PERFORMANCE COMPARISON BETWEEN DIFFERENT TYPE OF EVAPORATIVE COOLING SYSTEMS

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SUPERVISOR'S DECLARATION

I hereby declare that I have lead this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of the degree of Bachelor of Mechanical Engineering with Honours.

Signature : ....
Name of Supervisor : ....
Date : ....

DEDICATION

To my beloved family especially my father,

Tham You Fock

And also to my beloved mother,

Teng Sait May

Who keep me continuously motivated with their great support and encouragement throughout my Bachelor Degree program

ABSTRACT

The phenomenon of evaporative cooling is a common process in nature, whose applications for cooling air are being used since the ancient years. Evaporative cooling is simply based on the phenomenon of reducing the air temperature by evaporating water on it, hence it meets this objective with low energy consumption. Unlike air conditioning system, evaporative cooling is environmentally friendly with no greenhouse emissions. In this paper the performance of different types of cooling system approaches are being compared by improving the current evaporative systems. There are 3 different types of evaporative cooling system which are wet string, wet cylinder and multi water droplet. Improvements for evaporative cooling systems included modifications on changed of material of string, added more holes on wet cylinder and decreased the length of syringe. For temperature measurement, USB TC-08 data logger and thermocouple are used as instruments to measure the temperature of air during the experiment. The temperature was measured and recorded in the duration of 1 hour with 10 second interval of time. The temperature difference between inlet air and outlet was obtained to determine the performance of each evaporative cooling system. The results show that the multi water droplet evaporative cooling system has the best performance of cooling effect.

ACKNOWLEDGEMENT

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LIST OF ABBREVATIONS

DEC	Direct Evaporative Cooling
IEC	Indirect Evaporative Cooling
CHF	Critical Heat Flux
CFD	Computational Fluid Dynamic
PDA	Phase Doppler Anemometer

LIST OF SYMBOL

c_a	=	Dry air specific heat
c_v	=	Vapour specific heat
T_{a1}	=	Inlet temperature
T_{a2}	=	Outlet temperature
T_w	=	Water temperature
X_1	=	Inlet moisture content
X_2	=	Outlet moisture content
h_{fg}	=	Water evaporation
$\dot{m}_{da}$	=	Dry air mass flow rate
$\dot{m}_{wv}$	=	Rate of water consumption required for the evaporative cooling process
η	=	Cooling efficiency
T_{wb}	=	Wet bulb temperature of cooled air
$\dot{m}''$	=	Mass flux
q''	=	Heat flux
$c_{p,v}$	=	Specific heat of vapor
$c_{p,l}$	=	Specific heat of liquid
T_{sat}	=	Saturation temperature
T_{wall}	=	Wall temperature
T_{spray}	=	Spray temperature

CHAPTER 1

INTRODUCTION

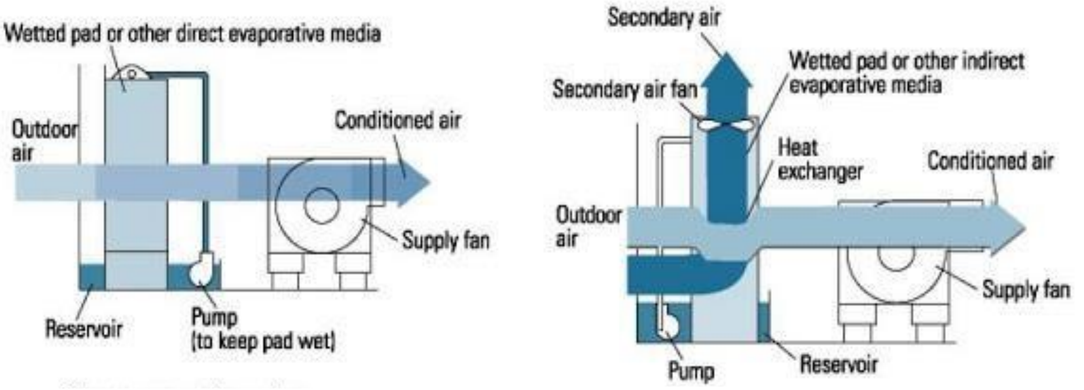
1.1 Background

Air conditioning system plays an imperative role in life. It has become more popular in life not only for human being but also for flora and fauna to create comfortable environment. The air conditioning system has one drawback which is it consumes a large amount of energy and releases greenhouse gases to the environment. Evaporative cooling is one of the alternatives to cool the air and it occurs naturally. The most common example the human experience is perspiration or sweat. When perspiration occurs, it absorbs heat from human body and evaporates to the air to cool human body (Kapilan et al., 2016).

Evaporative cooling system is a system that cools air and reduces the air temperature through the water evaporation process. The water must have heat applied to it to change from a liquid to a vapor. An evaporative occurrence means the heat is removed from the water that remains in liquid state then resulting in a cooler liquid. This evaporative cooling process is consuming less energy and no greenhouse gas emissions compared to air conditioning system. There are 2 main principle methods of evaporative cooling are commonly used, direct evaporative cooling (DEC) and indirect evaporative cooling (IEC) (Sirelkhatim et al., 2012).

DEC is the earliest, the most straightforward and common form of evaporative air conditioning. DEC can be applied only in places where relative humidity is low. This is because DEC adds moisture to the cool air and this might increase the relative humidity and create discomfort to user. Figure 1.1(a) shows the schematic diagram of a conventional DEC system that consists of evaporative media from wettable and porous material, fan blows air through the wetted medium, water tank, recirculation pump and water distribution system. DEC system is based on the conversion of sensible heat into latent heat of evaporated water. The sensible heat loss by the air is equal to the latent heat gain and the enthalpy of air is remain unchanged, since the process is adiabatic.

On the other hand, IEC involves heat exchanger to cool the air without increasing its moisture content and undergoes heat and mass transfer occurring in the heat exchanger. A conventional IEC system as shown in Figure 1.1(b) that consists of a heat exchanger, small fan, pump, water reservoir and water distribution lines. In this system, there are two streams of air, namely wet and dry passages. In dry passage, primary air is cooled and it is separated with secondary air and water flow in wet passage. The heat is removed from primary air through impermeable separating wall and evaporates water into secondary air, wet passage is where the evaporation occurs. Hence, evaporation in wet passage and heat removal in dry passage and both happen simultaneously causes heat and mass transfer (Rabah et al., 2013).



(a) Direct evaporative cooling system (b) Indirect evaporative cooling system

Figure 1.1: Schematic diagram of (a) direct evaporative cooling system and (b) indirect evaporative cooling system (Bhatia, 2012)

1.2 Problem Statement

Now, one of the popular issue that people concern about is climate change. The use of chlorofluorocarbon based refrigerants in the air-conditioning system increases the global warming and causes the climate change. Air conditioning system gives cool air but at the same time brings greenhouse gases to the environment. The climate change is expected to present a number of challenges for the built environment and an evaporative cooling system is one of the simplest and environmentally friendly cooling system. Evaporative cooling also the oldest method to cool the air with less energy consumption. One of the drawback of evaporative cooling is the temperature of cooled air is lower than that of air conditioning. There are several types of evaporative cooling system need to be discussed about which are wet cylinder, wet string and multi water droplet evaporative cooling system. The performance of these evaporative cooling system is compared after some modifications are made on the evaporative cooling system. Hence, the design of evaporative cooling system is the key to cool the air efficiently.

1.3 Objective

The objectives of this project are as follows:

1. To improve current evaporative cooling system
2. To compare the performance of different type of cooling system approaches

1.4 Scope of Project

The scopes of this project are:

1. The three different types of evaporative cooling system are improved with some modifications, which are refer to wet cylinder, wet string and multi water droplet evaporative cooling system.
2. The performance of each type of evaporative cooling system are compared and based on the temperature difference of the air.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter describes the literature review by referring journals, books, articles and any material regarding the project to obtain the data. Evaporative cooling system had been studied by many researchers before. Some of the topic are the history of evaporative cooling system, principle of evaporative cooling system, type of evaporative cooling system, application of the cooling system and many others. Some of the topics will be discussed in this chapter.

2.2 History of Evaporative Cooler

Evaporative cooling is a physical phenomenon with natural concept of pushing warm air through water or water-soaked pad to create a cool air with small amount of air moisture added to the air, the faster the rate of evaporation the greater the cooling effect. There have been various designs over the years. In early Ancient Egyptian times, paintings portray slaves fanning large and porous clay jars filled with water to cool the rooms of royal inhabitants which is a very early form of evaporative cooling ("The Interesting History," 2017). The common people of Rome cooled their home by hanging wet mats over the doors and windows of their homes in order to get a sense of cool breeze.

The first man made coolers that trapped wind and funnelled it past water at the base of the towers and into a building. This in turn kept the building cool at the time. In 1800 B.C the new England textiles factory began to use the evaporative cooling systems to cool their mills by using the air washers passed air through water spray (Liberty et al., 2013).

There is different type of evaporative cooler were constructed such as bamboo cooler and charcoal cooler. Bamboo coolers were constructed with bricks with hessian cloth which were used to wrap the bricks (Kapish et al., 2018). Other than that, charcoal coolers were produced because of its very porous structure that can hold water as air flows across this wet wall the temperature of air is decreased due to the loss of heat through evaporation of water (Chris, 2013). Rusten (1985) portrayed a few sorts of evaporative cooling that was been utilized in New Delhi, India in which a wetted tangle with fan was utilized to cool a nearby eatery.

2.3 Principles of Evaporative Cooling System

Evaporative cooling is the process by which the evaporation of water causes the cooling effect and hence reduce the temperature of a substance. The conversion of sensible heat to latent heat can cool the air by evaporating water and decreasing in the ambient air temperature (Patil et al., 2013). Sensible heat is the exchange of heat that changes the temperature of the system but without changing other physical state of the system such as volume or pressure. Contrarily, latent heat only changes the physical state of a substance without the change of temperature by evaporation or condensation (John and Will, 1997). This cooling system has been used on various scales from small space cooling to large industrial applications.

Air conditioning and refrigeration technologies are different with evaporative cooling because evaporative cooling can provide effective cooling simply require a water supply and electrical power. By wetting a surface and allowing the water to evaporate the effective cooling can be produced. Same principle when human is sweating during physical exertion the body is cooled by evaporating sweat from the skin and the cooling effect can be sensed. This simple concept of evaporative cooling is the fundamental for more mechanized and complex evaporative cooling systems.

The cooling effect achieved by the evaporative cooling system can result in high relative humidity of the air as the air that is unsaturated with moisture can absorb a certain additional amount of water vapor, in which case the heat contained in the air is absorbed by the vaporization of the water. This liquid-to-vapour phase change causes the simultaneous cooling of the air and of the water remaining in liquid state (Taye and Olorunisola, 2011).

Evaporative cooling occurs when air, that is dry, passes over a wet surface, the rate of evaporation of water is directly proportional to the cooling effect of the air (Liberty et al., 2013). The efficiency of an evaporative cooler depends on the humidity of the surrounding air. Dry air causes greater cooling because dry air can absorb a lot of moisture. Conversely, if the air that is saturated with water, there is no evaporation and no cooling occur. Generally, an evaporative cooling structure is made of a permeable material that is fed with water. Hot dry air is drawn over the material. The humidity of air in increased as the water evaporates into the air and in the meantime the temperature of the air is reduced (Kapilan et. al., 2016).

The water content in the saturated air increases faster than the temperature. Therefore, evaporative cooling is more effective in regions with hot and dry climates. Conversely, the potential for evaporative cooling decreases and tends to nil when air is close to humidity saturation levels. In humid climates, evaporative cooling may however be used at the condenser level in conventional refrigeration systems or heat exchangers for industrial processes (Lazzarin, 2015).

2.4 Direct Evaporative Cooling System

The conversion of sensible heat to latent heat is the fundamental principle of direct evaporative cooling (DEC). The working principle of DEC is by introducing water directly passes a porous wetted medium or water-soaked pad by using a blower to pull air. The air is filtered, cooled and humidified after passes through the permeable wetted medium. A recirculation pump keeps the permeable medium wet. These components combine to increase the rate of natural heat exchange process (Bhatia, 2012).

As the water absorbs heat from the air, the water evaporates and cools the air. The humidity of air increase causes the dry bulb temperature of the decrease, as a matter of fact, this is an adiabatic saturation process (Sirelkhatim and Emad, 2012). Some of the sensible heat of the air is changed into latent heat when water in the wetted medium is changed into water vapor and diffused into the air. The wet bulb temperature of the entering air is the minimum temperature that can be obtained.

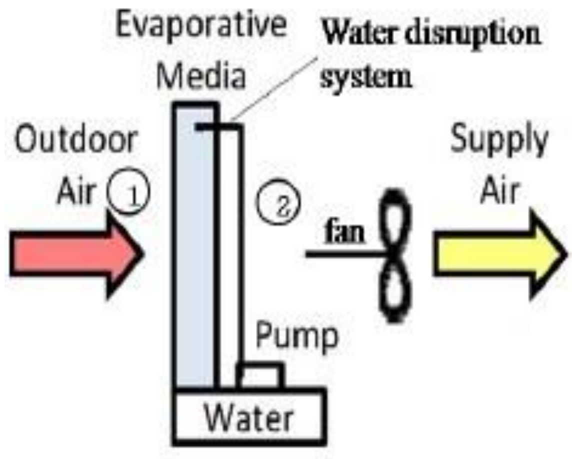


Figure 2.1: Schematic diagram of direct evaporative cooling (DEC) system (Boukhanouf et. al., 2015)

Spray humidifiers also considered one of the direct evaporative cooling. Spray humidifiers or spray nozzles deliver moisture to atmosphere using compressed air to ensure evaporation occurs. Prophet's Mosque in Medina, Saudi Arabia consists of the world's largest evaporative cooling system by using spray. The climate in Medina is hot and dry all year round and the temperature often rises to 50°C during day time. The King of Saudi Arabia saw an outdoor air conditioning system that vaporized water and having a cooling effect during a visit to the USA. Therefore, the King asked for installing a similar cooling system under the sun umbrellas in Medina. Water pumps and spray elements are installed in the mosque when all the systems are operating 50,000 litres of water can be vaporized in an hour. This successfully decrease the temperature across the site of up to 10°C (Leo Rasmussen, 2013).

Figure 2.2: The world's largest evaporative cooling system in Medina, Saudi Arabia (Leo Rasmussen, 2013)

The direct evaporative cooling has some major limitations including the increase in humidity of air may be undesirable, the lowest temperature that can be obtained is same as the wet bulb temperature of the outside air and the high concentration and precipitation of water deposits on the permeable wetted medium or other parts which causes blockage and corrosion and required frequent cleaning, replacing and servicing (Liberty et al., 2013).

2.5 Indirect Evaporative Cooling System

Indirect evaporative cooling (IEC) comprises of a heat exchanger and direct evaporative cooler. Unlike DEC, IEC uses the evaporative effect that add no moisture to the supply air system. IEC lowers the temperature of air via some type of heat exchanger arrangement, in which a secondary airstream is cooled by water and which in turn cools the primary airstream (Xie and Jiang, 2010). The cooled air never comes in direct contact with water or environment. In indirect evaporative cooling system both the dry bulb and wet bulb temperatures are reduced.

Indirect evaporative coolers do not add humidity to the air, but cost more than direct coolers and operate at a lower efficiency (Sirelkhatim and Emad, 2012).

In this method, there are two streams of air, one is primary air that is cooled sensibly without addition of moisture with heat exchanger, while another one is secondary air that carries away the heat energy from primary air. Secondary air usually is atmospheric air that is cooled by DEC and then supplied to heat exchanger. Secondary air cool primary air by using air-to-air heat exchanger. The primary air coming out from heat exchanger to the room has no moisture added for thermal comfort. IEC is suitable in hot and humid climate condition because it do not add humidity to the air but it cost more than DEC and running at a lower efficiency. The wet bulb effectiveness of IEC system is in the range of 40-80% (Riangvilaikul and Kumar, 2009).

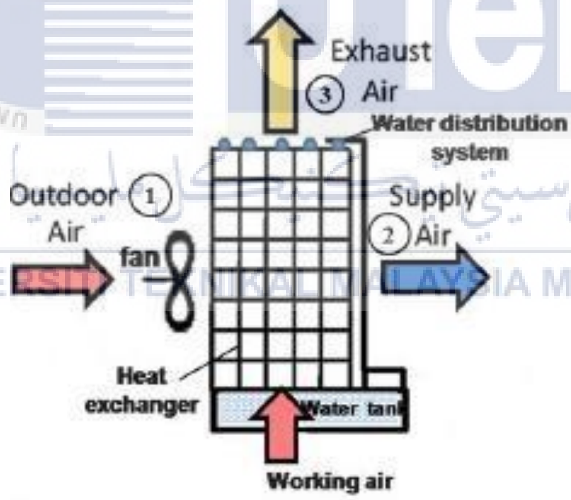


Figure 2.3: Schematic diagram of indirect evaporative cooling system (Boukhanouf et al., 2015)

In indirect evaporative cooling there are devices made of tubular or plate heat exchanger. The first remark to this kind of system originates from 1908, from a patent of a German inventor named Elfert. Later, window air cooler was developed as models and this allowed outside air to pass through a bank of fine horizontal tubes with the aid of a blower. At the same time, water was sprayed on the outer wall. Now, the metal tubes have been replaced by plastic tube to prevent corrosion (Patil et al., 2013).

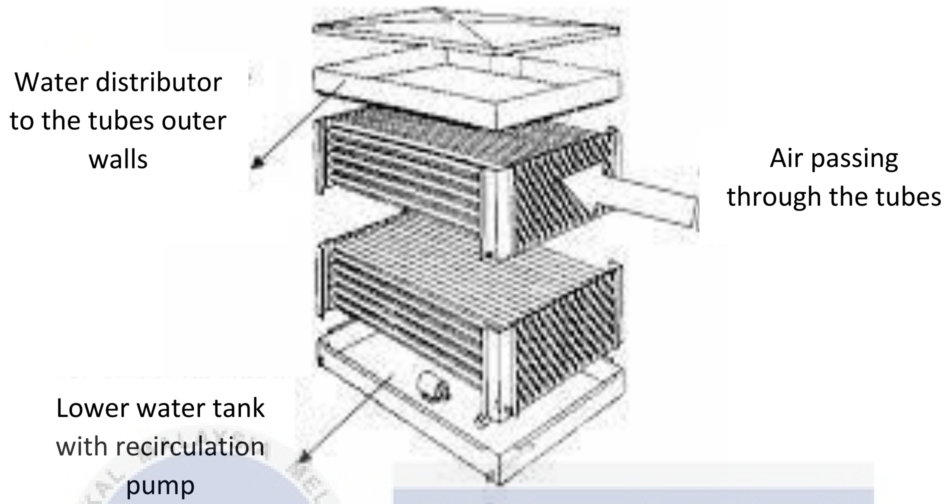


Figure 2.4: Tubular Indirect Evaporative Cooler (Patil et al., 2013)

Indirect evaporative cooling with a plate heat exchanger is the most popular and wide used. The first remark to this kind of system originates from 1934 and the design consisted two stages. In the first stage, spray humidifiers cooled the air with direct evaporative cooling. Subsequently, the cooled air is used in a plate heat exchanger to cool outside air which then supply into a cooled room and the high moisture content air is released outdoor (Stefano et al. 2017).

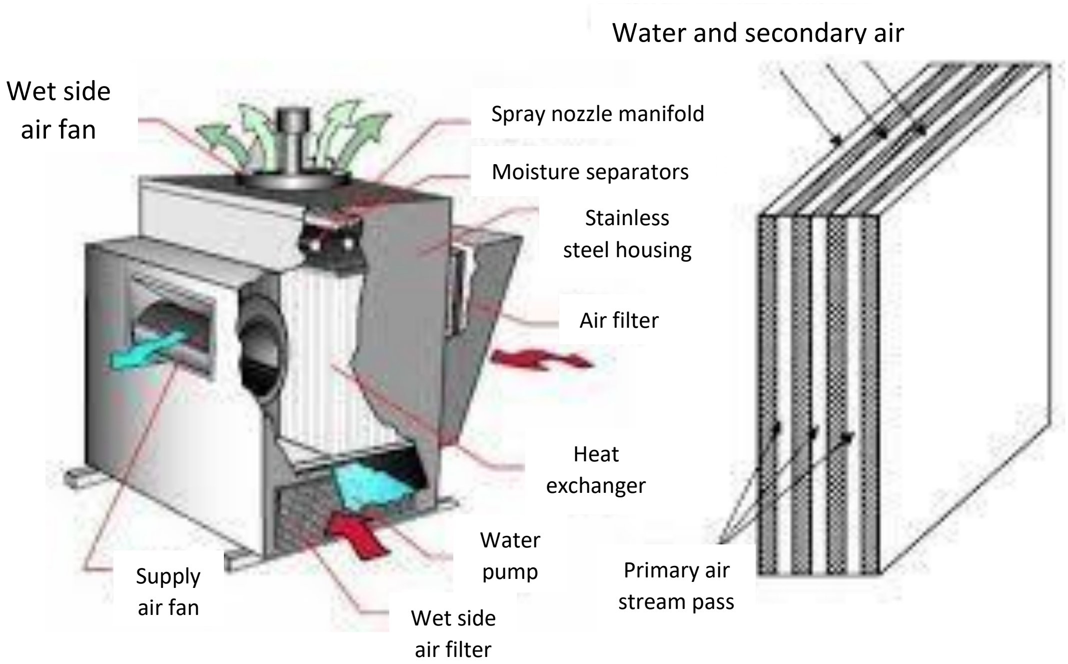


Figure 2.5: Configuration of the plate indirect evaporative cooler (Patil et al., 2013)

There are some important points to note that indirect evaporative cooling system do not add moisture to the room air stream and humidity level of the room will not increase, hence indirect evaporative coolers can recirculate air in the room (Palmer, 2002).

2.6 Psychrometric Chart

The psychrometric chart is a graphical representation that defines the relationships between the air temperature and relative humidity. Although this chart may look complicated but specific humidity, dew point and vapor pressure can be calculated and state point can also be found in this chart (Bhatia, 2012).

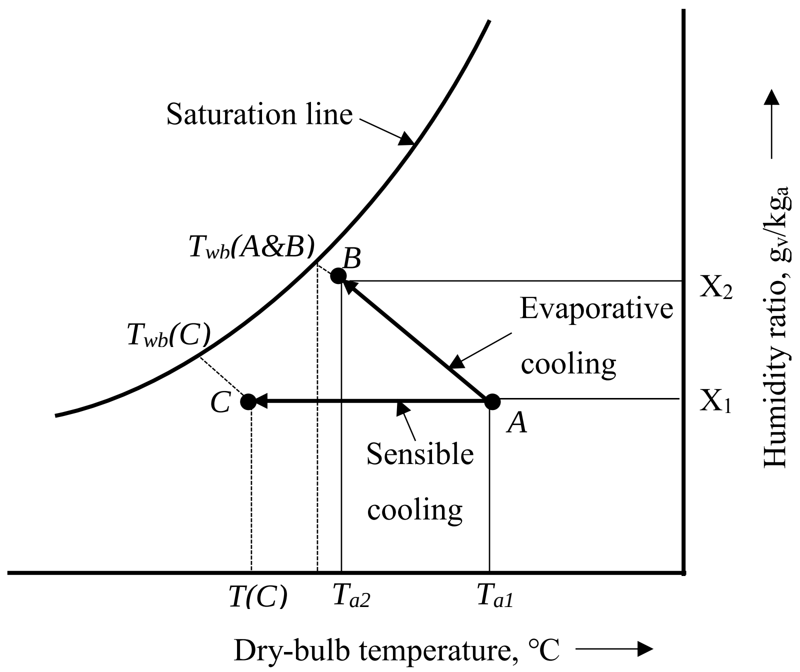


Figure 2.6: Evaporative cooling process in psychrometric chart (He et al., 2015)

The temperature of air is changed from A to C and the humidity ratio is remain constant during sensible cooling process. The dry bulb temperature is decreased by [T (A) – T (C)] at the same time wet bulb temperature is also decreased. The humidity ratio has no changes because there is no addition or loss of moisture to the air. In evaporative cooling process, both dry bulb temperature and humidity of air changes along the line AB which is constant wet bulb temperature. This is considered as adiabatic process where no heat gain or loss as sensible heat is converted to latent in the added water vapor (Robert et al., 2017). The adiabatic process between the warm dry air and water surface can be expressed as follows (Alharbi et al., 2014).

$$(T_{a1} - T_{a2}) + c_v X_1 (T_{a1} - T_{a2}) = (X_2 - X_1)[(T_{a2} - T_w) + h_{fg} \quad \text{Eq. (2.1)}$$

where c_a, T_{a1} and T_{a2} are dry air specific heat, inlet and outlet temperature respectively; c_v, X_1 , X_2, T_w and h_{fg} are the vapour specific heat, inlet moisture content, outlet moisture content, water temperature and water evaporation respectively.

The following equation is to calculate the rate of water consumption required for the evaporative cooling process.

$$\dot{m}_{wv} = \dot{m}_{da} \, (X_2 - X_1) \qquad \text{Eq. (2.2)}$$

where $\dot{m}_{da}$ is the dry air mass flow rate.

The closeness of cooled air can get to the state of saturation can be obtained by calculating the cooling efficiency. The equation of cooling efficiency is defined as follows (He et al., 2015).

$$\eta = \frac{T_{a1} - T_{a2}}{T_{a1} - T_{wb}} \times 100\% \qquad \text{Eq. (2.3)}$$

where T_{wb} is the wet bulb temperature of cooled air.

2.7 Spray Cooling

Spray cooling is a type of cooling method through evaporation. Spray cooling involving on phase change mechanism that able to remove heat (Yang et al., 2012). There are many cooling techniques had been discussed and investigated, spray cooling has been found to be one of the most efficient cooling technique. The advantages of spray cooling are it is lightweight, compact and has low surface temperature difference and reduced coolant flow rate (Zhang et al., 2015), it also has less flow rate demand, high heat dissipation capacity, low superheat, no temperature supershoot and no contact thermal heat with the heating surface (Wenlong et al., 2016).

Spray cooling has a number applications that is widely used in various field such as continuous casting process, electronics thermal control and metal quenching process. Spray cooling also acts as an important role in fire protection. A fire sprinkle system is operated by a discharge of water through the nozzle to the surrounding air to suppress or control the fire. The tiny water droplets have large surface area which in contact with unsaturated surrounding air encourages evaporation to occur. The heat release rate of the fire can be controlled and the spread of fire can be avoided by absorbing the high latent heat by water droplets during evaporation (Zhibin Yan et al., 2011).

Other than that, application of spray cooling is used in electronic devices such as avionic electronic equipment. Researchers conducted studies about spray cooling on electronic devices and focused on the experiment measurement of the critical heat flux (CHF) and heat transfer as a factor of affecting the efficiency of spray cooling. Spray cooling can take away the maximum heat per unit time and per unit area which is known as CHF (Zhang et al., 2015).

In steel industry, water cooling method is common with number of applications. For instance, relatively dilute spray used in the continuous casting process, higher pressure and denser sprays to cool mill rollers and laminar water 'curtains' or coarse sprays placed between rolling stands to cool metal sheet in the hot strip mill (Sharief et al., 2006).

There is several method to evaluate the performance of spray cooling. One of the method is computational approach by Computational Fluid Dynamic (CFD). CFD can evaluate the effectiveness of the spray cooling in terms of size and optimize the cooling system (Guechi et al., 2013). First thing to do by computational approach is to develop a numerical model in order to predict the heat transfer with phase change between a heated surface and a two-phase impinging jet. According to Yu Hou et al. (2013) research, for making it success there is some harsh problem to tackle such as film formation, droplet breakup, collision, coalescence and evaporation. For two-phase or multiphase flows, the dynamics equations and problems between the phases by jump relations at the interface can be solved by CFD simulation. The simulation is including the exchanges of mass, energy and momentum between the phases. For the numerical calculation of multiphase flows, there are two approaches which are the Euler Lagrange approach and the Euler-Euler approach (Vallet and Borghi, 2011).

The ratio of the CHF to the heat transfer capability of the fluid can determine the efficiency of spray cooling. The spray efficiency is generally defined as

$$\eta = \frac{\dot{q}"}{\dot{m}"[c_{p,l}(T_{sat} - T_{spray}) + h_{fg}]} \quad \text{Eq. (2.4)}$$

This equation is refer to the sensible heating of liquid from the spray impact temperature (it should be noted that this temperature is different from the temperature of liquid exiting the spray nozzle) to the saturation temperature, T_{sat} and the heat required to vaporize the liquid. However, this equation does not define the heat transfer to the vapor. There is another more appropriate definition to determine the efficiency spray cooling, since the vapor generated at the surface can be superheated to the wall temperature (Kim, 2007).

$$\eta = \frac{\dot{q}"}{\dot{m}"[c_{p,l}(T_{sat} - T_{spray}) + h_{fg} + c_{p,v}(T_{wall} - T_{sat})]} \quad \text{Eq. (2.5)}$$

The performance of spray cooling is influenced by many factors. These factors are important to optimize spray parameter in heat transfer mechanism. The factors can be categorised into four: spray characteristics, surface characteristics, fluid characteristics and the external environment characteristics.

Spray characteristics are including droplet velocity, droplet Sauter mean diameter, droplet flux, spray flow rate and spray angle. All these spray characteristics are related to fluid characteristics such as inlet pressure and ambient temperature which have an impact on heat transfer. For spray characteristics measurement, Phase Doppler Anemometer (PDA) system is used and it is an accurate and efficient interference-free measurement technology. There is two important dynamics parameters droplet axial velocity, u and Sauter mean diameter, d_{32} are described as follow:

$$u = \frac{1}{n}\left(\sum_{t-\Delta t/2}^{t+\Delta t/2} \sum_{i=1}^{n} u_i\right) \qquad \text{Eq. (2.6)}$$

$$d_{32} = \frac{\left(\sum_{t-\Delta t/2}^{t+\Delta t/2} \sum_{i=1}^{n} d_i^3\right)}{\left(\sum_{t-\Delta t/2}^{t+\Delta t/2} \sum_{i=1}^{n} d_i^2\right)} \qquad \text{Eq. (2.7)}$$

The discharged droplet is the crucial element for spray cooling and the main reason that affecting the performance. Nozzle structure and spray conditions are related controlled variable and the spray characteristics, including droplets diameter, velocity and distribution angle are all controllable. In order to achieve efficient heat transfer in spray system, tiny and uniform droplets with high velocity plays an important role (Wenlong et al., 2016).

2.8 Factors Affecting Rate of Evaporation

Evaporative cooling can reduce the temperature and increase in relative humidity of air. There are several factors that will affect the performance of evaporative cooling and all these factors are interact with each other. The limitations are included from the design of evaporative cooling system itself to the environmental condition. The main factors of affecting the performance of evaporative cooling are discussed as follows.

2.8.1 Air Movement

The rate of evaporation of water is influenced by the air movement or air velocity by natural wind or fan. The humidity of the air is raised while the evaporation process is occurring. If the humid air remains in state, the rate of evaporation will decrease. Therefore, it is important that the airborne water particles that are in the air can be swept away easily by high velocity stream of air. When the humidity of the air in the particular region is reduced and replaced with drier air, this will allow more water molecules to dissipate into the air (Liberty et al., 2013).

Zhao et al. (2008) introduced a new counter-flow heat and mass exchanger used in the indirect evaporative dew point cooling system. A numerical simulation was carried out to optimise the operating condition of the exchanger and the results indicated that the air velocity affects the cooling effectiveness. It also claimed that a counter-flow arrangement is better than cross-flow because it can create higher temperature difference between the adjacent airstreams. It was found that the wet bulb effectiveness can be achieved up to 130% and dew point effectiveness of up to 90%.

2.8.2 Wet Media Material

The selection of media is imperative for high performance of evaporative cooling system. Wet media in an evaporative cooler usually made up from porous and permeable material with large surface area to hold liquid water (Boukhanouf et al., 2015). In order to select a wet media material few elements must be considered which is their effectiveness, availability, cost, safety and environmental factors according to Wanphen and Nagano (2009). Lately, IEC system cooling application in building is focusing on porous ceramic due to its durability, accessibility, good thermal conductivity, availability in different porosities, sufficient water-retaining capacity and high contact surface between solid and fluid phases (Boukhanouf et al., 2015). Riffat and Zhu (2004) applied porous ceramic material as the cooling source for indirect evaporative cooler.

2.8.3 Relative Humidity of the Air

Relative humidity of the air is the measurement of the amount of water vapor in the air expressed as a percentage of the amount needed for saturation at a specific temperature. The air is capable of holding a portion of the total quantity of water when the relative humidity of the air is low. Under this condition, the air is capable of absorbing additional moisture, hence with all other conditions favourable, the rate of evaporation will be higher, and thus the efficiency of the evaporative cooling system is expected to be higher (Liberty et al., 2013).

According to Sirelkhatim and Emad (2012), during the experiment, the cold water supplied through the cooling coil that consists of heat exchanger. When the outer surface of the coil is equal to the dew point temperature of the outdoor air, a sensible cooling process exists which means the humidity ratio is remained constant.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter describes the methodology used in this project to obtain comparison data for the three types of evaporative cooling system in order to choose the highest efficiency of the evaporative cooling system. The flow chart of the project is shown in Figure 3.1. This project starts by studying the working principle of evaporative cooling system with the existing evaporative cooling systems. Installation of a software called PicoLog Recorder to collect the experimental result with data logger. Afterwards, analysis the existing different types of evaporative cooling system on their efficiency. Improvement on the existing evaporative cooling systems need to be done and the final experimental result is collected. Comparison of the efficiency on three types of evaporative cooling system by using the data collected based on the temperature difference.

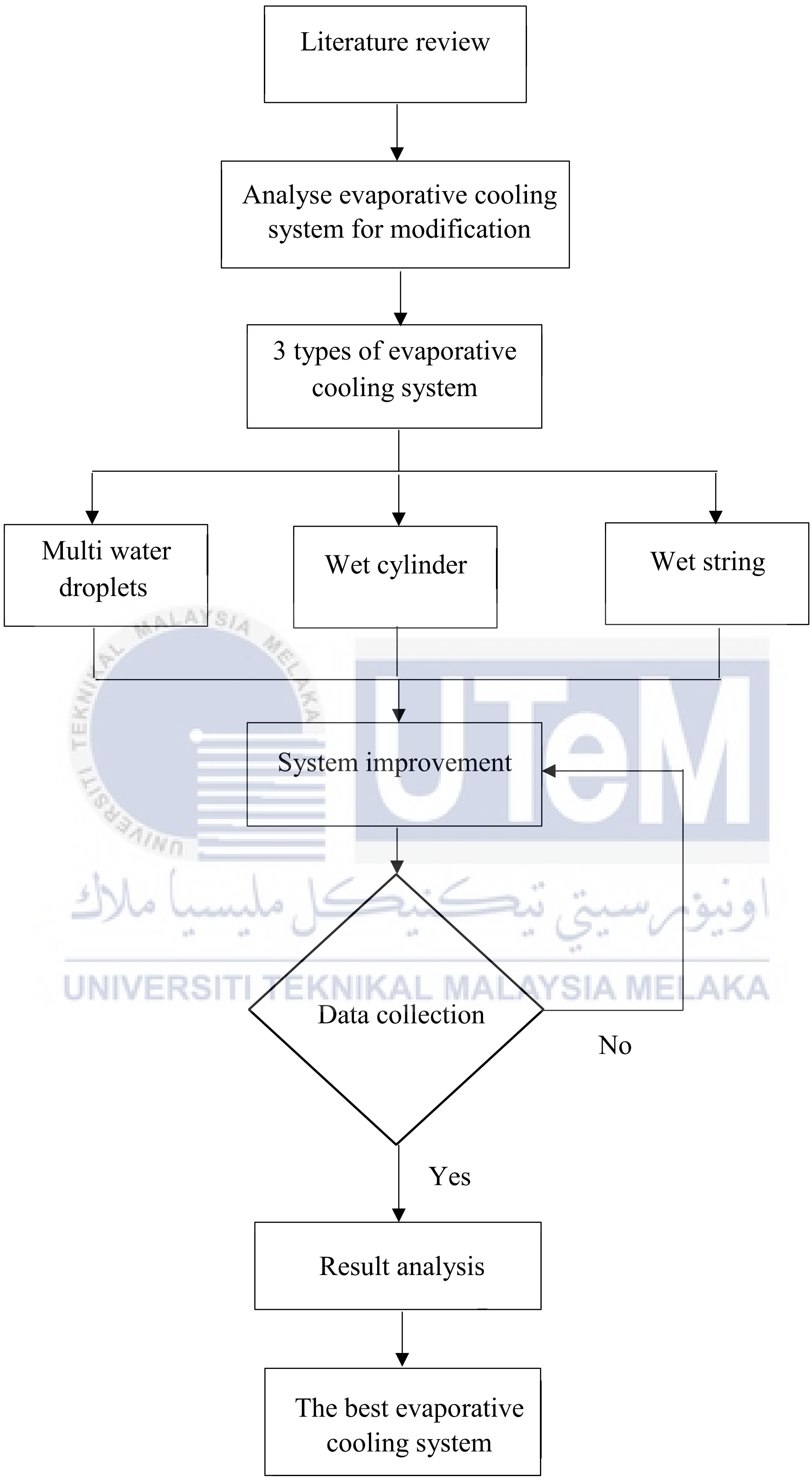


Figure 3.1: Flow chart of the methodology

3.2 General Experimental Setup

The schematic diagram of general experimental setup for existing evaporative cooling system is shown as Figure 3.2. The system can be divided into three section: fan section, cooling section and air straightener section. The frame of the system is made from steel hollow square bar with size 25mm × 25mm × 1mm.

For air straightener section, plastic straws were used to act as air straightener to make sure the air flow is in axial direction. Metal net was used to hold all the plastic straws in orderly manner. For fan section, electric box fan was used to draw the outdoor air into the system. Another important component in this system is the frame wall, polystyrene foam acts as the frame wall to insulate the system. By doing this, the system will create an insulator around the frame which reduce the amount of heat entering the system. For cooling section, a water tank, water pump and hose were prepared to supply water to the configuration tank.

Thermocouple and data logger were used to collect the data of air temperature. Aquarium water pump was used to pump water from the water tank through the hose to the configuration tank. In order to increase the performance of the evaporative cooling system there were several improvements were made.

In cooling section, there are three different types of configuration tank with different approaches were used. The arrangement of wet cylinder, wet string and multi water droplet on different configuration tanks are shown in Figure 3.3, 3.4 and 3.5 respectively. The modifications made on each type of evaporative cooling system will be discussed in the following.

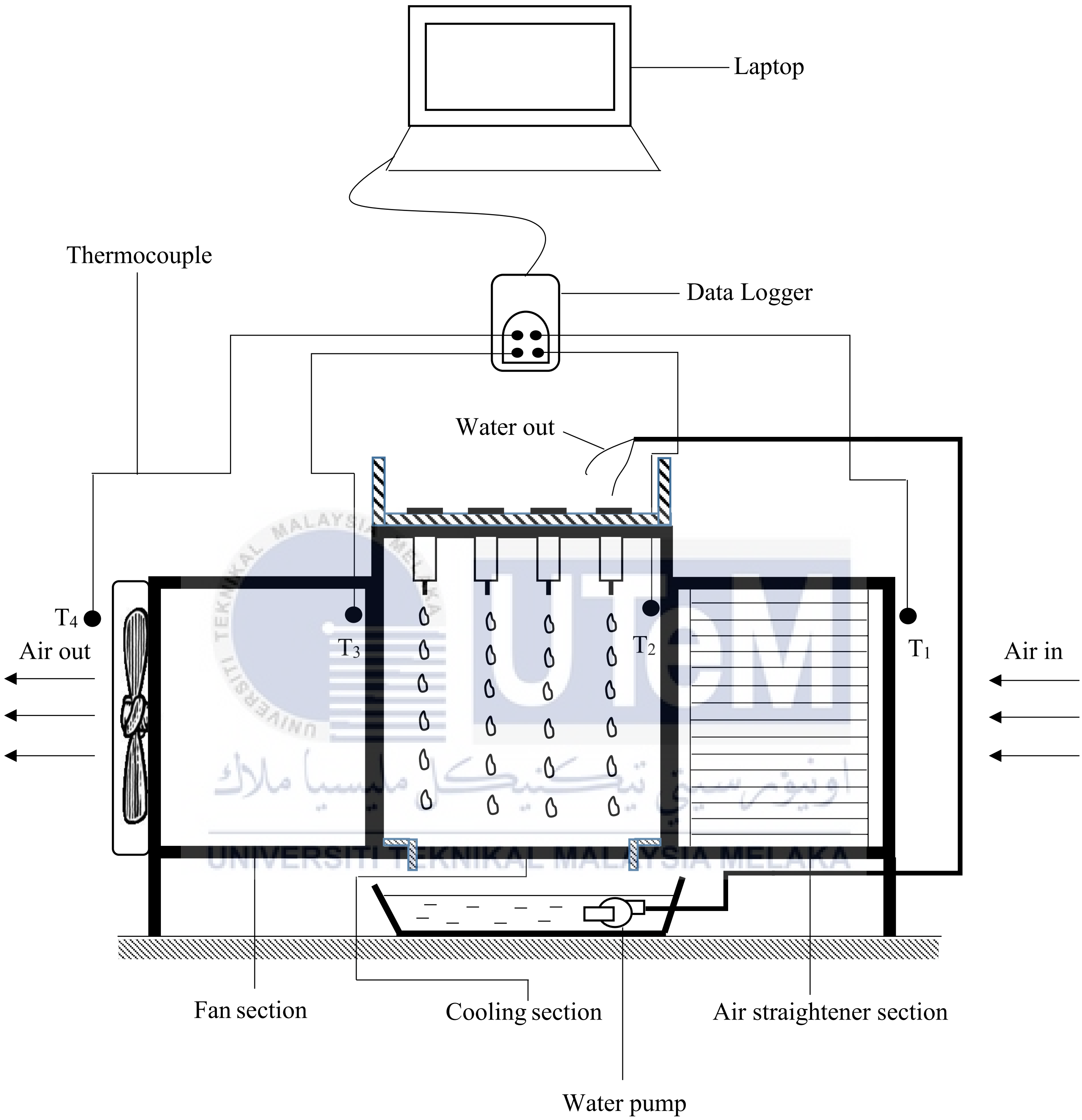
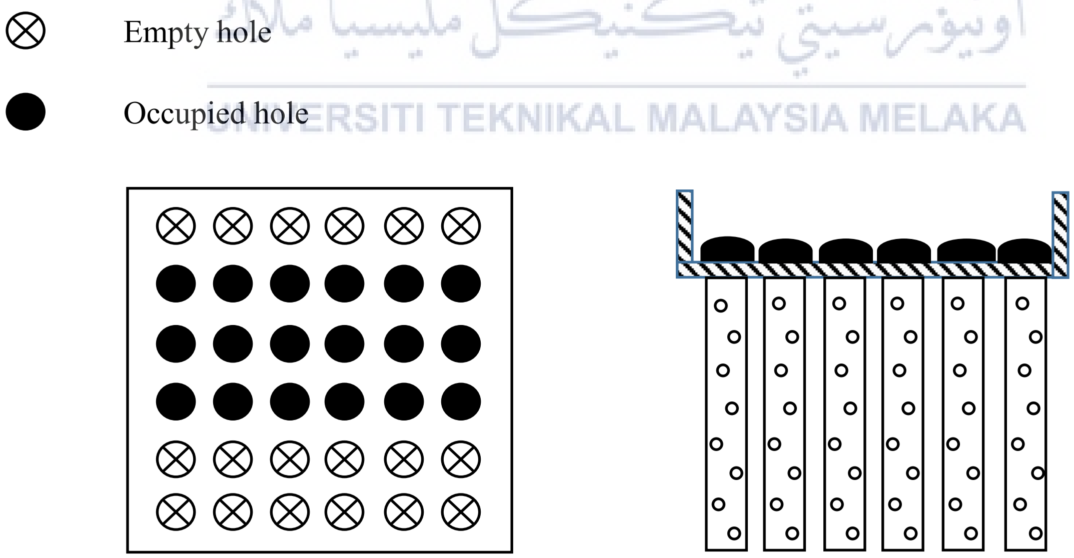


Figure 3.2: Schematic diagram of experiment setup

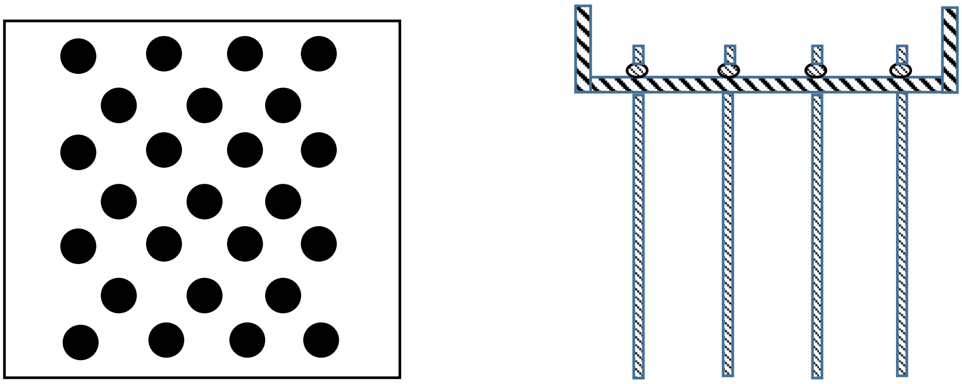
There were four thermocouples placed at four different positions. The first thermocouple, T_1 was placed at the beginning of air straightener section (inlet of the system). The second thermocouple, T_2 was placed at the end of air straightener section. The third thermocouple, T_3 was placed at the end of cooling section and the last thermocouple, T_4 was placed at the end of fan section.

The results are illustrated by comparison graph that will be discussed in Chapter 4. The results are discussed and focused on the temperature difference between inlet air (T_1) and outlet air (T_4) and the temperature difference between air after straightener (T_2) and air after cooling section (T_3). The performance of the evaporative cooling system is evaluated based on the temperature difference between inlet air (T_1) and outlet air (T_4). The larger the temperature difference between inlet air (T_1) and outlet air (T_4), the higher the performance of the evaporative cooling system.



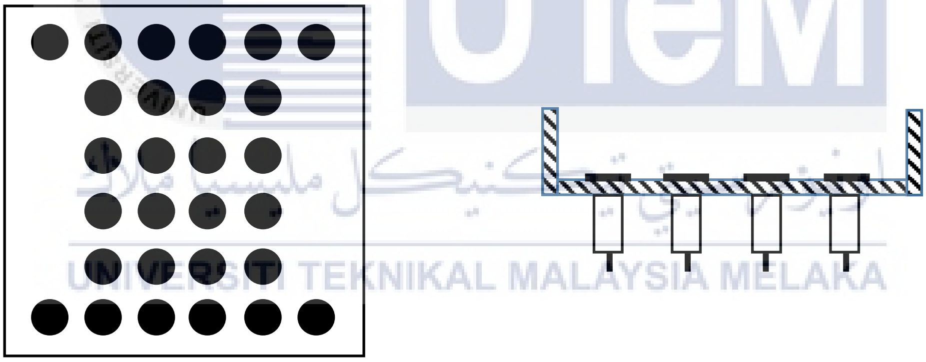
(a) (b)

Figure 3.3: (a) Top view of arrangement of wet cylinder on configuration tank, (b) Side view of wet cylinder



(a) (b)

Figure 3.4: (a) Top view of arrangement of wet string on configuration tank, (b) Side view of wet string



(a) (b)

Figure 3.5: (a) Top view of arrangement of wet syringe on configuration tank, (b) Side view of wet syringe

3.2.1 Wet Cylinder Evaporative Cooling System

The wet cylinder configuration tank was fabricated using galvanised metal sheet. The configuration tank was designed with holes on it in order to insert cylinder to allow water to flow through it. 18 wet cylinder and used cloth acted as the cooling media in this evaporative cooling system. PVC pipes with 25 mm diameter were cut into 54 mm in length and drilled 18 holes on each of the PVC pipe with 10 mm diameter. Used cloth was added inside every PVC pipe to act the wet media when water is absorbed by the used cloth. Figure 3.6 shows the wet cylinder before modification.

Figure 3.6: Wet cylinder evaporative cooling system

The wet cylinder was drilled 18 holes on every PVC pipe before modification as shown in Figure 3.6. After modification refer to Figure 3.7, there were 18 more holes were added on every PVC pipe and made sure every PVC pipe was drilled with the same pattern of hole. By doing this, there was more water flow out of the cylinders and form a water layer to undergo evaporation and cool the air.

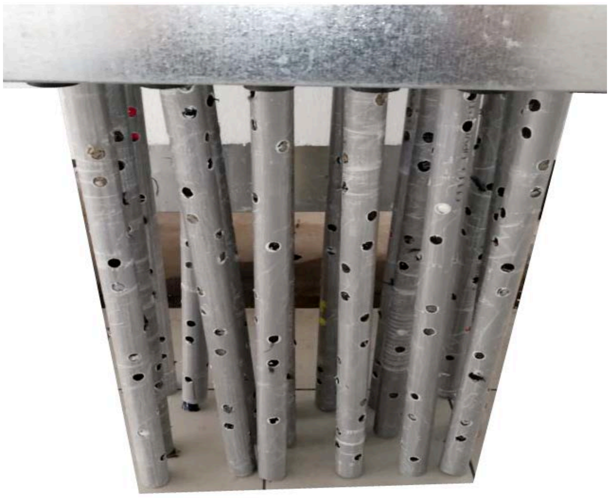


Figure 3.7: Wet cylinder evaporative cooling system after modification

The arrangement of the wet cylinder was placed from the second row to the fourth row in order to achieve a constant heat transfer in one designated area as shown in Figure 3.8. In Figure 3.9, silicone sealant was used to seal the wet cylinder to avoid leaking.

Figure 3.8: Configuration tank with wet cylinder

Figure 3.9: Wet cylinder with silicon sealant

3.2.2 Wet String Evaporative Cooling System

For wet string configuration tank also fabricated by using galvanised metal sheet. In this case, the configuration tank was designed with holes in order to insert the strings. There were 25 strings with length 500 mm and diameter 9 mm were placed at the cooling section. The strings were tied with knot to prevent it from slipping away at the hole of configuration tank. The strings would absorb water from the configuration tank and the wetted strings would eventually become the cooling media in this evaporative cooling system. Figure 3.10 shows the wet string before modification.

Figure 3.10: Wet string evaporative cooling system

After modification, cotton string from mop was used as cooling media to replace the original nylon string as shown in Figure 3.11. There were 25 cotton strings that were cut with the same length and diameter as the original one to avoid experimental error. Cotton string is considered as a good water absorbent so more water could be absorbed fully by the cotton string throughout the whole experiment. The wet strings were tied with a knot to prevent it from slipping as shown in Figure 3.12.

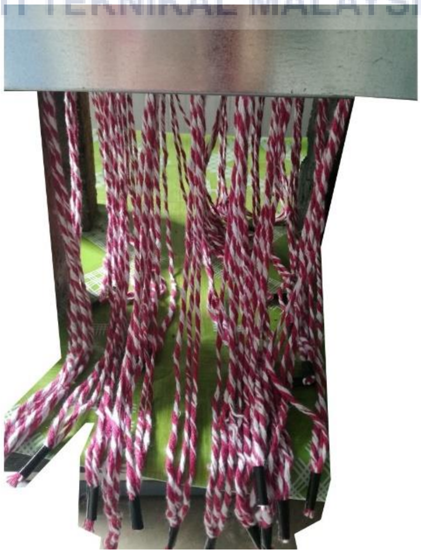


Figure 3.11: Wet string evaporative cooling system after modification

Figure 3.12: Configuration tank with wet string

3.2.3 Multi Water Droplets Evaporative Cooling System

The droplet generator configuration tank was fabricated using galvanised metal sheet. The configuration tank was designed with holes on it in order to insert syringe to let water flow in droplet. 30 ml Luer slip type syringe was used in the droplet generator but the piston was removed to allow water to flow in easily. The length of the syringe is 9cm long beneath the configuration tank as shown in Figure 3.13. The hole size at the tip of the syringe is too big for water to flow in droplet manner. So, modelling clay was used to manipulate the size of the hole at the tip by putting some of the modelling clay at the tip to block the existing hole. Then, slowly inserted a needle at the tip of the syringe to create a small hole to allow water to come out in form of droplet.

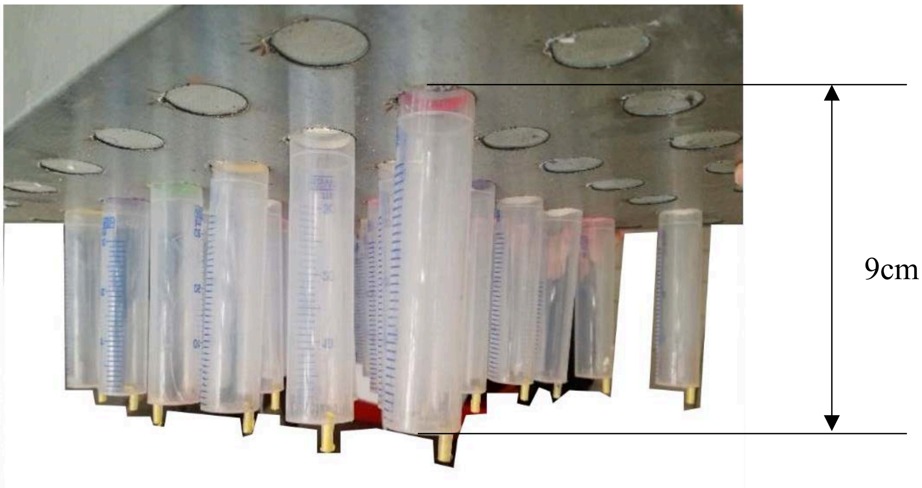


Figure 3.13: Multi water droplet evaporative cooling system

Modification was made on the multi water droplet evaporative cooling system by reducing the length of the syringe to 5cm long beneath the configuration tank as shown in Figure 3.14. By doing this, there were larger surface of water droplet expose to the air. In Figure 3.15 shows, the syringes were sealed with plasticine to prevent leaking.

Figure 3.14: Multi water droplet evaporative cooling system after modification

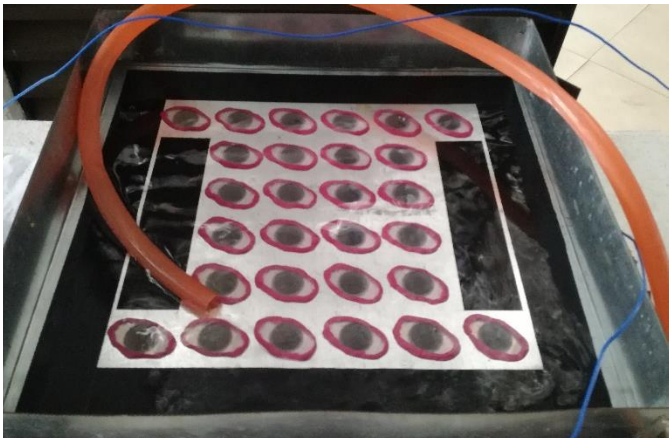


Figure 3.15: Configuration tank with wet syringe and sealed with plasticine

3.3 Summary of Modification

Table 3.1 shows the summary of modifications and the reason on each type of evaporation cooling system.

Type of evaporative cooling system	Modification	Reason of modification
Wet cylinder	• Sealed with silicone sealant • Made 2 time more holes than before • Rearranged the cylinder arrangement to 3 rows in the middle	• Prevent leaking • Allow more water flow • Achieve constant heat transfer
Wet string	• Changed the nylon string to cotton string	• Absorb more water
Multi water droplet	• Sealed with plasticine • The syringe was pulled out and left 5 cm from the configuration tank to the end of the syringe	• Prevent leaking • Allow more water surface area for evaporation

Table 3.1: Modification on 3 approaches of evaporative cooling system

3.4 Temperature Measurement

The instruments that used to measure the temperature are thermocouple and data logger. Data logger is a temperature measuring and recording device that can simply plug in the data logger into a USB port on computer and plug in the thermocouples. The model of data logger used in this project is USB TC-08 from Pico Technology which consists of 8 number of channels and the operating temperature is from 0 to 50°C. The type of thermocouple used is type K. Type K is the most common type of thermocouple because it is accurate, reliable, inexpensive, and has a wide temperature range.

Before the experiment, a software called PicoLog Recorder was installed in computer to measure and record the temperature. In this experiment, 4 number of type K thermocouples were used and placed at different position. The temperature of air at the inlet of the apparatus (air in), air after the air straightener, air before entering the fan and air at the outlet of the system (air out) were measured and recorded in the duration of 1 hour with 10 second interval of time. Figure 3.16 shows the sample result from PicoLog Recorder.

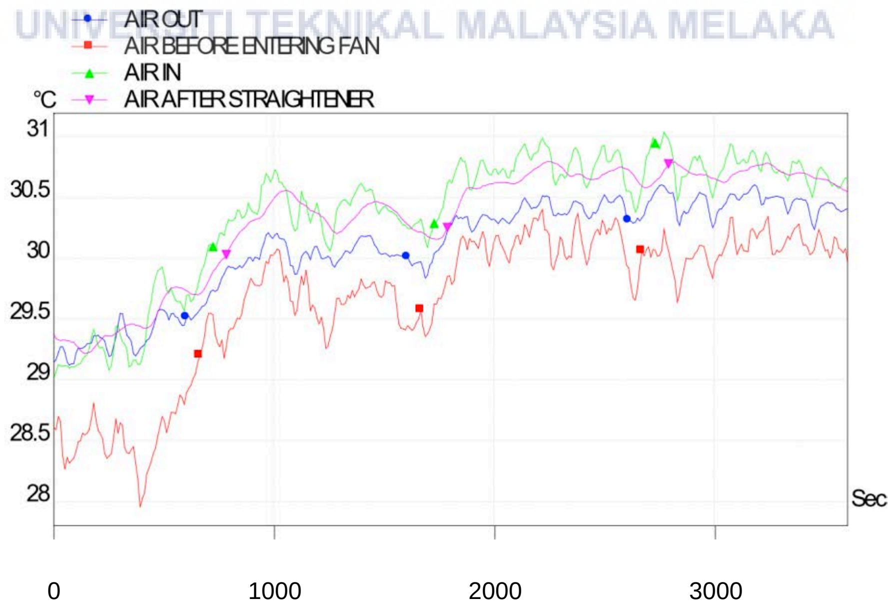


Figure 3.16: Sample result from PicoLog Recorder

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

In this chapter, the analysis of the data collected are present in line graph. The content of the line graph including the temperature difference of air before and after modification and the comparison graph before and after modification for all three approaches of evaporative cooling system. The performance of the three approaches of evaporative cooling system will be discussed based on the results obtained.

4.2 Results and Discussion

4.2.1 Modification Effect on Wet Cylinder Evaporative Cooling System

Figure 4.1 shows the temperature difference between inlet air and outlet air (T_1-T_4) of wet cylinder evaporative cooling system before and after modification. Figure 4.2 shows the temperature difference between air after straightener and air after cooling section (T_2-T_3) of wet cylinder evaporative cooling system before and after modification.

Temperature difference (T_1-T_4) for wet cylinder evaporative cooling system

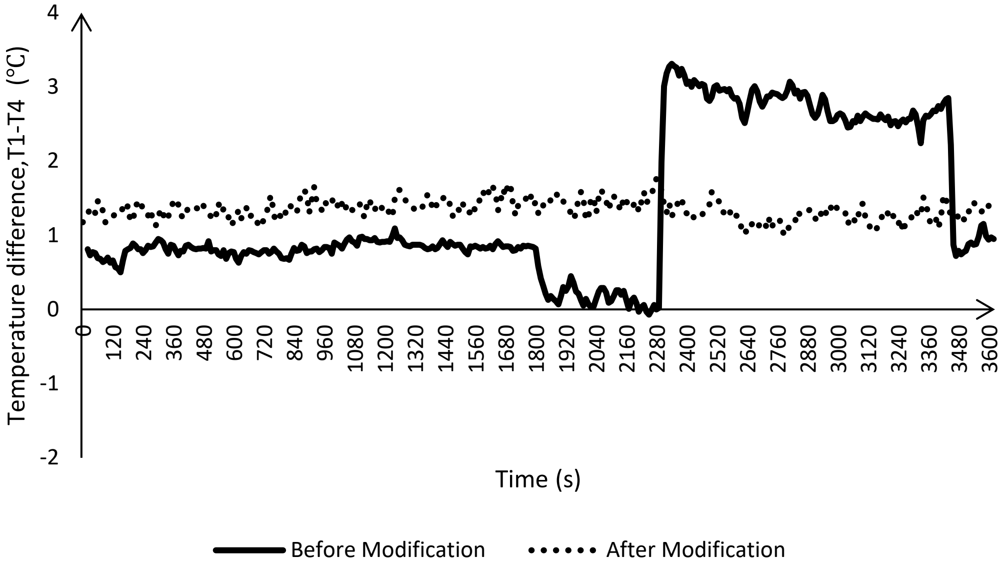


Figure 4.1: Temperature difference (T_1-T_4) comparison for wet cylinder evaporative cooling system before and after modification

Temperature difference (T_2-T_3) for wet cylinder evaporative cooling system

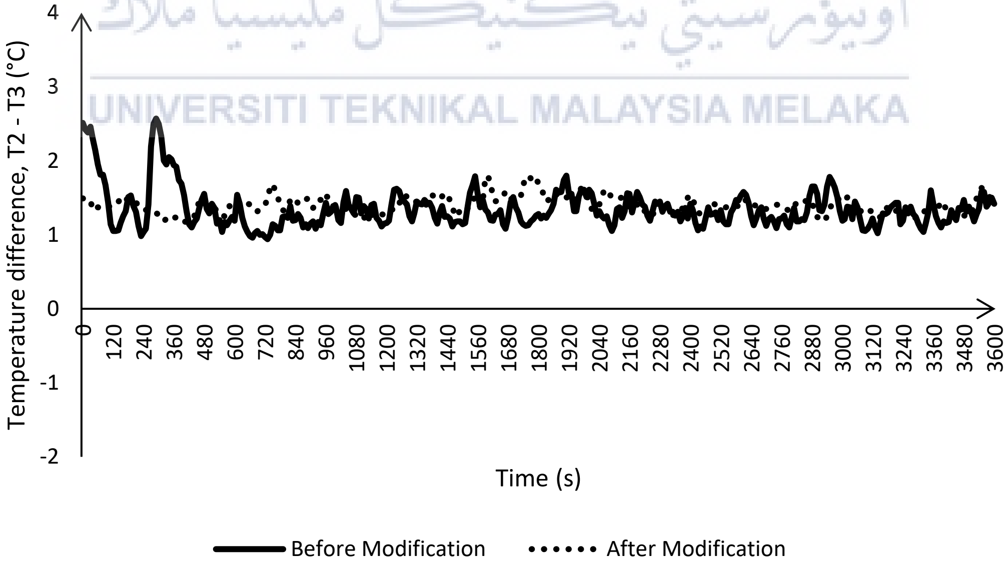


Figure 4.2: Temperature difference (T_2-T_3) comparison for wet cylinder evaporative cooling system before and after modification

According to Figure 4.1, the temperature difference between inlet air and outlet air of wet cylinder evaporative cooling system before modification at time between 2280s to 2320s has a dramatically plunge from 1.98°C to 3.31°C. The highest temperature difference is 3.31°C at 2320s and the lowest is -0.07°C at 2250s.

After modification, the wet cylinder evaporative cooling system has the maximum temperature difference of 1.76°C at 2280s and the minimum temperature difference of 0.99°C at 2790s. However, the data obtained is considered stable throughout the whole experiment.

Before modification, the fluctuation occurs at time between 1800s to 2280s and 2280s to 2320s most probably is due to the malfunction of thermocouple. Thermocouple has less stability because thermoelectric voltage developed along the length of the thermocouple wire may be influenced by corrosion. The temperature difference from one end of the wire to the other is the sum of all the voltage differences along the wire from end to end, it is also known as thermoelectric voltage. Hence, the stability of thermocouple may change 1-2°C every year.

The next experiment was conducting after the modification on wet cylinders were made. Every equipment and electronic device was checked and made sure no error occur. All the 18 wet cylinders were drilled 18 more holes in order to make more flows of water. The wet cylinders were arranged in 3 rows consecutively to prevent loss of water. Besides, the wet cylinders were sealed by silicone sealant to avoid leaking at the configuration tank.

Based on Figure 4.1, the overall temperature difference between inlet air and outlet air of wet cylinder evaporative cooling system after modification is more consistent compare to the temperature difference between inlet air and outlet air of wet cylinder evaporative cooling system before modification. At the time before 2280s, the temperature difference between inlet air and outlet air of wet cylinder evaporative cooling system after modification is larger. The minimum temperature difference also increased from -0.07°C to 0.99°C. The results obtained have proven that making more flows of water can increase the rate of evaporation and the overall cooling effect.

Based on Figure 4.2, before modification the maximum temperature difference between air after straightener and air after cooling section is 2.57°C at 290s while the minimum temperature difference between air after straightener and air after cooling section is 0.94°C at 730s.

After modification the temperature difference between air after straightener and air after cooling section has the maximum temperature difference of 1.80°C at 1780s and the minimum temperature difference of 1.17°C at 410s.

In this case, the temperature difference between air after straightener and air after cooling section after modification has no significant difference. However, from the beginning of the experiment until 120s there is a sharp decrease in the graph, this is due to the instability of air flow inside the system in the beginning of the experiment.

4.2.2 Modification Effect on Wet String Evaporative Cooling System

Figure 4.3 shows the temperature difference between inlet air and outlet air (T_1-T_4) of wet string evaporative cooling system before and after modification. Figure 4.4 shows the temperature difference between air after straightener and air after cooling section (T_2-T_3) of wet string evaporative cooling system before and after modification.

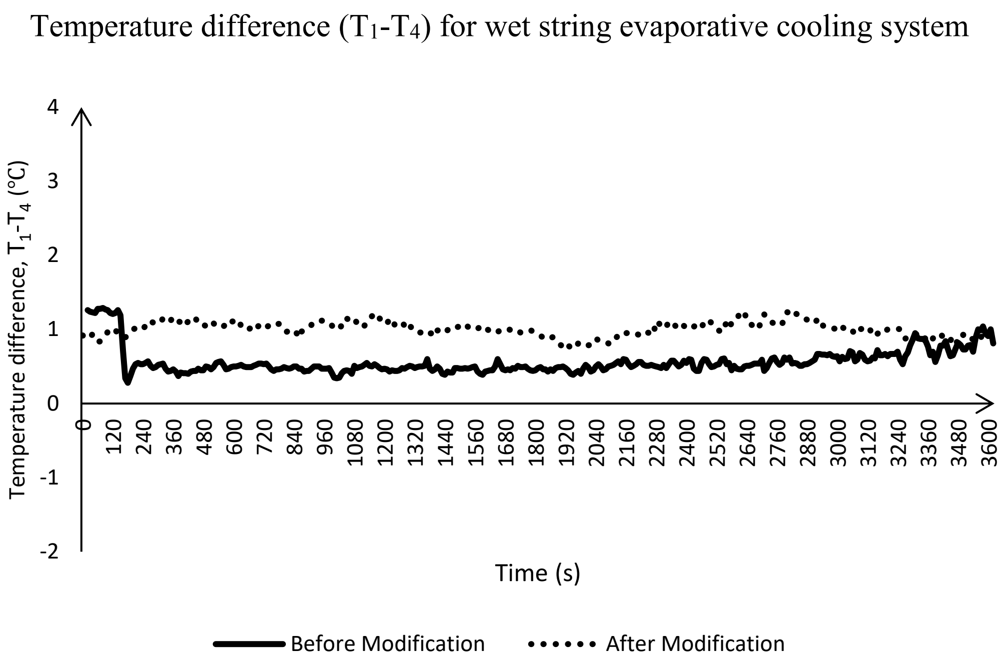


Figure 4.3: Temperature difference (T_1-T_4) comparison for wet string evaporative cooling system before and after modification

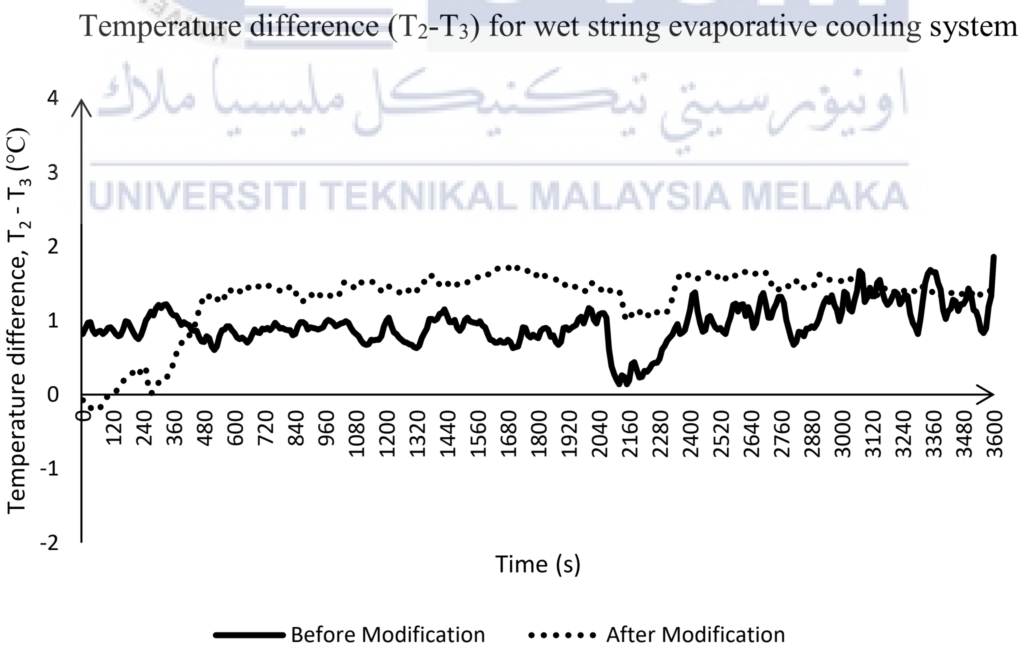


Figure 4.4: Temperature difference (T_2-T_3) comparison for wet string evaporative cooling system before and after modification

According to Figure 4.3, the temperature difference between inlet air and outlet air before modification is declined significantly from 1.26°C at 120s to 0.28°C at 160s. The highest temperature difference is 1.29°C at 60s and the lowest is 0.28°C at 160s. The significant decline at 120s is due to wrong experimental set up. Thermocouples were placed at four different position on the evaporative cooling system, but due to inappropriate method was used, the thermocouples were moving from the original position. Hence, the data collected consists of error which shows large decline on the line graph.

After modification wet string evaporative cooling system has the maximum temperature difference goes up to 1.26°C at 2820s and the minimum temperature difference is 0.74°C at 1960°C. The temperature difference is consistent throughout the whole experiment with only 0.52°C difference between the maximum value and minimum value.

Based on the line graph, the overall temperature difference between inlet air and outlet air of wet string evaporative cooling system after modification is much higher than that of before modification. Even though the maximum temperature difference after modification is less 0.03°C compare to the maximum temperature difference before modification, but the overall performance of wet string evaporative cooling system after modification is better.

Based on Figure 4.4, the maximum temperature difference between air after straightener and air after cooling section is 1.86°C at 3600s while the minimum temperature difference between air after straightener and air after cooling section is 0.14°C at 2120s and 2150s before modification.

The temperature difference of wet string evaporative cooling system has the maximum temperature difference of 1.72°C at 1680s and the minimum temperature difference of -0.22°C at 40s.

4.2.3 Multi Water Droplet Evaporative Cooling System

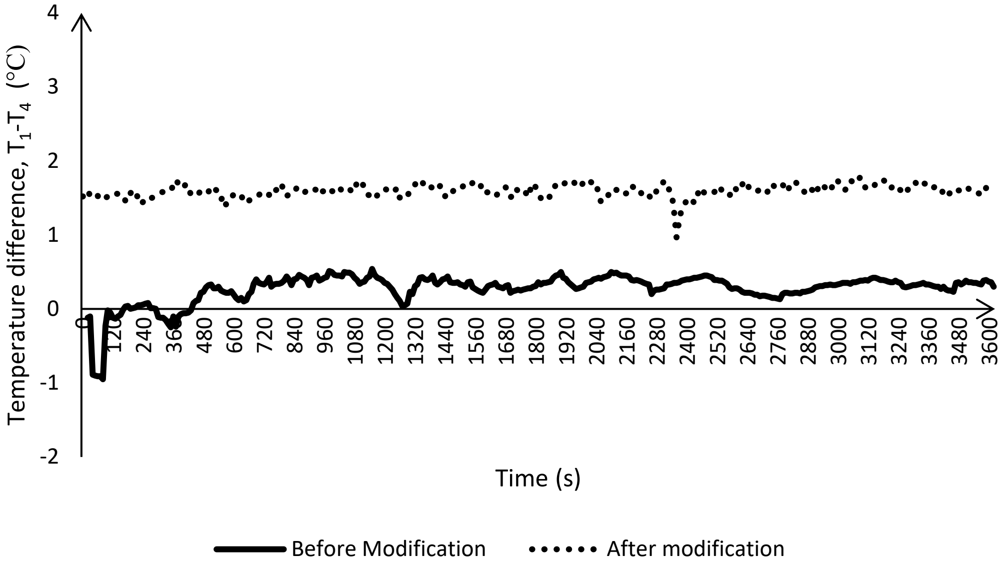
Figure 4.5 shows the temperature difference between inlet air and outlet air (T_1-T_4) of multi water droplet evaporative cooling system before and after modification. Figure 4.6 shows the temperature difference between air after straightener and air after cooling section (T_2-T_3) of multi water droplet evaporative cooling system before and after modification.

According to Figure 4.5, the temperature difference of multi water droplet evaporative cooling system before modification is dropped significantly from -0.1°C at 10s to -0.95°C at 60s. The highest temperature difference is 0.54°C at 1130s and the lowest is -0.95°C at 60s.

After modification the temperature difference between inlet air and outlet air has the maximum temperature difference of 1.78°C at 3090s and the minimum temperature difference is 0.97°C at 2360s. There is a steep decline between 2330s and 2360s.

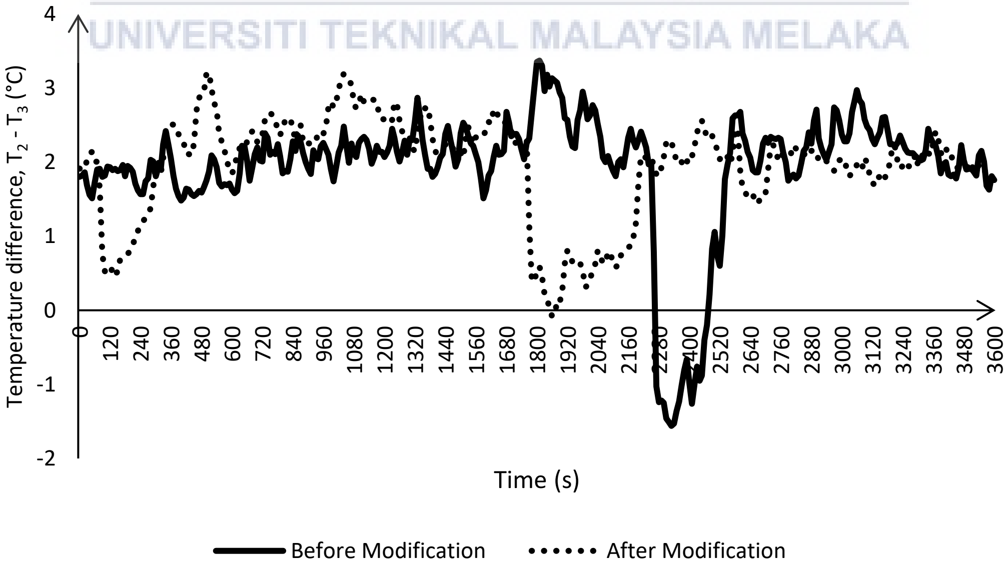
This line graph explains there is significant difference on the temperature difference between before modification and after modification. The maximum temperature difference after modification is 1.78°C and the maximum temperature difference before modification is 0.54°C. The difference between these two values is 1.24°C which means the multi droplet evaporative cooling system had improved after modification.

Temperature difference (T_1-T_4) for multi water droplet evaporative cooling system



Graph 4.5: Temperature difference (T_1-T_4) comparison for multi water droplet evaporative cooling system before and after modification

Temperature difference (T_2-T_3) for multi water droplet evaporative cooling system



Graph 4.6: Temperature difference (T_2-T_3) comparison for multi droplet evaporative cooling system before and after modification

Based on Figure 4.6, the maximum temperature difference between air after straightener and air after cooling section is 3.37°C at 1810s while the minimum temperature difference between air after straightener and air after cooling section is -1.56°C at 2330s. The temperature difference at 2210s is dropped dramatically to -1.56°C at 2330s.

After modification the average temperature difference has the maximum temperature difference of 3.21°C at 510s and the minimum temperature difference of -0.08°C at 1860s. The line graph shows the temperature difference changed unsteadily throughout the whole experiment especially at 1750s, the temperature difference declined sharply to -0.08°C at 1860s.

The experiment was held at outdoor, the surrounding temperature is changing depends on the weather of that day. Although the surrounding temperature would not has much impact on the temperature difference of the evaporative cooling system but the weather do contribute some impacts on the data collected. Weather like thunderstorm would affect the surrounding air flow rate and heat transfer. The strong wind can flow in the evaporative cooling system through the gaps and hence affecting heat transfer. Caragh and Roger (2012) found that from their research the heat loss from the boundary layer is created by increasing the wind speed the nest. The greater the wind speed, the greater the thermal conductivity.

4.2.4 The Effect of Evaporative Cooling on Different Approaches

Figure 4.7 shows the temperature difference between inlet air and outlet air (T_1-T_4) of three different approaches of evaporative cooling system before modification. Figure 4.8 shows the temperature difference between inlet air and outlet air (T_1-T_4) of three different approaches of evaporative cooling system after modification.

Temperature difference (T_1-T_4) for different evaporative cooling approaches

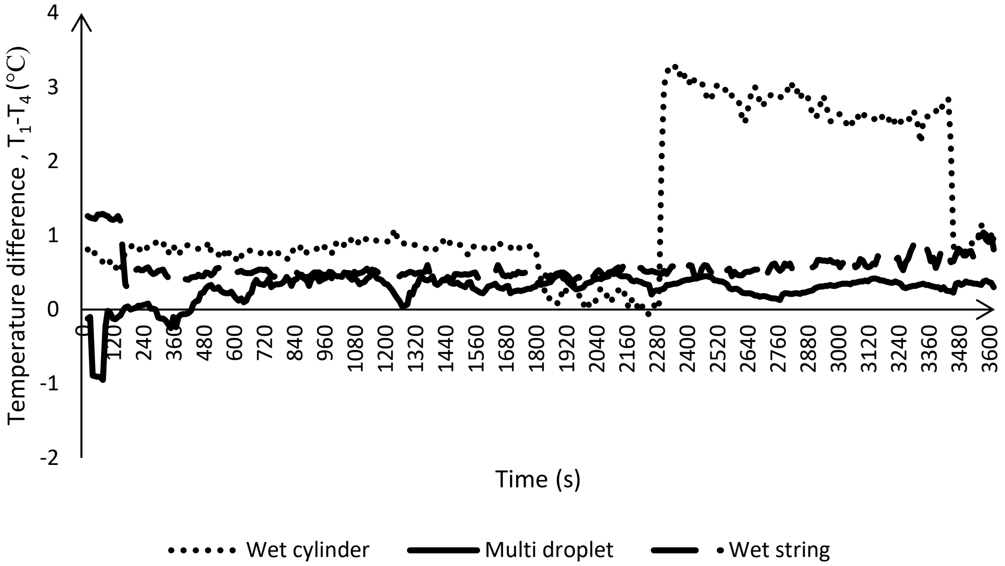


Figure 4.7: Temperature difference (T_1-T_4) comparison for different evaporative cooling approaches before modification

Temperature difference (T_1-T_4) for different evaporative cooling approaches

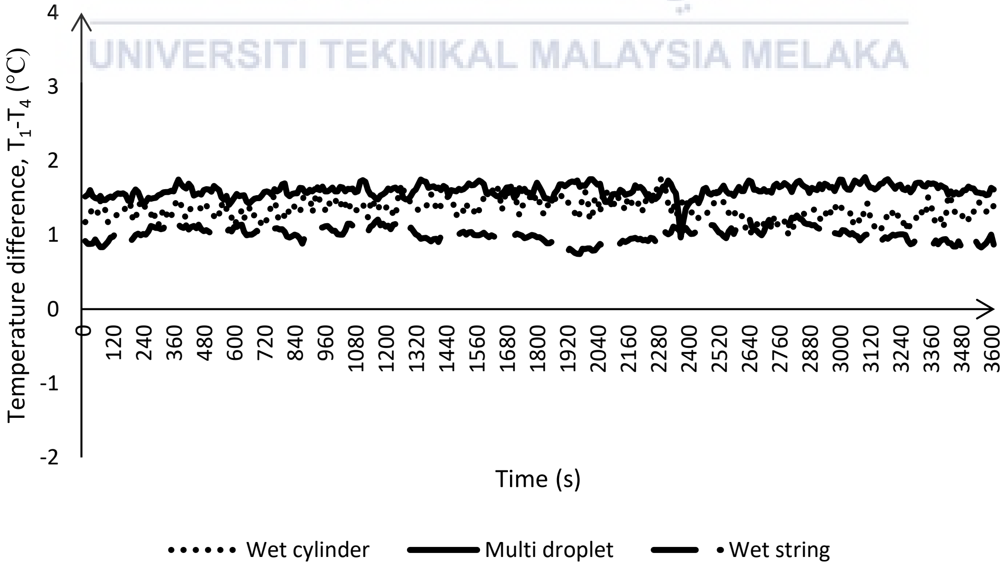


Figure 4.8: Temperature difference (T_1-T_4) comparison for different evaporative cooling approaches after modification

According to Figure 4.7, wet cylinder evaporative cooling system reached the highest temperature difference which is 3.31°C. Next, the second highest temperature difference is 1.29°C by wet string evaporative cooling system and the multi droplet evaporative cooling system has the lowest temperature difference which is 0.54°C.

Before modification wet cylinder evaporative cooling system has the best performance of cooling effect while the next is wet string evaporative cooling system and the last is multi droplet evaporative cooling system.

The graph shows the temperature difference between inlet air and outlet air obtained during 1 hour of experiment on 3 different approaches of evaporative cooling system after modification. According to graph 4.8, multi droplet evaporative cooling system reached the highest temperature difference which is 1.78°C. Next, the second highest temperature difference is 1.76°C by wet cylinder evaporative cooling system and the wet string evaporative cooling system has the lowest temperature difference which is 1.26°C.

After modification, the multi droplet evaporative cooling system has the best performance of cooling effect among the 3 approaches. The length of syringe had adjusted to 5cm and the size of hole was increased by using a needle with 0.6mm diameter. The modification had increased the surface area of the water droplet that expose to the air. The large surface area of water droplet promotes evaporation when expose to heat.

The wet string evaporative cooling system has the lowest temperature difference compare to the other two approaches. Wet string evaporative cooling system was modified by using cotton string to replace the original nylon string to increase the absorption of water. However, based on the experimental results the temperature difference had decreased when the absorption of water by the string had increased. This phenomena may due to the rate of evaporation of water is low when the water is fully absorbed by the cotton string.

Figure 4.9 shows the temperature difference between air after straightener and air after cooling section (T_2-T_3) of three different approaches of evaporative cooling system before modification. According to Figure 4.9, multi droplet evaporative cooling system reached the highest temperature difference which is 3.37°C. Next, the second highest temperature difference is 2.57°C by wet cylinder evaporative cooling system and the wet string evaporative cooling system has the lowest temperature difference which is 1.86°C.

Figure 4.10 shows the temperature difference between air after straightener and air after cooling (T_2-T_3) of three different approaches of evaporative cooling system after modification. According to Figure 4.10, multi droplet evaporative cooling system reached the highest temperature difference which is 3.21°C. Next, the second highest temperature difference is 1.80°C by wet cylinder evaporative cooling system and the wet string evaporative cooling system has the lowest temperature difference which is 1.72°C.

Thermocouples at T_2 and T_3 are nearest to the cooling section. In order to take the data of the temperature of air at the beginning and the end of cooling section, thermocouples at T_2 and T_3 have the chance to sense the temperature of water from the cooling media. Hence, there are fluctuations on the Figure 4.10.

Based on the line graph below, multi droplet evaporative cooling system has the highest temperature difference between air after straightener and air after cooling section among the three approaches which has the same result with the temperature difference between inlet air an outlet air after modification.

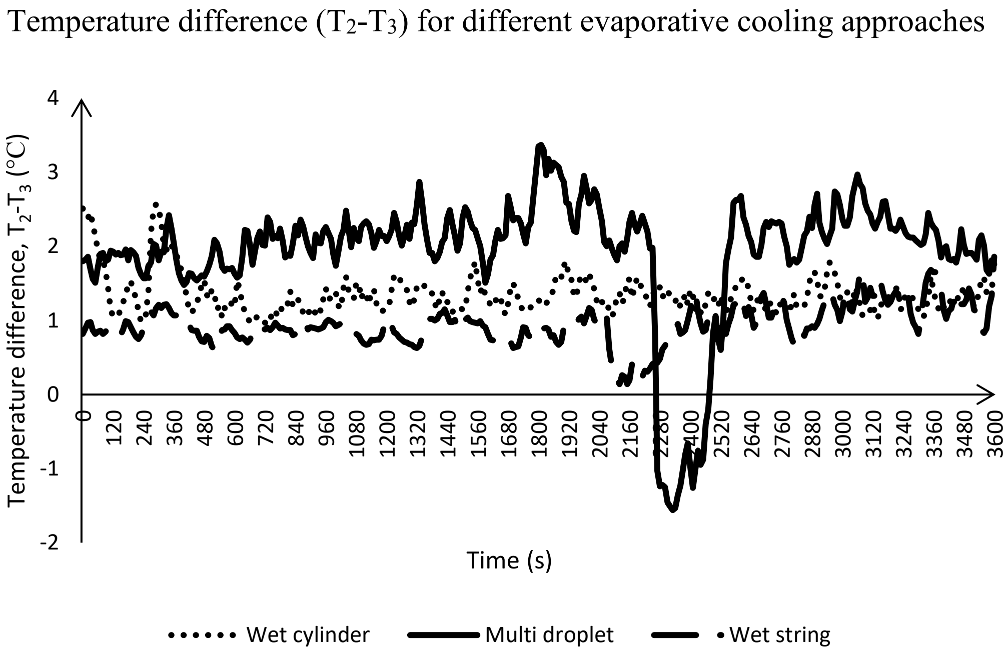


Figure 4.9: Temperature difference (T_2-T_3) comparison for different evaporative cooling approaches before modification

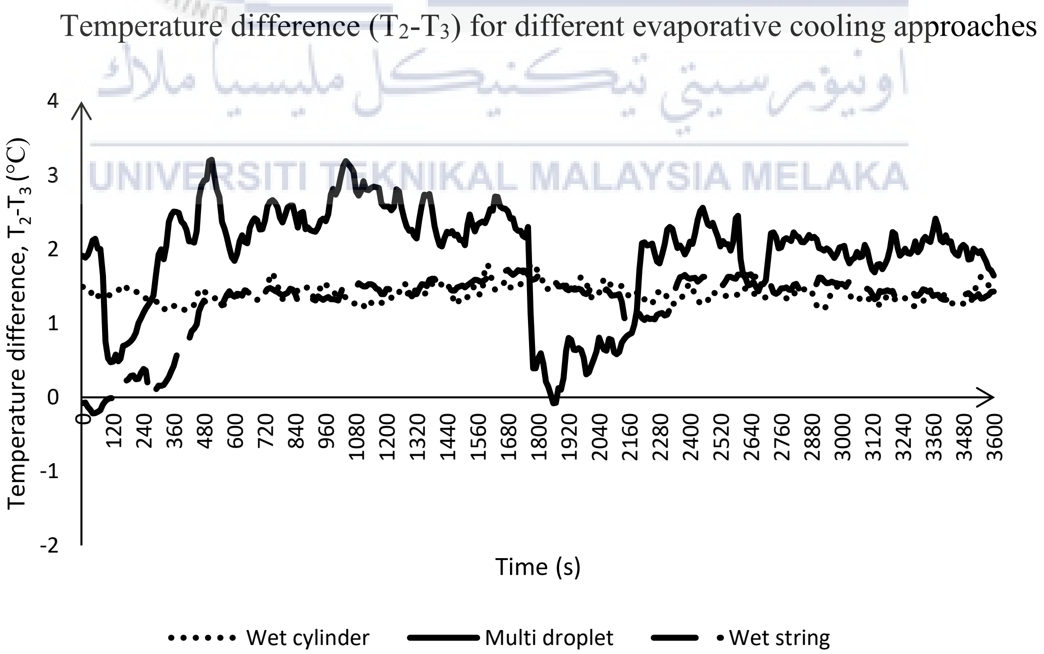


Figure 4.10: Temperature difference (T_2-T_3) comparison for different evaporative cooling approaches after modification

From graph 4.8 and graph 4.10 show that for multi droplet evaporative cooling system the temperature difference between inlet air and outlet air (T_1-T_4) is 1.78°C while the temperature difference between air after straightener and air after cooling section (T_2-T_3) is 3.21°C. For wet cylinder evaporative cooling system, the temperature difference between inlet air and outlet air (T_1-T_4) is 1.76°C while the temperature difference between air after straightener and air after cooling section (T_2-T_3) is 1.80°C. For wet string evaporative cooling system, the temperature difference between inlet air and outlet air (T_1-T_4) is 1.26°C while the temperature difference between air after straightener and air after cooling section (T_2-T_3) is 1.72°C.

The reason of why the line graph is plotted with the temperature difference between air after straightener and air after cooling section (T_2-T_3) versus time is because the temperature within the evaporative cooling system has lower heat loss compare to the temperature of inlet and outlet air. Based on the graph 4.8 and graph 4.10 and the data collected, it can be concluded that, for multi droplet evaporative cooling system, the T_2-T_3 is 80.3% higher than T_1-T_4. For wet cylinder evaporative cooling system, the T_2-T_3 is 2.3% higher than T_1-T_4. For wet string evaporative cooling system, the T_2-T_3 is 36.5% higher than T_1-T_4. Although the temperature difference without heat loss was determined but the temperature difference between inlet air and outlet air should be focused and the performance of evaporative cooling system is based on the temperature difference between inlet air and outlet air (T_1-T_4).

CHAPTER 5

CONCLUSION AND RECOMMENDTION FOR FUTURE RESEARCH

The performance of the evaporative cooling system is mainly depend on the rate of evaporation. The three different approaches of evaporative cooling systems have their own strength. However, the purpose of this research is to compare the performance of the three approaches of evaporative cooling system.

Wet string evaporative cooling system has the poorest performance because the average temperature difference between inlet air and outlet air is the lowest. Although the string had changed to cotton string but the impact on lower the temperature of air is less. Next, the performance of wet cylinder evaporative cooling system is between wet string and multi water droplet evaporative cooling system. Modification on wet cylinder does not make the perfect form of water layer so the average temperature difference between inlet air and outlet air did not reach higher. Multi water droplet evaporative cooling system has the best performance among the three approaches. Since the surface area of water is larger for evaporation in multi water droplet approach, there is more significant cooling effect at the outlet air.

Multi droplet has the similar concept with spray cooling. A spray of small droplets impinging on a hot surface, hence there is an increase of effectiveness of heat transfer causes a cooling mechanism with phase change known as spray cooling (Incropera and Dewitt, 2002). The large surface on small droplets expose to surrounding air causes evaporation. The higher the rate of evaporation, the more significant of cooling effect to the surrounding air.

There are some recommendations for future research including adding ice cube to water, decreasing the size of evaporative cooling system and fabricating nozzle at fan section. By adding ice cube to the water, the water temperature will decreasing. When the water temperature is low this will increase the rate of evaporation because the sensible heat loss by the air is equal to the latent heat gain by the water. Furthermore, the size of the evaporative cooling system affects the performance of the evaporative cooling system. This is because there is less heat loss within the evaporative cooing system, the line graphs in Chapter 4 can explain this. Lastly, nozzle has smaller size than the outlet of the fan section. When air flow through a pipe with a smaller size it will experience a larger air velocity at the same time the temperature of air will decrease.

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