditioner usage (Chong et al., 2015).

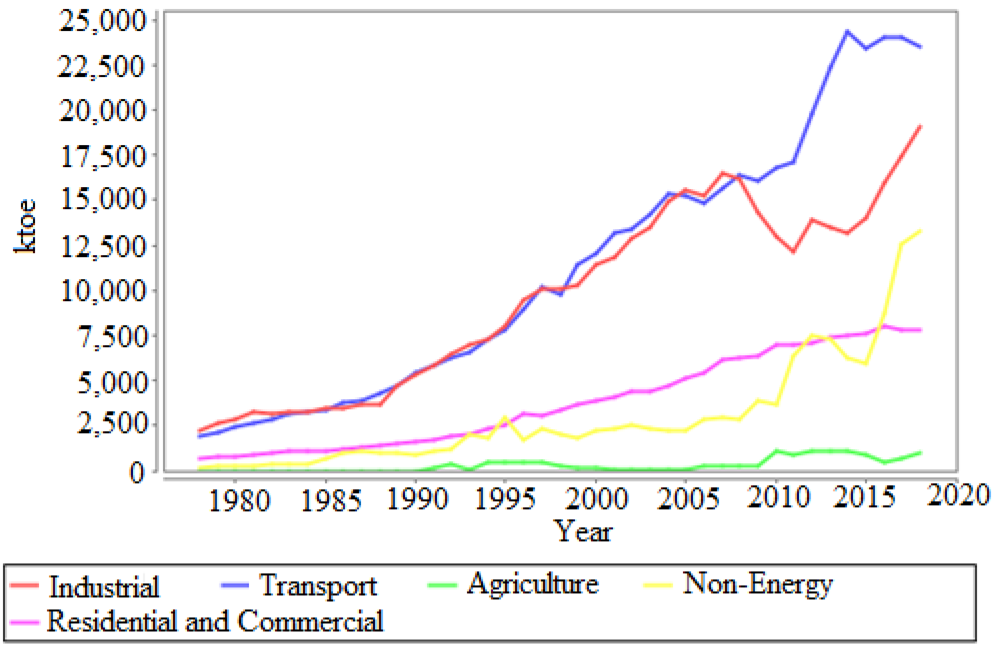


Figure 2.1: The Energy Demand by Sectors (Tenaga, 2017).

The population of Malaysia at year 2018 is 32.4 million with estimation of hitting 32.6 million at year 2019 (Mahidin, 2019). The Malaysia population is forecasted to hit 41.5 million at year 2040 (Malaysia, 2016). The increasing of Malaysia's population lead to the increasing demand for building and commercial. Nonetheless, the increasing for energy demand to accommodate the increasing of population. The building, for example houses and working places, however, is an important aspect for human life.

The household electricity consumption at year 2010 is 801.3 kWh per capita. The household electricity consumption has increased by 24.63 % to 998.7 kW per capita at year 2016 (Statista, 2020). For commercial, the air conditioner takes the biggest portion in energy consumption, which is 64 %. While for residential, the usage of air conditioner occupies 11.9 % of the total energy consumption of residential in Malaysia (Chong et al., 2015). 40 % of the world energy consumed for keeping the indoor comfortable (Geetha and Velraj, 2012). Indoor comfortableness is important in developing country like Malaysia which can be seen in the percentage of air conditioner usage to the total energy consumption.

2.2 Computation of Heat Transfer in Cool Roof

The heat transfer process is important in the analysis of cool roof system. The heat emitted by the sun radiation reach the roof surface and enter the attic region by conduction process.

Figure 2.2 shows the mechanism of heat transfer in cool roof system. The practice of two control volumes, CV_1 and CV_2 is used to determine the heat transfer mechanism. From the CV_1 control volume enclosed area, the heat is coming in from ambient surrounding to the thermal reflective coating and metal deck roof, while some heat is reflected away by radiation and convection and enter the CV_2. From the CV_2 control volume enclosed area, the heat that is going through the CV_1 control volume now acts as the heat input for CV_2 control volume, the heat then continues to enters and releases from CV_2 (Yew et al., 2018).

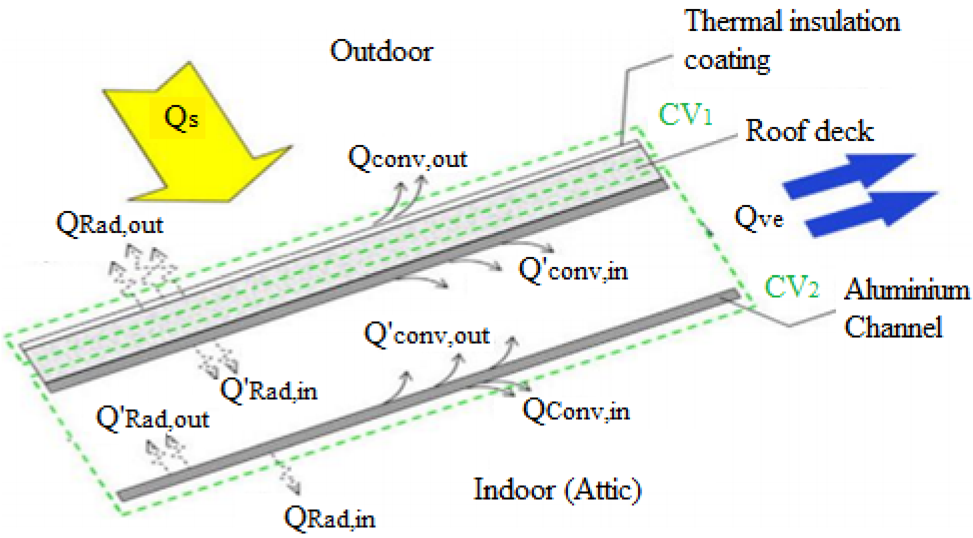


Figure 2.2: The Heat Transfer Process (Yew et al., 2018).

The flow of heat from ambient surrounding to roof, attic and inner space is proved by the second law of thermodynamics. The second law of thermodynamics declared the moving of heat from high temperature to low temperature. The equations 2.1 and 2.2 are generated by the conservation of energy at control volume CV_1 and CV_2 respectively. The conservation of energy in this case is the same amount of heat input and heat output.

$$Q_s = Q_{Rad,out} + Q_{Conv,out} + Q_{cond} \tag{2.1}$$

where

Q_s = Heat emitted from the halogen light bulb that shined on roof, W

$Q_{Rad,out}$ = Radiation heat that reflected away from roof coating, W

$Q_{Conv,out}$ = Convection heat that reflected away from roof, W

Q_{Cond} = Conduction heat passing through the metal deck roof, W

$$Q_{Cond} = Q_{Rad,in} + Q_{Conv,in} + Q_{ve} \tag{2.2}$$

where

Q_{Cond} = Conduction heat entering to cavity from metal deck roof, W

$Q_{Rad,in}$ = Radiation heat entering the attic region, W

$Q_{Conv,in}$ = Convection heat entering the attic region, W

Q_{ve} = Heat removed due to the improved moving air cavity, W

From equation 2.1, the heat absorbed by the roof due to the heat emitted from sun can be reflected away by the reflectivity of the roof coating by radiation and convection. The present of coating prevent the full amount of heat absorbed by the roof from transferring into the roof cavity by conduction of metal deck.

From equation 2.2, the heat that is not reflected away at first control volume now act as the heat input to the roof cavity. The heat then dissipated to the attic region by radiation and convection. By the design of moving air cavity, a portion of the heat is removed instead of dissipated into the attic region. The moving air cavity, the aluminium channel provides a space for the heat to move up and finally removed to the surrounding by the second law of thermodynamics. The heat removal rate of the moving air cavity is expressed in equation (2.3).

$$Q_{ve} = \dot{m}C_p(T_{out} - T_{in}) \tag{2.3}$$

where

$\dot{m}$ = Mass flow rate of air inside moving air cavity, the aluminium channel, kg/s

C_p = Specific heat at atmospheric pressure, J/kg·K

T_{out} = Outlet temperature at moving air cavity, K

T_{in} = Inlet temperature at moving air cavity, K

2.3 Modern Building Design

Modern building design requires the conservation of building energy. A cool and green roof is proved to promote the building's energy savings yet more environmental friendly than the standard roof (Gagliano et al., 2015). A modern cool roof lowers the required cooling load to 54 % and it is the most efficient technologies (Romeo and Zinzi, 2013).

2.3.1 Active Attic Ventilation

Hybrid system is the most suitable roof design for the environment condition in Malaysia. Hybrid system is an effective attic ventilation roof design which compose of both the inlet and outlet properties. The attic ventilation is promoted by the combination of inlet and outlet (Karam M Al-Obaidi et al., 2014).

One of the fans that is designed for attic ventilation is the solar-powered attic ventilation fans (SPAVFs). The main purpose for attic ventilation in hot countres is to discharge the heat in attic region to the surrounding. The high temperature roof deck in hot countries is due to the long period of sunlight radiation. Figure 2.3 demonstrates the using of SPAVF on the roof, with a solar powered attic fan attached to the solar panel (Yu and Moore, 2015).

Figure 2.3: The SPAVF (Yu and Moore, 2015).

Figure 2.4 shows the comparison of temperature at normal attic and attic with SPAVF when the solar insolation on respective days are similar, which were 5436 Wh/m^2 and 5202 Wh/m^2 (Yu and Moore, 2015). The daily average temperature was 27 ℃. At fan OFF condition, the highest temperature recorded at normal attic was 47.7 ℃. At fan ON condition, the highest temperature recorded at attic with SPAVF was 39.3 ℃. This proves the effectiveness of fan usage at attic, by reducing the highest temperature by 8.1 ℃.

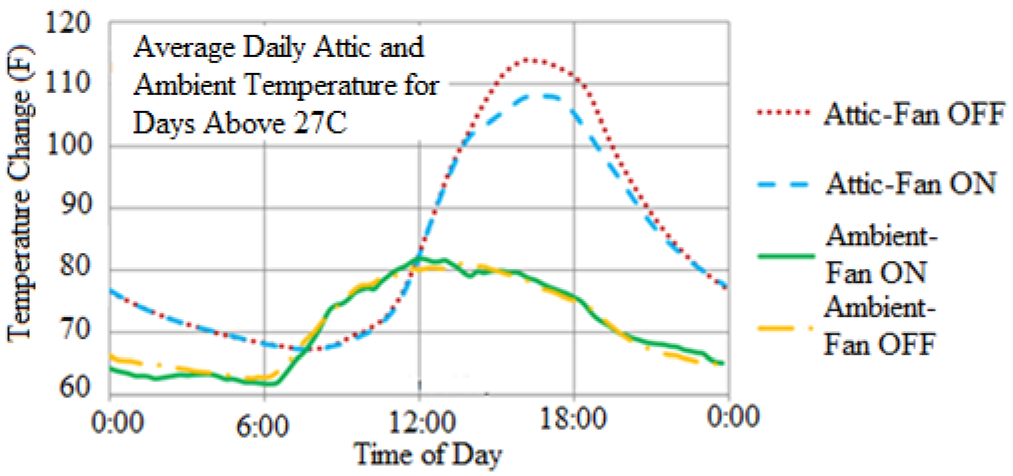


Figure 2.4: The Recorded Temperature (Yu and Moore, 2015).

2.3.2 Foamed Concrete Roof

The main materials to construct foamed concrete are cement, sand, water and foaming agent. The materials are mixed in certain proportion to obtain the desire properties. The foam agent decides the ratio of air bubbles in the cement paste before the paste are left to dried. The drying of cement paste with air-void forms the lightweight foamed concrete. The foamed concrete is known for its high strength-to-weight ratio, high flowability, high thermal insulation, low density and low cement percentage (Amran et al., 2015). The lightweight roof can be added with epoxy resin, fly ash and cotton waste to improve the thermal and sound isolation performance (Binici et al., 2012).

Lightweight foamed concrete reduces the structure load of a building which then promote energy conservation and decrease the labor power and cost needed. The construction of foamed concrete is an advanced building process which involved only drilling, cutting and nailing. The cost of conventional concrete is 1.3 to 2.0 times of foamed concrete. The compressive strength of foamed concrete is up to 58 MPa while conventional concrete ranges from 30 MPa to 150 MPa (Amran et al., 2015). However, 58 MPa of strength is enough for typical housing in Malaysia.

The cell like microstructure of foamed concrete results in a higher acoustic insulation than conventional concrete. The foamed concrete has thermal conductivity of 0.66 W/(m·K) at 1600 kg/m^3 while normal concrete has thermal conductivity of 1.6 W/(m·K) at 2200 kg/m^3. Hence, it is concluded that the thermal conductivity relates proportionally to density. When the density increases, the thermal insulation decreases. For fire resistance, concrete can last 2 to 3.5 hours if the densities range 950 kg/m^3 to 1200 kg/m^3 (Amran et al., 2015).

The water-cement ratio of foamed concrete can be controlled by foaming. The water-cement (w/c) ratio can affect the viscosity and pore structure of cement which then affects the strength of cement. Foamed concrete is a less pollution construction approach due to its less waste and ease amending in its production process. Different w/c ratios (0.40, 0.45, 0.50, 0.55, 0.60) were studied and it is concluded that by increasing the w/c ratio, the small pores can be reduced effectively which then reduce the happening of stress concentration at these pores. However, if the w/c ratio exceed the optimal level, the cement paste will lose its bubble maintaining capability (Liu et al., 2016).

2.3.3 Evaporative Cooling Building

An evaporative cooling building with its wall built by the porous ceramic pipes vertically help cool the building whenever the water evaporates inside the wall. The wall is soaked in water at its lower end. When air flow across the pipes, it will evaporate the water. Hot air becomes cool air, and cool water becomes hot water. The porous properties of the wall thus promote the water sucking capability by capillary attraction (Chen et al., 2015).

The evaporative cooling can be achieved by utilizing the cooling tower. The enhancing of air flow rate and reducing of water flow rate can produce an effective cooling tower. A low approach low temperature cooling tower has a better capability than the standard industrial cooling tower when the air flow rate and water flow rate is fixed. The difference of the two models is more obvious at off peak period (Nasrabadi and Finn, 2014).

Moreover, the evaporative cooling effect at roof can be achieved by building the roof with water-retaining roof brick as shown in Figure 2.5 (Han et al., 2017). Rainwater will be flow and keep in the water-retaining bricks, which then interrupt the incoming sunlight during the day and remove the radiation and heat by means of evaporation. For a regular roof, with the presence of water-retaining bricks the indoor temperature will have an average drop of 9.94 ℃ (Han et al., 2017).

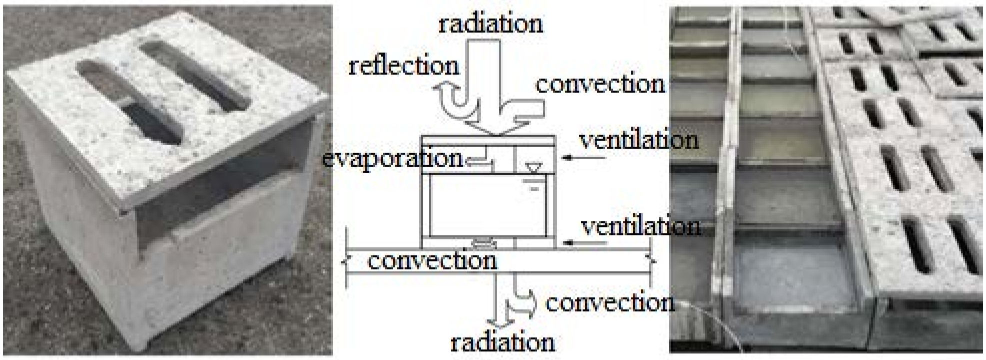


Figure 2.5: The Water-Retaining Roof Bricks (Han et al., 2017).

The combination effect of water-retaining bricks and radiation shield on roof has greatly reduce the cooling load demand. At 16:00, where the indoor temperature supposed to be 33.7 ℃ at regular roof, the combination effect had lowered the temperature to 31.7 ℃ (Han et al., 2017). However, this design might not be applicable in winter, but it will be suitable for all year summer country like the Malaysia. The spraying of 5 kg of water over the roof surface for 40 minutes can lower the cooling load to 14.72 % (Nayak et al., 2020).

2.4 Radiative Roof

Radiative roof can restrict or even block the heat from entering the roof deck to reduce attic's thermal load. Radiative roof is a thermal break for attic and living space. The heat isolate performance increases with the thickness of the insulation layer. Radiative roof acts as the heat insulation radiant and the heat transfer barrier (Karam M. Al-Obaidi et al., 2014).

The radiative air-cooling system composed of parallel connectors which built under the roof to draw cool surrounding air into the roof. When cool air is drawn into the roof, the cool air can mix with the air inside the attic and hence reduce the attic temperature. Figure 2.6 shows the radiative air cooler which uses Aluminium sheet as radiative medium and polyethylene film is placed on top of the metafilm as insulation medium (Zhao et al., 2019). The baffle is created and built in the design as shown in Figure 2.6 to promote heat flow by the concept of air turbulence. The maximum temperature difference between the shingle roof and radiative air cooler is 21.0 ℃ at 21cm fiberglass insulation (Zhao et al., 2019).

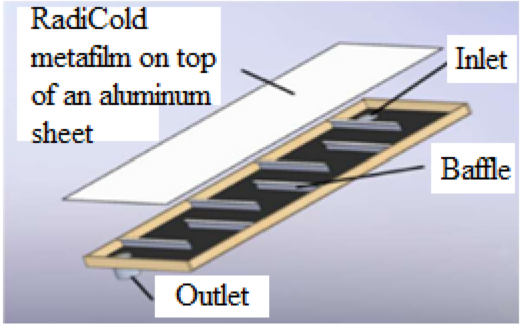


Figure 2.6: The Radiative Air Cooler (Zhao et al., 2019).

The first version of radiative roof is natural materials while later evolved to artificial white and high reflective colored materials (Santamouris, 2014). The albedo, which is one of the radiative material, can act as a water proof material at the roof application (Pisello et al., 2016). Coatings of high reflectivity can be mixed into the building paint to reduce the building’s cooling load (Cozza et al., 2015). A cool paint can maximumly lower the indoor temperature to 5 ℃ (Dias et al., 2014).

2.4.1 The Aerogel-based Radiant Barrier

An energy efficient house properly utilizes the thermal properties of solar receiving roof, attic floor insulation and attic air ventilation. For a radiant barrier system, it composed of a reflective material which reflect the heat than conduct or absorb heat, and a thermal insulation material which act as the heat conduction barrier. The radiative heat transfer is the main reason for high attic temperature (Kosny et al., 2018).

One of the examples of radiant barrier is the aerogel blanket. For an aerogel blanket prototype, it was 10 mm thick with thermal conductivity of

14.5 mW/(m·K). An aerogel blanket consists of reflective material on both sides of its face. Figure 2.7 shows the aerogel-based radiant barrier test model, which consisted of either reflective or non-reflective surface, 1.1 cm of oriented strand board (OSB), 9 cm of air cavity and 1 cm of aerogel (Kosny et al., 2018).

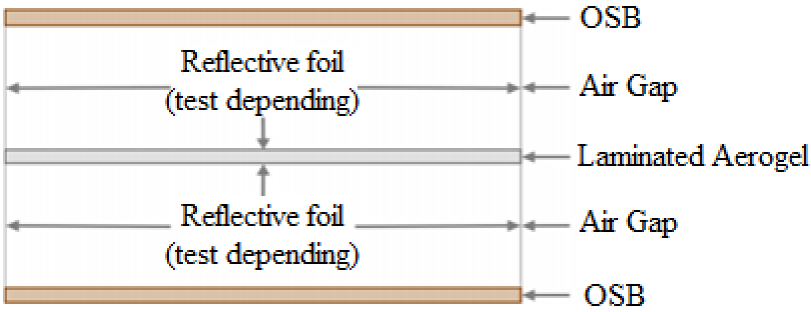


Figure 2.7: The Aerogel-Based Radiant Barrier (Kosny et al., 2018).

The air gap insulation can prevent the heat generated in house to escape and the cool temperature outside to enter the house during winter (Ouédraogo et al., 2018). Figure 2.8 shows the results of implementing the aerogel blanket into the attic region. The results show that the attic is averagely 9 °C hotter without the implementation of aerogel blanket. The attic was also 10 °C to 12 °C cooler when aerogel blanket is used because of the prevention of radiative heat transfer by the high thermal resistance and reflective material. While at night, the aerogel blanket attic is 2 °C to 3 °C warmer. This proves that the aerogel blanket able to remove more heat during day time and maintain more heat during the night (Kosny et al., 2018).

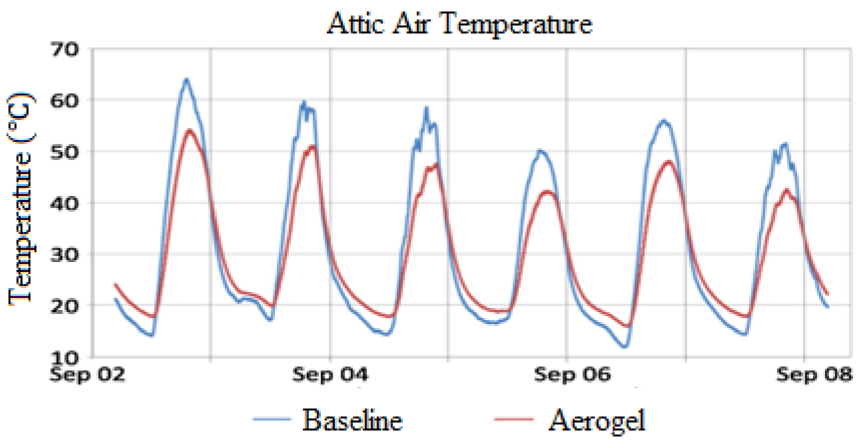


Figure 2.8: Results of Aerogel Blanket (Kosny et al., 2018).

The aerogel-based radiant barrier can initially prevent the heat transfer, however by times the Aluminium foil will soil on the upward facing surface. The degradation of Aluminium foil is due to the deposition of dirt and dust (Kosny et al., 2018). If the attic is properly kept clean, the aerogel can be helpful to reduce the attic temperature, associate with the low budget needed.

2.4.2 Insulation in Solar Passive Roof Designs

Implementing the mineral insulator in paint can lower the building's energy consumption to 17 % (Azemati et al., 2013). A cool-colored tile can be made with attaching a silica insulating layer below the roof tile which can highly rejected the solar radiation (Ferrari et al., 2016). The implementation of insulation in passive roof act as the barrier for radiant and conduction heat transfer (Ong, 2011).

A roof solar collector can facilitate the temperature reduction in attic region. Few roof samples were conducted outdoor and compared the attic temperature. Figure 2.9 (a, b, c, d, e, f) show the model for passive roof designs. The insulation blanket as shown in Figure 2.9 consisted of the attachment of Aluminium foil with fiberglass. For Figure 2.9(b) and (e), the insulation blanket is suspended below the roof by wire mesh. While for Figure 2.9(c), the insulation blanket lay on the ceiling board. For Figure 2.9(f), the roof and ceiling were opened a size of hole to induced the air movement by buoyancy effect (Ong, 2011).

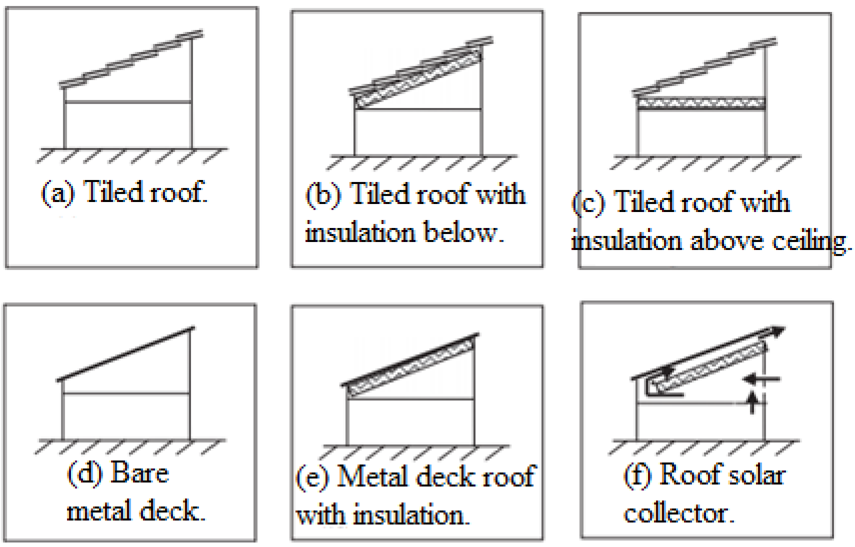


Figure 2.9: The Model for Passive Roof Designs (Ong, 2011).

The roof inclination is 15 ° from horizontal. Copper constantan thermocouple is used as temperature recorder. Figure 2.10 shows the attic temperature of different passive roof design (Ong, 2011). The highest attic temperature recorded at tile roof model with insulation blanket on ceiling, followed by typical tile roof model. The lowest attic temperature recorded at roof solar collector model, followed by insulation layer suspended below the metal deck roof model.

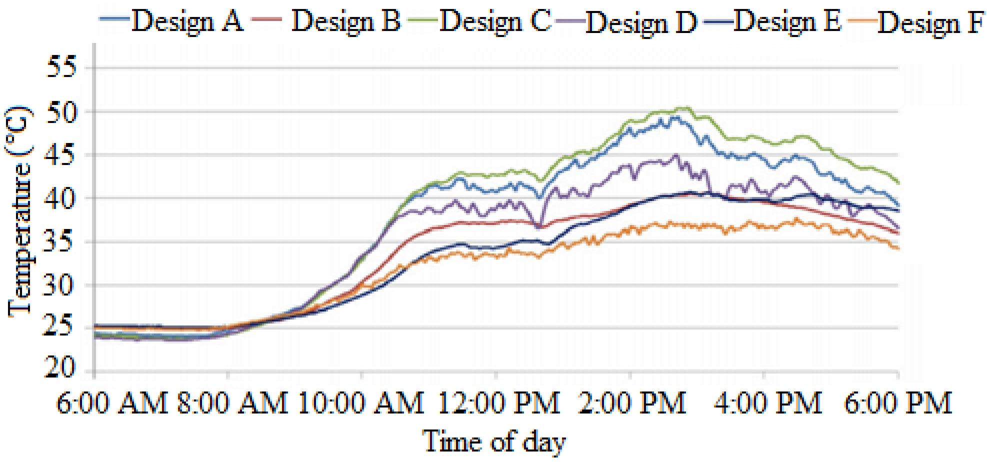


Figure 2.10: The Attic Temperature of Passive Roof Designs (Ong, 2011).

The roof collector design is averagely 13 °C lower than uninsulated tile roof. For ceiling temperature, the insulated design is averagely 4 °C cooler than uninsulated design in tile roofs (Ong, 2011). Hence, it was concluded that with insulation layer, it results in a higher roof temperature, while the coolest model is the solar collector roof which provides the air ventilation from the hole made at attic and ceiling. Insulation itself is not enough to cool the roof. Although insulation prevent the heat transferred to the living space, some active design like a hole at the ceiling and roof is important to remove the heat trapped at attic. The insulation is better to suspended below the roof than put on top of the ceiling to reduce the heat space.

Fly ash can be made into permeable insulation layer to reject the incoming heat flux (Mozumder and Singh, 2012). A roof with insulation layer made with rockwool and polystyrene foam can lower the air conditioner consumption (Jim, 2014). Lastly, a mixed recycled wool and polyester fiber is a good thermal and sound insulation material (Patnaik et al., 2015).

CHAPTER 3

METHODOLOGY AND WORK PLAN

3.1 Introduction

The cool roofing model was constructed with a lightweight foam concrete tile. The lightweight foam concrete tile was fabricated with a density of 1250 kg/m^3 and a water cement ratio of 0.6. Then, the improved moving air cavity was constructed with steel rod and Aluminium sheet. After that, seven solar powered fans were connected horizontally and tied to a plastic mesh. This cool roofing system implemented lightweight foam concrete roofing tile, improved moving air cavity, solar powered fans and rockwool. Each elements were added in stages at different roof designs.

The cool roof models were constructed to evaluate the performance of attic temperature reduction by both the passive and active approaches. After that, four thermocouples were fixed with Aluminium tape on the roof surface, attic, ambient and air channel. The experiment was conducted for 30 minutes under heat exposure from two spotlight lamps of power 500 W each. The experiment was repeated for six roof designs. Figure 3.1 shows the experimental flow chart.

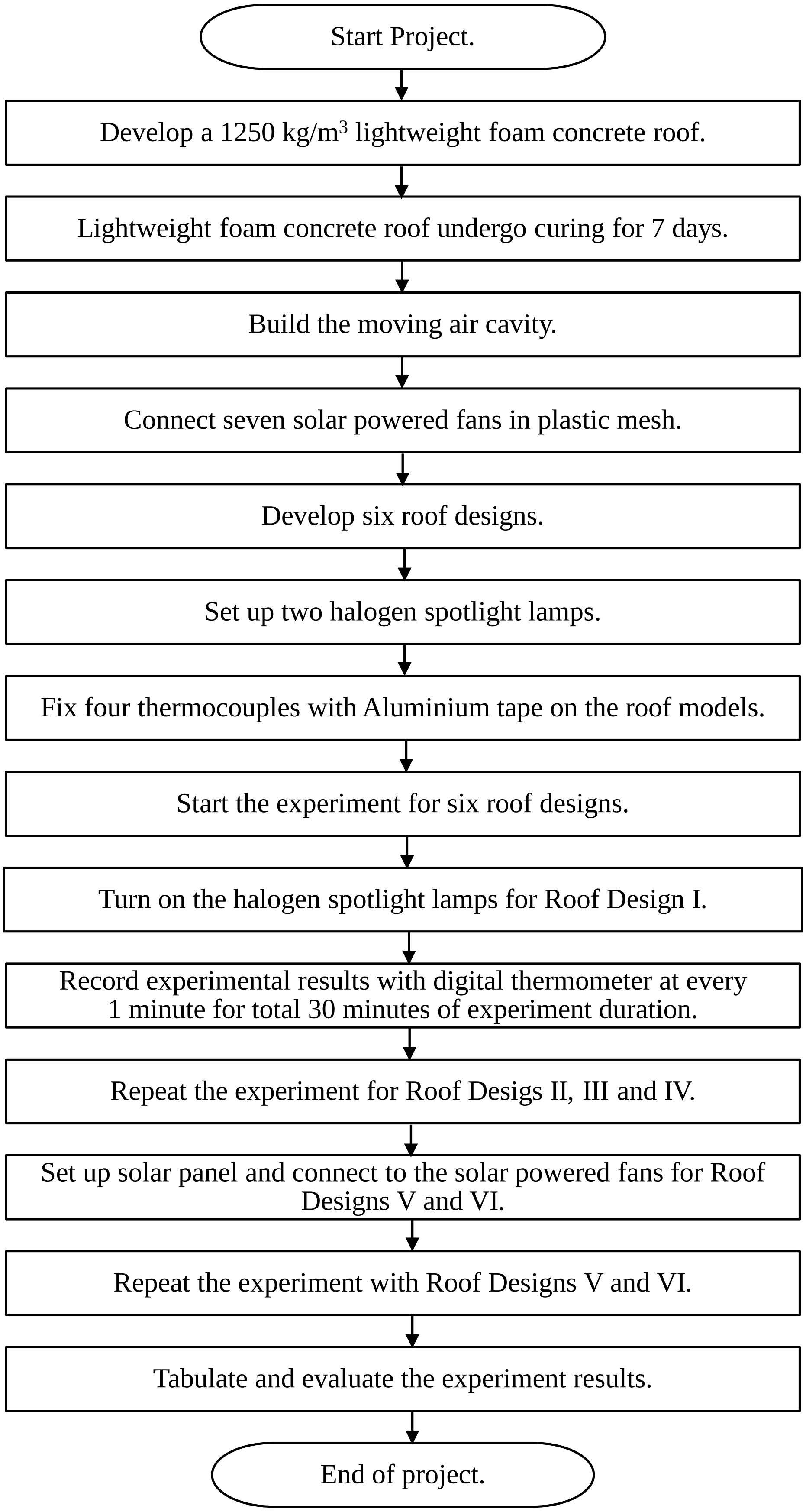


Figure 3.1: The Experimental Flow Chart.

3.2 Experimental Design

The basic model of this cool roofing system is the attic region. The basic model was built by Perspex of thickness 5 mm. The dimension of the basic model was 340 mm in length, 360 mm in width and 490 mm in height. Figure 3.2 shows the dimension of the basic model with roof area 412 mm in length and 340 mm in width and was inclining at 30°.

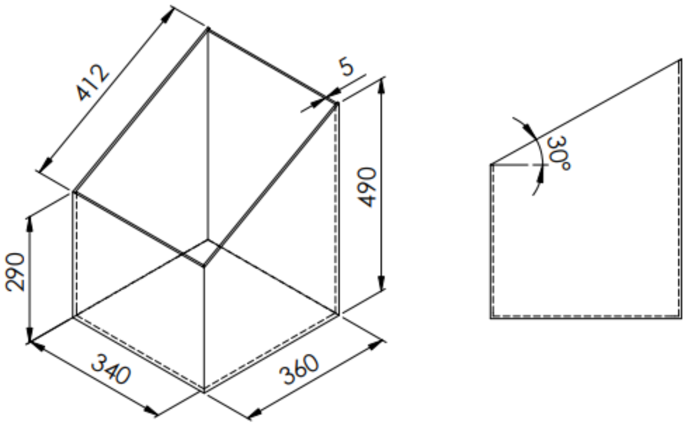


Figure 3.2: The Dimension of Basic Cool Roof Model in Millimeter.

3.2.1 Lightweight Foam Concrete Tile

The lightweight foam concrete tile was constructed in the workshop. The water to cement ratio of this roof model was fixed at 1:0.6, while the cement to sand ratio was fixed at 1:1. Then, 1.8 kg of cement and sand were measured separately, and were mixed with 3.0 kg of water. The details of each ingredient and mixing proportion is listed in Table 3.1.

Table 3.1: Details of Each Ingredient.

Foam Concrete Ingredient	Mix Proportion	Mass (kg)	Density (kg/m^3)
Cement	0.6	1.8	1440
Sand	0.6	1.8	1631
Water	1.0	3.0	997

Figure 3.3 shows the lightweight foam concrete's cement paste was drying in a mould with two layers of wire mesh. After the paste was dried in mould, the concrete was soaked in water as curing processs for 7 days. The mass of foam needed to create a targeted foamed concrete density of 1250 kg/m^3 was calculated with mix proportioning of foamed concrete equation (3.1) after the base mix density was measured and determined (Dhir and McCarthy, 2006). The base mix mass was 6.6 kg and the foam density is was 50 kg/m^3. The cement paste was added with 0.5 % of calcium stearate and 2.6 % of eggshell.

Figure 3.3: The Lightweight Foam Concrete Tile in a Mould.

$$F_m = B_m F_d \left(\frac{1}{T_d} - \frac{1}{B_d}\right) \tag{3.1}$$

where

F_m = Foam mass, kg

B_m = Base mix mass, kg

F_d = Foam density, kg/m^3

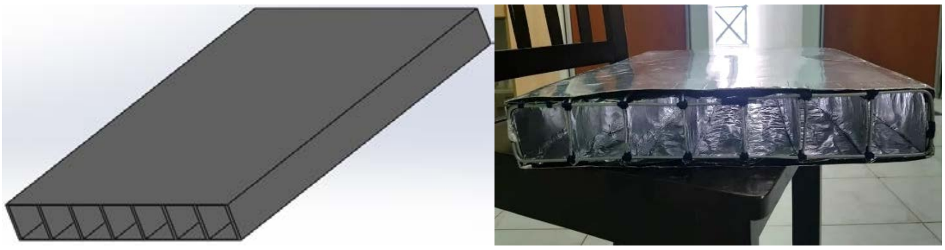
T_d = Target density of foamed concrete, kg/m^3

B_d = Base mix density, kg/m^3

The base mix density was measured at 2500 kg/m^3, hence the mass of foam required for mixing was calculated to be 0.132 kg. The final dimension of lightweight foam concrete tile after the curing process was 460 mm in length, 360 mm in width and 30 mm in height.

3.2.2 Improved Moving Air Cavity (MAC)

The improved moving air cavity (MAC) was sandwiched between the roof and attic region. The surface of MAC was built with Aluminium sheet and the channel inside of MAC was built with Aluminium foil as shown in Figure 3.4. The structure was supported by steel rod.

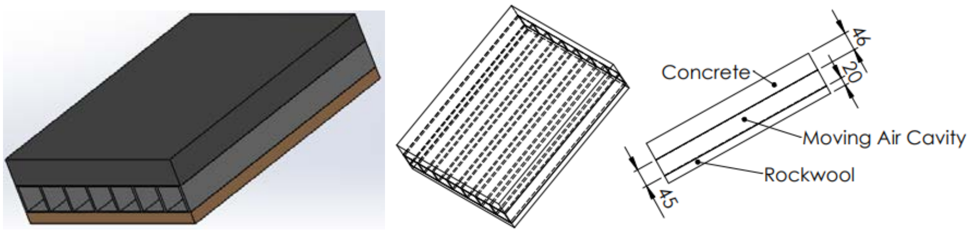


(a) (b)

Figure 3.4: The Moving Air Cavity (a) Solidworks (b) Experimental.

The bottom surface of improved MAC housed one additional layer of rockwool. Rockwool was more preferred to placed at the bottom of MAC than above. This is due to design consideration, as rockwool unable to support the weight of foam concrete roof and would have compressed the rockwool, thus placing it bottom can rely on the base attic model to spread out the weight of foam concrete roof. Moreover, placing rockwool at the top surface of MAC will cause excessive heat to trapped on the roof surface instead of channeling them out. Hence, this rockwool was designed to be place on the bottom surface of improved MAC.

The air channel cavities which were surrounded by Aluminium foil act as heat radiant reflector and barrier when work together with rockwool. The thickness of foamed concrete was 46 mm and rockwool was 20 mm. The design and dimension of improved MAC as implemented with concrete roof and rockwool is shown in Figure 3.5.



(a) (b)

Figure 3.5: The Moving Air Cavity with Concrete and Rockwool (a) Solidworks (b) 3D Drawing.

Since the channels were separated into seven by Aluminium foil and steel rod, the channels acted as the side for heat exchange to maintain the cool temperature at attic. The air channels were 43 mm wide, they allowed 3 mm of tolerance when 40 mm size of solar powered fans were used.

3.2.3 Solar Powered Fans

Seven solar powered fans of dimension 4 cm × 4 cm were connected horizontally and tied to a plastic mesh. The improved moving air cavity (MAC) accommodated seven channels to place solar powered fans that were tilted 30° from vertical axis to align with the channel direction. The solar powered fans were placed at the inlets of MAC as shown in Figure 3.6. The fans were connected to solar panel for power source.

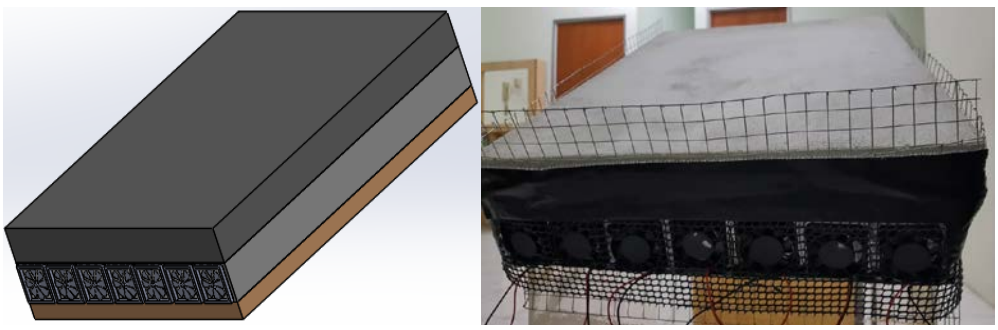


Figure 3.6: The Solar Powered Fans in MAC (a) Solidworks (b) Experimental.

The air channel with uniform parallel design maximized the space in moving air cavity to accommodate air. Air can act as a thermal insulation system to stop the heat conducted through the roof from transferring downwards to the attic. The departmentalized design of moving air cavity followed the dimension of solar powered fans. It is to ensure that all the cool air induced by the solar powered fans enter the moving air cavity completely. Each solar powered fans had their own air channel to prevent the flow interruption from the other solar powered fans which will slow down the rate of air flow and heat transfer.

3.3 Experimental Set Up

The experimental set up was divided into roof set up, halogen spotlight lamp set up and temperature sensor set up. Six sets of data were collected which are from Roof Designs I, II, III, IV, V and VI.

3.3.1 Roof Set Up

This project had six roof models. The normal metal deck (Design I), the white metal deck (Design II) and the foam concrete roof (Design III) are shown in Figure 3.7. Furthermore, the foam concrete roof with MAC (Design IV), the foam concrete roof with MAC and solar powered fans (Design V) and lastly with one additional layer of rockwool (Design VI) are shown in Figure 3.8. These six roof prototypes were studied and investigated based on the efficiency of attic temperature reduction.

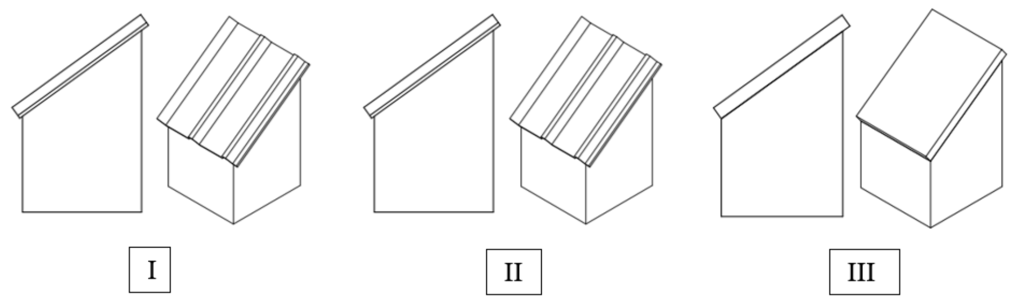


Figure 3.7: The Roof Designs I, II and III.

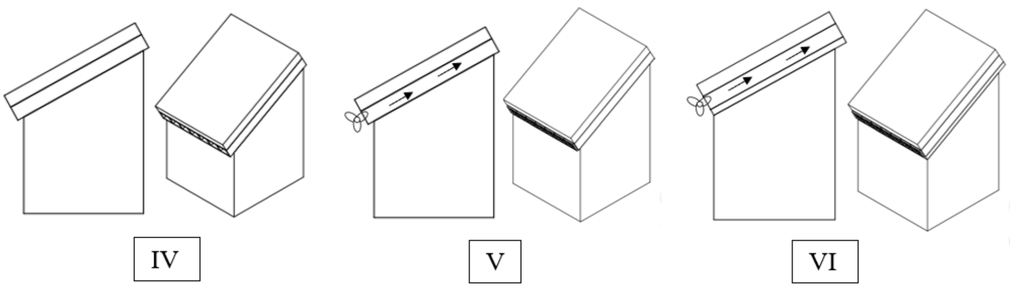


Figure 3.8: The Roof Designs IV, V and VI.

3.3.1.1 Metal Deck Roof (Design I)

The roof design in Figure 3.7 (I) was the basic design for a conventional metal deck roof. The red metal deck roof was the controlled experiment.

3.3.1.2 Metal Deck Roof Coated with TRC (Design II)

The roof design in Figure 3.7 (II) was the metal deck roof coated with white reflective surface, the thermal reflective coating (TRC). TRC was made with titanium dioxide pigment and chicken eggshell waste. TRC can reflect the heat from the sunlight away. The white color of TRC is known to have the highest thermal reflectivity among all other colors. TRC was the passive cool roofing design, it reflected the heat away and prevented the heat from accumulated on the roof.

3.3.1.3 Foamed Concrete Roof (Design III)

The roof design in Figure 3.7 (III) was the basic design of this cool roofing system without the MAC and solar powered fans. The roof was made with lightweight foam concrete tile with water cement ratio of 0.6 and a concrete density of 1250 kg/m^3. A lightweight foam concrete tile is a more practical approach to conduct the roof experiment than metal deck roof.

3.3.1.4 Foam Concrete Roof with Improved MAC Implemented (Design IV)

The Roof Design III was then added with the improved moving air cavity (MAC). The improved MAC was placed below of lightweight foam concrete tile as shown in Figure 3.8 (IV). The air moving space inside of MAC act as the heat elimination system. The heat absorbed by the roof and the heat trapped in attic region can be discharged to the surrounding based on convection effect. Air ventilation was promoted when the heat absorbed from the sunlight was discharged back to the surrounding effectively. The straight and departmentalized design of improved MAC reduce the air drag effect and maximise the moving air space to promote the air flow rate.

3.3.1.5 Foam Concrete Roof with Solar Powered Fans Implemented at Improved MAC (Design V)

Roof Design IV was then added with solar powered fans at each channels of improved MAC as shown in Figure 3.8 (V). The solar powered fans suck in cool ambient air and promote the warm air removal rate when force convection occurred inside the improved MAC. This was an active cool roofing approach where air movement was improved. The solar powered fans are useful when the surrounding is not windy.

3.3.1.6 Foam Concrete Roof with Solar Powered Fans and Rockwool Implemented at Improved MAC (Design VI)

Lastly, Roof Design V was added with one additional layer of rockwool in between the improved MAC and attic region as shown in Figure 3.8 (VI). The purpose of this design is to determine whether heat barrier is useful in lowering the attic temperature and whether the heat radiative barrier is effective. This rockwool which placed underneath of the improved MAC act as a heat barrier, where heat is terminated from transferring into the attic region. The heat is trapped at the bottom surface of MAC due to the heat barrier effect. Solar powered fans then remove the trapped heat.

3.3.2 Halogen Spotlight Lamp Set Up

The halogen spotlight lamp acted as a source of sunlight heat in this project. The lamp provided the necessary heat source for the roof warming and the light source for the solar panel. In this project, two 500 W lamps were placed 45° from the vertical axis and the distance of the lamps and roof surface was fixed at 30 cm as shown in Figure 3.9.

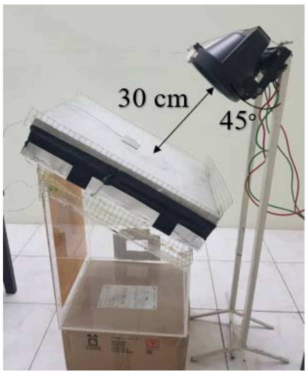


Figure 3.9: The Halogen Spotlight Lamp Set Up.

3.3.3 Temperature Sensor Set Up

Four temperature sensors of K-type thermocouple were used at the assigned location and set up as shown in Figure 3.10. The first thermocouple, Thermocouple A was placed on the roof surface for all the roof designs to measure the roof temperature. The second thermocouple, Thermocouple B was placed 200 mm vertically downwards from Thermocouple A and it was to measure the attic temperature.

Then, the third thermocouple, Thermocouple C was used to measure the ambient temperature. Lastly, the fourth thermocouple, Thermocouple D was placed at the moving air cavity. Thermocouple D was used at all roof designs except Roof Designs I, II and III. The sensors were fixed with Aluminium tape. The data were recorded every 1 minute for total experiment duration of 30 minutes.

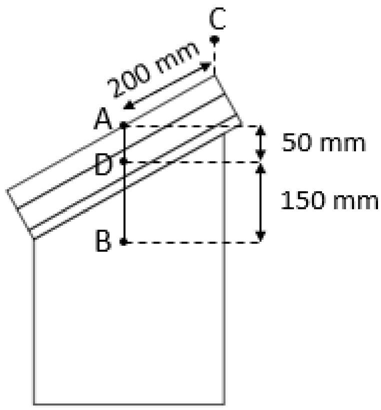


Figure 3.10: The Thermocouple Set Up.

3.3.4 Solar Panel and Solar Powered Fan Set Up

One solar panel with 18.0 V of voltage at maximum power, 21.8 V of voltage at open circuit and 1000 V of maximum system voltage was used to supply the electricity to run the solar powered fans. The using of solar panel is to imitate the real-life solar powered attic fans. Moreover, the using of solar panel can better determine the feasibility of using the solar powered fans at attic temperature reduction, which included the solar panel's range of power managed to supply.

Seven solar powered fans were connected in parallel circuit. The solar powered fans circuit were connected to the solar panel. One 500 W halogen spotlight lamp was set up to shine on the solar panel as the source of sunlight to produce solar power. Figure 3.11 shows the experimental setup of solar panel and the solar powered fans.

Figure 3.11: The Solar Panel and Solar Powered Fans Set Up.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Metal Deck Roof (Design I)

The experiment was started with a controlled experiment roof model composed solely of a conventional red metal deck. Figure 4.1 shows the results obtained and presented in a graph of temperature versus time for a total experiment duration of 30 minutes.

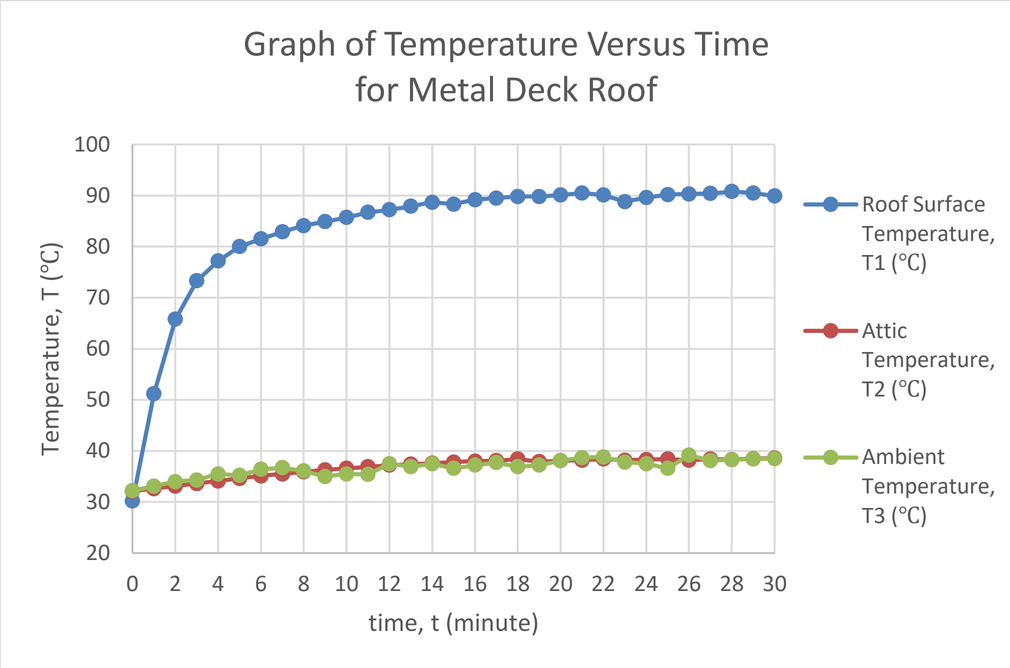


Figure 4.1: Performance of Metal Deck Roof.

The maximum roof surface temperature recorded for this red metal deck roof was 90.8 °C. During the first 2 minutes when the roof surface temperature had the steepest gradient, the increase rate of roof surface temperature for metal deck was 17.8 $°C/min$ as shown in Figure 4.1. The high temperature increase rate proves the high thermal conductivity of metal deck, which is at 44.8 W/mK (Singh et al., 2016).

For ambient temperature, initially the ambient temperature was at 32.2 °C, after one minute of lamp exposure, the ambient temperature increase to 33.1 °C, and reached maximum of 39.2 °C with an average increase rate of

0.21 $℃/min$. The gradual increase of ambient temperature demonstrated the hot outdoor situation during daytime.

For attic temperature variation, the attic temperature was lower than ambient temperature initially for 8 minutes. Then, the attic temperature was roughly the same as ambient temperature with maximum 38.6 ℃ at 30th minute and increase rate of 0.2167 $℃/min$. This outcome is proven when the metal deck roof is used, the house structure maintained as hot as the ambient temperature. The natural ventilation did not carry the heat away as metal roof is like an opened roof, the heat can penetrate into the building directly and immediately.

4.2 Metal Deck Roof Coated with Thermal Reflective Coating (TRC) (Design II)

The experiment was continued with the second roof model, a metal roof coated with Thermal Reflective Coating (TRC) in white colour. Figure 4.2 shows the results obtained and presented in a graph of temperature versus time for this Roof Design II.

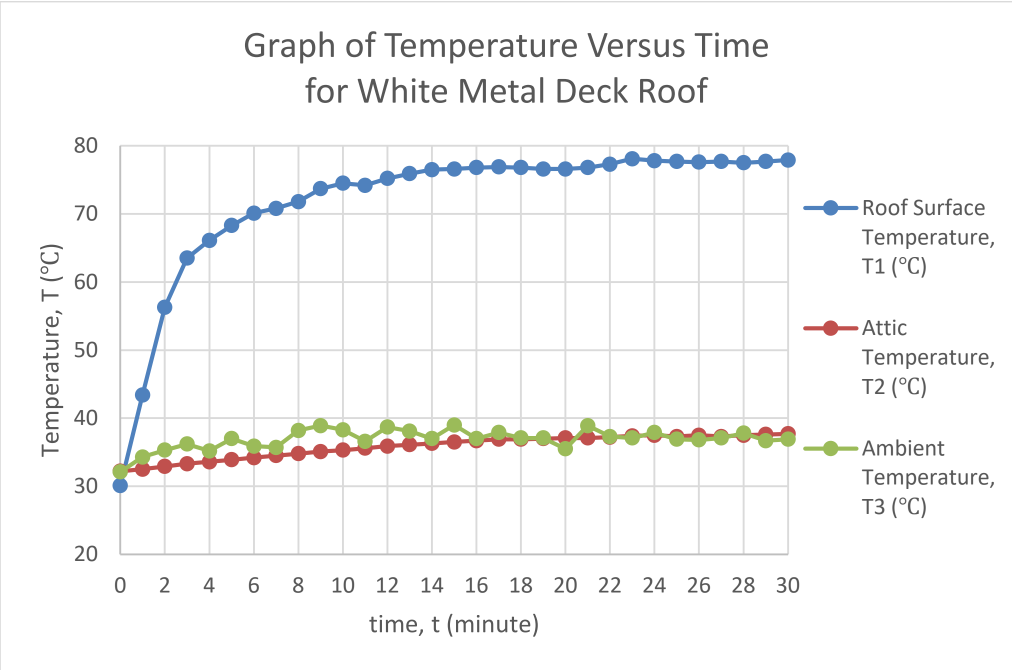


Figure 4.2: Performance of White Metal Deck Roof.

For roof surface temperature, the maximum recorded temperature for white metal roof was 78.1 ℃. The maximum roof surface temperature for a normal red metal roof without TRC coated was 90.8 ℃, by applying the TRC coating, it reduced the roof surface temperature to 12.7 ℃. The practice of TRC coating is important in real roof design, as the metal roof trapped unnecessary heat and radiate the heat throughout the surrounding and also into the building.

During the first 2 minutes in roof surface temperature variation, the increase rate was 13.1 $℃/min$, as compared to the metal roof without TRC (17.8 $℃/min$), the white metal roof was 4.7 $℃/min$ lower than red metal roof during the steepest temperature increase period. This outcome proved the usefulness of white reflective coating in reflecting the heat from spotlight lamp away.

For ambient temperature, the maximum recorded temperature was 38.9 ℃ at 30th minute with an average increase rate of 0.16 $℃/min$. By utilizing the white coating, the increase rate reduced 0.05 $℃/min$ and the maximum recorded temperature reduced 0.3 ℃. For attic temperature variation, the attic temperature was lower than ambient temperature for 21 minutes. After that, the attic temperature was almost the same as ambient.

However, if compare with red metal roof, the maximum attic temperature of white metal roof was 0.9 ℃ lower than red metal roof at 37.7 ℃. The average increase rate was 0.0334 $℃/min$ lower at 0.1833 $℃/min$. Although the metal roof is a high thermal absorber, due to the reflective coating’s high reflectivity properties, it decreases the heat gain (Triano-Juárez et al., 2020).

4.3 Foamed Concrete Roof (Design III)

The experiment was continued with metal roof removed and replaced with a lightweight foam concrete roof, a more practical roof design approach. Figure 4.3 shows the result obtained and presented in a graph of temperature versus time for this Roof Design III.

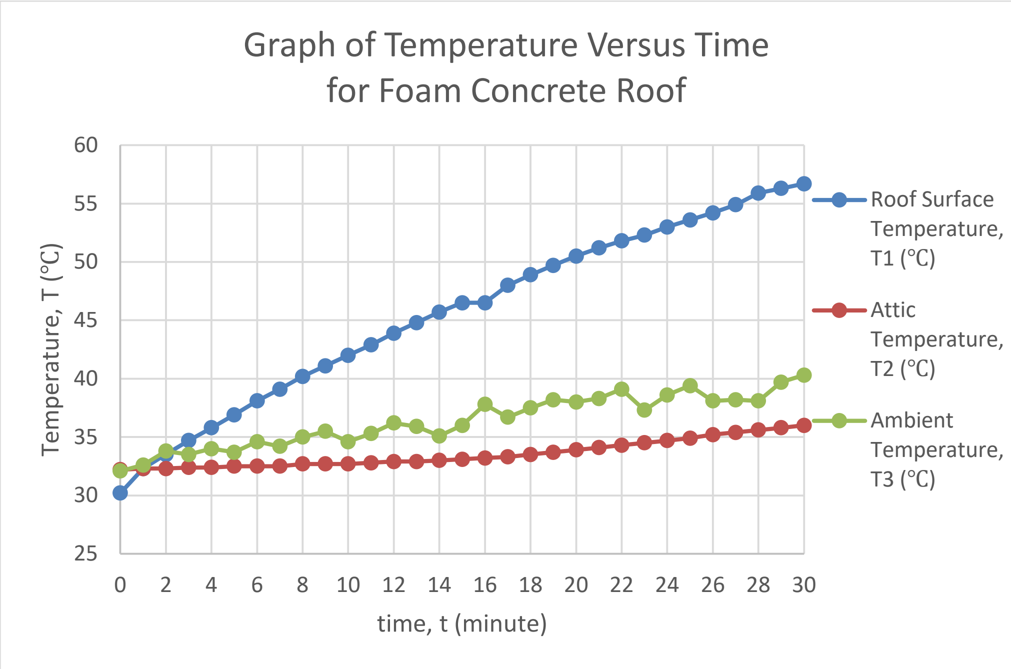


Figure 4.3: Performance of Foamed Concrete Roof.

For roof surface temperature, the temperature increased slowly throughout the experiment when the roof was replaced with foam concrete. Both the previous metal roofs had steep gradient at the first 2 minutes exposed to spotlight, 17.8 $℃/min$ for normal metal roof and 13.1 $℃/min$ for white metal roof. Foam concrete however, reached 1.65 $℃/min$ only during the first 2 minutes exposed to light.

The maximum roof surface temperature achieved by foam concrete roof was 56.7 ℃, which was 34.1 ℃ lower than red metal roof and 21.4 ℃ lower than white metal roof. This can be proven by the foam concrete's lower thermal conductivity and thermal absorptivity. Foam concrete's thermal conductivity limits from 0.24 to 0.74 W/mK due to the existence of voids (Ganesan et al., 2015). Roof is the major solar heat collector where 40 % of the energy will be consumed for top-floor buildings, hence roof material is an essential element for the cool roofing system (Gao et al., 2017). By utilizing foam concrete in the building design, it can reduce the amount of heat trapped at the roof surface.

For the comparison of ambient and attic temperature, the attic temperature was lower than ambient temperature throughout the experiment as shown in Figure 4.3. This was different with the metal roof experiments. In their attic temperature variation especially in the later experiment duration, the trend of attic temperature followed the ambient temperature variation.

For ambient temperature, the maximum temperature recorded was 40.3 ℃ at 30th minute with an average increase rate of 0.2733 $℃/min$. For attic temperature, the maximum temperature recorded was 36.0 ℃, which was lower than the metal decks by 2.6 ℃ and 1.7 ℃ respectively. The average increase rate of attic temperature was 0.1267 $℃/min$, which was lower than the metal decks by 0.09 $℃/min$ and 0.0566 $℃/min$ respectively. Foam concrete roof is a better heat insulator than metal roof, hence the attic region had lower temperature increase rate despite the higher ambient temperature.

4.4 Foam Concrete Roof with Improved Moving Air Cavity Implemented (Design IV)

The experiment was continued with the implementation of improved moving air cavity (MAC) at the previous foam concrete roof model. Figure 4.4 shows the result obtained and presented in a graph of temperature versus time for Roof Design VI.

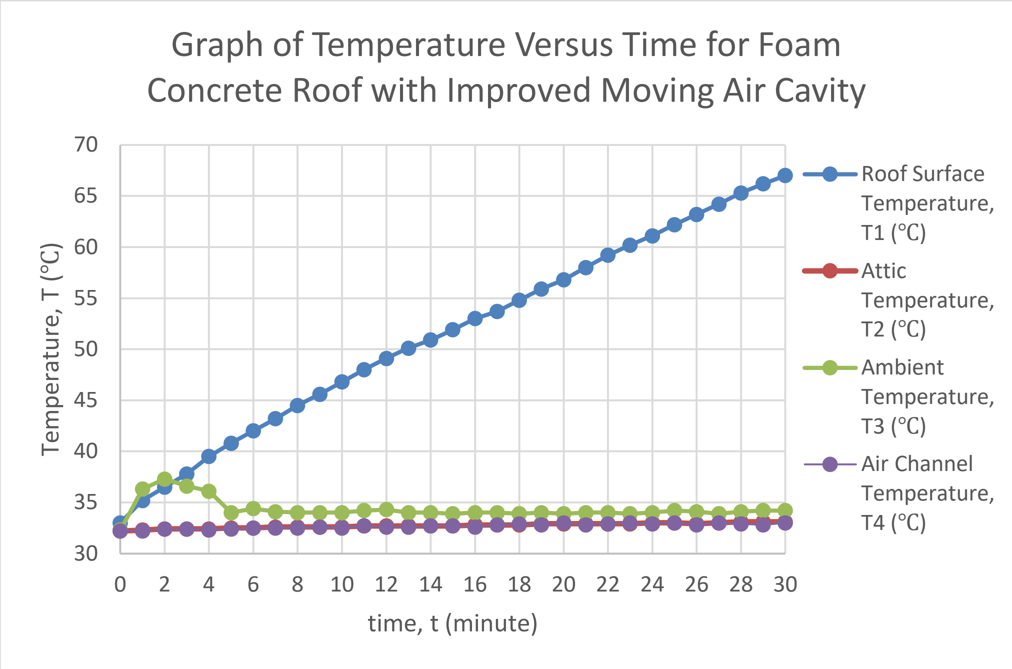


Figure 4.4: Performance of Foam Concrete Roof with Improved MAC.

Roof surface temperature increased slowly as shown in Figure 4.4 due to the low thermal conductivity of foam concrete and reached a maximum recorded temperature of 67.0 ℃ and increase rate of 1.1333 $℃/min$. The maximum recorded temperature was 23.8 ℃ and 11.1 ℃ lower than the metal decks.

For ambient temperature, the average increase rate was 0.0633 $℃/min$, which was 0.21 $℃/min$ lower than the foam concrete without MAC. The ambient temperature had a lower increase rate due to the radiative design of MAC. The radiative surface of MAC promoted the radiative heat transfer, when the whole heat dissipation process was promoted and the heat absorption rate was reduced, it will be favourable to the surrounding (Chen and Lu, 2020).

For attic and air channel temperature, they were lower than the ambient temperature throughout the experiment as shown in Figure 4.4. The attic temperature variation was similar with the air channel temperature as shown in Figure 4.4. The highest maximum attic temperature recorded was 33.1 ℃, which was 2.9 ℃ lower than foam concrete without MAC. For attic temperature average increase rate of 0.03 $℃/min$, it was 0.0967 $℃/min$ lower than foam concrete without MAC.

By adding the improved MAC underneath the foam concrete roof, the average attic temperature increase rate showed a decrease of 76.32 %. This proved the efficiency of MAC's parallel radiative air cooler in promoting the heat transmission and flowing rate. With this high emissive material, the heat is transferred back to the surrounding continuously, which then executed the passive cooling (Chen and Lu, 2020).

4.5 Foam Concrete Roof with Solar Powered Fans Implemented at the Improved Moving Air Cavity (Design V)

The experiment was continued with the implementation of solar powered fans at the improved moving air cavity (MAC) of foam concrete roof. Figure 4.5 shows the results obtained and presented in a graph of temperature versus time for Roof Design V.

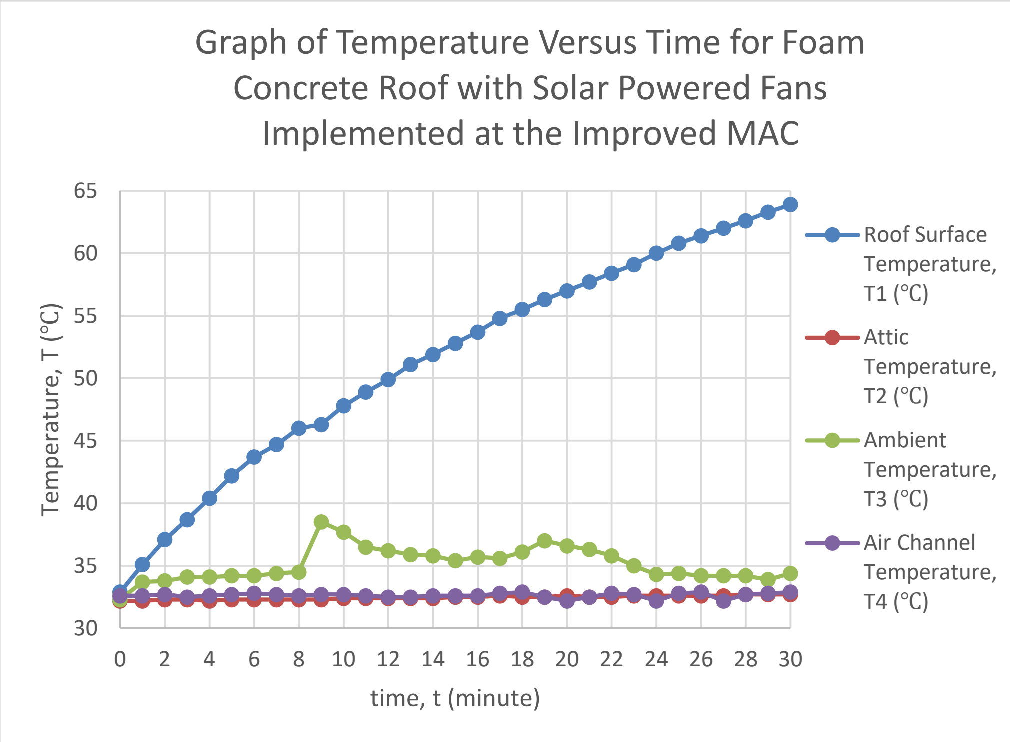


Figure 4.5: Performance of Foam Concrete Roof with Solar Powered Fans Implemented at Improved MAC.

For roof surface temperature, the maximum temperature recorded was 63.9 °C, which was 3.1 °C lower than foam concrete with MAC but without solar powered fans. The roof temperature increase rate was 1.0333 $°C/min$, which was 0.01 $°C/min$ lower than roof design without solar powered fans. For ambient temperature, the average increase rate was 0.07 $°C/min$. By implementing foam concrete roof with solar powered fans at MAC, the ambient temperature increase rate had reduced 66.67 % when compare with metal roof (0.21 $°C/min$). With the combination of lower thermal conductivity roof material, radiative heat barrier and active element fan, the ambient temperature was also benefited.

For the comparison of air channel and attic temperature, the attic temperature was in most case, lower than the air channel temperature as shown in Figure 4.5. The highest recorded attic temperature and the average attic temperature increase rate was 32.7 ℃ and 0.0167 $℃/min$, which was 0.4 ℃ and 0.0133 $℃/min$ lower than roof without solar powered fans.

At this experiment, three spotlight lamps were used instead of two spotlight lamps as in the previous experiment to supply solar power. Hence, even with one extra heat source, the low attic temperature had proved the efficiency of solar powered fans with expected air flow rate of 0.68 m/s in removing the heat at air channel inside of MAC to keep the structure cool (Yew et al., 2018).

Moreover, the attic temperature increase rate had showed a decrease of 92.29 % when compared with the normal metal roof. This amount of decrease had 15.97 % improved when solar powered fans were implemented in this MAC. Air circulation is important in keeping the attic cool with channelling out the heat (Sun et al., 2013). Solar powered fans had successfully kept the model cool and maintained at a temperature lower than the ambient by active approach with the combination of thermal break at the improved MAC.

4.6 Foam Concrete Roof with Solar Powered Fans and Rockwool Implemented at the Improved Moving Air Cavity (Design VI)

This experiment was ended with the last roof design by rockwool attached at the bottom of improved moving air cavity (MAC). Figure 4.6 shows the results obtained and presented in a graph of temperature versus time.

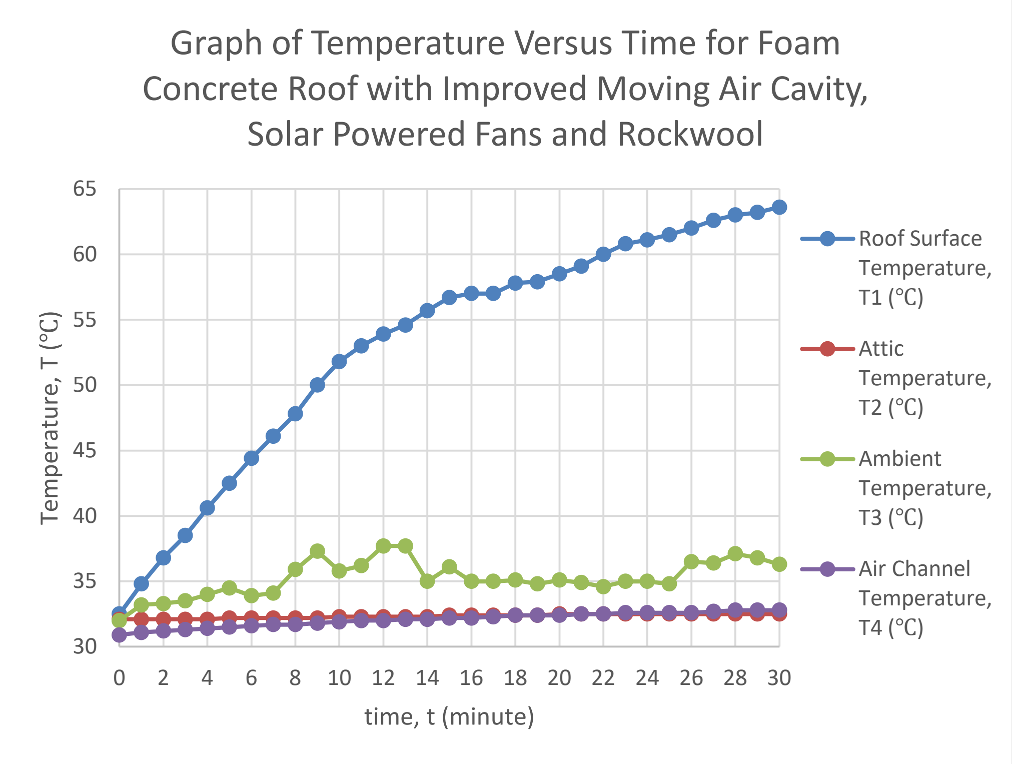


Figure 4.6: Performance of Foam Concrete Roof with Solar Powered Fans and Rockwool Implemented at Improved MAC.

For roof surface temperature, the maximum recorded temperature was 63.6 ℃ with average increase rate of 1.0367 $℃/min$. For ambient temperature, the average increase rate was 0.1433 $℃/min$. The roof surface maximum temperature had decreased 29.96 % and the average ambient temperature increase rate had reduced 31.76 % compared to normal metal roof.

The attic temperature showed a lower trend than the air channel temperature at later experiment duration as shown in Figure 4.6. For attic temperature, the maximum temperature recorded was 32.5 ℃ with average increase rate of 0.0133 $℃/min$. With one additional layer of rockwool placed underneath the MAC, the maximum attic temperature was 0.2 ℃ lower when compared to roof model without rockwool. Rockwool is the heat insulation material where the heat will be stopped from transferring into the structure through the roof. This can be seen in the trend of attic temperature where the initial attic temperature of 32.1 ℃ was maintained unchanged for 4 minutes as shown in Figure 4.6.

The average attic temperature increase rate for this added rockwool roof model was only 3.4×10^{-4} ℃$/min$ lower than roof model without rockwool, the Roof Design V. The existence of heat insulator can affect the heat convective at attic. The insulator will trapped the heat at the attic from escaping to outside where the trapped heat can increase in amount after some time (Tuck et al., 2020).

However, the attic temperature remained cool at 32.5 ℃ in the last 10 minutes. This roof design which implemented MAC, solar powered fans and rockwool had the longest duration of maintaining the initial attic temperature and reached one constant final temperature, hence for short period of heat exposure, this design will be efficient in keeping the structure cool.

4.7 Variation of Roof Surface Temperature

The roof material was varied from metal roof to foam concrete roof. Figure 4.7 shows the variation of roof surface temperature for Roof Designs I to VI throughout the experiment duration.

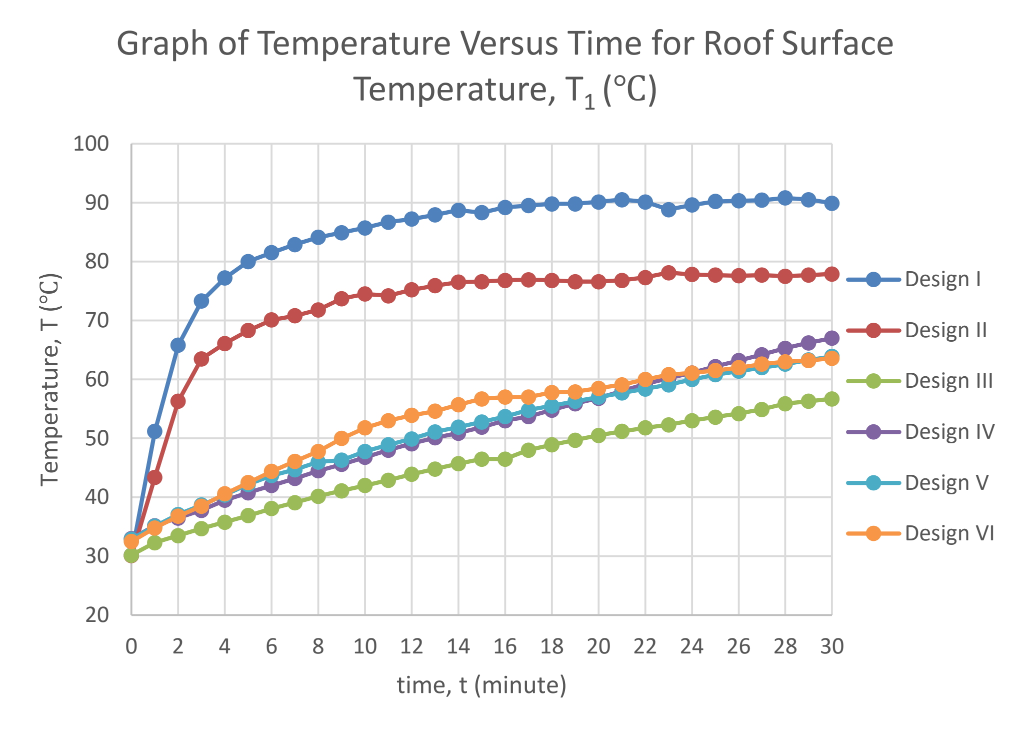


Figure 4.7: Variation of Roof Surface Temperature.

In overall, the foam concrete roof had lower roof surface temperature than metal deck roof as shown in Figure 4.7 where the use of foam concrete roof was applied in Roof Designs III to VI. The use of white reflective coating at metal roof for Design II reduced the maximum roof surface temperature at Design I from 90.8 °C to 78.1 °C, which was a decrease of 13.99 %. White reflective coating produced excellent solar reflectance of 0.8 and high thermal emittance which had proved to reduce the temperature increase at roof surface (Synnefa et al., 2007).

With the use of lightweight foam concrete roof in Roof Design III had lowered the maximum temperature at white metal roof of 78.1 °C to 56.7 °C, which showed a decrease of 27.4 %. Furthermore, if Design III was to compare with conventional metal roof in Design I, the maximum roof surface temperature had decreased 37.56 %.

The trend showed the benefit of using foam concrete roof as the roof material. The lightweight foam concrete is a good thermal insulator, thus it is a cheap and advanced roof technology, which is known as the roof insulator (Raj et al., 2020). Foam concrete roof can slow down the roof surface temperature increasing rate, where if it is applied in real construction, the roof can emit lesser heat not only to the attic, but to the surrounding as well.

4.8 Variation of Air Channel Temperature

The improved moving air cavity (MAC) was placed below the foam concrete roof and it contained seven air channels. Figure 4.8 shows the variation of air channel temperature for roof designs with MAC implemented in the Roof Designs IV, V and VI.

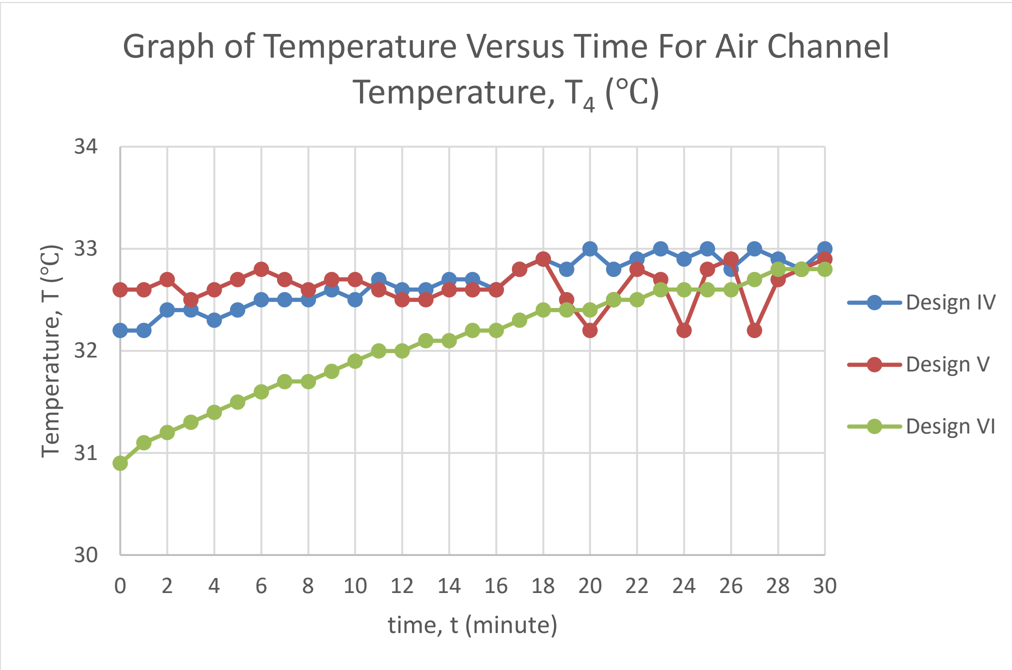


Figure 4.8: Variation of Air Channel Temperature.

For roof design without the solar powered fans, the Roof Design IV performed a steady air channel temperature variation as shown in Figure 4.8. After the solar powered fans had implemented into the MAC in the Roof Design V, had showed a more fluctuated air channel temperature variation as shown in Figure 4.8.

For MAC without solar powered fans, the air channel temperature increase rate was 0.0267 $℃/min$, thus 0.0167 $℃/min$ higher than MAC with solar powered fans, which was at 0.01 $℃/min$. The minimum temperature recorded for MAC was 32.2 ℃ even after 20 minutes of heat exposure, and it happened three times, during 20^{th}, 24^{th} and 27^{th} minute. The solar powered fans can provide expected 0.68 m/s of air flow rate (Yew et al., 2018). Hence, with the mass of air promoted by the solar powered fans into the MAC, the air channel was maintaining cool.

Solar powered fans induce the surrounding cooler air and remove the heat trapped at MAC. Since the induced air flow rate (0.68 m/s) was considered low as compared to the long channel of moving air cavity, the cool air needed time to reach the thermocouple which lead to the fluactuation of air channel temperature in Roof Design V. The happening of fluactuation also because of the heat transfer between the induced cool air and the heat transmitted from the roof. When the heat transfer happened, it increased the temperature, while when the cool air reached, it decreased back the temperature of air.

For roof design added with rockwool, the Roof Design VI, performed much a steady temperature variation than Design V although they both implemented the fans as shown in Figure 4.8. Moreover, Roof Design VI possessed the lowest average air channel temperature 32.13 ℃, compare with Roof Design IV and V of 32.69 ℃ and 32.63 ℃. The addition of rockwool underneath the MAC stabilized the air channel temperature.

By introducing the insulation layer, the thermal amplitude can be lowered and the thermal delay can be created (Almeida et al., 2019). As observed from Figure 4.8, Roof Design VI possessed a lower air channel temperature. By introducing rockwool underneath MAC, the heat is trapped and delayed at MAC and will get blown away by fans more efficiently. Since the spotlight was a uniform heating source, rockwool thus created the uniform thermal delay at MAC which lead to the uniform temperature increase as shown in Figure 4.8.

4.9 Variation of Attic Temperature

The attic temperature experienced large variation on different roof design. Roof Designs I and II were constructed with normal and white metal roof. Roof Designs III to VI were constructed with foam concrete roof with each roof design added with moving air cavity (MAC), solar powered fans and rockwool in stages. Figure 4.9 shows the variation of attic temperature for different roof designs.

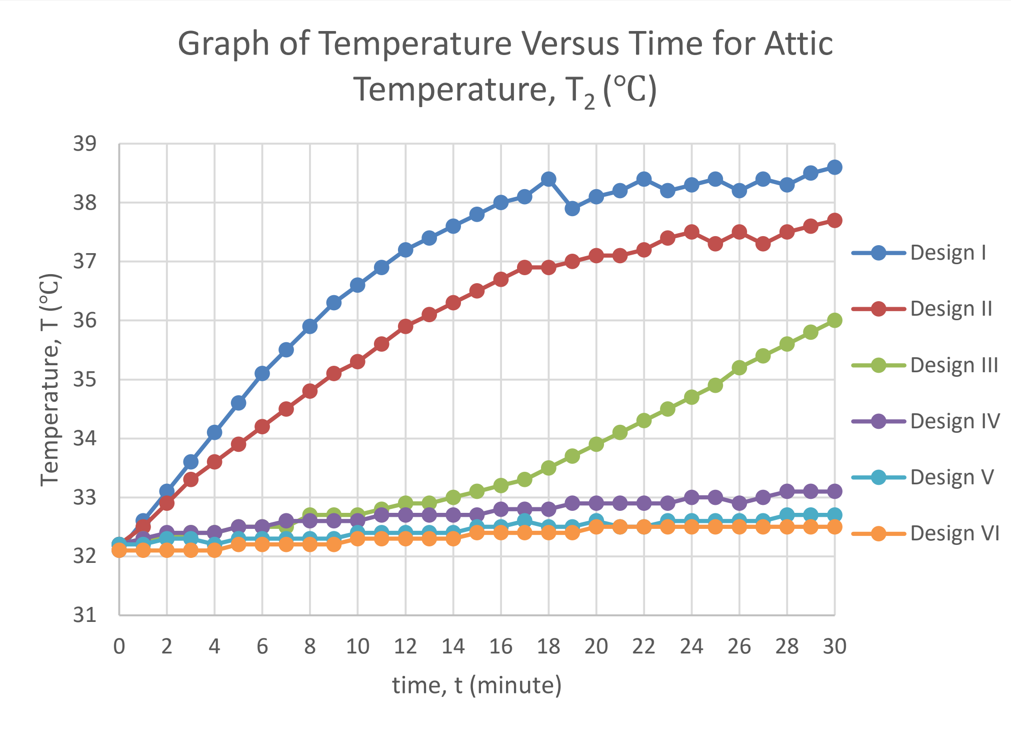


Figure 4.9: Variation of Attic Temperature.

According to Figure 4.9, the attic temperature increased rapidly when metal deck roof was applied in roof Designs I and II. Then, when foam concrete roof was applied solely in roof Design III without the MAC and solar powered fans, the attic temperature increased slower but did not set down at any temperature although the gradient is lower than metal deck roof. However, after the improved MAC was introduced at roof Designs IV to VI, the attic temperature performed a steady variation. Table 4.1 shows the average attic temperature increasing rate for each of the roof design.

Table 4.1: The Average Attic Temperature Increase Rate for Different Roof Design.

Roof Design	Roof Design Characteristics	Average Attic Temperature Increase Rate (℃/min)
I	Metal Deck Roof	0.2167
II	White Metal Deck Roof	0.1833
III	Foam Concrete Roof	0.1267
IV	Foam Concrete Roof with MAC	0.0300
V	Foam Concrete Roof with MAC and Solar Powered Fans	0.0167
VI	Foam Concrete Roof with MAC, Solar Powered Fans and Rockwool	0.0133

Without the MAC, the foam concrete roof solely had average attic temperature increase rate of 0.1267 ℃/min. After the MAC was added, it dropped to 0.03 ℃/min, which was a decrease of 76.32 %. The improved MAC promoted the passive radiative cooling. Passive radiative cooling dissipated extra heat to surrounding through the structure’s outlet without the need of power input (Liu, Zhang, et al., 2020). Material of silver coating possessed 97 % of solar reflectivity and 96 % of infrared emissivity (Gentle and Smith, 2015). In this experiment, passive radiative cooling was achieved by silver colour coating on Aluminium sheet in the improved MAC. Heat is dissipated and removed from MAC by the help of great heat emissivity characteristics of MAC.

Without the solar powered fans, the average attic temperature increase rate was 0.03 ℃/min in Roof Design IV. After the solar powered fans were added in Roof Design V, it fell to 0.0167 ℃/min. The solar powered fans work as the active cooling system to improve the moving air cavity ventilation. With the combination of passive radiative cooling and active solar powered fans, the average attic temperature increase rate achieved low attic temperature increase rate at 0.0167 ℃/min for roof Design V.

After insulation layer rockwool was implemented at roof Design VI, the average attic temperature further dropped to 0.0133 $℃/min$. Furthermore, according to Figure 4.9, the line graph of roof Design VI showed the lowest temperature trend. The combination of rockwool insulation and high reflectivity aluminium can minimize the effect of non-radiative heat exchange, the source of heat radiated into the structure (Liu, Zhou, et al., 2020). The performance for each roof designs in reducing the attic temperature was evaluated by the change of attic temperature as shown in Figure 4.10.

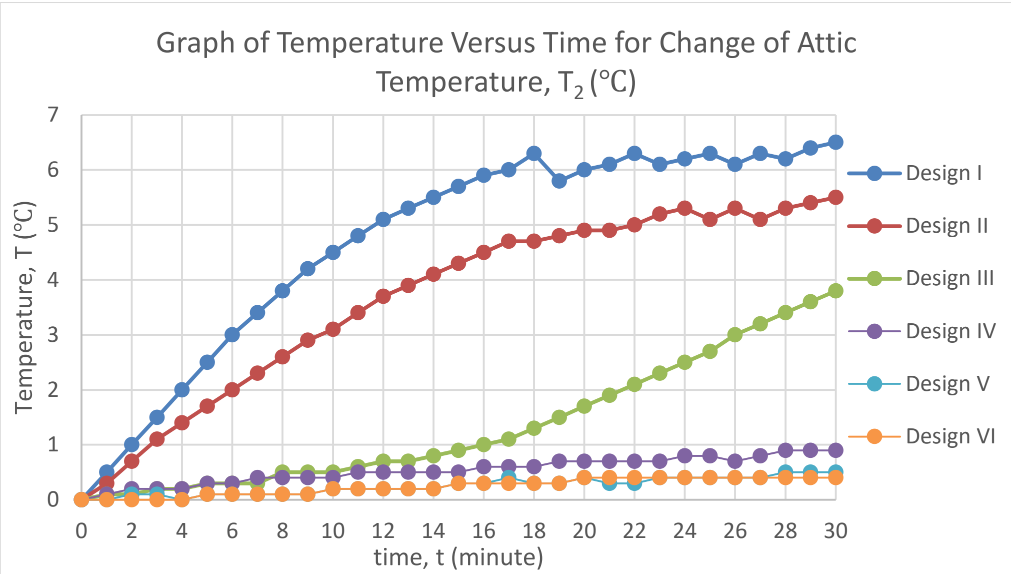


Figure 4.10: The Change of Attic Temperature.

The use of metal roof in Design I had raised the attic temperature maximumly by 6.5 ℃ as shown in Figure 4.10. The use of foam concrete roof with improved MAC implemented with solar powered fans and rockwool in Design VI had raised the attic temperature minimumly by 0.4 ℃. The roof design in Design VI was considered as the best cool roofing design in keeping the attic cool.

The cool roofing system in Roof Design VI also works the best in maintaining the initial cooler attic temperature. According to Figure 4.10, the attic temperature remained unchanged for up to 4 minutes initially and reached one unchanged final attic temperature at 32.5 ℃ after just 20 minutes of heat exposure. This is because rockwool acted as the thermal break and heat conduction barrier. By adding rockwool into MAC together with the solar powered fans, it can keep the attic cool and stabilizes the attic temperature at constant heat exposure.

4.10 Summary

The conventional metal deck roof was compared with a new cool roof system. The cool roofing system combined the integration of foam concrete roof with the implementation of solar powered fans and rockwool at the improved moving air cavity (MAC). For foam concrete roof, except being the protective roof layer, it is also a thermal insulation layer due to its lower thermal conductivity than metal roof.

The moving air cavity implemented highly reflectivity surface which promoted the radiative cooling. The solar powered fans improve the mass flow of air for better heat transfer between ambient air and heat trapped at roof structure. The rockwool underneath the moving air cavity played the role of thermal break. The performance of each roof designs is summarised in Table 4.2. Roof Design VI had the lowest increase of attic temperature and maintained the coolest attic.

Table 4.2: Summary Performance of Different Roof Design.

Roof Design	I	II	III	IV	V	VI
Type of Roof	Metal	Metal with White Surface	Foam Concrete	Foam Concrete	Foam Concrete	Foam Concrete
Utilize Moving Air Cavity	No	No	No	Yes	Yes	Yes
Utilize Solar Powered Fans	No	No	No	No	Yes	Yes
Utilize Rockwool	No	No	No	No	No	Yes
Maximum Roof Surface Temperature (°C)	90.8	78.1	56.7	67.0	63.9	63.6
Average Air Channel Temperature (°C)	-	-	-	32.69	32.63	32.13
Maximum Attic Temperature (°C)	38.7	37.7	36.0	33.1	32.7	32.5
Increase of Attic Temperature (°C)	6.5	5.5	3.8	0.9	0.5	0.4
Average Ambient Temperature (°C)	36.82	37.08	36.51	34.39	35.22	35.35

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

With the rising of Malaysia’s economic activities and population, the demand for cooling load in housing and industrial building is escalating. In order to meet the indoor comfortableness requirement yet maintaining the substantial building growth, the cool roof system becomes an important study in modern roof design. In this study, a cool roofing system was designed and its efficiency in keeping the attic region cool was compared with the conventional metal deck roof.

The metal deck roof was upgraded to lightweight foam concrete tile, while the moving air cavity, solar powered fans and rockwool were added in stages as different roof designs. Six roof prototypes were built and exposed to spotlight halogen lamp for 30 minutes. The variation of temperature at roof surface, ambient, air channel and attic were recorded by thermometer.

Firstly, after the thermal reflective coating was implemented at the metal deck roof, the maximum attic temperature reduced from 38.6 ℃ to 37.7 ℃. By introducing the highly reflective coating at metal deck, the attic showed a reduction of 0.9 ℃. Then, the metal deck roof was replaced by foam concrete roof, which then further reduced the maximum attic temperature up to 1.7 ℃ from 37.7 ℃ to 36.0 ℃. This proved the ability of foam concrete roof as the roof insulator due to its lower thermal conductivity. The heat is transferred slower in foam concrete roof, which had lesser heat conducted through the roof and enter the attic region.

Then, the moving air cavity (MAC) was installed underneath the foam concrete roof. The attic temperature then further reduced by 2.9 ℃ and reached 33.1 ℃ as compared with the foam concrete roof without the MAC. The roof design with MAC showed a decrease of 5.5 ℃ in attic region as compared to the original metal roof. MAC’s radiative silver surface of high emissivity properties increases the heat dissipation rate, thus acts as the passive radiative cooling system.

Then, solar powered fans were introduced at the inlets of MAC which further increased the attic temperature difference to 5.9 ℃ as compared to normal roof. The maximum attic temperature achieved was 32.7 ℃. Solar powered fans were the active cooling approach. They increase the air mass flow rate in air channel and by promoting the air circulation, the heat transfer between the sucked in cool ambient air and the heat conducted from roof is increased. The heat thus removed through the air channels in MAC.

Rockwool which acted as the insulation layer and thermal break was installed underneath the MAC. The attic temperature achieved 32.5 ℃, the lowest maximum attic temperature of all roof designs. This roof design with foam concrete roof integrated with MAC, solar powered fans and rockwool performed the stablest and coolest attic temperature. The attic temperature remained unchanged for the last 10 minutes and it is the only roof design with this stabilizing performance in keeping the attic cool.

In conclusion, this eco-friendly cool roofing system has the ability to reduce the attic temperature by up to 6.2 ℃ as compared to normal roof design with the passive and active cooling approaches.

5.2 Recommendations for Future Work

The duration of experiment can increase from 30 minutes to 1 hour or longer for more accurately evaluate the performance of cool roof system. The increasing of heat exposure duration can further evaluate the performance of cool roof system for its capability of removing the heat. Under longer heating duration, whether the rate of heat storage lower than the rate of heat removal is an important study. This is also another practical practice when the roof will be exposed to sunlight up to hours.

Furthermore, in order to study in depth the capability and performance of solar powered fans, researcher can add more thermocouples at the moving air cavity to measure the temperature of air at different location. In this experiment, only one thermocouple was used at the moving air cavity. Thermocouples can be placed at the inlet, middle and outlet of moving air cavity to study in depth the distribution of heat in moving air cavity and whether the current air mass flow rate is sufficient. By manipulating different air mass flow rate, the optimum air mass flow rate to eject the heat efficiency can be determined.

Lastly, in order to increase the mass flow of air in moving air cavity, the current solar powered fans can be replaced by solar powered fans with higher power. Higher power fans can induce more mass flow of air, thus increasing the heat transfer rate between the heat conducted through the roof and ambient air. The power of solar powered fans used in this project was 1.08 W. For a DC brushless small fan, the small fan model available in the market can be as high as 2.52 W. However, the price per small fan will be increase from RM 3.99 to RM 23.50 each. With higher power of fans, the heat in the moving air cavity can be removed at a higher rate.

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APPENDICES

APPENDIX A: Figures

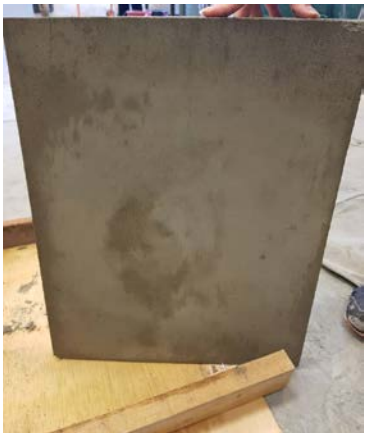


Figure A-1: Lightweight Foam Concrete Ready for Curing Process.

Figure A-2: The Structure of Moving Air Cavity.

Figure A-3: Model of the Metal Deck Roof (Roof Design I).

Figure A-4: Model of the Metal Deck Roof with Thermal Reflective Coating (Roof Design II).

Figure A-5: Model of the Foam Concrete Roof (Roof Design III).

Figure A-6: Model of the Foam Concrete Roof with Moving Air Cavity (Roof Design IV).

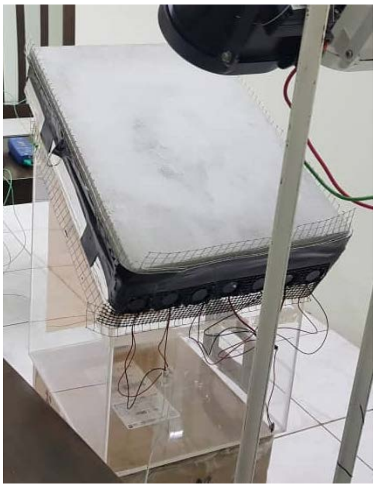
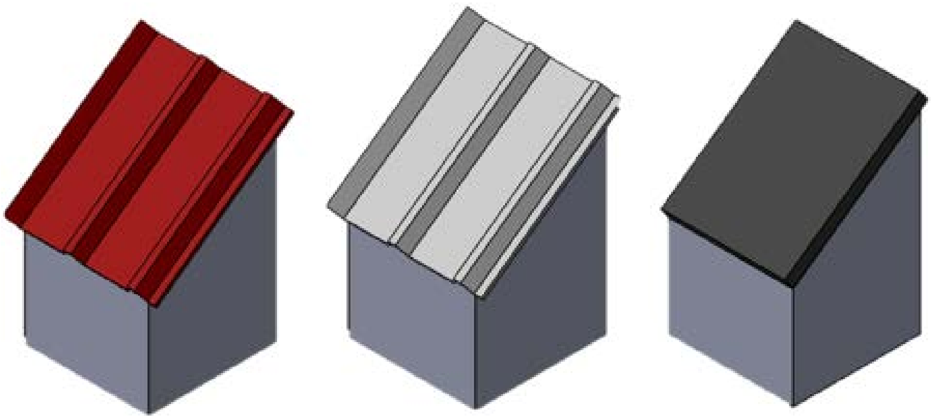


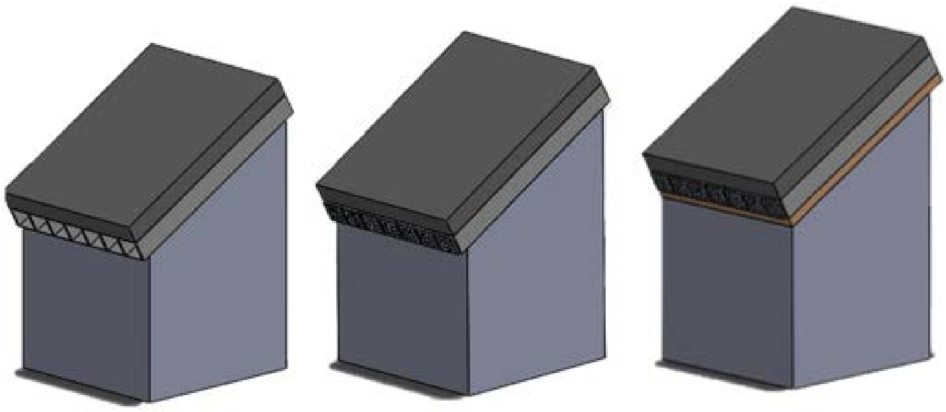
Figure A-7: Model of the Foam Concrete Roof with Moving Air Cavity and Solar Powered Fans (Roof Design V).

Figure A-8: Model of the Foam Concrete Roof with Moving Air Cavity, Solar Powered Fans and Rockwool (Roof Design VI).



(a) (b) (c)

Figure A-9: Roof Models in Solidworks (a) Roof Design I (b) Roof Design II (c) Roof Design III.



(a) (b) (c)

Figure A-10: Roof Models in Solidworks (a) Roof Design IV (b) Roof Design V (c) Roof Design VI.

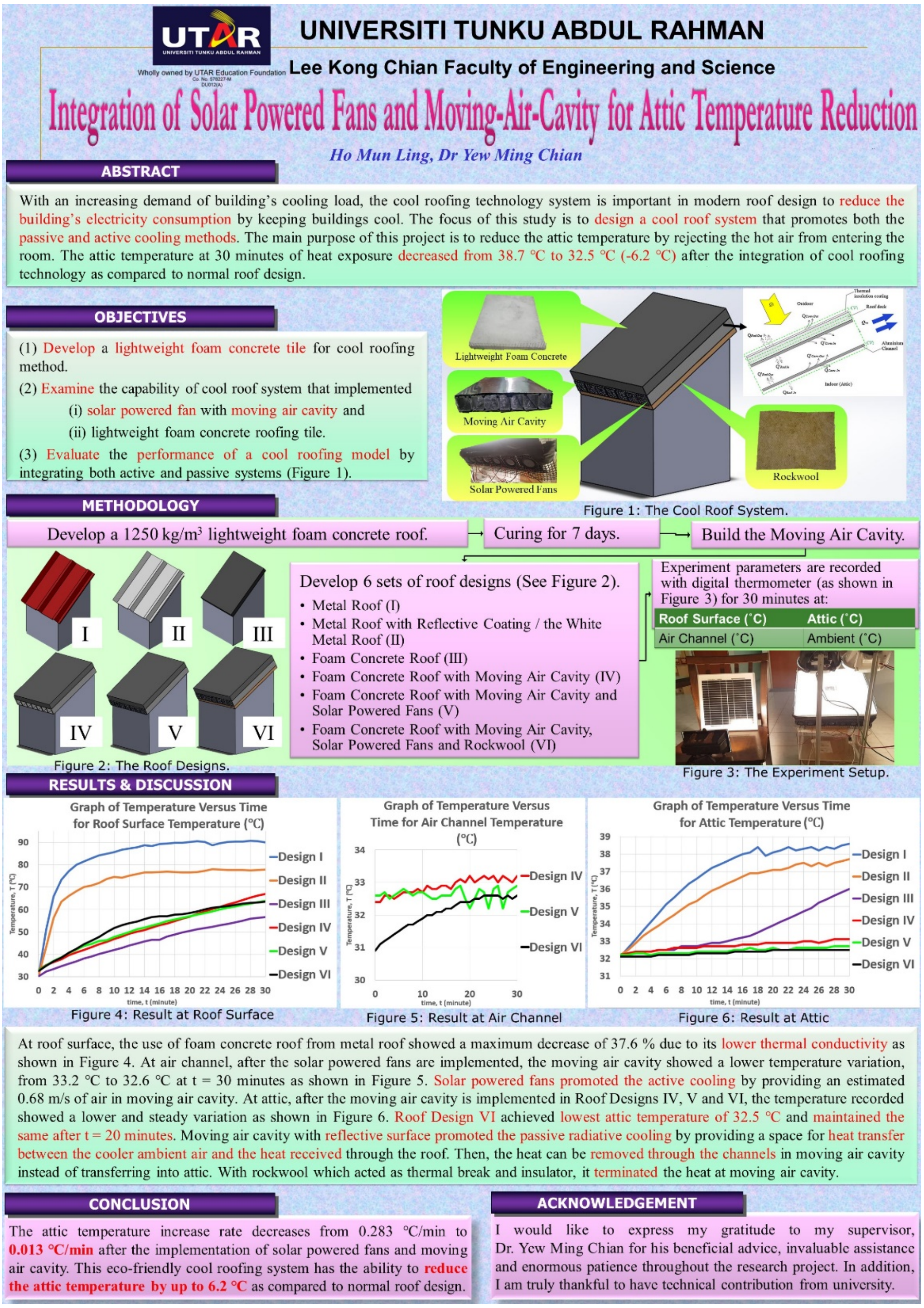


Figure A-11: The Cool Roofing System Poster.

APPENDIX B: Tables

Table B-1: Results Recorded for Metal Deck Roof (Roof Design I).

Time (minutes)	Roof surface Temperature, T_1 (℃)	Attic Temperature, T_2 (℃)	Ambient Temperature, T_3 (℃)
Initial	30.2	32.1	32.2
1	51.2	32.6	33.1
2	65.8	33.1	34.0
3	73.3	33.6	34.3
4	77.2	34.1	35.5
5	80.0	34.6	35.2
6	81.5	35.1	36.4
7	82.9	35.5	36.7
8	84.1	35.9	36.1
9	84.9	36.3	35.0
10	85.7	36.6	35.5
11	86.7	36.9	35.4
12	87.2	37.2	37.5
13	87.9	37.4	36.9
14	88.7	37.6	37.5
15	88.3	37.8	36.6
16	89.2	38.0	37.2
17	89.5	38.1	37.7
18	89.8	38.4	36.9
19	89.8	37.9	37.2
20	90.1	38.1	38.1
21	90.5	38.2	38.7
22	90.1	38.4	38.8
23	88.8	38.2	37.8
24	89.6	38.3	37.5
25	90.2	38.4	36.6

26	90.3	38.2	39.2
27	90.4	38.4	38.1
28	90.8	38.3	38.3
29	90.5	38.5	38.4
30	89.9	38.6	38.5

Table B-2: Results Recorded for Metal Deck Roof with Thermal Reflective Coating (Roof Design II).

Time (minutes)	Roof surface Temperature, T_1 (℃)	Attic Temperature, T_2 (℃)	Ambient Temperature, T_3 (℃)
Initial	30.1	32.2	32.1
1	43.4	32.5	34.3
2	56.3	32.9	35.3
3	63.5	33.3	36.2
4	66.1	33.6	35.2
5	68.3	33.9	37.0
6	70.1	34.2	35.9
7	70.8	34.5	35.7
8	71.8	34.8	38.2
9	73.7	35.1	38.9
10	74.5	35.3	38.3
11	74.2	35.6	36.6
12	75.2	35.9	38.7
13	75.9	36.1	38.1
14	76.5	36.3	37.0
15	76.6	36.5	39.0
16	76.8	36.7	37.0
17	76.9	36.9	37.9
18	76.8	36.9	37.1
19	76.6	37.0	37.1
20	76.6	37.1	35.5

21	76.8	37.1	38.9
22	77.3	37.2	37.3
23	78.1	37.4	37.1
24	77.8	37.5	37.9
25	77.7	37.3	36.9
26	77.6	37.5	36.8
27	77.7	37.3	37.1
28	77.5	37.5	37.8
29	77.7	37.6	36.7
30	77.9	37.7	36.9

Table B-3: Results Recorded for Foam Concrete Roof (Roof Design III).

Time	Roof surface Temperature, T_1 (°C)	Attic Temperature, T_2 (°C)	Ambient Temperature, T_3 (°C)
Initial	30.2	32.2	32.1
1	32.3	32.3	32.6
2	33.5	32.3	33.8
3	34.7	32.4	33.5
4	35.8	32.4	34.0
5	36.9	32.5	33.7
6	38.1	32.5	34.6
7	39.1	32.5	34.2
8	40.2	32.7	35.0
9	41.1	32.7	35.5
10	42.0	32.7	34.6
11	42.9	32.8	35.3
12	43.9	32.9	36.2
13	44.8	32.9	35.9
14	45.7	33.0	35.1
15	46.5	33.1	36.0
16	46.5	33.2	37.8

17	48.0	33.3	36.7
18	48.9	33.5	37.5
19	49.7	33.7	38.2
20	50.5	33.9	38.0
21	51.2	34.1	38.3
22	51.8	34.3	39.1
23	52.3	34.5	37.3
24	53.0	34.7	38.6
25	53.6	34.9	39.4
26	54.2	35.2	38.1
27	54.9	35.4	38.2
28	55.9	35.6	38.1
29	56.3	35.8	39.7
30	56.7	36.0	40.3

Table B-4: Results Recorded for Foam Concrete Roof with Moving Air Cavity (Roof Design IV).

Time	Roof surface Temperature, T_1 (℃)	Attic Temperature, T_2 (℃)	Ambient Temperature, T_3 (℃)	Air Channel Temperature, T_4 (℃)
Initial	33.0	32.2	32.3	32.2
1	35.2	32.3	36.3	32.2
2	36.5	32.4	37.3	32.4
3	37.8	32.4	36.6	32.4
4	39.5	32.4	36.1	32.3
5	40.8	32.5	34.0	32.4
6	42.0	32.5	34.4	32.5
7	43.2	32.6	34.1	32.5
8	44.5	32.6	34.0	32.5
9	45.6	32.6	34.0	32.6
10	46.8	32.6	34.0	32.5
11	48.0	32.7	34.2	32.7

12	49.1	32.7	34.3	32.6
13	50.1	32.7	34.0	32.6
14	50.9	32.7	34.0	32.7
15	51.9	32.7	33.9	32.7
16	53.0	32.8	34.0	32.6
17	53.7	32.8	34.0	32.8
18	54.8	32.8	33.9	32.9
19	55.9	32.9	34.0	32.8
20	56.8	32.9	33.9	33.0
21	58.0	32.9	34.0	32.8
22	59.2	32.9	34.0	32.9
23	60.2	32.9	33.9	33.0
24	61.1	33.0	34.0	32.9
25	62.2	33.0	34.2	33.0
26	63.2	32.9	34.1	32.8
27	64.2	33.0.	33.9	33.0
28	65.3	33.1	34.1	32.9
29	66.2	33.1	34.2	32.8
30	67.0	33.1	34.2	33.0

Table B-5: Results Recorded for Foam Concrete Roof with Moving Air Cavity and Solar Powered Fans (Roof Design V).

Time	Roof surface Temperature, T_1 (℃)	Attic Temperature, T_2 (℃)	Ambient Temperature, T_3 (℃)	Air Channel Temperature, T_4 (℃)
Initial	32.9	32.2	32.3	32.6
1	35.1	32.2	33.7	32.6
2	37.1	32.3	33.8	32.7
3	38.7	32.3	34.1	32.5
4	40.4	32.2	34.1	32.6
5	42.2	32.3	34.2	32.7
6	43.7	32.3	34.2	32.8

7	44.7	32.3	34.4	32.7
8	46.0	32.3	34.5	32.6
9	46.3	32.3	38.5	32.7
10	47.8	32.4	37.7	32.7
11	48.9	32.4	36.5	32.6
12	49.9	32.4	36.2	32.5
13	51.1	32.4	35.9	32.5
14	51.9	32.4	35.8	32.6
15	52.8	32.5	35.4	32.6
16	53.7	32.5	35.7	32.6
17	54.8	32.6	35.6	32.8
18	55.5	32.5	36.1	32.9
19	56.3	32.5	37.0	32.5
20	57.0	32.6	36.6	32.2
21	57.7	32.5	36.3	32.5
22	58.4	32.5	35.8	32.8
23	59.1	32.6	35.0	32.7
24	60.0	32.6	34.3	32.2
25	60.8	32.6	34.4	32.8
26	61.4	32.6	34.2	32.9
27	62.0	32.6	34.2	32.2
28	62.6	32.7	34.2	32.7
29	63.3	32.7	33.9	32.8
30	63.9	32.7	34.4	32.9

Table B-6: Results Recorded for Foam Concrete Roof with Moving Air Cavity, Solar Powered Fans and Rockwool (Roof Design VI).

Time	Roof surface Temperature, T_1 (℃)	Attic Temperature, T_2 (℃)	Ambient Temperature, T_3 (℃)	Air Channel Temperature, T_4 (℃)
Initial	32.5	32.1	32.0	30.9
1	34.8	32.1	33.2	31.1

2	36.8	32.1	33.3	31.2
3	38.5	32.1	33.5	31.3
4	40.6	32.1	34.0	31.4
5	42.5	32.2	34.5	31.5
6	44.4	32.2	33.9	31.6
7	46.1	32.2	34.1	31.7
8	47.8	32.2	35.9	31.7
9	50.0	32.2	37.3	31.8
10	51.8	32.3	35.8	31.9
11	53.0	32.3	36.2	32.0
12	53.9	32.3	37.7	32.0
13	54.6	32.3	37.7	32.1
14	55.7	32.3	35.0	32.1
15	56.7	32.4	36.1	32.2
16	57.0	32.4	35.0	32.2
17	57.0	32.4	35.0	32.3
18	57.8	32.4	35.1	32.4
19	57.9	32.4	34.8	32.4
20	58.5	32.5	35.1	32.4
21	59.1	32.5	34.9	32.5
22	60.0.	32.5	34.6	32.5
23	60.8	32.5	35.0	32.6
24	61.1	32.5	35.0	32.6
25	61.5	32.5	34.8	32.6
26	62.0	32.5	36.5	32.6
27	62.6	32.5	36.4	32.7
28	63.0	32.5	37.1	32.8
29	63.2	32.5	36.8	32.8
30	63.6	32.5	36.3	32.8