ACTIVE COOL ROOF SYSTEM FOR THE 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 **"ACTIVE COOL ROOF SYSTEM FOR THE ATTIC TEMPERATURE REDUCTION"** was prepared by **WONG SONG WEI** 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

This research project investigates the cooling effect of an active cool roof system which is designed to enhance the comfortability of building 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 insulating coating (TIC), MAC-solar powered fan, and rainwater harvesting system as a space cooling device for houses in Malaysia. Four small scale cool roof models were designed and fabricated to investigate the attic temperature cooling performance that executed by different cool roof configurations. The model simulation was carried out indoor by utilising the halogen lamp as the replacement for solar irradiation provided by the sun. The surrounding ambient temperature was controlled to be around 29.8 ℃ during the model testing. The temperature of the roof top surface, MAC aluminium tube, and the attic region was measured by K-type thermocouples in order to evaluate the cooling effect of the cool roof designs. Two active cooling methods were introduced in this research project which are the MAC-solar powered fan and rainwater harvesting system. All the solar fans were energized by the solar isolation that received by the solar panel which considered as a carbon neutrality energy. The solar powered fans were incorporated into the MAC which accelerated the airflow rate within the cavity and reject the hot air out before it transfer to the attic region. Meanwhile, the rainwater harvesting system was implemented to cool down the roof top temperature that reduce the rate of heat transfer from the roof top to the attic region. An automated actuate system (thermostat) was installed with the water pump to reduce the roof top temperature efficiently. In addition, a small scale cooling tower, solar panel, solar powered fan, and power filter were installed to enhance the cooling performance of the rainwater harvesting system. The result of this eco-friendly cool roof system (design Z) has successfully reduced the attic temperature by 4 ℃ compared to the normal TIC coated cool roof model (design W). As result, this integrated cool roof design comprises the ability to enhance the comfortability of building occupants with sustainable renewable energy.

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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

Energy is an essential quantitative property that empower everything in our daily life. As a developing country, the rate of energy consumption in Malaysia has been risen significantly due to the expansion of construction and population increase. Based on the energy consumption report, buildings are one of the major energy consumer which consumed up to 40% of the total global energy. By the year of 2030, about 50% of the global energy is expected to be consumed by building sector.

A survey conducted by National Energy Balance (NEB) shows that the building sector in Malaysia has consumed up to 48% of the generated electricity in the country (As shown in Figure 1). Residential buildings consume 24,709 Giga watts (Gwh) while the commercial building consume up to 38,645 (Gwh) (Hassan et al., 2014). The demand of electricity in Malaysia was increase about 8.9 % form 132,199 Gwh in the year 2015 to 144,024 Gwh in 2016 (Hasan, 2017).

As a tropical country, most of the places in Malaysia experiences hot and humid climate with constant mean air throughout the year. Thus, an electricity consumption of about 1,167 kWh was contributed by the air conditioners which considered as the biggest electricity consumer in Malaysia (Tetsu Kubota, Sangwoo Jeong, Doris Hooi Chyee Toe, 2010).

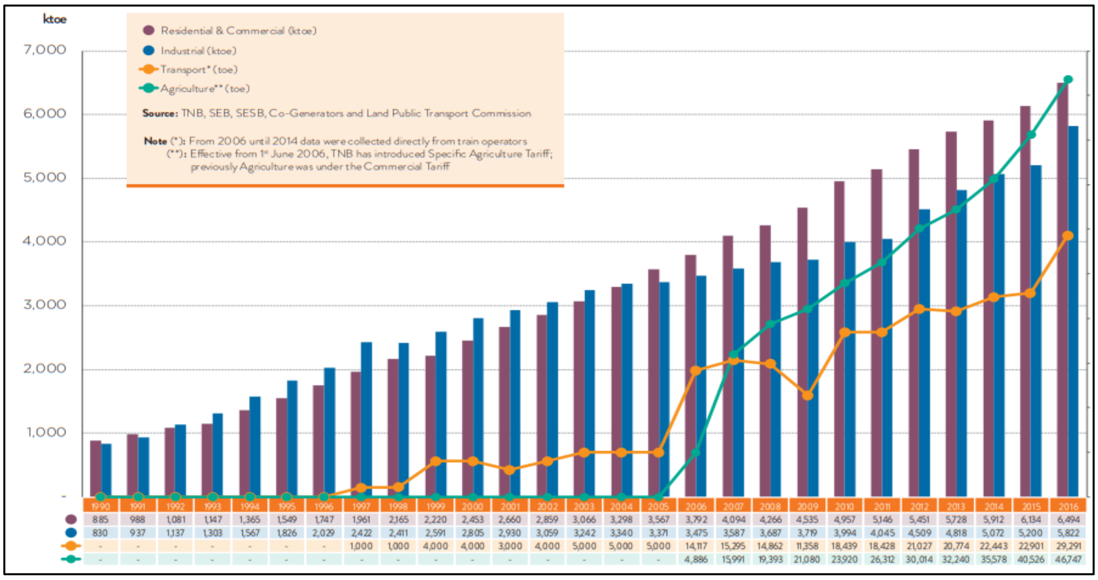

Figure 1.1:Malaysia’s Electricity Consumption from year 1990 to 2016 (Appendix C)

As compared between the roof and the vertical wall of the building, most of the heat was gained by the roof due to its exposure rate from the sun is higher during the daytime. In general, most of the roof top design in Malaysia was constructed by the uppermost roof top and a gypsum celling board below it. The roofing materials commonly used in Malaysia are the concrete roof tiles (85%) followed by clay tiles (10%) and also metal deck (5%) for the low cost houses and factories (Yew et al., 2013). By using all those materials without insulation coating, heat will easily transmitted through the roof which will generated the heat in the attic region. Furthermore, most of the buildings ventilation are poor and fairy airtight that mostly due to the lack of air circulation. As results, the heat transmitted through the roof will keep circulate in the attic region which produce heat to the ambient air of inside the building. Therefore, several effective cool roof systems had been developed.

A cool roof system is considered as a roofing system that have the capability to reflect the radiated heat from the sun and reduce the rate of heat transfer through the roof in order to reduce the heat transmitted as compare with the standard designed of roofing system (Mishra, 2016). By introduced this roofing system in the tropical country, it improves the comfort level inside the buildings which acted as a low cost method to save the energy. Besides that, the attic ventilation will be improved by the cool roof system due to the heat transference mechanism has been reduced which mean that the heat transfer through the roof to attic region was greatly reduced. Consequently, the heat gained by the ceiling of the building was tremendously decrease which also greatly reduce the need for mechanical cooling system such as air conditioner.

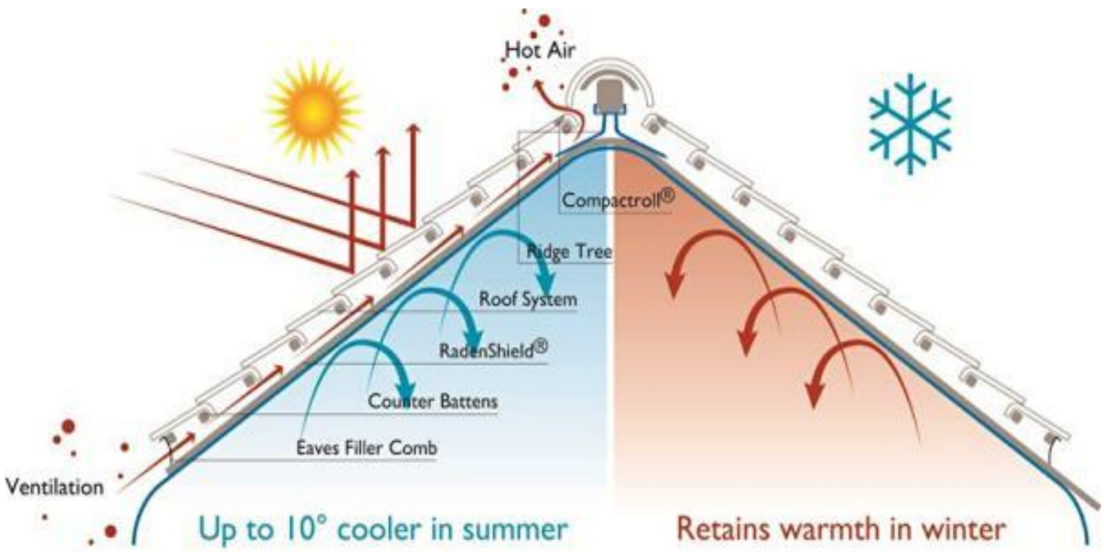

Figure 1.2: Cool roof system analysis (Mishra, 2016)

1.2 Importance of the Study

The result of this present study may have significant impact on the performance of roofing system in terms of active cool roof operation. The temperature at the attic region which located between the roof and ceiling will tremendously reduce to minimize the transference mechanism of heat through the living space. As result, the energy consumption and the emission of greenhouse gases by the building sector might be greatly reduced.

The major focus in this research project is to improve the moving air cavity of the cool roof system to avoid the radiated heat trapped in the attic region. Furthermore, an active cooling system for the roof tile will be implemented to reduce the heat that radiated from the sun to the roof tile. Energy resources can be conserved so that the impact cause by the global warming can be mitigated.

1.3 Problem Statement

Malaysia is considered as an equatorial climate country which having a hot-humid climate all the year. According to the statistics from year 1825 to 2015, the average temperature in Malaysia was around 32℃ and 23℃ respectively between March and August while there will be a slight decrease of maximum temperatures around 29℃ between November and January (Trading Economics, 2017). Figure 1.3 shows the average temperature in Malaysia between years of 1825 to 2015. As results, this type of climate leads to uncomfortable conditions which nonconductive for human comfort and productivity.

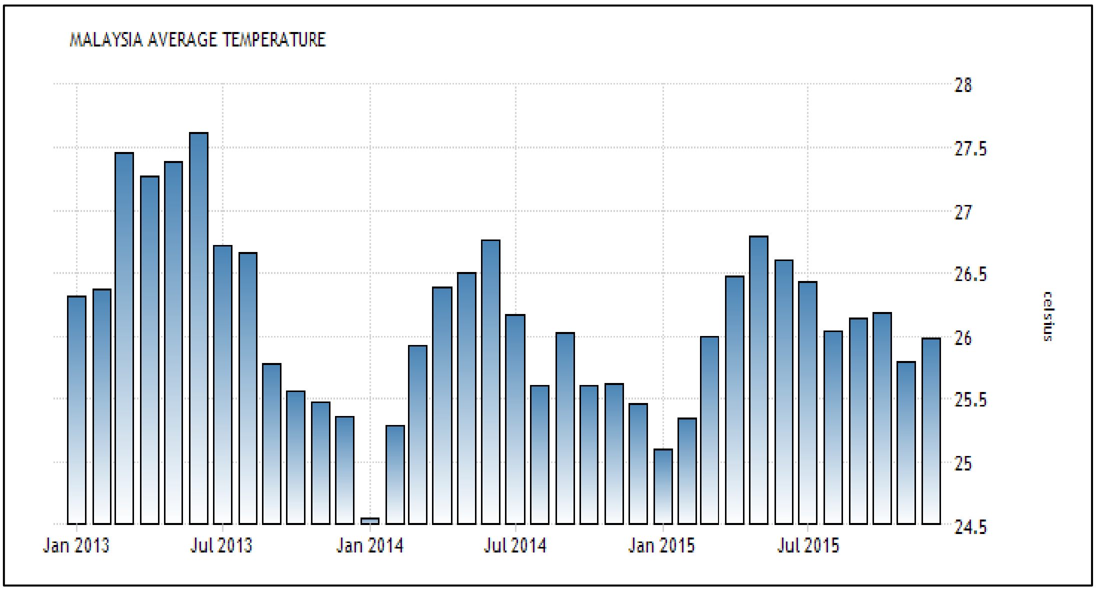

Figure 1.3: Malaysia Average Temperature (Trading Economics, 2017)

In Malaysia, the average electricity consumption are rises rapidly annually which showed a figure around 2,533 GWh per year. Based on the statistic report, the electricity consumption in year 1971 and 2008 was recorded 3,464 GWh and 94,278 GWh respectively. By year 2020, electricity consumption is expected to increase about 30% while the present value is about 124,677 GWh (Christopher Teh, 2011). The issue of high energy consumption occurred when heat form solar radiation is transmitted and absorbed by the roof surface. This heat will further transmit through the roof tile and trapped in the attic which resulting a hot ceiling.

The heat will radiate and transfer from the hot ceiling to the occupants inside the building which resulting an increase of temperature inside the indoor space. Furthermore, the level of discomfort ability will increase due to the temperature increase generally in both of the surface building and the ambient air inside the building. The demand for cooling and ventilation system will greatly increase which implied that more air conditioning system will be used resulting the increase of utility bills.

Based on technical data recorded, the typical temperatures for a house on bright day without attic ventilation (with an outdoor temperature of 32℃), the temperature at the roof top surface may reach a maximum 77℃ while the temperature at the attic floor can potentially achieved to 60℃. With this sunny condition, it further producing an uncomfortable environment in rooms which directly beneath the attic region (INC, 2013).

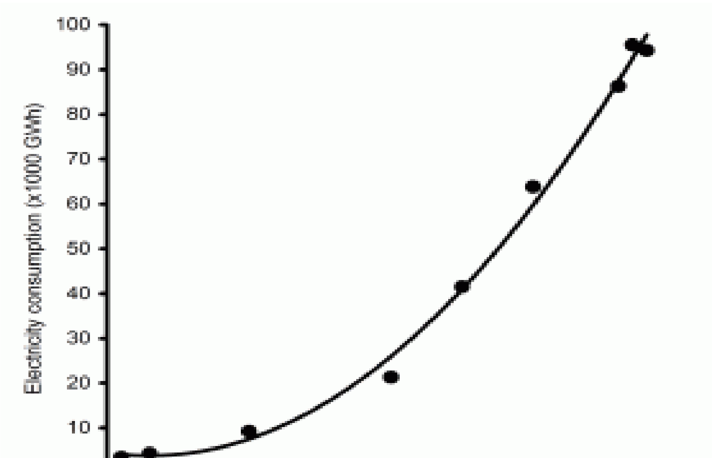

Figure 1.4: Electricity consumption rate (INC, 2013)

From all these indications that had been mentioned, an alternative design method is needed to overcome these issues and it is found that the cool roof system is an appropriate method. Insulation and reflective coating in roof design is the primary step taken in cool roof system in order to reduce the heat gain from the sun. While minimizing the heat transfer into the attic, the moving air cavity system also implemented as an active cool roof system that avoid the heat keep trapped inside the attic which cause heat transfer through the ceiling. Therefore, an active cooling system is required in roof cooling system.

1.4 Aims and Objectives

The main aim of this study is to reduce the temperature at the attic region which located between the roof and the ceiling. In order to achieve the aim, the specific objectives of this study are defined:

1. To evaluate the performance of the cool roof system that implemented by the thermal insulation coating and moving air cavity solar powered fans system
2. To evaluate evaporative roof cooling system by using water supply as the agent to reduce the temperature of the roof tile.
3. To study a cooling method in order to reduce the temperature of the recycled heated water.

1.5 Scope and Limitation of the Study

The working scope of the current study is to reduce the attic temperature by using active cool roof system with the MAC and rainwater harvesting system. This study consist some limitations:

- Weather condition in the location study (Malaysia) is differ in term of solar intensity, air humidity, and average precipitation. The statistical data will not represent the general use of the studying subject.
- The roof inclination angle varies across houses even within the same country. The modal use in the study might not be universally applicable

1.6 Contribution of the Study

The contribution of this project may help to reduce the attic temperature in the roof configuration thus enhance the comfortability of the building occupants with little of energy consumption. A renewable energy was utilized as an energy source for the active cool roof system which enrolled in the practices of sustainable development.

1.7 Outline of the Report

In this report, literature review has been discussed and commented in Chapter 2. Methodology, experimental set up, and roof configuration of different designs have been explained in Chapter 3. Furthermore, cooling effect of the cool roof system has been recorded and discussed in Chapter 4. The conclusions and recommendations have been presented in Chapter 5.

CHAPTER 2

LITERATURE REVIEW

2.1 Electricity Consumption in Malaysia

Since Malaysia independence in 1957, a tremendous economic growth has been witnessed accompanied with the growth in electricity demand especially on the industrial and manufacturing sectors. Based on the final electricity consumption report by Suruhanjaya Tenaga Energy Commission, the electricity demand by the residential sector was increased gradually each year and become one of the main electricity consumer sector in Malaysia. In year 1978, the electricity energy demand was accumulated up to 604 ktoe and by the end of year 2016 the figure was put at 12,392ktoe representing an increase of 2052 % which can be shown in Figure 2.1 (Tenaga, 2017).

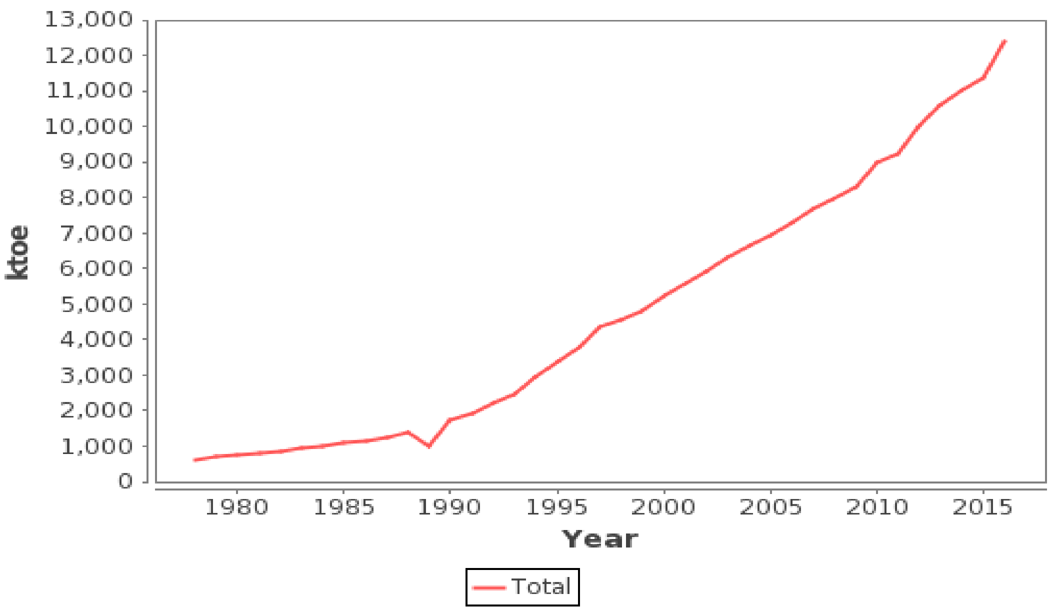

Figure 2.1: The total electricity consumption from year 1978 to 2016 (Tenaga, 2017)

The average residential electricity consumption per capita in Malaysia from year 2000 to 2015 was about 712 kilowatts per hour. In other words, the consumption of energy by the residential sector will be 59.37 kWh per month. Based on data the illustrated in Table 2.1, the electricity consumed by the household was radically increased from 484.1 kWh in year 2000 to 902.6 kWh in year 2014 (Statista, 2016).

The electricity demand by the residential sector represents an important part of total energy consumption in Malaysia.

A study of the household energy consumption was carried out in Malaysia as a reason of the consumption rate keep increasing every year. According to the study from Kubota, the air conditioning contributed about 44 % of the total electricity consumption which consider as the main electricity consumer appliances. Thus, an electricity consumption of about 1,167 kWh was contributed by the air conditioners which acted as the biggest electricity consumer (Tetsu Kubota, Sangwoo Jeong, Doris Hooi Chyee Toe, 2010). In fact, the total number of households with air-conditioning in Malaysia has dramatically increase from 229,000 to 775,000 (6.5 % to 16.2 %) in the year of 1990 and 2000 respectively which showed by the national census (Malaysia, 2000). Thus, the electricity consumption for cooling system was considered as the largest portion in the total consumption.

Table 2.1: Household electricity consumption per capita in Malaysia from 2000 to 2014 (Statista, 2016)

Year	Consumption in kilowatt hours per capita
2000	484.1
2001	525.8
2002	553.2
2003	583.8
2004	605.6
2005	628.9
2006	670.7
2007	695.1
2008	713.0
2009	753.3
2010	801.1
2011	801.8
2012	851.9
2013	892.8
2014	902.6

2.2 Literature Review

As compare between the roof and the vertical wall of the building, most of the heat was gained by the roof due to its exposure rate from the sun is higher during the daytime. The solar radiated energy which mainly come from the sun generates the heat that cause an impact to the roof surface. The heat that absorbed by the roof top surface was transferred and trapped in the attic region. As results, the heat that trapped in the attic region will further transfer and radiate to the gypsum ceiling board that cause the temperature of the ceiling board to increase. Furthermore, the level of discomfort ability will increase due to the temperature increase generally in both of the surface building and the ambient air inside the building. This results an increase of energy consumption form the necessity for mechanical cooling system such as air-conditioning in order to reduce the transmitted heat.

The heat transfer mechanism of the cool roof system give a significant impact on the studied of active attic cooling system. The heat from the halogen light bulb will transmitted through the roof surface into the attic by conduction and the heat that accumulated at the attic will further transfer into indoor or evacuated by the ventilation system that implemented at the attic region. The mechanism of the heat transfer through the cool roof system can be illustrated in Figure 2.2 (Yew et al., 2018).

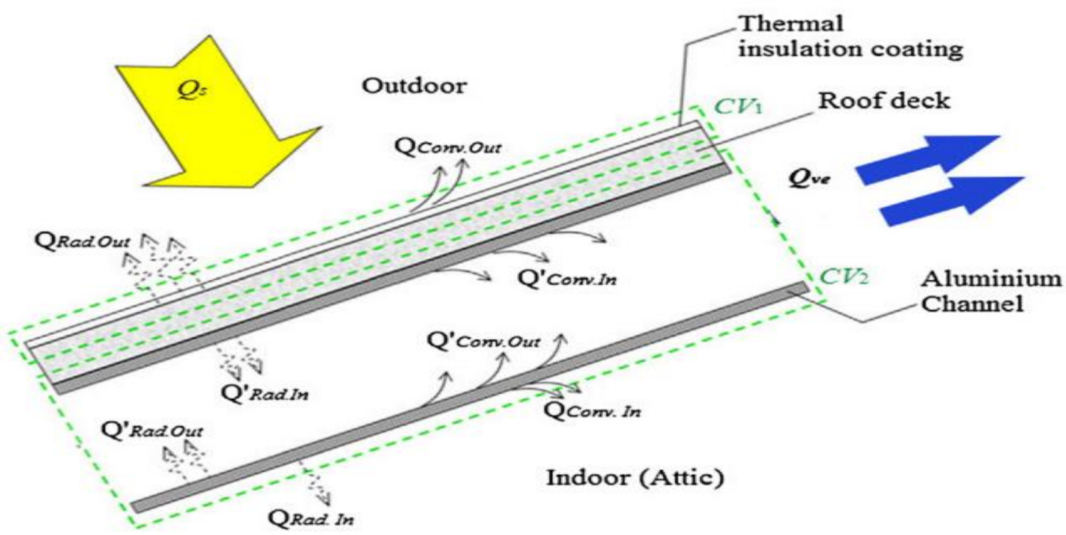

Figure 2.2: Mechanism of heat transfer in cool roof system (Yew et al., 2018)

The heat transfer mechanism of the integrated cool roof system was analyzed by implemented two control volumes CV_1 and CV_2 by the following equations (2.1) and (2.2).

$$Q_s = Q_{Rad,Out} + Q_{Conv,Out} + Q_{Cond} \tag{2.1}$$

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

Where

Q_s = Heat from light bulb above the roof (W).

$Q_{Rad,Out}$ = Radiation heat reflected from roof top (W).

$Q_{Conv,Out}$ = Convention heat transfer from the top of the roof (W).

Q_{Cond} = Conduction heat transfer from deck into the roof (W).

$Q_{Rad,In}$ = Radiation heat transfer to inside of roof (W).

$Q_{Conv,In}$ = Convention heat transfer into inside of roof (W).

Q_{ve} = Ventilation heat transfer out of the roof (W).

By considering the equations of (2.1) and (2.2), there is an interrelationship between this two control volumes. The heat transfer from CV_1 to CV_2 via the roof deck was conducted by the heat transfer conduction Q_{Cond} which act as a link to connect both of the control volumes. When the bulb above the roof surface operate, the heat energy from the light will transfer to the roof surface through convention and radiation. At the meanwhile, some of the heat was rejected out by the reflective coating and the properties of low thermal conductivity of the coating material which contributed by the $Q_{Conv,Out}$ and $Q_{Rad,Out}$ in the in CV_1 as expressed in the equation (2.1)

As mentioned above, the heat will be transferred from the CV_1 to CV_2 by the heat transfer conduction Q_{Cond} which mean that the heat transfer reduction process will also be taken in order to decrease the temperature in the attic. In the second control volume, the heat transfer was decreased by the hot air that being vented out through the moving air cavity aluminum tube. The natural ventilation at the aluminum channel act as an important role to evacuate out the hot air that heated by the heat transferred from the CV_1 due to the temperature different between the roof deck and the environment.

In the second control volume, the reduction in heat transfer is attributed to the hot air being vented out through the aluminum channel. The natural ventilation at the aluminum channel act as an important role to evacuate out the hot air that heated by the heat transferred from the CV_1 due to the temperature different between the roof deck and the environment. The performance of the heat removal rate that implemented by the moving air cavity can be obtained from the equation (2.3).

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

Where

$\dot{m}$ = Mass flow rate of the removed air (kg/s)

C_p = Specific heat at atmospheric pressure (J/kg K)

T_{in} = Indoor air temperature (K)

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

2.3 Water to Air Heat Exchanger with Evaporative Cooling System

This system is mainly implemented to improve the performance of the green roofs system thought the heat of the building will transfer out or cool down by the heat exchanger of the water tank that installed to perform the phase change and evaporative cooling (Berardi, La Roche and Almodovar, 2017). This studied was carried out by Umberto Berardi in order to discuss the improvement of the thermal comfortability inside the building which can be obtained through the conceptual heat transfer mechanism from the phase change of water to air heat exchanger with the evaporative cooling system .

2.3.1 Water to Air Heat Exchanger (WAHE)

The conceptual design of the water to air heat exchanger system was firstly introduced by Bourne and Springer, before an insulated roof tank was envisioned by LaRoche and Givoni (Almodovar and La Roche, 2019). Previous research showed that the WAHE system have the capability to cool the air inside the test cells efficiently by 10℃ while the temperature outside is above 35℃. The cooling mechanism of the WAHE obtained a high similarity as compare to the earth to air heat exchangers (EAHE) cooling system which mainly due to the heat sink effect. In addition, there are some advantages provide by the WAHE system compared to an EAHE system especially the properties of thermal conductivity. However, the thermal properties of the water such as the thermal conductivity and thermal capacity were greater than the thermal properties of the soil which improve the cooling effect performance (Rosa et al., 2018).

Some of the cities in North American have implemented the working principle of the water air heat exchanger to the deep water source cooling systems (DWSC) in the last few decade (Enware Energy, 2013). The cooling operation is mainly implemented by the heat sink which occurred in a large body of cold water. In general, the sink temperature is the main factor that affect the energy efficiency of a system which exchange heat with a heat sink. In order to simulate the results, an experimental model for the WAHE cooling system was illustrated which shown in Figure 2.3.

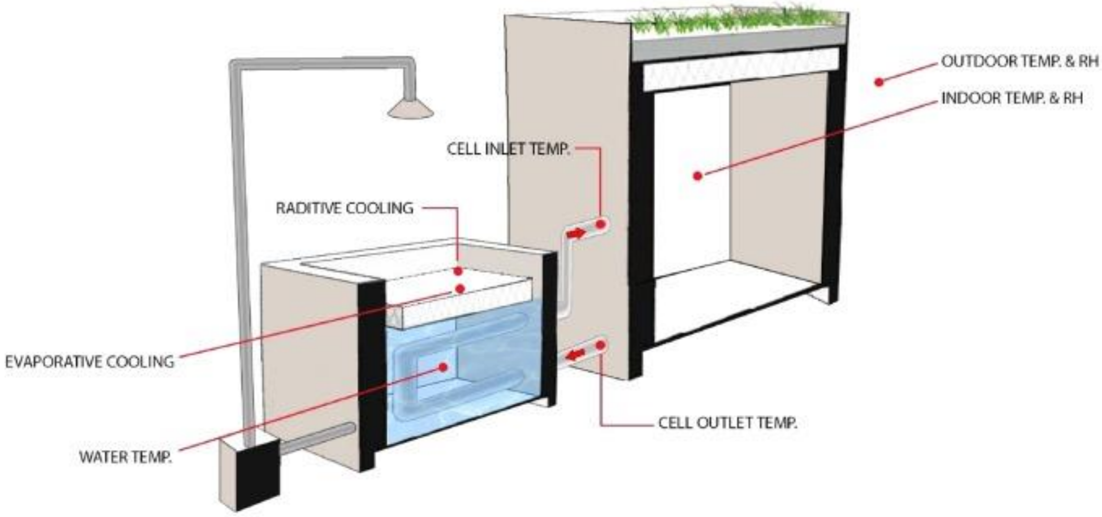

Figure 2.3: Water to Air Heat Exchanger Cooling System (UmbertoBerardi, 2017)

A WAHE was constructed by a water tank which the heat transfer mechanism take place by the heat exchanger and evaporative cooling system that cool the building indirectly that resulting in energy consumption reduction for mechanical cooling system. Besides that, a fan is implemented inside the pipe that connecting the test modal and the water tank which operate according to the cooling condition in order to improve the airflow rate of the system. Consequently, the inlet and outlet air was circulated by forced convection through the WAHE instead of free convection that impact by the buoyancy effect.

Besides that, a thermal protection drifting polystyrene was secured on the top of the water tank to avert overheating amid the day time, while a pump splashed water for the evaporative cooling was introduced above the insulation. The heat from the cell was being transferred by the WAHE inside the water tank through the surrounding pipe, the cooled water will pump back to the test cell in order to reduce the inside room temperature.

The WAHE efficiency in various air flow rates, pipe lengths, and diameters in reducing the ambient air temperature inside the test modal were studied and reported in Table 2.2. One of the parameter that strongly affect the performance of the WAHE system is the pipe diameter of the air flow channel. Based on the results that stated in the report of series 3, the increase of pipe diameter and air velocity will increase the cooled airflow that affected the cooling performance (Berardi, La Roche and Almodovar, 2017). As results, the maximum water temperature (23°C) in this series is higher than temperature recorded in series 1 and 2 due to the water absorbed and dissipated more heat from the air flowing through the WAHE. Meanwhile, the potential cooling effect of the WAHE system was obviously higher which result in about 6°C reduction of the air temperature inside the building.

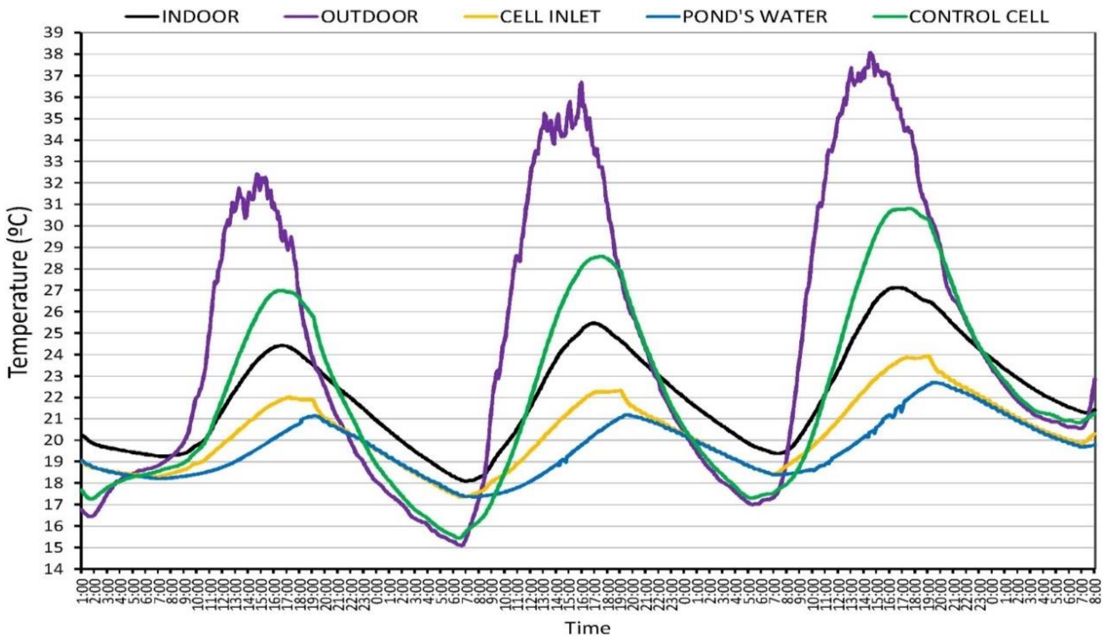

Figure 2.4: Temperature measured over three days in the series 3

Table 2.2: Main characteristics of the WAHE system in various parameter

	Series 1	Series 2	Series 3	Series 4	Series 5	Series 6	Series 7	Series 8
Connecting pipe *	¾" insulated PVC pipe	¾" insulated PVC pipe	4" insulated PVC	4" insulated PVC	4" insulated PVC	4" insulated PVC	4" insulated PVC	4" insulated PVC
Underwater pipe	¾" PVC pipe	¾" PVC pipe	4" alumi-num pipe	4" alumi-num pipe	4" alumi-num pipe	4" alumi-num pipe	4" alumi-num pipe	4" alumi-num pipe
Pipe length	3.5 m	3.5 m	3.5 m	3 m	2.5 m	2 m	1.5 m	1 m
Airflow rate	1.5 m/s	1 m/s	1.5 m/s	1.5 m/s	1.5 m/s	1.5 m/s	1.5 m/s	1.5 m/s
Fan operation	from 7 am to 7 pm	from 7 am to 7 pm	all the time	all the time	all the time	all the time	all the time	all the time
Spray operation	from 7 pm to 7 am	from 7 pm to 7 am	from 7 pm to 7 am	from 7 pm to 7 am	from 7 pm to 7 am	from 7 pm to 7 am	from 7 pm to 7 am	from 7 pm to 7 am
TDR **	0.213	0.160	0.595	0.572	0.571	0.535	0.511	0.471

The cooling performance of the test cell was indicated by the Temperature Different Ratio (TDR) in this studied which mean that the higher the temperature between the ambient temperature and the interior temperature of cell, better performance generated. As results, a maximum temperature different of 10°C between the ambient and indoor temperature was recorded. In other words, the maximum indoor temperature will below 26°C whereas the ambient temperature was about 36°C. A significant cooling effect was performed by this system as shown in Figure 2.4.

2.3.2 Evaporative Cooling for Water Tank

The evaporative cooling system was introduced to improve the cooling performance of the WAHE system by released the heat that had been absorbed from building through the water tank. An indirect evaporative cooling was implemented by this system due to the cooling process was not directly applied to the ambient air inside the building.

The evaporative cooling system was implemented for the purpose to cool the water that absorbs the heat from the building. An indirectly cooling process was operated by this system as it do not have the direct interchange of heat through the temperature of the building. During night time, the heat that absorbed by the water was being released through the evaporative cooling due to the temperature different between the ambient and warmed water inside the water tank (Berardi, La Roche and Almodovar, 2017). The heat transfer mechanism for the cooling process in this system can be categorized into two stages. Firstly, the hot air of the building will pass through the heat exchanger that the heat was cooled by the water tank with the cool water inside the tank. Secondly, the water inside the water tank was being cooled by the evaporative cooling system by utilized the spray above the insulation board. Therefore, the cooled water inside the water tank was acted as an intermediate sink while the ambient air outside the building was considered as a final sink.

Based on the previous research, the thickness of the thermal insulated board on the water tank was designed to be in 3 cm (Tavana et al., 1980). In addition, the white color paint was specially designed as a solar radiation reflector which reduce the heat transfer from the sun to the water tank. For the evaporative cooling system, the spray was suggested to place 0.5 m above the center of the water tank as the height was known as the minimum suggested height to this system (Roche, Almodovar and Yeom, 2016).

The performance of the cooling effect through the evaporative cooling system was evaluated by the sensors which placed on the floating insulation board during the night time while the spray above the water tank operated. Two sensor will be utilized in this system to evaluate the cooling effect as mention above. The first sensor will be placed at the center of the insulation board in order to measure the temperature of the water that directly sprinkler from the spray. Furthermore, the second sensor was utilized to evaluate the temperature of the water after it passed through the insulation board in order to study the evaporative cooling effect. As results, the water temperature in the tank was successfully reduced by the evaporative cooling effect which cooled the building indirectly as shown in Figure 2.5.

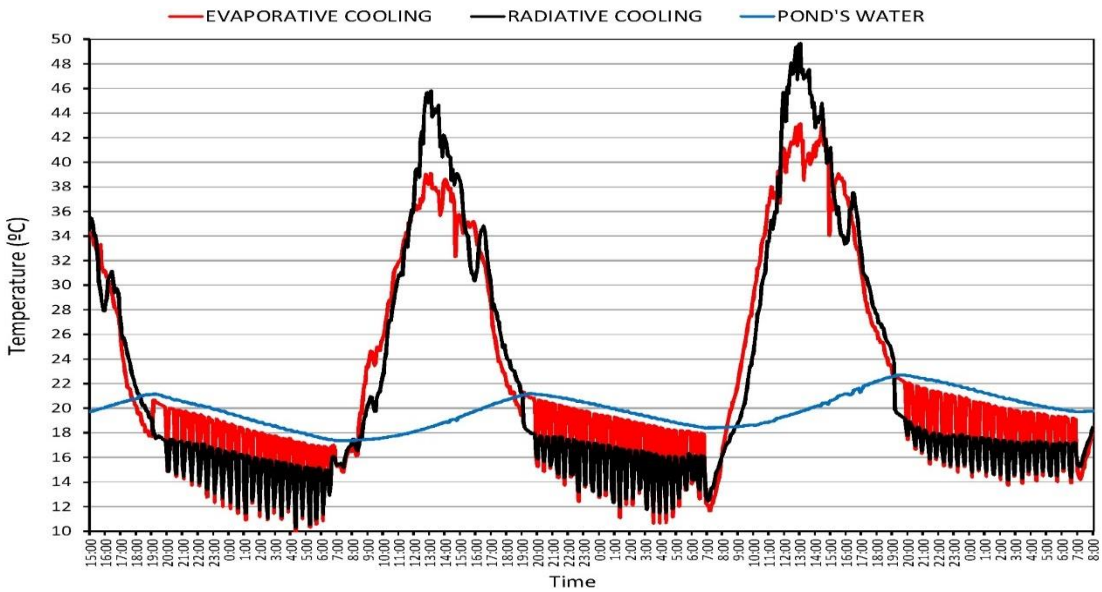

Figure 2.5: Temperature measured on the floating insulating panel over three days in the series 3

2.4 Post-rainfall Evaporation from Porous Roof Tile on Building Cooling

Rainfall occurs frequently in tropical country such as Malaysia has greatly impact the thermal performance of the buildings due to the evaporative cooling effect that generated by the rainwater. The energy performance of the buildings which affected by the effect of evaporative rainfall was investigated by Rao in Singapore (Aurelio Diaz and Osmond, 2017). An experiment was carried out in order to simulate the rainfall over the buildings as a plastered brick wall was being spayed through the water during the hot sunny day. As results, the energy consumption of the test room was reduced up to 25% by the effect of evaporation cooling. Besides that, the performance of evaporative cooling wall on the energy saving by the porous tile in the Chinese city of Guangzhou was studied by Zhang et al. Based on the research done by Zhang about 35.29% to 68.27% of the air conditioning energy consumption has been reduced by the rainfall simulated room as compared between the two room with the same construction orientation and dimension (Zhang et al., 2018).

2.4.1 Water Storage Medium

A porous tile that located at the exterior surface of building was treated as a medium for water storage. The dimension of the tile was designed to be 10 mm height, 50 mm width, and 240 mm long which generate up to 11.80% of the mass saturated water content. In this research, the solar and thermal absorptance of the porous tiles were investigated by a spectrophotometer for different water contents. Based on the result which shown in the Figure 2.6, the solar absorptance will increases as the water content increases. As results, a linear relationship has been formed as the solar absorptance is directly proportional to the mass water content which can be expressed by equation 2.3. This result is due to the relative refractive index of the water content is lower than the roof rile which implied that more incident photons from the heat sources will be absorbed and radiated through the medium.

$$\alpha_s = 0.667\, w_c + 74.182 \qquad (2.3)$$

$$w_c = \frac{m_{wet} - m_{dry}}{m_{dry}} \qquad (2.4)$$

The term mass water content (w_c) is characterized as the proportion of the mass of water in the medium to mass of dry medium as expressed in equation 2.4. Impact on the solar absorptance by the mass water content is greater than the thermal absorptance which can be observed form Figure 2.7. The dry specimen consist of 0.83 thermal absorption while for the wet specimen the thermal absorptance oscillates between 0.88 and 0.94 which taking 0.89 as the average value.

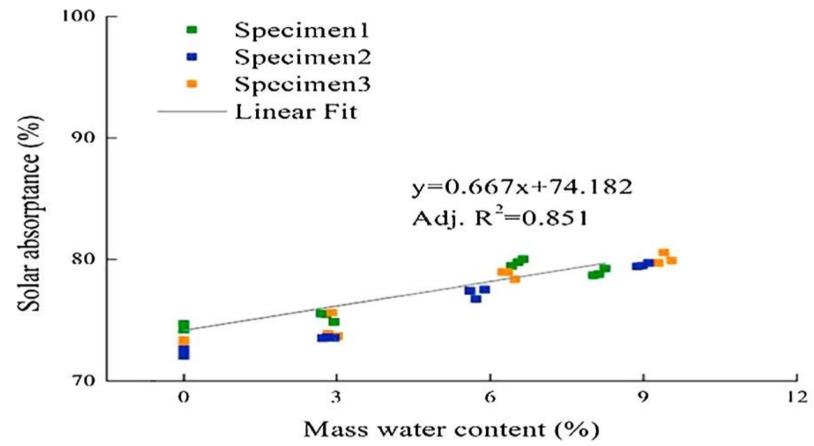

Figure 2.6: Solar absorptance vs water content

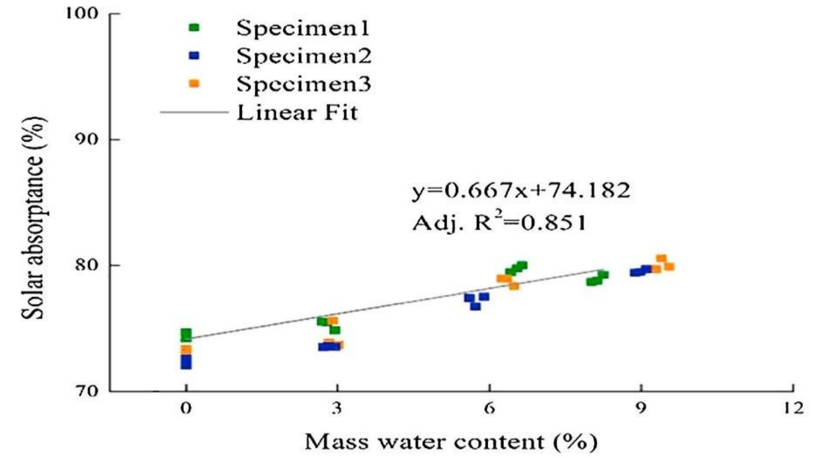

Figure 2.7: Thermal absorptance vs water content

2.4.2 Cooling Load Saving Potential

Cooling loads of the room was significantly decreased by the water evaporation from the porous tiles evaporation roof due to the heat transfer between the internal surface of the roof and the room space was decreased (Zhang et al., 2018). Based on the simulated results obtained by Qinglin Meng with duration of seven-day in summer, it shows that the cooling load accumulated from the room with evaporation cool roof system was 151.5 kWh which is 15.3 % lower than the room with the non-evaporation cool roof system.

The maximum cooling load was reduced which can be observed in Figure 2.8. Based on the results, it can be concluded that the maximum value of the cooling load reduction will obtained after four to five hours after the peak occurrence of evaporation rate. Two peak value of the cooling load reduction have been observed which one occurred five hours later than the maximum evaporation rate of 0.56 kg/m^2

while the other occurred four hours later than the maximum evaporation rate of $0.63\ kg/m^2$.

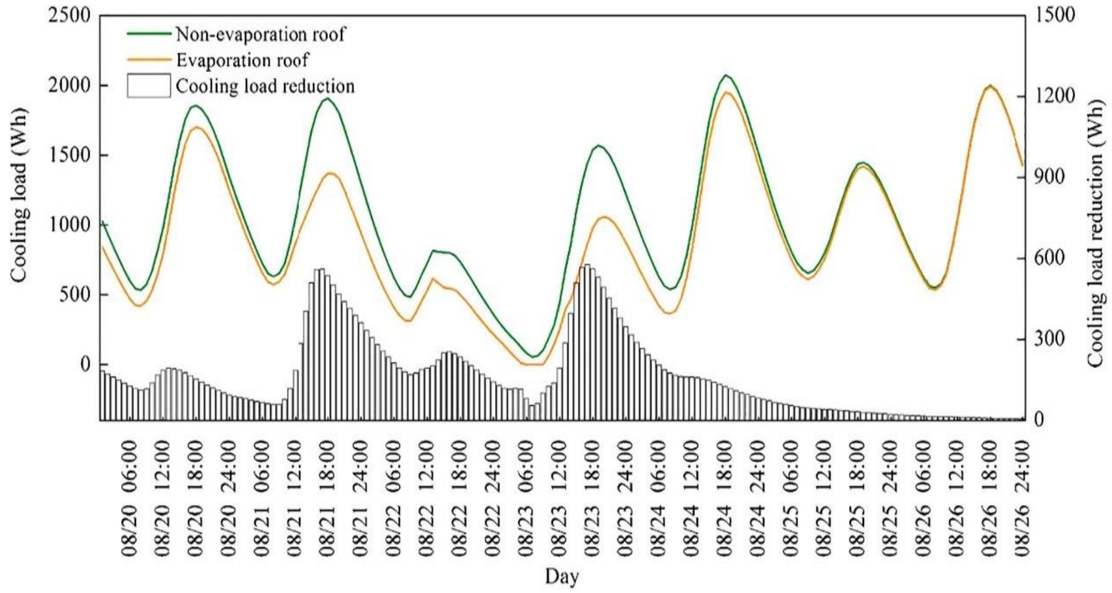

Figure 2.8: Temporal variation of cooling loads of non-evaporation and evaporation roofs.

CHAPTER 3

METHODOLOGY AND WORK PLAN

3.1 Introduction

An active cool roof system model simulation was built to investigate the effect of attic cooling by the reduction of heat transfer through the roof tile. Two active cooling methods were introduced in this research study, which are moving air cavity (MAC) solar powered fan and rainwater harvesting system. The solar powered fan is incorporated into the moving air cavity which accelerated the airflow rate within the cavity and reject the hot air out before it transfer to the attic region. Meanwhile, the rainwater harvesting system was implemented to the model by using the harvested water through collecting devices as a medium to cool down the roof temperature which considered as evaporative cooling mechanism. The water pump that activated the rain harvesting system was triggered by thermostat based on the pre-set temperature.

3.2 Experimental Design

Attic region is the major skeleton for the model in this cool roof model. A Perspex with a thickness of 5mm is used to fabricate the attic region of the model. The dimension of the attic region is 340mm long x 360mm wide x 490mm height with an inclination of 30° from the horizontal line as shown in Figure 3.1.

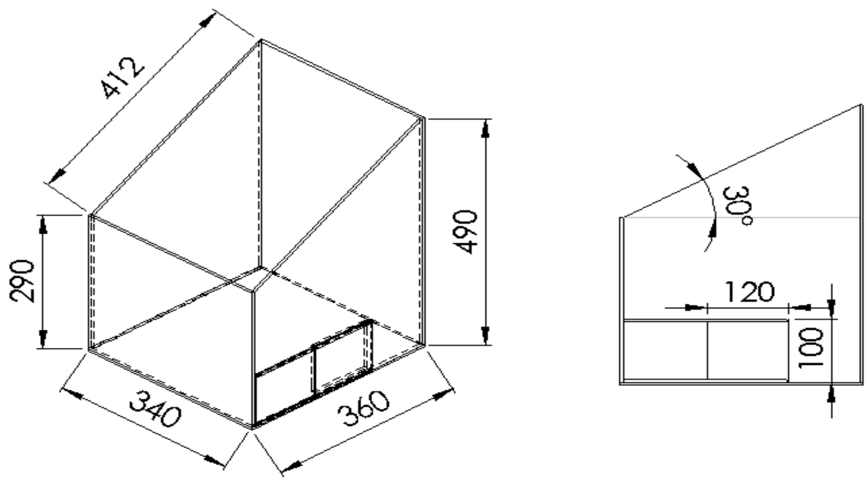

Figure 3.1: Dimensions of Small Scale Attic Region Model

An attic inlet with a dimension of 120mm long x 100mm width was opened at the side of model and it can be covered by a sliding door which specially designed to close the attic inlet. The purpose of this design was used to cool down the heated attic region and provides ease of thermal couple installation inside the attic region.

3.2.1 Moving Air Cavity (MAC) Solar Powered Fan

MAC solar powered fan was implemented to enhance the cooling behaviour of the cool roof system by eliminate the heat that transmitted through the roof tile.

3.2.1.1 Moving Air Cavity (MAC)

The moving air cavity channel was construed by aluminium foil and steel rod as shown in Figure 3.2. Aluminium was used as the material for this design due to its high thermal transitivity characteristic. The inlet dimension of the MAC channel is designed to be smaller than the outlet dimension. In other words, a cubical cone shape was form by gradually increased the size of the cavity form the inlet dimension to the outlet dimension.

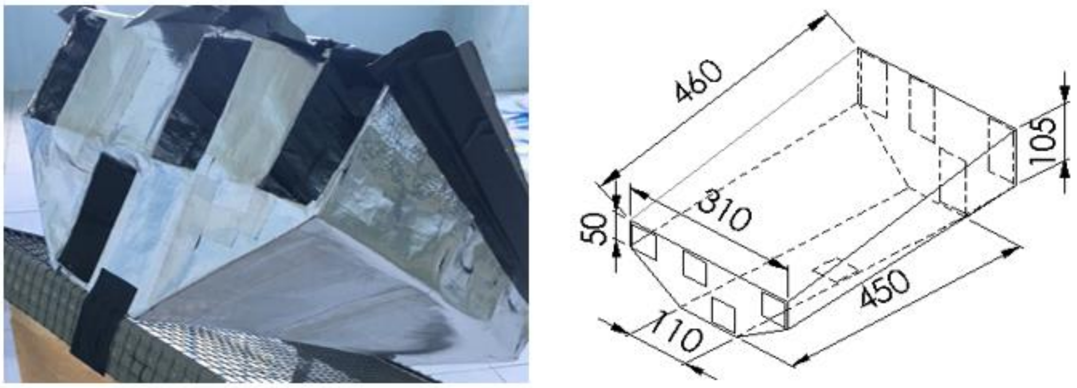

Figure 3.2: Moving Air Cavity with Dimensions

Furthermore, the bottom area of the cavity also deigned to be smaller than the area of the top cavity which with the dimension of 450 mm (length) x 110 mm (width) and 460 mm (length) x 310 mm (width) respectively (refer Figure 3.2). The structure of the MAC was designed based on the buoyancy effect which enhance the removal rate of the hot air through the cavity outlet. The density of the hot air is lower than the cool air and it tends to flow upward according to the buoyancy effect. This design decreased the number of solar powered fan installed by providing a smooth path which directs the hot air to the high removal rate channel that directly interact with the solar powered fan.

3.2.1.2 Solar Powered Fan

A forced convection was implemented with the solar powered fan in order to increase the airflow rate inside the cavity that remove the hot air before it transfer to the attic region. Solar energy was utilized to power the fans based on the solar irradiance received by the solar panel. During daytime, solar powered fan were automatically energized by the solar panel to improve the cooling efficiency of the moving air cavity. Conversely, the fans were be switch of during the night time since the solar irradiation is insufficient to power the fans. As result, the solar panel was considered as a sensor which switch on or off the fans automatically according to the irradiation received.

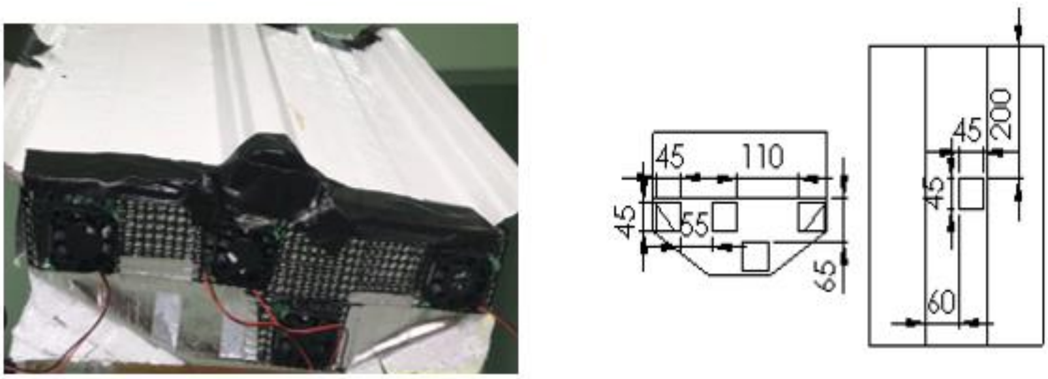

Figure 3.3: Solar powered fan installed location

The solar panel used in this project provides maximum power of 10.08 W ($I_{mp} = 0.56A, V_{mp} = 18v$) at the standard test condition ($irradiation = 1000W/m^2$, solar cell temperature =25°C, air mass = 1.5). Five solar powered fans with a dimension of 5cm x5cm were installed in this model to investigate the cooling efficiency of the MAC. The fans were installed according to the position which can be illustrated in Figure 3.3. Four solar powered fan were installed at the inlet cavity to increase the airflow rate inside the cavity. Meanwhile, one of the fan was installed at the bottom cavity to drag the hot air that trapped in the attic region to the MAC which increase the cooling effect of the system.

3.2.2 Rainwater Harvesting System

Rainwater Harvesting system is mainly implemented to cool down the roof top temperature that reduce the rate of heat transfer from the roof top to the attic region. As the name of the system, rainwater was utilized as a cooling agent that directly absorbs the heat form the roof top. This system applied the sustainable environment concept by using renewable source as the main cooling agent that perform the cooling without environmental damaging effect. The rainwater harvesting system usually comprises there major components which are the catchment area, conveyance system, and the water storage system.

The rainwater harvesting system incorporated in this model was controlled and triggered by the thermostat which applied the cooling effect at the specific temperature. In this model, the area of the roof tile was considered as the catchment area for the harvesting system. Water flowed from the roof tile will collected at the gutter which made by a half-cut cylindrical pipe. The conveyance devices such as gutter, funnel, cylindrical plastic container, and the L-shape fixed support are set up to convey the water form rooftop to the cooling tower. After the water flowed through a small scale self-fabricated cooling tower, it will enter to the plastic container that used to store the collected water which shown in Figure 3.4.

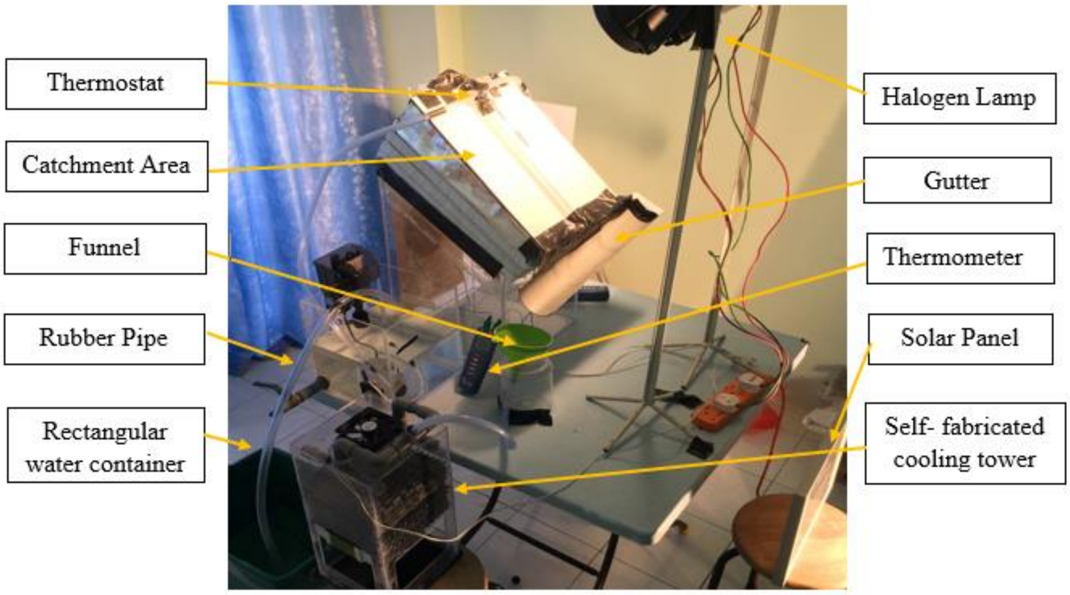

Figure 3.4: Experimental Setup for Rainwater Harvesting System

The cooling system of this rainwater harvesting system was investigated in order to reduce the temperature of the attic region. The water collected in the storage tank was used as the cooling agent to cool down the temperature of the roof top which indirectly reduce the attic temperature. When the roof top temperature reached 40°C, water pump will be triggered by the thermostat which pumped the cool water to the roof top through the rubber pipe in order to cool down roof top temperature. The heated water was collected by the gutter and flow to the cooling tower in order to release the heat absorbed during the flow path at the roof top. As result, the water was cooled and stored in the water tank which considered as a complete flow cycle in this cool roof system. The cooling flow cycle can be illustrated by the schematic drawing shown in Figure 3.5.

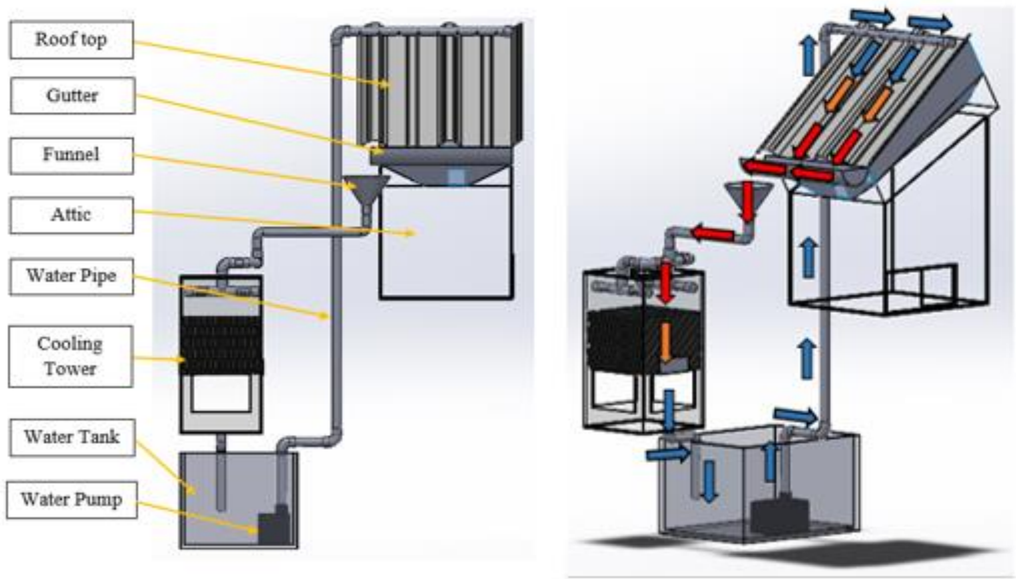

Figure 3.5: Cooling Flow Cycle of Rainwater Harvesting System

3.2.2.1 Water Pump Integrated with Thermostat

A submersible water pump was used as an actuator that transfer the cool water from the water storage tank to roof top. The maximum pressure head of this pump is 1.3 meter which energized by an AC current as shown in Figure 3.6. As mentioned, the water pump will be triggered by the thermostat when the desired temperature achieved in the setting of temperature sensor. The variation of the temperature sensing for this thermostat is around $\pm$ 5°C which means the pump will be triggered between 35°C to 45°C as the pre-setting temperature is 40°C.

This water pump was specially designed and modified with the thermostat that performed an automation control which mentioned above. Thermostat was used as a regulator that triggered the water pump based on temperature value pre-set in the data. It has one connected temperature sensor and four connectors which are labelled as "1","2", "C", and "E" (earth). The live wires of the water pump and power filter were connected to the connector "C" which indicated as the output of the thermostat. Meanwhile, the neutral wires of the three pin plug (power source) was connected with the water pump and power filter. The connector "E" which indicated as the earth of the circuit was connected to the earth wire from the power source as illustrated in Figure 3.7. In addition, the live wire form the three pin plug was connected to the connector "2" that complete the circuit design for this thermal sensing triggered pump.

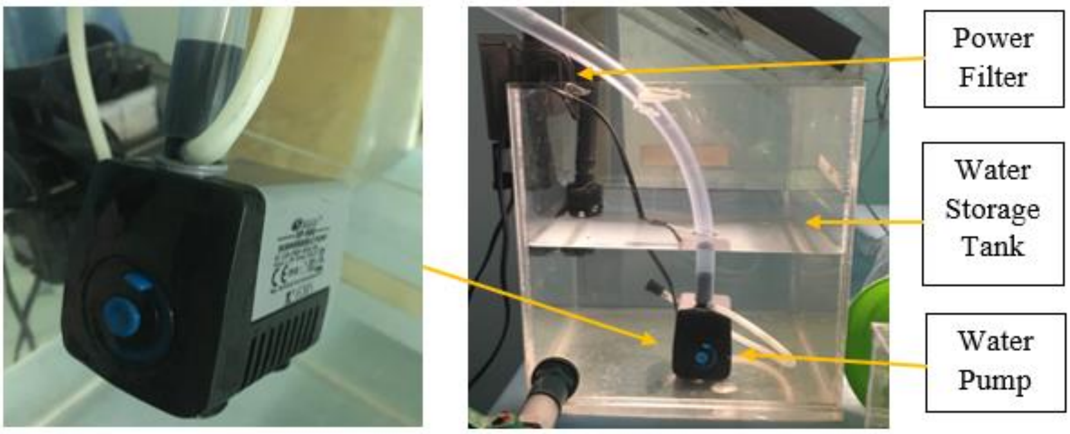

Figure 3.6: Water Pump

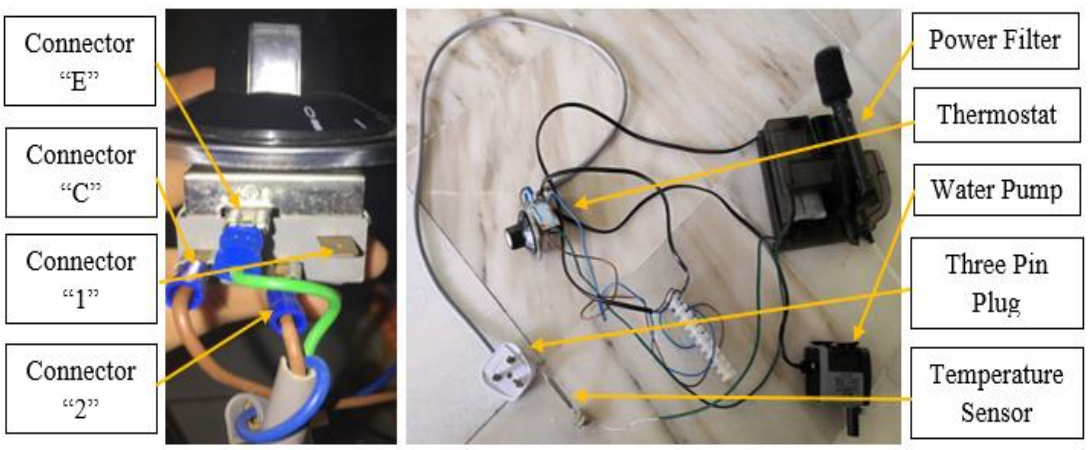

Figure 3.7: Circuit Connection of Thermal Sensing Triggered Pump

3.2.2.2 Cooling Tower

The cooling tower was designed to reduce the temperature of the heated water which flowed from the roof top. The heat of the roof top was absorbed by the cool water and release at the cooling tower to ensure the water temperature in the storage tank are feasible for cooling system. The design concept is based on the commercial cooling tower which installed in current industrial.

The cooling tower in this model was construed by the acyclic with dimensions of 210 mm (length) x 210 mm (width) x 410 mm (height). The heated water will flowed through a bunch of cooling fill from the top of cooling tower to the bottom pipe connection. The main objective of this cooling fill is to increase the total contact area of the heated water that enhance the effect of convection. A honey comb shape was designed as the cooling fill that further increase the contact area. Each fill was cut and arranged in stepped structure which direct the flow of the heated water as shown in Figure 3.8.

Furthermore, a solar powered fan was installed at the top of cooling tower in order to induce the bulk movement of the air inside the tower. In this case, ambient cool air will entered the cooling tower through the inlet window opened at the side panel. The inlet window was cut by the laser cutter with dimension of 100 mm (length) x 150 mm (wide). The heated air will exit the cooling tower through the suction of the solar powered fan. Heat transfer was perform during the cooling fill that successfully release the heat energy form the water. In addition, a halogen lamp was used to provide irradiation to the solar panel that energized the solar fan. The materials required for cooling tower fabrication was listed in Table 3.1.

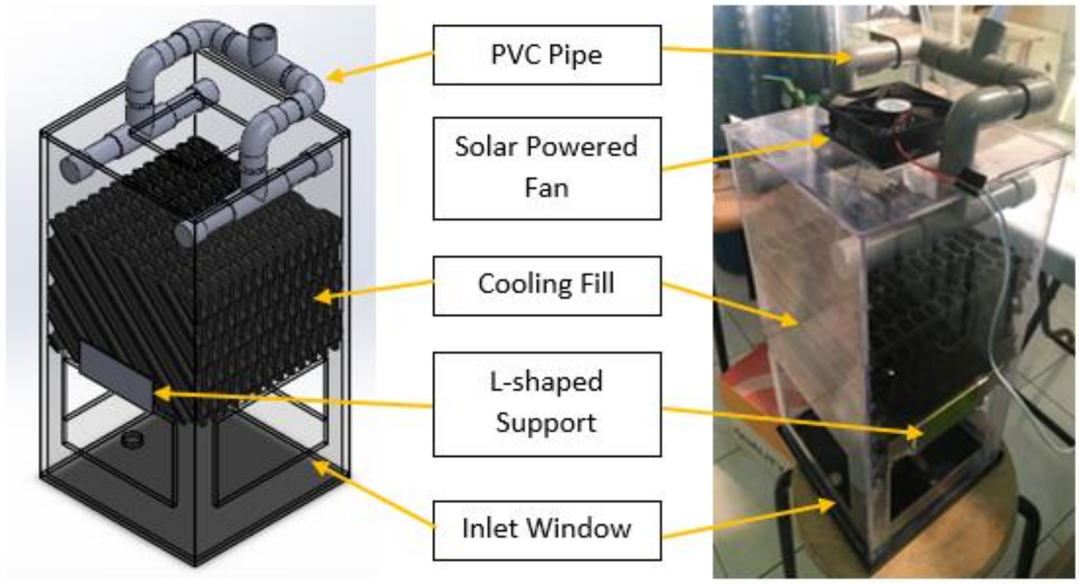

Figure 3.8: Cooling Tower

Table 3.1: Materials for Small Scale Cooling Tower Fabrication

Material	Dimension	Quantity
Acyclic (side)	400 mm x 210 mm (length x width)	4
Acyclic (top, bottom)	210 mm x 210 mm (length x width)	2
Plastic grill	210 mm x 210 mm (length x width)	10
L-shape fill support	100 mm x 40 mm (length x width)	2
Solar powered fan	90 mm x 90 mm (length x width)	1
PVC pipe	50mm x 22mm (length x outer diameter)	4

3.3 Experimental Set Up

3.3.1 Roof Configuration

In this project, four small scale roof designs which labelled as Design W, Design X, Design Y, and Design Z were constructed and investigated among their cooling effect as shown in Figure 3.9.

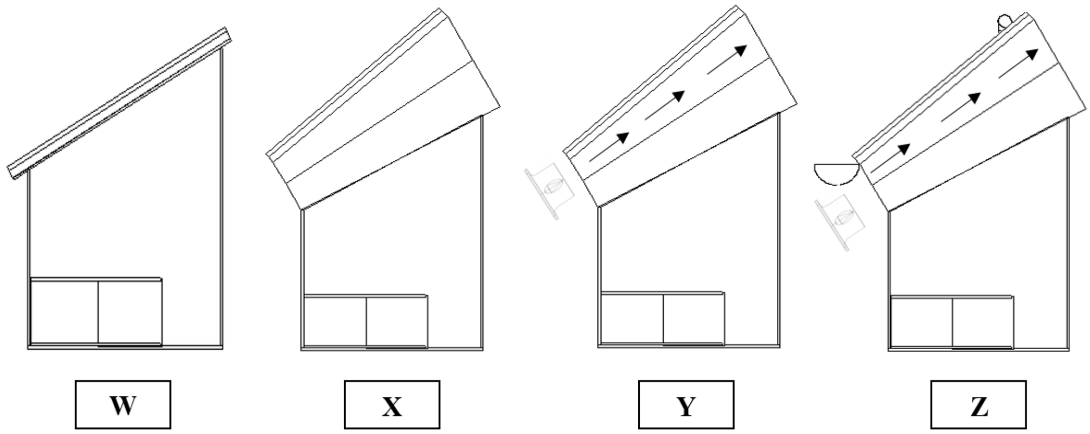

Figure 3.9: Four Types of Roof Configuration

3.3.1.1 Roof System Coated with TIC (Design W)

In this design, a white solar reflective paint with thermal insulation coating (TIC) was coated at the top of metal roof as illustrated in Figure 3.9 (W). This coating reduce the temperature of the roof top by reflecting heat from the surface and eventually decreased the heat transfer to the attic region. The roof configuration was considered as a passive cool roof system that rejecting the heat by the coating without any actuator that perform the cooling effect actively. This model was evaluated as a based model in order to compare and investigate the cooling effect of the active cool roof system.

3.3.1.2 TIC Coated Roof System with MAC (Design X)

The TIC coated roof system was incorporated with the moving air cavity in this model design as shown in Figure 3.9 (X). The MAC was installed underneath the roof tile that act as a heat executor that remove the heat before it transfer to the attic region. An attic ventilation system was constructed by this airflow cavity that reduce the temperature at the attic region. Heat trapped in the attic will transfer to this MAC and executed out to the ambient air which the temperature is lower compare to the attic temperature.

3.3.1.3 TIC Coated Roof System with MAC-Solar Powered Fan (Design Y)

The different between the Design X and Design Y is an addition solar powered fan was introduced in this roof configuration as shown in Figure 3.9 (Y). Solar powered fan was installed to increase the flow rate inside the MAC that improve the cooling efficiency. Forced convention was implemented by the solar powered fan that remove the hot air form the attic region to ambient air. In this case, hot air that trapped in the attic region was drawn by the solar fan to the MAC in order to reduce the attic temperature.

3.3.1.4 TIC Costed Roof System, MAC-Solar Powered Fan, Rainwater Harvesting System (Design Z)

All the feature implemented in Design X and Design Y was combined to form the roof configuration of Design Z. In other words, this design comprises there major elements which are roof system coated with TIC, moving air cavity incorporated with solar powered fan, and rainwater harvesting system as shown in Figure 3.9 (Z). The rainwater harvesting system was a newly implemented system that uses the rainwater as a cooling agent to reduce the temperature of the roof top directly. The conveyance system was designed in this model to provide a smooth harvesting system that reduce the attic temperature efficiently.

3.3.2 Halogen Lamps Set Up

Halogen Lamp was used as a heat emitter in this project in order to heat up the roof top model. Halogen lamp creates light by heating the filament inside the bulb that generate a lot of heat during operation. As result, 90% of the energy was wasted to generate heat that make the efficiency much lower than the fluorescent lamp which only wasted 30% energy in heat. In other way, halogen lamp was considered as a good heating agent that provide irradiation and heat radiation during operation.

In this project, two halogen lamp were setup according to an incident angle of 10° and 15° respectively with the model roof top. The distance of the halogen lamps from roof centre was 45 cm and 47 cm respectively as shown in Figure 3.10.

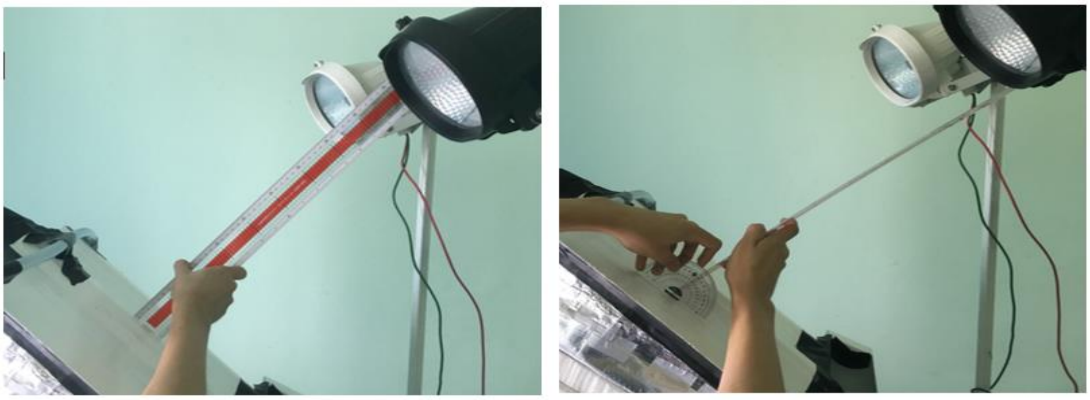

Figure 3.10: Location of Halogen Lamp

3.3.3 Sensor Location and Data Logger

The data logger was setup to record the measured temperature form the thermocouple. Four K-type thermocouple were used to measure the roof top temperature, attic temperature, MAC aluminium tube, and ambient temperature. In this case, two thermometer was used to provide four channel data monitoring throughout the experiment.

The position of the thermocouple was fixed throughout the four model testing in order to compare the cooling efficiency of each roof configuration as shown in Figure 3.11. The thermocouple sensor 1 was directly attached to the roof top surface whereas the sensor 2 was positioned inside the MAC channel which 30 mm below the sensor 1. The thermocouple that installed at the attic region was positioned 150 mm below the second sensor in the MAC channel. All data were be recorded at one minute interval throughout the 30 minutes cool roof testing.

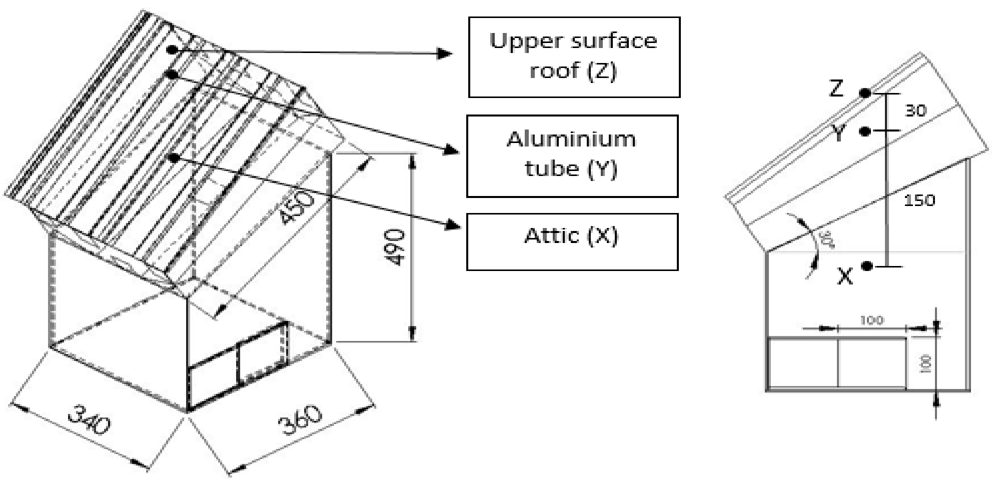

Figure 3.11: Sensors Location

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Metal Deck Roof with Thermal Insulation Coating (Design W)

The data obtained from the results of the metal deck roof with thermal insulation coating was plotted in graph as shown in Figure 4.1. In this roof configuration, the roof top temperature and attic temperature reached a maximum of 44.4℃ and 33.9℃ respectively. This experiment was carried out under a stable ambient temperature condition, which began with 29.2℃ and ended with 30.4℃ throughout 25 minutes of the heating process. The rate of increment in ambient temperature was $0.048\ ℃/min$ due to the heat generated by the halogen lamp being transferred to the surrounding ambient air of the model.

Based on the graph obtained in Figure 4.1, the gradient of the curve for roof top temperature decreased dramatically from 43.7℃ to 44.4℃. In this case, the temperature of roof top surface was considered become constant after 15 minutes of heating process. The roof top temperature increased with a rate of $2.63\ ℃/min$ for the first three minutes from 29.6℃ to 37.5℃. Meanwhile, the attic temperature increased from 29.5℃ to 30.4℃ with a rate of $0.3\ ℃/min$ for the first three minutes and became constant after 21 minutes of testing.

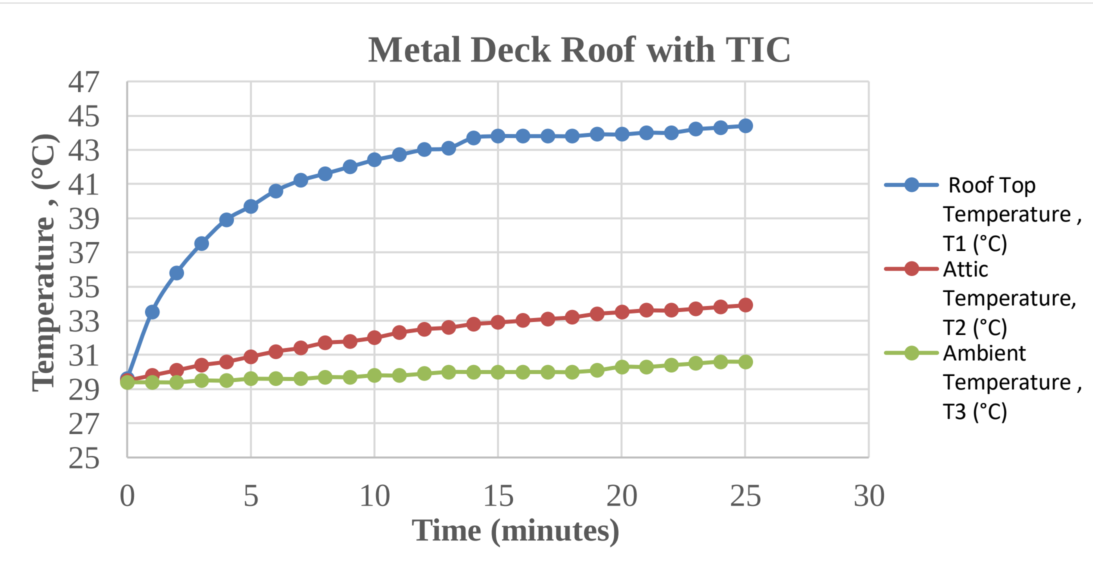

Figure 4.1: Performance of metal deck roof system with thermal insulation coating (Design W)

4.2 Metal Deck Roof Coated with Thermal Insulation Coating and Moving Air Cavity (Design X)

The data obtained from TIC coated roof system with moving air cavity (MAC) was plotted as shown in Figure 4.2. For this roof configuration, the maximum temperature of the roof top and MAC aluminium tube were 43.8℃ and 32.5℃ respectively. The temperature of attic region reached a maximum of 31.4℃ for this cool roof system with closed attic inlet.

The ambient temperature increased at a rate of $0.04\,℃/min$ due to the ambient air surrounding the model was heated by the halogen lamp. As a result, a condition of a constant ambient temperature was provided during the testing operation that began and ended with a temperature of 29.4℃ and 30.4℃ respectively.

The roof top temperature increased dramatically from 29.6℃ to 35.8℃ for the first 3 minutes and reached a constant temperature at approximately 43.7℃ after 21 minutes of heating process. The rate of temperature increament in aluminium tube and attic for the first 3 minutes were $0.23\,℃/min$ and $0.03\,℃/min$ respectively. Based on the results, the rate of temperature increament in the aluminium tube was higher than the rate in attic region due to the MAC which was directly attached below the roof top that received much higher transmission of heat. Both the temperature of aluminium tube and attic reached a constant temperature after 23 minutes of testing.

In this roof configuration, the maximum temperature difference between the roof top surface and attic region was 12.4℃. This temperature variance was much higher than the maximum temperature difference which measured to be 1.1℃ between the aluminium tube and attic region. In this case, the maximum temperature variance between the aluminium tube and roof top surface was 11.3℃ as shown in Figure 4.2. The attic temperature was increased about 2℃ throughout the 25 minutes of heating process from 29.6℃ to 31.4℃. The implementation of MAC played an important role on attic temperature cooling effect.

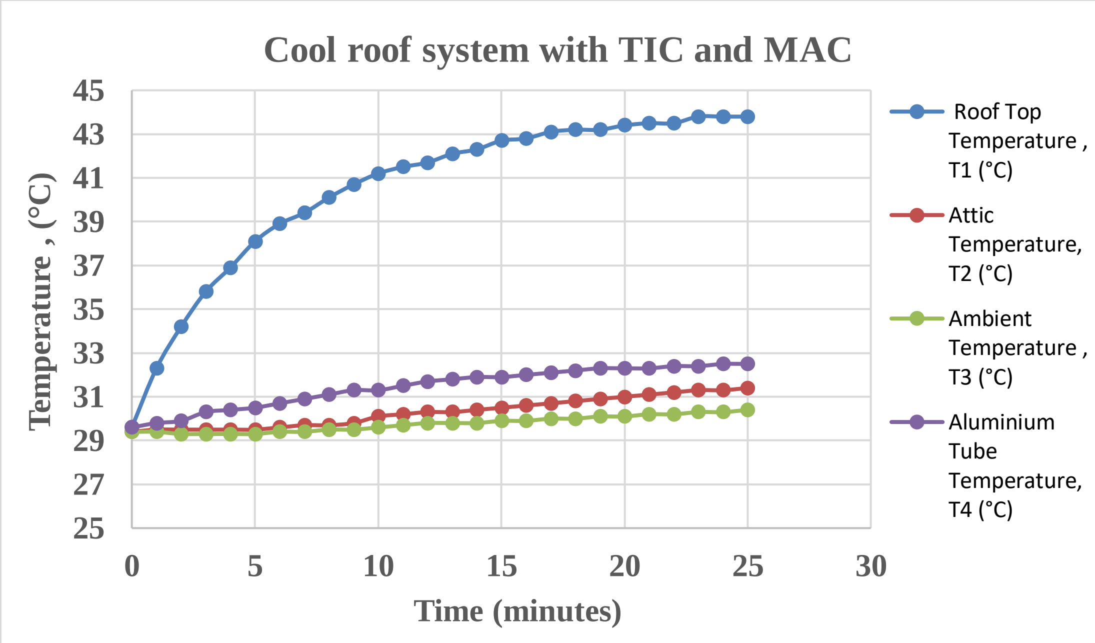

Figure 4.2: Performance of metal deck roof coated with the thermal insulation coating and moving air cavity (Design X)

4.3 Metal Deck Roof Coated with Thermal Insulation Coating and MAC-Solar Powered Fan (Design Y)

The results of metal deck roof coated with TIC and MAC-solar powered fan was plotted in graph as shown in Figure 4.3. For this cool roof system, the roof top temperature and aluminium tube temperature reached a maximum of 42.5°C and 31.8°C respectively. The graph obtained in Figure 4.3 shows that the peak temperature for the enclosed attic region was 30.9°C. The rate of increase in ambient temperature was $0.036\ °C/min$ due to the heat generated by the halogen lamp being transferred to the ambient air surrounding the testing model. In this case, a condition of constant ambient temperature was provided during the testing operation that started and finished with a temperature of 29.4°C and 30.3°C respectively.

The roof top temperature increased significantly from 29.6°C to 35.4°C for the first 3 minutes and reached a constant temperature at approximately 42.4°C after 21 minutes of heating process. Meanwhile, the rate of temperature increment in aluminium tube and attic for the first 3 minutes was $0.21\ °C/min$ and $0\ °C/min$ respectively. As a result, the attic temperature remained constant at 29.4°C for the first 5 minutes of heating process due to the heat transmitted from roof top being executed by the MAC-solar powered fan before it was transferred to the attic region. The temperature of the aluminium tube and attic both became constant after 22 minutes of testing.

For this cool roof system (Design Y), the maximum temperature difference between the roof top surface and the attic region was 11.6℃. This temperature variance was larger than the maximum temperature difference which was measured to be 10.7℃ between the roof top surface and MAC aluminium tube. In addition, the maximum temperature variance between the aluminium tube and attic region was 0.9℃ as shown in Figure 4.3. The attic temperature increased only about 1.5℃ throughout the entire testing (25 min heating process) from 29.4℃ to 30.9℃.

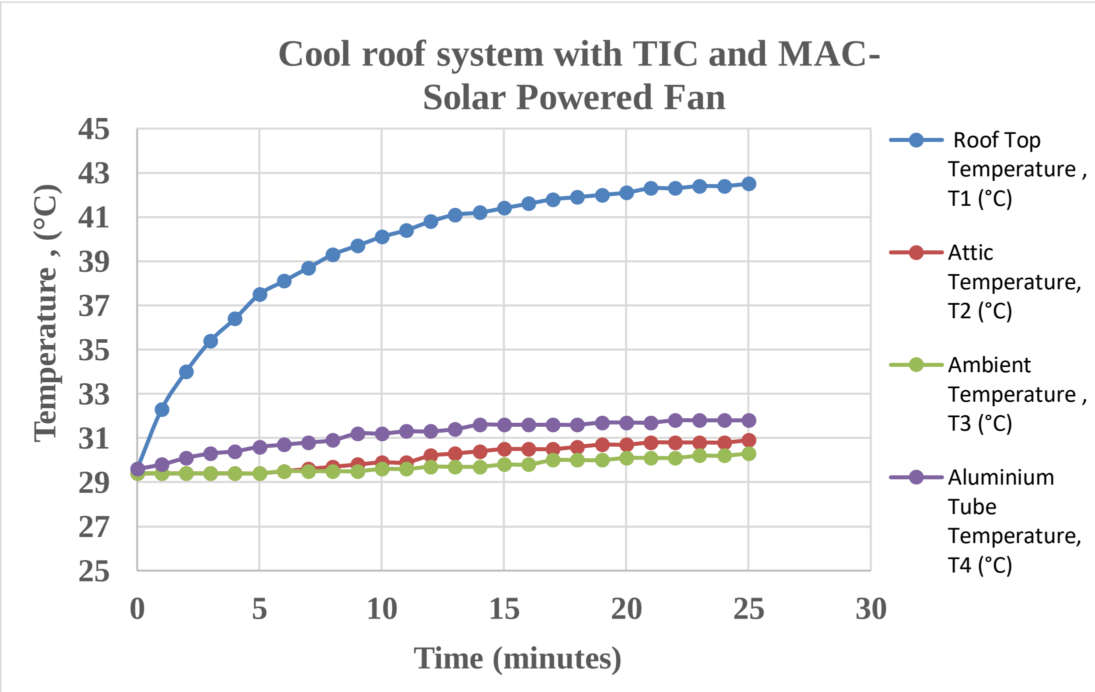

Figure 4.3: Performance of metal deck roof coated with the TIC and MAC-solar powered fan (Design Y)

4.4 Metal Deck Coated with TIC, MAC-Solar Powered Fan, and Rainwater Harvesting System

The result obtained from the TIC coated roof system with MAC-solar powered fan and rainwater harvesting system was plotted in graph as shown in Figure 4.4. For this roof configuration, the maximum temperature of the roof top and MAC aluminium tube were 41.7°C and 31.5°C respectively. The temperature of the enclosed attic region reached a maximum of 29.9°C for this cool roof system.

The ambient temperature increased at a rate of $0.056\,°C/min$ due to the ambient air surrounding the model was heated by the halogen lamp. As a result, a condition of a constant ambient temperature was provided during the testing operation that started and finished with a temperature of 29.4°C and 30.8°C respectively.

The roof top temperature was fluctuated throughout the entire heating process due to the cooling effect provided by the rainwater harvesting system. It increased dramatically from 29.6°C to 35.5°C for the first 3 minutes and reached the maximum temperature of 41.7°C after 10 minutes of heating process. This temperature was considered as a turning point in this graph since the temperature dropped rapidly after this point as shown in Figure 4.4.

As a result, the roof surface temperature deceased in a rate of $3.7\,°C/min$ from 41.7°C to 30.6°C . After 3 minutes of cooling process provided by the rainwater harvesting system, the roof top temperature increased gradually and reached the second peak temperature of 40.1°C in 7 minutes. A significant drop of roof surface temperature was occurred after the 21 minutes of testing and increased at a rate of $3\,°C/min$ from 31.2°C to 37.2°C throughout the entire testing process for this roof configuration.

Based on the graph obtained, the two peak temperatures of the roof top surface were 41.7°C and 40.1°C, which was similar to the thermostat actuate temperature of 40°C that was measured by the thermal sensor. This phenomenon analysed that the reduction of roof surface temperature was due to the implementation of rainwater harvesting system. Furthermore, the rate of temperature increament in aluminium tube and attic for the first 3 minutes was $0.3\,°C/min$ and $0\,°C/min$ respectively. As a result, the attic temperature remained constant at 29.4°C for the first 5 minutes of heating process due to the heat transmitted from roof top being executed by the MAC-solar powered fan before it was transferred to the attic region.

In this roof configuration (Design Z), the maximum temperature difference between the roof top surface and attic region was 11.8°C. This temperature variance was much higher than the maximum temperature difference which measured to be 10.2°C between the roof surface and MAC aluminium tube. In this case, the maximum temperature variance between the aluminium tube and roof top surface was 1.6°C as shown in Figure 4.4. The attic temperature only increased 0.5℃ throughout the 25 minutes of heating process from 29.4℃ to 29.9℃. The MAC-solar powered fan incorporated with rainwater harvesting system increased the comfort level of building occupants by the reduction of attic temperature.

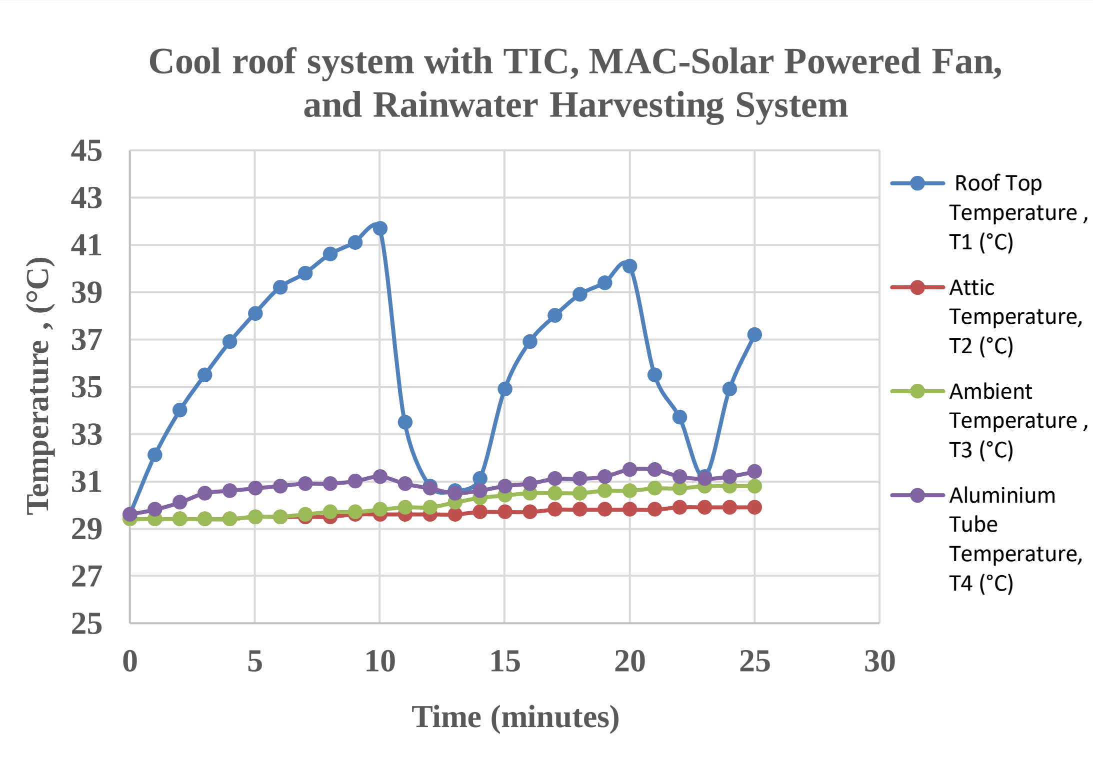

Figure 4.4: Performance of metal deck roof coated with the TIC, MAC-solar powered fan, and rainwater harvesting system (Design Z)

4.5 Comparison of Roof Top Temperature

The roof top temperature for four types of roof configuration which labelled as Design W, Design X, Design Y, and Design Z were plotted in graph as shown in Figure 4.5. A logarithmic curve was presented by the roof top temperature of design W, X, and Y which increased significantly for the first 3 minutes and reached an equilibrium after 21 minutes of heating process. This result indicates that the temperature slope was ever-decreasing as time increases. In contrast, the roof temperature for design Z fluctuated throughout the entire 25 minutes of heating process as illustrated in Figure 4.5.

The roof top temperature of TIC coated roof system (Design W) resulted in a higher temperature of 44.4℃ compared to the other cool roof designs (Design X, Y, and Z) that incorporated with the moving air cavity which was installed between the roof top and the attic region. The MAC provides a natural convection in cool roof design X that reduces the roof surface temperature from 44.4℃ to 43.8℃ by temperature gradient of the mobile air. The heat conducted through the roof surface increased the density of the mobile air inside the MAC due to the thermal expansion. As a result, the heated air became less dense and evacuated out from the MAC channel before the heat was transferred to the attic region.

The roof configuration of design Y further decrease the roof top temperature by the incorporation of solar powered fan from 44.4℃ to 42.5℃. In other words, the solar powered fan had reduced approximately 1.3℃ of roof top temperature as compared with the normal MAC system in Design X. This result is due to the force convection induced by the solar powered fan that increased the removal rate of the hot air inside the MAC channel. The cooling effect performed by this cool roof design (Y) through the reduction of roof top temperature can be shown in Figure 4.5.

The combination of TIC, MAC-solar powered fan, and rainwater harvesting system on design Z have significantly reduced the roof top temperature from 41.7℃ to 30.6℃. The average roof top temperature difference between the design W and design Z was 5.54℃. Moreover, the maximum roof top temperature in design Z is hard to compare with other design due the fluctuation characteristic of the temperature. This fluctuation indicates that the rainwater harvesting system directly reduces the temperature from the surface of the roof top. Water was used as a cooling agent that directly contacts with the roof top surface in order to absorb and release the heat energy from the roof top. The peak temperature of this cool roof system can be manipulated by the thermostat actuate temperature that was set to be 40℃ in this experiment.

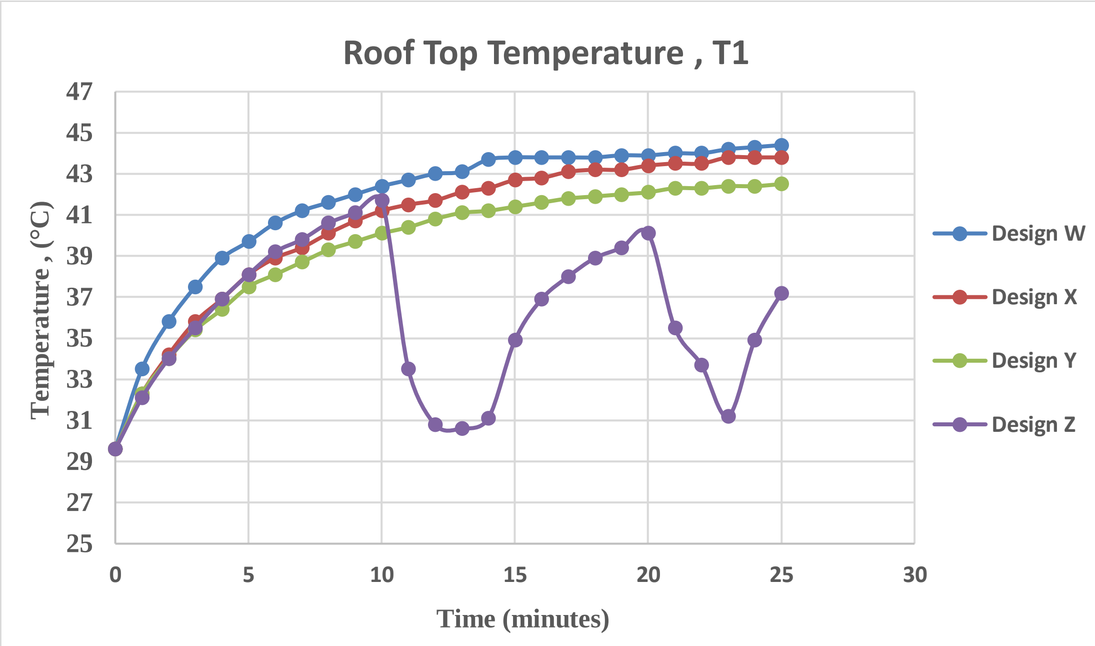

Figure 4.5: Comparison of Roof Top Temperature

4.6 Comparison of Attic Temperature

The comparison of attic temperature for the four cool roof designs were plotted in a graph as shown in Figure 4.6. Based on the results obtained from roof design W, the attic temperature increased rapidly from 29.6°C to 39.7°C for the first 5 minutes and gradually increased at a rate of $0.235\ ℃/min$ throughout the 25 minutes of heating process. In contrast, the attic temperature of the other three design model remained constant for the first 5 minutes and slightly increasing until it reached an equilibrium after 22 minutes of heating process. As a result, the cool roof system implemented in design W has the highest attic temperature which reached a maximum of 33.9 ℃ as compared to the other 3 cool roof design.

The maximum attic temperature difference between the cool roof design W and design X was 2.5°C. This result indicates the application of moving air cavity that was installed between the roof top and attic region. The MAC was inclined with an angle that was designed based on the characteristic of fluid thermal expansion which enhance the convective velocity of the air inside the cavity. According to the researcher Pradhan, the convective velocity of the heated surface will increases as the angle of inclination increases (Abhijit Guha, Akshat Jain and Kaustav Pradhan, 2019). In this case, the heat energy trapped in the attic region will be transferred to the MAC which reduces the temperature inside the attic region.

The cool roof system in design Y additionally decreases the attic temperature of design W form 33.9 ℃ to 30.9 ℃. In other words, the solar powered fan has reduced approximately 0.5 ℃ of attic temperature as compared with the normal MAC system in design X. The temperature difference in this testing was small due the limitation of heating process. As a result, the solar powered fan increased the convective velocity of the fluid which accelerated the hot air removal rate inside the MAC. Figure 4.5 shows the performance of attic temperature reduction in design Y (TIC coated roof, MAC-solar powered fan).

Design Z has achieved the lowest attic temperature about 29.9 ℃ among the other cool roof design model that proposed in this project. The maximum attic temperature difference between the design W and design Z was 4 ℃. This result indicates that the TIC coated roof system with MAC-solar powered fan and rainwater harvesting system have significantly reduced the attic temperature from 33.9℃ to 29.9℃. The rainwater harvesting system that implemented in this design indirectly cooled the attic temperature by decreasing the roof top temperature. The heat was insulated and absorbed by this system in order to reduce the heat energy transferred into the enclosed attic region. The features combined in this roof configuration has reduce the attic temperature of approximately 4 ℃ as compared to the normal TIC coated roof system.

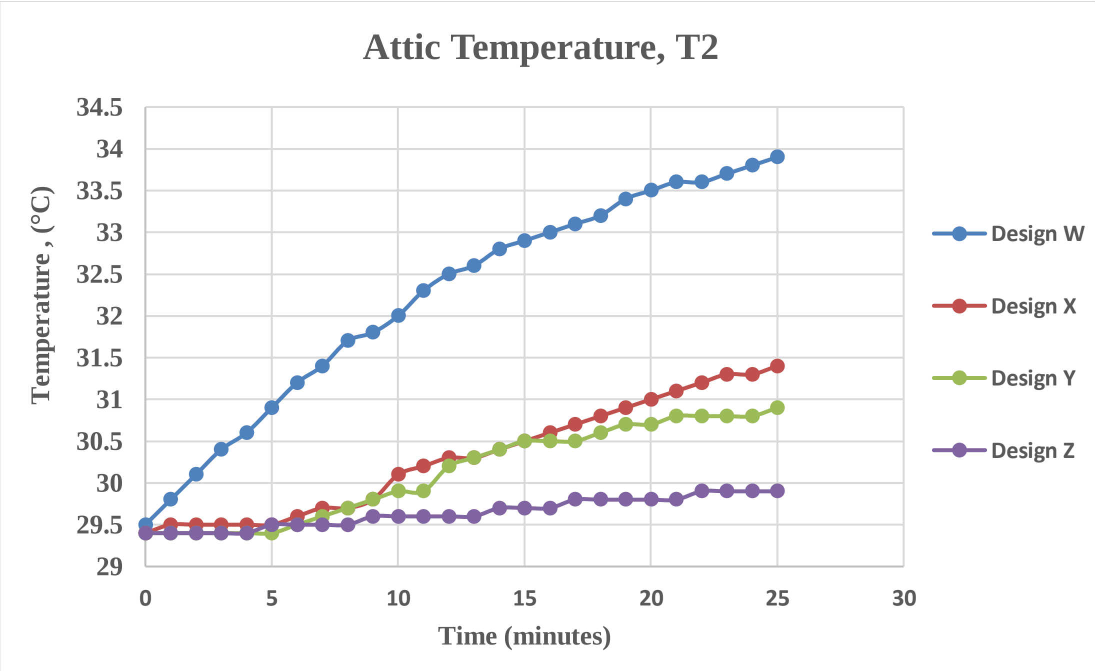

Figure 4.6: Comparison of Attic Temperature

4.7 Comparison of MAC Aluminium Tube Temperature

The MAC aluminium tube temperature for three types of roof configuration which labelled as Design X, Design Y, and Design Z were plotted in a graph as shown in Figure 4.6. Based on the results obtained, the temperature inside the cavity for all cool roof designs increased with a rate of $0.2\ ℃/min$ for the first 5 minutes of heating process. The cavity temperature in design X and design Y continually increased and reached an equilibrium after 22 minutes of testing whereas the temperature in design Z started fluctuating from 10 minutes throughout the entire heating process.

The temperature of the normal MAC that implemented in design X resulted in the highest temperature of $32.5℃$ compared to other two cool roof designs (design Y and Z). Solar powered fan that incorporated with MAC in design Y reduced the aluminium cavity temperature from $32.5℃$ to $31.8℃$. This positive result indicates that the solar powered fan further enhances the cooling effect of the attic region through the temperature reduction in MAC aluminium tube. Based on the effect of mass flow rate on convective heat transfer coefficient studied by Piyush Sabharwal, the heat transfer coefficient will increase as the mass flow rate increases (Sabharwall, Utgikar and Gunnerson, 2009). As a result, the heat removal rate will increase when the mass flow rate in the MAC increases under the presence of solar powered fan.

The MAC temperature in design Z was fluctuated with a maximum and minimum temperature of $31.5℃$ and $30.5℃$ respectively after the 10 minutes of heating process. The trend of the MAC temperature has a high similarity with the temperature trend of roof top in this roof configuration. In this case, the temperature of the aluminium tube was directly affected by the cooling effect performed by the rainwater harvesting system. Figure 4.7 shows the MAC temperature gradient deceased gradually after the roof top temperature reached $40℃$. This result was due to the cooling operation of the rainwater harvesting system which was controlled by the thermostat that was set to be $40℃$ in order to actuate the system. Generally, the MAC temperature in design Z achieved the lowest temperature of $30.5℃$ as compared to the other cool roof designed.

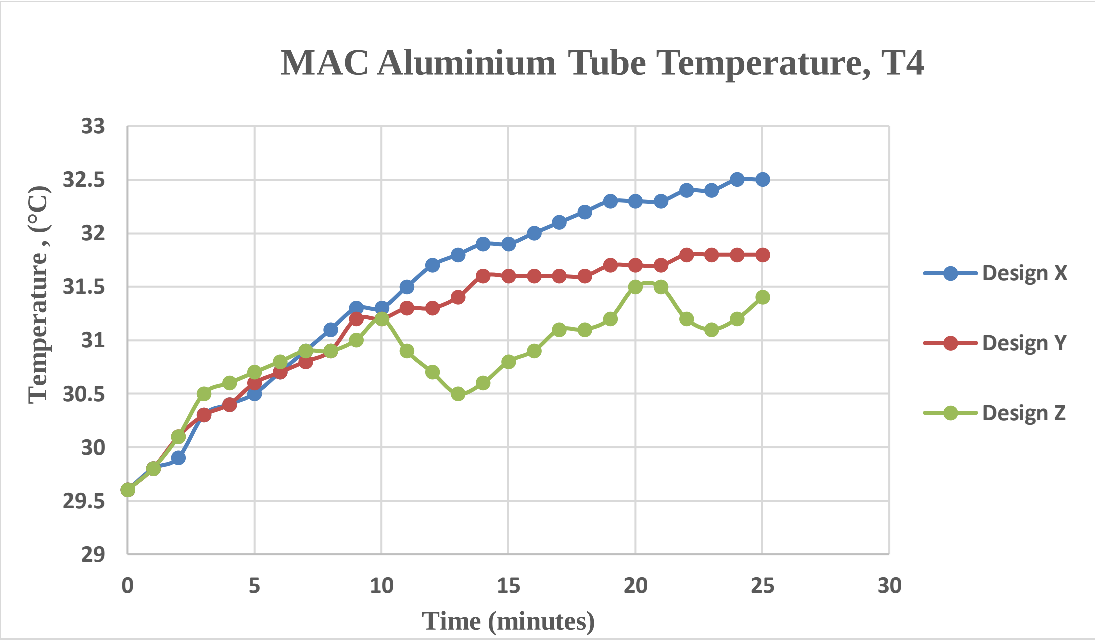

Figure 4.7: Comparison of MAC temperature

4.8 Summary

The cooling performance of all cool roof designs were analysed and tabulated in Table 4.1. Based on the result obtained, design Z achieved the lowest attic temperature compared to other cool roof designs. This indicates that the combination of TIC coated roof system with MAC solar powered fan and rainwater harvesting system played an important role in attic temperature reduction.

Table 4.1: The Cooling Effect of Four Cool Roof Designs

Roof Configuration	Maximum Roof Top Temperature (°C)	Maximum MAC Al-tube Temperature (°C)	Maximum Attic Temperature (°C)	Average Ambient Temperature (°C)
Design W	44.4	-	33.9	29.9
Design X	43.8	32.5	31.4	29.8
Design Y	42.5	31.8	30.9	29.7
Design Z	40.0	31.5	29.9	29.9

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In this research project, an active cool roof system that integrated with different roof configuration was investigated to enhance the attic temperature reduction. Four cool roof prototype was fabricated and tested indoor with a solar simulation by halogen lamp. The combination of MAC solar powered fan and rainwater harvesting system (Design Z) performed a best cooling effect among the other cool roof designs. A temperature reduction of up to 4℃ (from 33.9℃ to 29.9℃) in attic region was achieved as compared with the normal TIC coated roof system in Design W.

A solar powered fan was implemented into the cool roof system that additionally reduce about 0.5 ℃ of attic temperature as compared with the normal MAC system in design X. A force convection was introduced by the solar powered fan that increase the convective velocity of the air inside the cavity. As result, the removal rate of the hot air will be accelerated by this configuration in order to decrease the heat transfer into the attic region.

The rainwater harvesting system showed a significant reduction in roof top temperature from 41.7℃ to 30.6℃ as the cooling duration was set to be 3 minutes by the system. The heat radiated by the halogen lamp was directly absorbed and insulated by the cooling agent in this system that resulted a temperature reduction in roof top temperature. As result, the rate of temperature increase in the attic region was reduced by the reduction of heat energy transferred from the roof top to the attic region.

In conclusion, this low cost eco-friendly cool roof system is able to reduce the attic temperature that enhance the comfortability inside the building with little effect on the environment.

5.2 Recommendations for future work

For future works, a commercial attic roof model can be fabricated to investigate the cooling effect of the cool roof designs in outdoor for real-life simulation. The temperature variation of the roof top will be larger as compare to the solar irradiation generated by the halogen lamp. In this case, the cooling effect might be more significant as the roof top temperature variation increased. Furthermore, the ambient temperature variation might take into account in order to compare the performance of the cool roof design with the commercial roof deck.

Besides, a digital thermostat can be installed to the rainwater harvesting cool roof system that improve the sensitivity of the thermal sensor. A fully automated system may be incorporated with the water pump that increase the accuracy of the cool effect implemented by the cool roof design.

In addition, a smart data logger can be installed that automatically recorded the temperature results from the thermocouple that might improve the research working environment in future.

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APPENDICES

APPENDIX A: Tables

Table A-1: Results obtained from **Metal Deck Roof with TIC (Design W)**

Time (minutes)	Roof Top Temperature , T1 (°C)	Attic Temperature, T2 (°C)	Ambient Temperature , T3 (°C)
Initial	29.6	29.5	29.4
1	33.5	29.8	29.4
2	35.8	30.1	29.4
3	37.5	30.4	29.5
4	38.9	30.6	29.5
5	39.7	30.9	29.6
6	40.6	31.2	29.6
7	41.2	31.4	29.6
8	41.6	31.7	29.7
9	42.0	31.8	29.7
10	42.4	32.0	29.8
11	42.7	32.3	29.8
12	43.0	32.5	29.9
13	43.1	32.6	30.0
14	43.7	32.8	30.0
15	43.8	32.9	30.0
16	43.8	33.0	30.0
17	43.8	33.1	30.0
18	43.8	33.2	30.0
19	43.9	33.4	30.1
20	43.9	33.5	30.3
21	44.0	33.6	30.3
22	44.0	33.6	30.4
23	44.2	33.7	30.5
24	44.3	33.8	30.6
25	44.4	33.9	30.6

Table A-2: Results obtained from **Cool roof system with TIC and MAC (Design X)**

Time (min)	Roof Top Temperature , T1 (°C)	Attic Temperature, T2 (°C)	Ambient Temperature , T3 (°C)	Al Tube Temperature, T4 (°C)
0	29.6	29.4	29.4	29.6
1	32.3	29.5	29.4	29.8
2	34.2	29.5	29.3	29.9
3	35.8	29.5	29.3	30.3
4	36.9	29.5	29.3	30.4
5	38.1	29.5	29.3	30.5
6	38.9	29.6	29.4	30.7
7	39.4	29.7	29.4	30.9
8	40.1	29.7	29.5	31.1
9	40.7	29.8	29.5	31.3
10	41.2	30.1	29.6	31.3
11	41.5	30.2	29.7	31.5
12	41.7	30.3	29.8	31.7
13	42.1	30.3	29.8	31.8
14	42.3	30.4	29.8	31.9
15	42.7	30.5	29.9	31.9
16	42.8	30.6	29.9	32.0
17	43.1	30.7	30.0	32.1
18	43.2	30.8	30.0	32.2
19	43.2	30.9	30.1	32.3
20	43.4	31.0	30.1	32.3
21	43.5	31.1	30.2	32.3
22	43.5	31.2	30.2	32.4
23	43.8	31.3	30.3	32.4
24	43.8	31.3	30.3	32.5
25	43.8	31.4	30.4	32.5

Table A-3: Results obtained from **Cool roof system with TIC and MAC-Solar Powered Fan (Design Y)**

Time (min)	**Roof Top Temperature , T1 (°C)**	**Attic Temperature, T2 (°C)**	**Ambient Temperature , T3 (°C)**	**Al Tube Temperature, T4 (°C)**
Initial	29.6	29.4	29.4	29.6
1	32.3	29.4	29.4	29.8
2	34.0	29.4	29.4	30.1
3	35.4	29.4	29.4	30.3
4	36.4	29.4	29.4	30.4
5	37.5	29.4	29.4	30.6
6	38.1	29.5	29.5	30.7
7	38.7	29.6	29.5	30.8
8	39.3	29.7	29.5	30.9
9	39.7	29.8	29.5	31.2
10	40.1	29.9	29.6	31.2
11	40.4	29.9	29.6	31.3
12	40.8	30.2	29.7	31.3
13	41.1	30.3	29.7	31.4
14	41.2	30.4	29.7	31.6
15	41.4	30.5	29.8	31.6
16	41.6	30.5	29.8	31.6
17	41.8	30.5	30.0	31.6
18	41.9	30.6	30.0	31.6
19	42.0	30.7	30.0	31.7
20	42.1	30.7	30.1	31.7
21	42.3	30.8	30.1	31.7
22	42.3	30.8	30.1	31.8
23	42.4	30.8	30.2	31.8
24	42.4	30.8	30.2	31.8
25	42.5	30.9	30.3	31.8

Table A-4: Results obtained from **Cool roof system with TIC, MAC-Solar Powered Fan, and Rainwater Harvesting System (Design Z)**

Time (min)	Roof Top Temperature , T1 (°C)	Attic Temperature, T2 (°C)	Ambient Temperature , T3 (°C)	Al Tube Temperature, T4 (°C)
Initial	29.6	29.4	29.4	29.6
1	32.1	29.4	29.4	29.8
2	34.0	29.4	29.4	30.1
3	35.5	29.4	29.4	30.5
4	36.9	29.4	29.4	30.6
5	38.1	29.5	29.5	30.7
6	39.2	29.5	29.5	30.8
7	39.8	29.5	29.6	30.9
8	40.6	29.5	29.7	30.9
9	41.1	29.6	29.7	31.0
10	41.7	29.6	29.8	31.2
11	33.5	29.6	29.9	30.9
12	30.8	29.6	29.9	30.7
13	30.6	29.6	30.1	30.5
14	31.1	29.7	30.3	30.6
15	34.9	29.7	30.4	30.8
16	36.9	29.7	30.5	30.9
17	38.0	29.8	30.5	31.1
18	38.9	29.8	30.5	31.1
19	39.4	29.8	30.6	31.2
20	40.1	29.8	30.6	31.5
21	35.5	29.8	30.7	31.5
22	33.7	29.9	30.7	31.2
23	31.2	29.9	30.8	31.1
24	34.9	29.9	30.8	31.2
25	37.2	29.9	30.8	31.4

APPENDIX B: Alternative Design (Cooling Tower)

The initial design of the cooling tower fill was constructed by aluminium plate which arranged accordingly to the water flow as shown in Figure 1. This aluminium plate was purposely designed and tilted with an angle to increase the total contact surface area of the water with the plate. The basic design concept is similar with the fabricated prototype with application to increase the heat transmission rate between the hot water and the cool air that cooled down the harvesting heated rainwater. However, the fabrication process of this design was difficult due to the angle of inclination between the steel rod and the plate is hard to control. As result, this design was replaced by the new design which proposed and fabricated in this prototype.

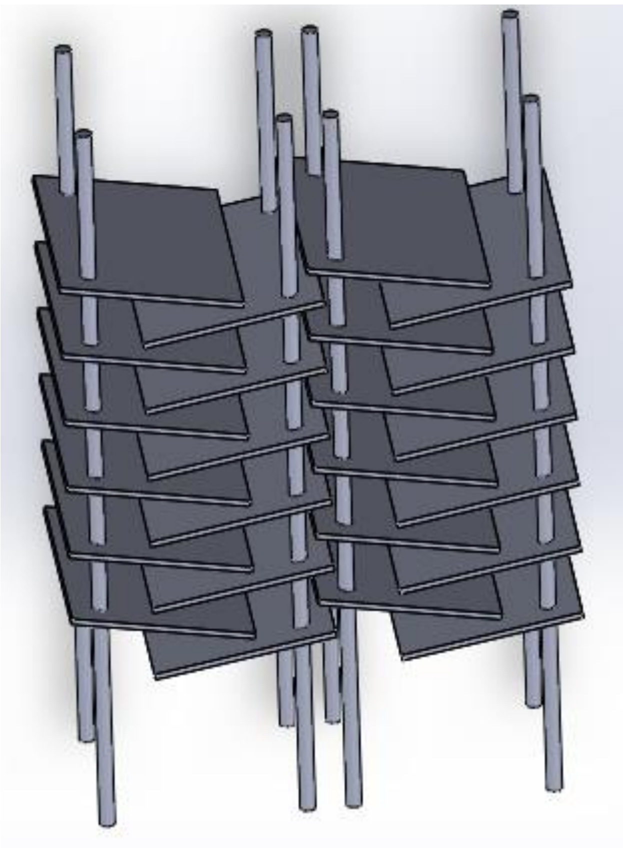
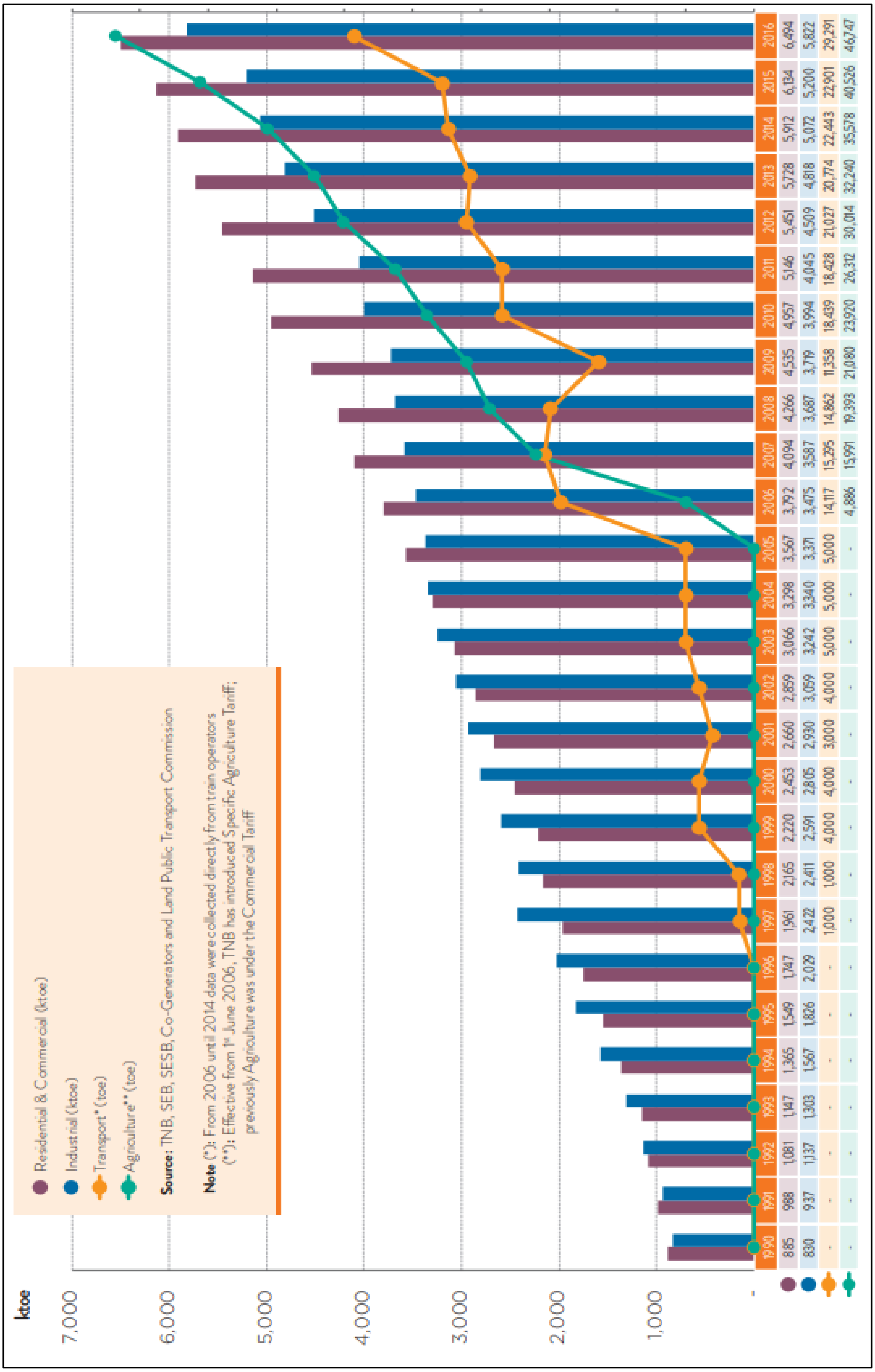


Figure 1: Cooling Tower Fill

APPENDIX C: Malaysia's Electricity Consumption from year 1990 to 2016



	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
Residential & Commercial (ktoe)	885	988	1,081	1,147	1,365	1,549	1,747	1,961	2,165	2,220	2,453	2,660	2,859	3,066
Industrial (ktoe)	830	937	1,137	1,303	1,567	1,826	2,029	2,422	2,411	2,591	2,805	2,930	3,059	3,242
Transport* (toe)	-	-	-	-	-	-	-	1,000	1,000	4,000	4,000	3,000	4,000	5,000
Agriculture** (toe)	-	-	-	-	-	-	-	-	-	-	-	-	-	-

	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Residential & Commercial (ktoe)	3,298	3,567	3,792	4,094	4,266	4,535	4,957	5,146	5,451	5,728	5,912	6,134	6,494
Industrial (ktoe)	3,340	3,371	3,475	3,587	3,687	3,719	3,994	4,045	4,509	4,818	5,072	5,200	5,822
Transport* (toe)	5,000	5,000	14,117	15,295	14,862	11,358	18,439	18,428	21,027	20,774	22,443	22,901	29,291
Agriculture** (toe)	-	-	4,886	15,991	19,393	21,080	23,920	26,312	30,014	32,240	35,578	40,526	46,747