Evaporative Cooler As an Air Inlet Treatment Of Gas Turbine

By

Mohd Eazaq Farommi Bin Hamat (6763)

Dissertation submitted in partial fulfilment of
the requirements for the
Bachelor of Engineering (Hons)
(Mechanical Engineering)

JUNE 2008

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
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TRONOH, PERAK

June 2008

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

MOHD EAZAQ FAROMMI BIN HAMAT

LIST OF ABREVIATIONS

CUF	Centralized Utility Facilities
TES	Thermal Energy Storage
ISO	International Standard Organization
RH	Relative Humidity
LiBr	Lithium-Bromide
CT	Combustion Turbine

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ABSTRACT

This author is studying the air inlet treatment of gas turbine. This is due to the problem of lower efficiency of gas turbine when deal with the hot and dry air. This problem also rises in the CUF Kertih, Terengganu power plant. The gas turbine cannot achieve the maximum power output. The performance of a gas turbine varies significantly with ambient air temperature. As the air temperature rises, its density decreases, resulting in reduced mass flow through the compressor and turbine, thereby causing a corresponding reduction in turbine output. Actually, nowadays many technologies are used in the world regarding the cooling air inlet gas turbines. They have proved that this kind air treatment can increase the power output capacity. In this project, author will be studying on existing technologies out there used in the industry and discuss the most common technologies used. Make some analysis and comparison of each technology. The selected system is evaporative cooler. Evaporative cooler is the most widely used technology in the world in order increase the power output of the gas turbine. This is the most cost effective technology being used in the power plants. In fact, in hot and humid regions, it often isn't possible to accomplish more than about -9 to -12°C of cooling. The experiment was carried out with the evaporative cooler prototype in order to make some data analysis. The result show that evaporative cooler reduced the inlet temperature hence increased the power output of gas turbine.

ACKNOWLEDGEMENT

In the name of ALLAH, Most Gracious Merciful, alhamdulillah, His willing has made it possible for me to complete my Final Year Project, and resilience and good health given to me end up with this dissertation. Sincere gratitude to my supervisor, Mr. Rahmat Iskandar Khairul Shazi Shaarani, for his guidance, inspiration and support through the course of this project. In addition, his patience and encouragement from the beginning of my involvement in this project under title Evaporative Cooler as an Air Inlet Treatment of Gas Turbine. Also my utmost gratitude goes to all individuals who helping me including lab technicians, Mr. Jailani for his support, my friends for their encouragement along the project period. My heartfelt gratification also goes to all the authors of journals which are related to this project for their information in order to complete this project. Finally, special thanks for others that involved direct or indirectly in my project, without them this project will not be as successful as it is.

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND OF STUDY

Nowadays the gas turbine is a major player in the huge power generation market. As [1] said, the first gas in production for electrical power generation was introduced by Brown Boverif Switzerland in 1937. Almost all electrical power on earth is produced with a turbine of some type. A turbine is a rotary engine that extracts energy from a fluid flow. Very high efficiency turbine about 40% of the thermal energy, with the rest exhausted as waste heat. There are many different kind of turbine available. Some common ones are gas turbine, steam turbine, wind turbine, and locomotive turbine. It has been an issue on how to increase the efficiency of a turbine based on the factors that affects its performance.

There are currently 6 nos. of gas turbine in Centralized Utility Facilities Kertih Terengganu. Five of them operate simultaneously and one remains off as back up. Gas turbine engines are sometimes referred to as turbine engines. Such engines usually feature an inlet, fan, compressor, combustor and nozzle in addition to one or more turbines. Theoretically, each gas turbine in the plant is able to produce about 36MW of power. However due to some factor effecting the power production of the gas turbine, it is almost impossible to achieve the output power of about 36MW.

1.2 PROBLEM STATEMENT

1.2.1 Problem identification

Nowadays gas turbine are installed in many places from desert to coastal, tropical, arctic, agricultural, oil fields, etc[2]. Problem occurs when gas turbine air inlet temperature is high. It will affect the performance of gas turbine itself. Gas turbine cannot maximize the power output because of the high air inlet temperature. With our local climate of wet and dry throughout the year, it is impossible to keep constantly low air inlet temperature naturally.

1.2.2 Significance of the project

There are several improvement methods to reduce the air inlet temperature. These methods have their own advantages and limitations according the specified places. For instance evaporative cooler is a good way to reduce the air intake temperature. So this project will study the characteristic of the evaporative cooler.

1.3 OBJECTIVE & SCOPES OF STUDY

In order to complete this project within the time limit, several objectives for this study have been identified and listed such as below:

1. Study on the effects of air intake temperature to the gas turbine generator performance.
2. Identification of most common possible solution to the problem
3. Design a simple test rig to test the principle of evaporative cooler using media pad.
4. Calculation to predict the impact of evaporative coolers on gas turbine performance.

CHAPTER 2

LITERATURE REVIEW

2.1 Gas Turbine Theory

2.1.1 Gas Turbine Cycles.

A schematic diagram for a simple-cycle, singleshaft gas turbine is shown in Figure 2.1. Air enters the axial flow compressor at point 1 at ambient conditions. Since these conditions vary from day to day and from location to location, it is convenient to consider some standard conditions for comparative purposes. The standard conditions used by the gas turbine industry are 59 F/15 C, 14.7 psia/1.013 bar and 60% relative humidity, which are established by the International Standards Organization (ISO) and frequently referred to as ISO conditions[2,3,7,8,9].

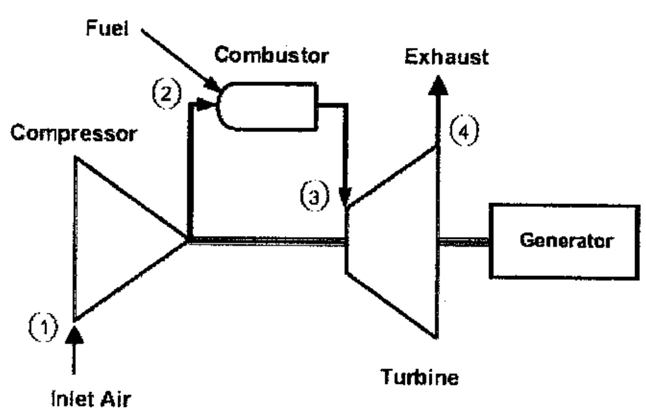


Figure 2.1: Simple-cycle, single-shaft gas turbine [5]

Air entering the compressor at point 1 is compressed to some higher pressure. No heat is added; however, compression raises the air temperature so that the air at the discharge of the compressor is at a higher temperature and pressure. Upon leaving the compressor, air enters the combustion system at point 2, where fuel is injected and combustion occurs. The combustion process occurs at essentially constant pressure. Although high local temperatures are reached within the primary combustion zone, the combustion system is designed to provide mixing, burning, dilution and cooling. Thus, by the time the combustion mixture leaves the combustion system and enters the turbine at point 3, it is at a mixed average temperature.

In the turbine section of the gas turbine, the energy of the hot gases is converted into work. This conversion actually takes place in two steps. In the nozzle section of the turbine, the hot gases are expanded and a portion of the thermal energy is converted into kinetic energy. In the subsequent bucket section of the turbine, a portion of the kinetic energy is transferred to the rotating buckets and converted to work. Some of the work developed by the turbine is used to drive the compressor, and the remainder is available for useful work at the output flange of the gas turbine. Typically, more than 50% of the work developed by the turbine sections is used to power the axial flow compressor [5]. As shown in Figure 2.1, single-shaft gas turbines are configured in one continuous shaft and, therefore, all stages operate at the same speed. These units are typically used for generatordrive applications where significant speed variation is not required.

A schematic diagram for a simple-cycle, twoshaft gas turbine is shown in Figure 2.2. The low-pressure or power turbine rotor is mechanically separate from the high-pressure turbine and compressor rotor. The low pressure rotor is said to be aerodynamically coupled. This unique feature allows the power turbine to be operated at a range of speeds and makes two shaft gas turbines ideally suited for variable speed applications. All of the work developed by the power turbine is available to drive the load equipment since the work developed by the high-pressure turbine supplies all the necessary energy to drive the compressor. On two-shaft machines the starting requirements for the gas turbine load train are reduced because the load equipment is mechanically separate from the high-pressure turbine.

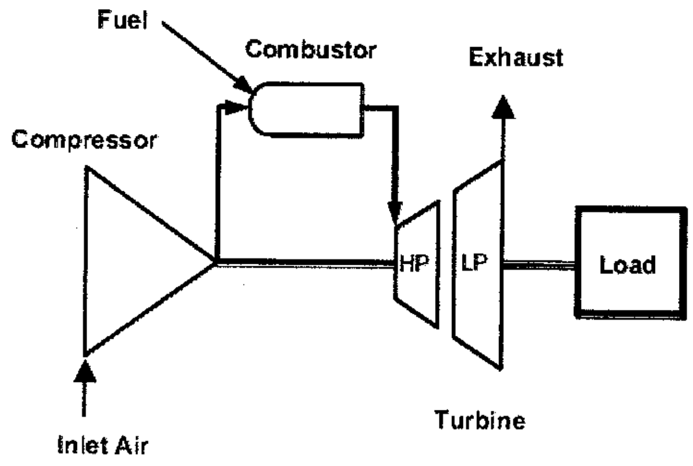


Figure 2.2: Simple-cycle, two-shaft gas turbine [5]

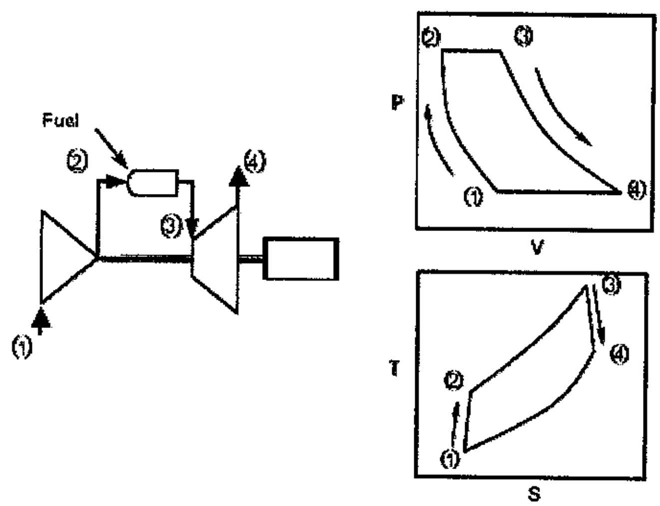


Figure 2.3: Brayton Cycle [5]

2.1.2 The Brayton Cycle

The thermodynamic cycle upon which all gas turbines operate is called the Brayton cycle. Figure 2.3 shows the classical pressure-volume (P-V) and temperature-entropy (T-S) diagrams for this cycle. The numbers on this diagram correspond to the numbers also used in Figure 2.1. Path 1 to 2 represents the compression occurring in the compressor, path 2 to 3 represents the constant-pressure addition of heat in the combustion systems, and path 3 to 4 represents the expansion occurring in the turbine. The path from 4 back to 1 on the Brayton cycle diagrams indicates a constant-pressure cooling process. In the gas turbine, this cooling is done by the atmosphere, which provides fresh, cool air at point 1 on a continuous basis in exchange for the hot gases exhausted to the atmosphere at point 4. The actual cycle is an "open" rather than "closed" cycle, as indicated.

2.1.3 Combine Cycle

A typical simple-cycle gas turbine will convert 30% to 40% of the fuel input into shaft output. All but 1% to 2% of the remainder is in the form of exhaust heat. The combined cycle is generally defined as one or more gas turbines with heat-recovery steam generators in the exhaust, producing steam for a steam turbine generator, heat-to-process, or a combination thereof. Figure 2.4 shows a combined cycle in its simplest form. High utilization of the fuel input to the gas turbine can be achieved with some of the more complex heat-recovery cycles, involving multiple-pressure boilers, extraction or topping steam turbines, and avoidance of steam flow to a condenser to preserve the latent heat content. Attaining more than 80% utilization of the fuel input by a combination of electrical power generation and process heat is not unusual. Combined cycles producing only electrical power are in the 50% to 60% thermal efficiency range using the more advanced gas turbines.

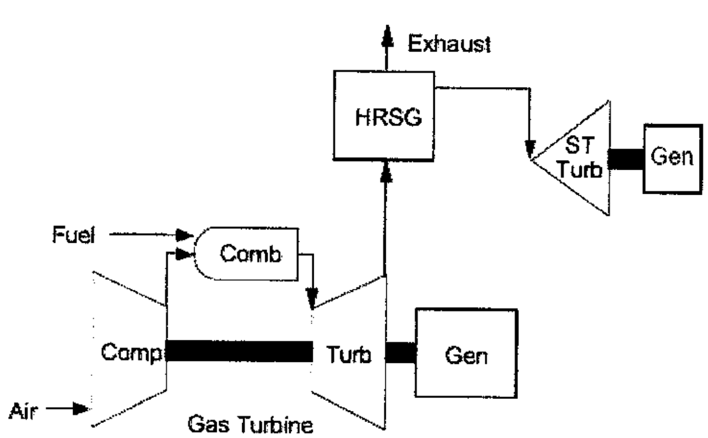


Figure 2.4: Combine Cycle [5]

2.2 Air Inlet Cooling

Cooling air inlet of gas turbine enables greater mass to be delivered by the compressor and hence enable the turbine to provide a greater power output. This is because mass flow rate is directly proportional to the mass flow rate of compressed air from the air compressor. When ambient temperature of air is above 15°C, the benefits of gas turbine air cooling include the following:

- Increased power output
- Reduced capital cost per unit of power plant output capacity
- Increase fuel efficiency
- Increases power output of steam turbines in combine cycles
- Improved predictability of power output by eliminating the weather variable

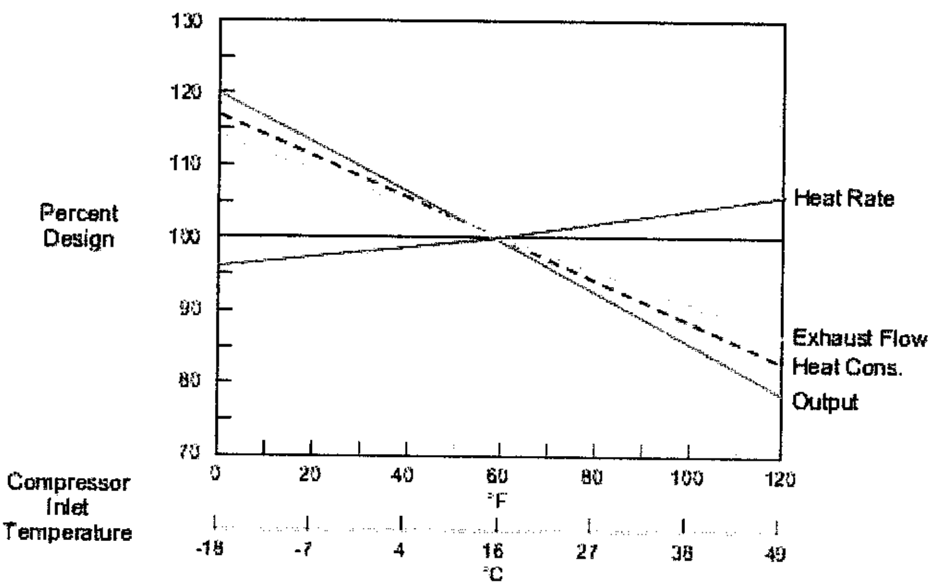


Figure 2.5: Effect of ambient temperature [5]

The basic theory of inlet cooling for gas turbine is simple enough. Combustion turbines are constant volume machines which is at a given shaft speed they always move at the same volume of air but the power output of gas turbine depends on the flow of mass through it. That's why on hot day, when air is less dense lead to mass air flow decrease and power output falls of. By feeding cooler air into the CT, mass flow increased, resulting good advantages as stated above. Another factor is the power consumed by the CT's compressor. The work required to compress air directly proportional to the temperature of the air, so reducing the inlet air temperature reduces the work of compressor and there is more work available at the power turbine output shaft.

2.3 Mechanical Chiller Systems

Mechanical chiller systems can cool the inlet air to much lower temperatures than those that are possible with evaporative cooling, and they can maintain any desired inlet air temperature down to as low as 42°F, independent of the ambient wet-bulb temperature [3,4,7,10]. The mechanical chillers used in these systems could be driven by electric motors or steam turbines. Inlet air is drawn across cooling coils, in which either chilled water or refrigerant is circulated, cools it to the desired temperature. The chilled water can be supplied directly from a chiller or from a Thermal Energy Storage (TES) tank that stores ice or chilled water. A TES is typically used when there are only a limited number of hours required for inlet air-cooling. TES can reduce overall capital costs because it reduces the chiller capacity requirements compared to the capacity required to match the instantaneous on-peak demand for cooling. Net power plant on-peak capacity is greater as less or no electric energy is required to operate the chillers as they charge the TES system the night before using lower cost off-peak electricity. Somewhat offsetting these benefits, a system with TES require a larger site footprint for the TES tank. In summary, the advantages of a mechanical refrigeration system are that it can maintain the inlet air at much lower temperatures than those possible by other technologies and achieves the desired temperatures independent of weather or climate conditions.

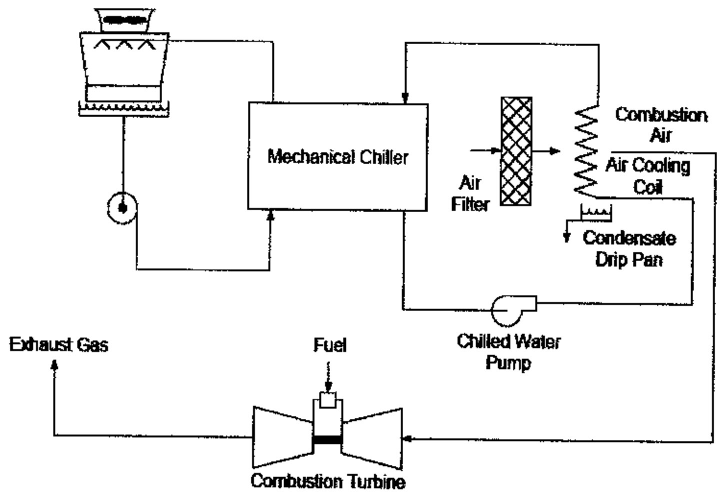


Figure 2.6: Schematic diagram for mechanical chiller system [3]

2.4 Absorption Cooling Systems

Absorption cooling systems are similar to the mechanical refrigeration systems, except that instead of using mechanical chillers, these systems use absorption chillers that require thermal energy (steam or hot water) as the primary source of energy, and require much less electric energy than the mechanical chillers. Absorption cooling systems can be used to cool the inlet air to about 50°F. Absorption chillers can be single-effect or double-effect chillers. The single-effect absorption chillers use hot water of 15psig steam, while the double-effect chillers require less steam, but need the steam at a higher pressure (115psig). The advantage of this system is that it has much less parasitic load, and its major disadvantage is that its capital cost is much higher than even mechanical refrigeration systems. The primary successful applications of absorption chillers are in power plants where there is excess thermal energy available and the conversion of this energy to high-value electricity is profitable for the user.

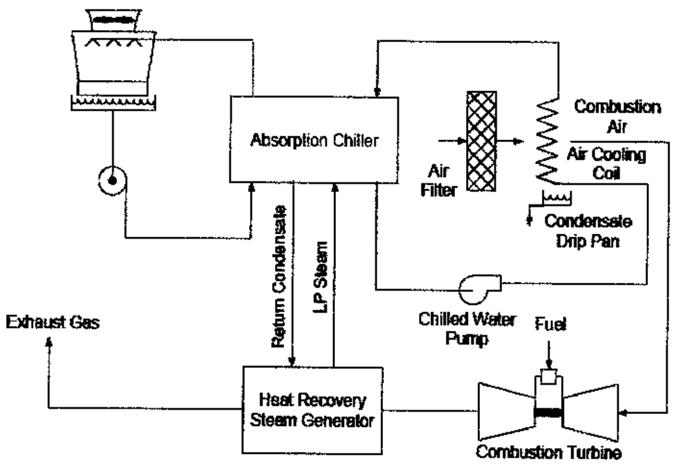


Figure 2.7: Schematic diagram of absorption chiller system[3]

2.5 Fogging Systems

Fogging is another form of evaporative cooling technology. This adds water to the inlet air in the form of a spray of very fine droplets.In this type of cooling, water is brought in contact with the incoming air. As water absorbs heat from the air and is evaporated, the air stream is cooled Fogging systems can produce droplets of variable size, depending on the desired evaporation time and ambient conditions. The water droplet size is generally less than 40 microns, and on average, about 20 microns. The water used for fogging typically requires demineralization. Fogging systems can cool the inlet air by 95-98 per cent of the difference between ambient dry-bulb and wet-bulb temperature. It is therefore slightly more effective than the wetted media. The capital cost of fogging is similar to that for the wetted media, and fogging systems also have similar limitations and disadvantages to those for wetted media. Fogging is the second most frequently applied technology for turbine air inlet cooling. Some gas turbine manufacturers do not allow fogging systems to be applied to their equipment due to compressor degradation and failures associated with fogging.

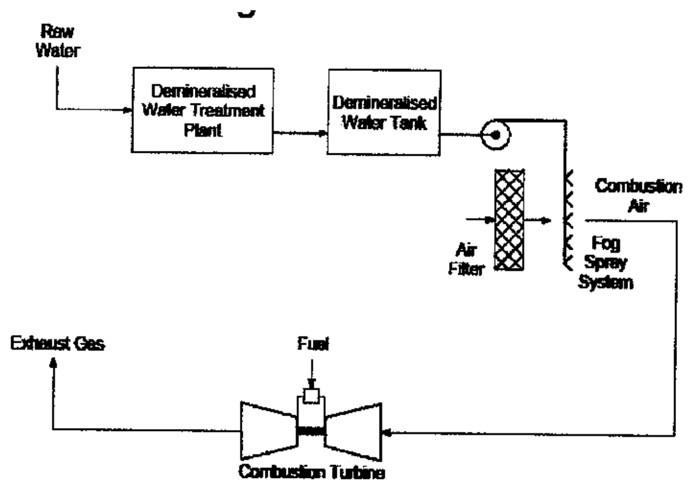


Figure 2.8: Schematic diagram of fog inlet air cooling system [3]

2.6 Evaporative Cooler Systems

Wetted media is an evaporative cooling technology in which cooling is achieved by the evaporation of water added to the gas turbine inlet air. In this technology, the inlet air is exposed to a film of water in a wetted media. A honey-comb-like medium is one of the most commonly used. The water used for wetting the medium may require treatment, depending upon the quality of water and the medium manufacturer's specifications. Wetted media can cool the inlet to within 85-95 per cent of the difference between the ambient dry-bulb and wet-bulb temperature. It is one of the lowest capital and operating cost options. Its main disadvantage is that the extent of cooling is limited by the wet bulb temperature and it is therefore dependent on the weather. It works most efficiently during hot and dry weather, and is less effective when ambient humidity is high. This is the most widely used technology.

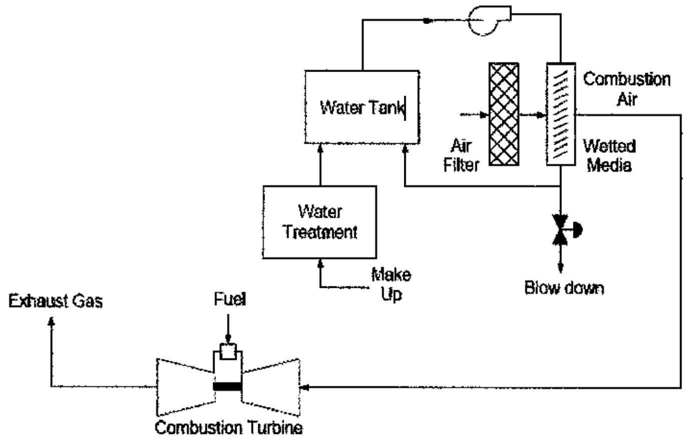


Figure 2.9: Schematic diagram of evaporative cooling [3]

2.6.1 Working Principle

Evaporative cooling involves heat and mass transfer. Heat and mass transfer are both in the evaporative cooler because heat transfer from the air to the water evaporates waters, and water evaporating into air constitutes mass transfer. Heat inflow actually can be describes as sensible and latent heat. Sensible heat affect in raising or lowering the temperature while latent heat produce change of state, e.g., freezing, melting , condensing or vaporizing. In evaporative cooler, sensible heat from air is transferred to the water, becoming latent heat as the water evaporates. The water vapor becomes part of the air and carries the latent heat with it. The air dry-bulb temperature decreased because it gives up sensible heat.

Typical evaporative cooler components are shown in the figure 2.10. When the cleaned air is directed from the air inlet filter system into the evaporative cooling media, it flows through the wetted media where it increases its moisture content by evaporation of water. Then the air is cooled and passes through the integral mist eliminator and finally, clean, cooled air is directed to the turbine inlet.

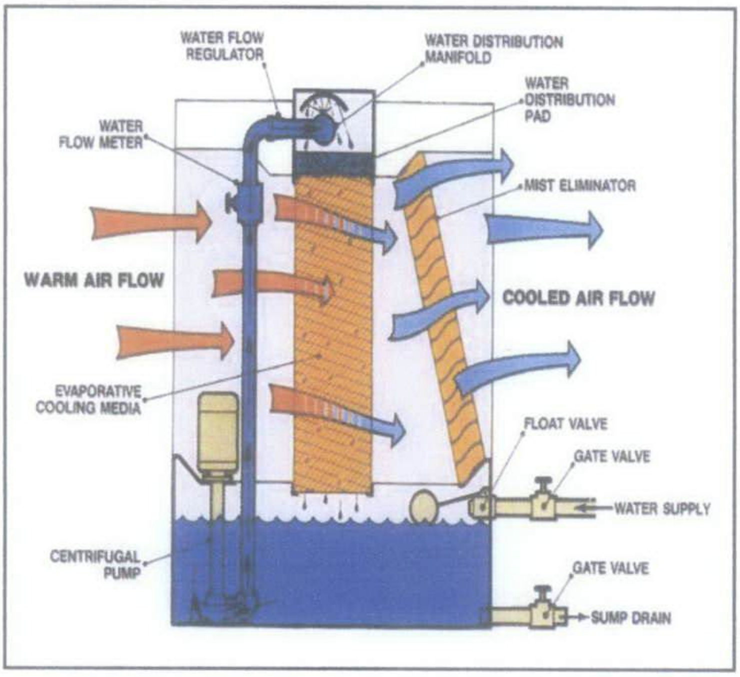


Figure 2.10: Evaporative cooler system

2.6.2 Cooler pads

The most popular evaporative cooler employs two categories of cooler pad: aspen excelsior and rigid cellulose media. The aspenpad cooler draws outside air into all four sides through metal panels that support the aspenpad. The aspen wood is used due to its properties of being odorless, chemically inert, and easily absorbent and wettable. The wood is shaved into excelsior strands generally between 0.25 and 2.5mm wide and thick with lengths of at least 25mm [11]. these strands are formed into rectangular pads approximately one inch thick and inserted into the vertical holders to prevent sagging. Figure 2.11 & 2.12 show a typical aspenpad in its holder with close up view of the aspenpad media.

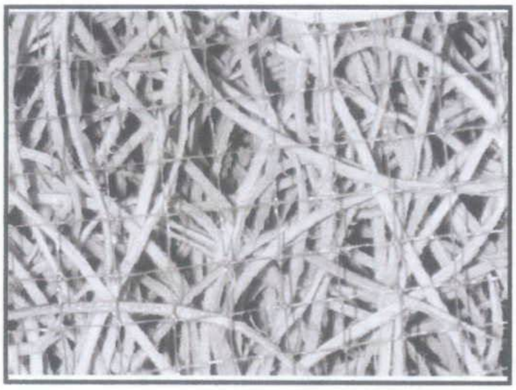


Figure2.11: Close up of aspenpad media [10]

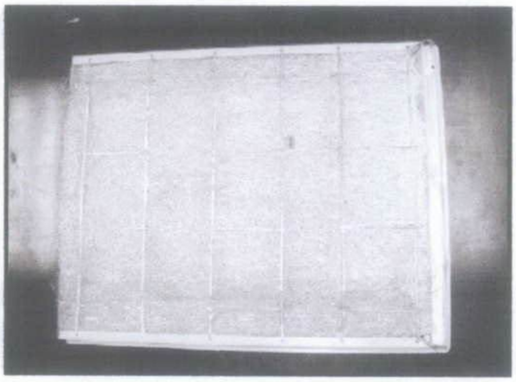


Figure 2.12: Aspenpad holder [10]

Rigid media pad are made of special wettable cellulose in corrugated sheets bonded together at opposing angles to form a 15-cm tick filter. The angles of the corrugated cellulose are intended to maximize air contact and evaporation. The rigid media pad has a longer useful life than aspenpads, but higher in initial cost. Figure 2.13 & 2.14 show a commercially available rigid media pad with close-up of the cellulose material.

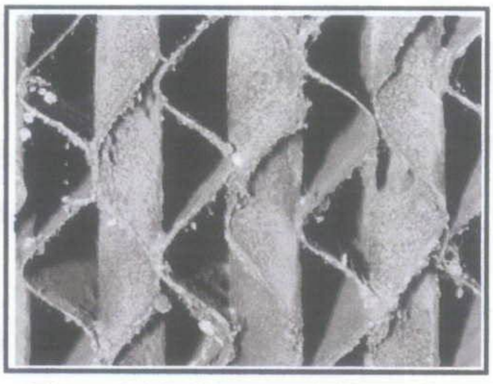


Figure 2.13: Close-up rigid media pad [10]

Figure2.14: Rigid media pad in its holder [10]

CHAPTER 3

PROJECT WORKS & METHODOLOGY

3.1 Fabrication Process

In order to achieve the objective of the project, the prototype of evaporative cooler has to be made. The first step is to set up basic design of the model. It is shown in the figure below:

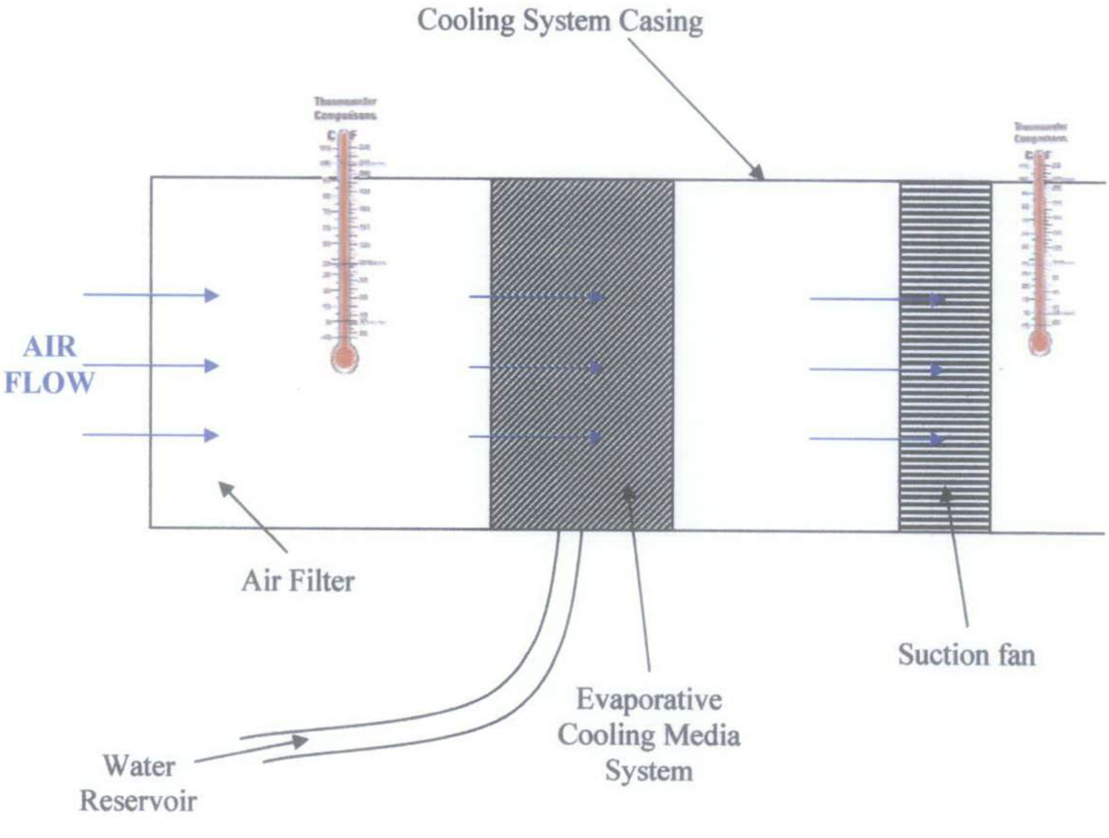


Figure 3.1: Diagram of the basic design of the prototype

Secondly, the model is designed into the three dimensional model using the CATIA software. The model is shown in the assembly design in page 17.

The next step is to fabricate the model using the necessary and suitable things and equipment which available in the market. The apparatus/equipment needed is summarized in the table:

No	Apparatus	Quantity
1	Perspex (4'x3')	2
2	Exhaust fan (8''x8'')	1
3	Water pump	1
4	Pipe (d=1", L = 30cm)	1
5	Water tubing (L=120cm)	1
6	Plastic net (1m x 1m)	1
7	L-shape bar (aluminum)- L=1m	6
8	Glass sealant	1

Table 3.1 : Apparatus for fabrication

3.1.1 Cooler pad/media

Cooler pad or media is firstly designed and fabricated. This cooler pad is an assembly of steel frame and the plastic net. The dimension of the frame is shown in the figure:

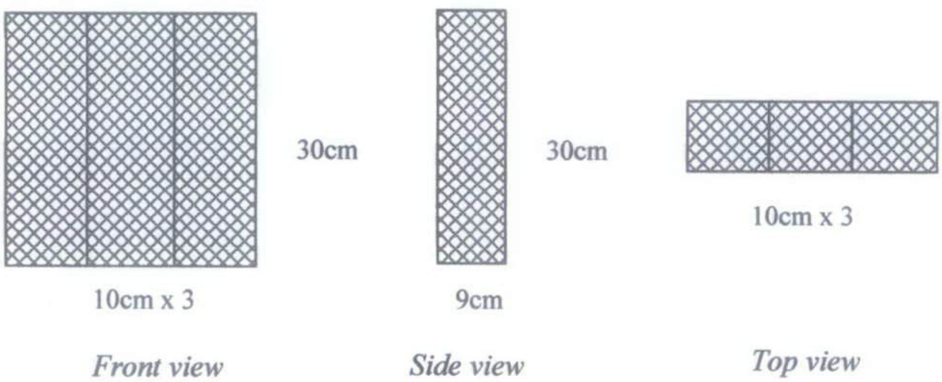


Figure 3.2: Dimension of the cooler pad

The frame was actually welded at the welding workshop at Tronoh. The dimension should be accurate so that it will not affect its function. After that the frame was covered with the plastic net and was half filled with the wood excelsior to form the cooler pad/media. Wood excelsior is actually wood ordinary wood chip then from the sawmill place. Finally design of the media/cooler pad as shown in the figure:

Figure 3.3: Cooler pad

3.1.2 Cooler Casing

The main material of the cooler casing was the Perspex. It then was assemble with the L shape bar using screw and rivet to form the casing. Below is the figure of the cooler casing:

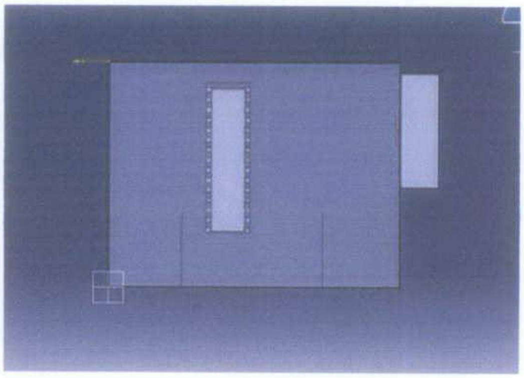
Figure 3.4: Cooler Casing

3.1.3 Assembly process

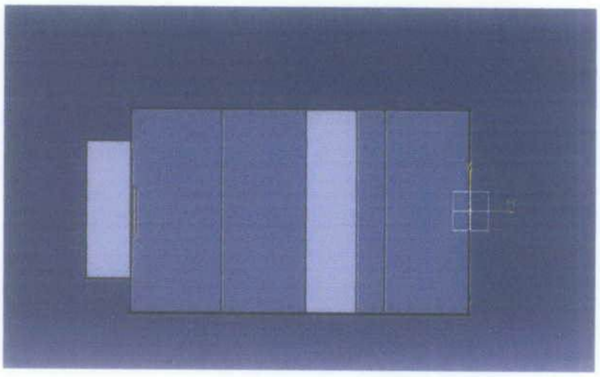
Final step was the assembly process of whole components mentioned before to form the evaporative cooler. All those components cooler casing, cooler pad, media, exhaust fan were assembled together. The evaporative cooler is now ready to be tested.

Assembly design

3D Engineering Drawing (CATIA)



Side view



Top view

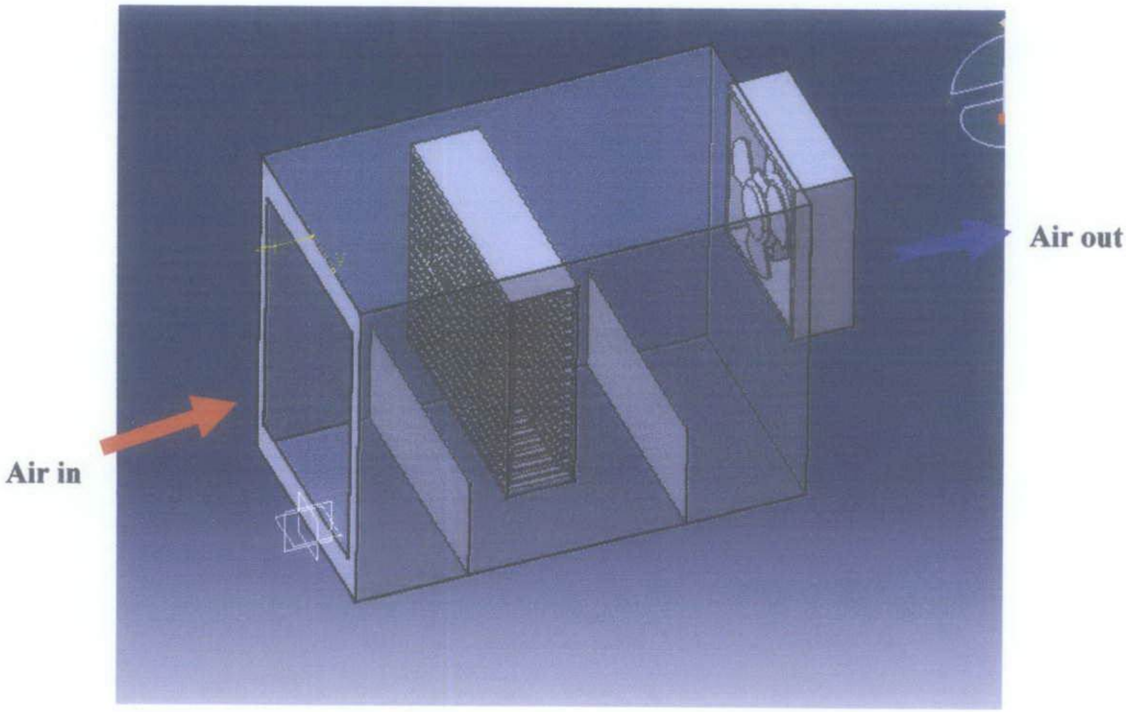
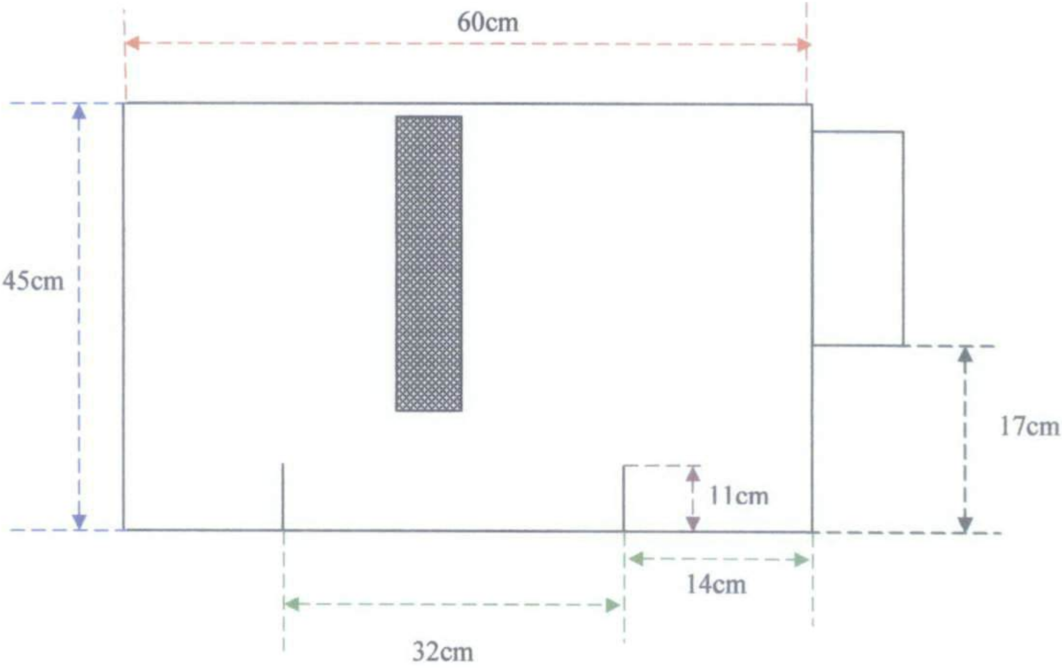


Figure 3.5: Engineering drawing of the evaporative cooler



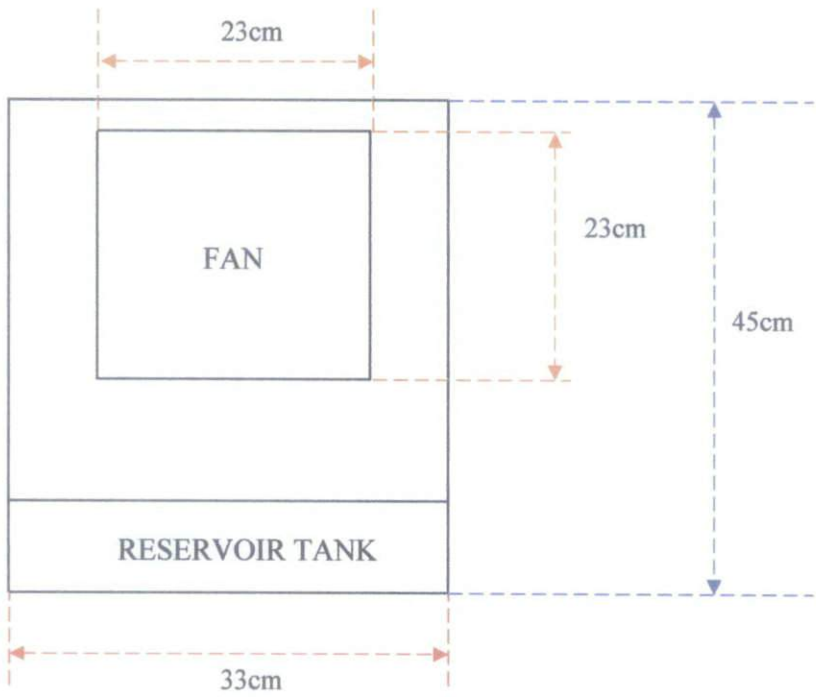


Figure 3.6: Dimension of the evaporative cooler

3.2 Experimental Set Up

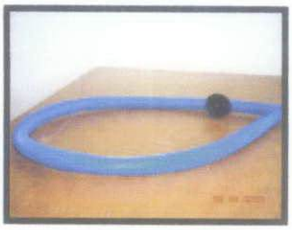
To set up the experiment, process of fabricating the prototype has been started. There are three main components of the prototype which covers suction system, cooler pad (media) and water circulation system. The suction system will draw the air through the pad while the pump in the water circulation system will deliver the water to the pad. Generally the pad is made with wood wool which shaved into excelsior strands generally between 0.25 and 25 mm wide and thick with lengths of at least 25 mm [11], but in this experiment the size of the wood is not consistent because of difficulty to measure and to shave the wood to the desired size. Most important thing is that the characteristic of the wood itself which easily absorbent and wettable. The wood is support with holder which made by steel and cover with net to prevent from sagging. The figures below show the pad and the arrangement of the design for experiment.

Water pump

Cooler pad

Piping

Assembly



Tubing

Exhaust fan

Cooler casing

Figure 3.7: Experimental Setup

3.2.1 Apparatus of the experiment

Evaporative Cooler Test Rig
Evaporative cooler prototype
Anemometer
Temperature gauge

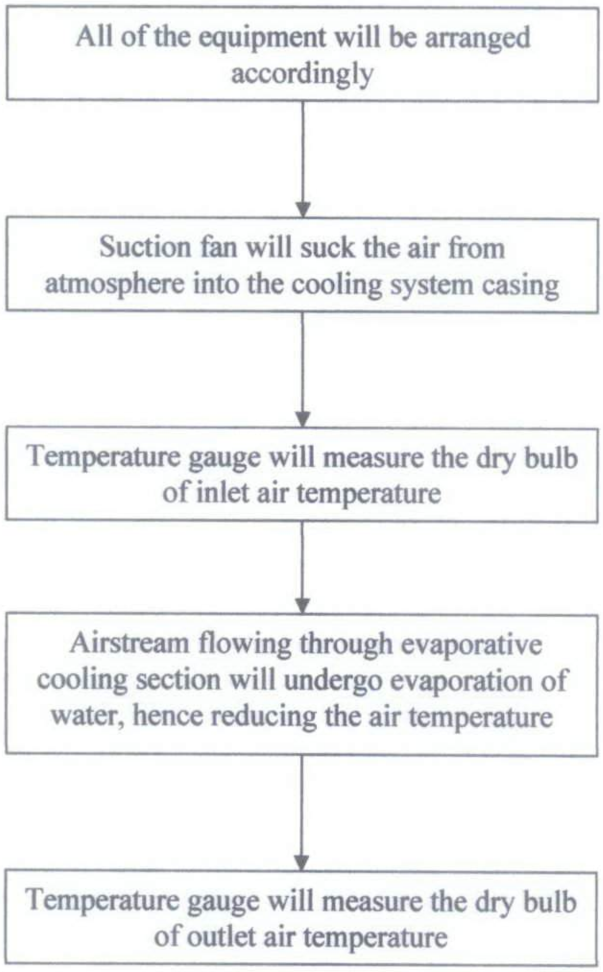
Table 3.2: Apparatus of the experiment

The experiment used the normal temperature gauge (thermometer) while specification of anemometer is mentioned in the table 3.3. This anemometer used is actually multifunctional device which actually the hygrometer (humidity gauge) is integrated together so that the humidity can be determined using humidity probe.

Specification of the Anemometer	
Manufacturer	EXTECH
Measurement Taken	Temperature (°C)
	Air velocity (m/s)
	Humidity (%)

Table 3.3: Specification of the Anemometer

The flow of the experiment was summarized as below:



CHAPTER 4

RESULTS & DISCUSSIONS

4.1 Comparison of Air Inlet Cooling

Before deciding to choose evaporative cooler system, the comparisons among the common inlet technologies are done through qualitative analysis and quantitative analysis. This evaluation is actually based on the economic and design consideration.

4.1.1 Qualitative analysis

Criteria	Evaporative Cooler	Fogging System	Chiller
Ambient Temperature	low temperature reduction	Low temperature reduction	significant temperature reduction
Operation & Maintenance	lowest cost O&M	lower cost O&M	high cost O&M
Installation	lowest cost O&M and easy to install	lowest cost O&M and a little bit complex to install	high cost O&M and is more complex to install
Design	simple and not complex	not so simple compared to evaporative cooler	complex
Relative Humidity	not suitable in high humidity region but can be improved	not suitable in high humidity region but can be improved	suitable in high humidity region
Fluid Properties	can use raw water	demineralised water	chilled water or refigerant

Table 4.1: Qualitative analysis of air inlet cooling technologies

4.1.2 Quantitative Analysis

Criteria	Weightage	Evaporative Cooler	Fogging System	Chiller
High Temperature reduction	3	2	2	3
Low cost Operation & Maintenance	3	3	2	1
Low cost & simplicity of Installation	3	3	2	1
Simplicity of Design	2	3	2	0
High Humidity region	2	1	2	3
Simplicity of fluid	2	2	1	1
	TOTAL	**36**	**28**	**23**

Legend	
Weight-age	***Score***
1 = Less effect	*0 = Do not meet criterion*
2 = Significant effect	*1 = Meet criterion*
3 = High effect	*2 = Highly meet criterion*
	3 = Extremely meet criterion

Table 4.2: Quantitative analysis of air inlet cooling technologies

4.1.3 Cost Effective

From previous comparison analysis, evaporative cooler is chosen. As mentioned before, it is chosen based on the economic and design consideration. To support the economic analysis, the cost effective evaluation is done which is the evaporative cooler is the most cost effective compared to the other technologies. This is because it does not require complex design and control for the operation. Below is the capital cost comparisons of inlet cooling systems:

Options	Relative costs
Evaporative cooler	1
Fog system (excluding water treatment plant)	2
Single stage LiBr absorption chiller	8
Single stage LiBr absorption chiller	10
Ammonia mechanical refrigeration system	9.5

Table 4.3: Capital cost comparisons of inlet cooling systems

From the table, it shows that all chillers have highest relative cost compare to the fog and evaporative cooler. Evaporative cooler is actually a good system because it does cool down the air and increase power output of the turbine with the lowest cost. For more understanding what contribute to the relative cost, refer to the table 4.4. This table shows the major contributor of O&M. The conclusion is simple, high O&M cost yields high relative cost.

Options	O&M Costs
Evaporative cooler	o Make up water o Water treatment (if applicable)
Fog system (excluding water treatment plant)	o Make up water o Demineralized water treatment o Injection pump power consumption
Single stage LiBr absorption chiller	o Steam o Cooling tower chemical treatment o Chiller maintenance o Electric power consumption
Single stage LiBr absorption chiller	o Steam o Cooling tower chemical treatment and make up water o Chiller maintenance o Electric power consumption
Ammonia mechanical refrigeration system	o Electric power consumption o Cooling tower chemical treatment and make up water o Chiller maintenance

Table 4.4: Major contributor of O&M

4.2 Psychometric Chart and Air Characteristics

A psychrometric chart presents physical and thermal properties of moist air in a graphical form. It can be very helpful in troubleshooting greenhouse or livestock building environmental problems and in determining solutions. Understanding psychrometric charts helps visualization of environmental control concepts such as why heated air can hold more moisture, and conversely, how allowing moist air to cool will result in condensation. The objective of this fact sheet is to explain characteristics of moist air and how they are used in a psychrometric chart.

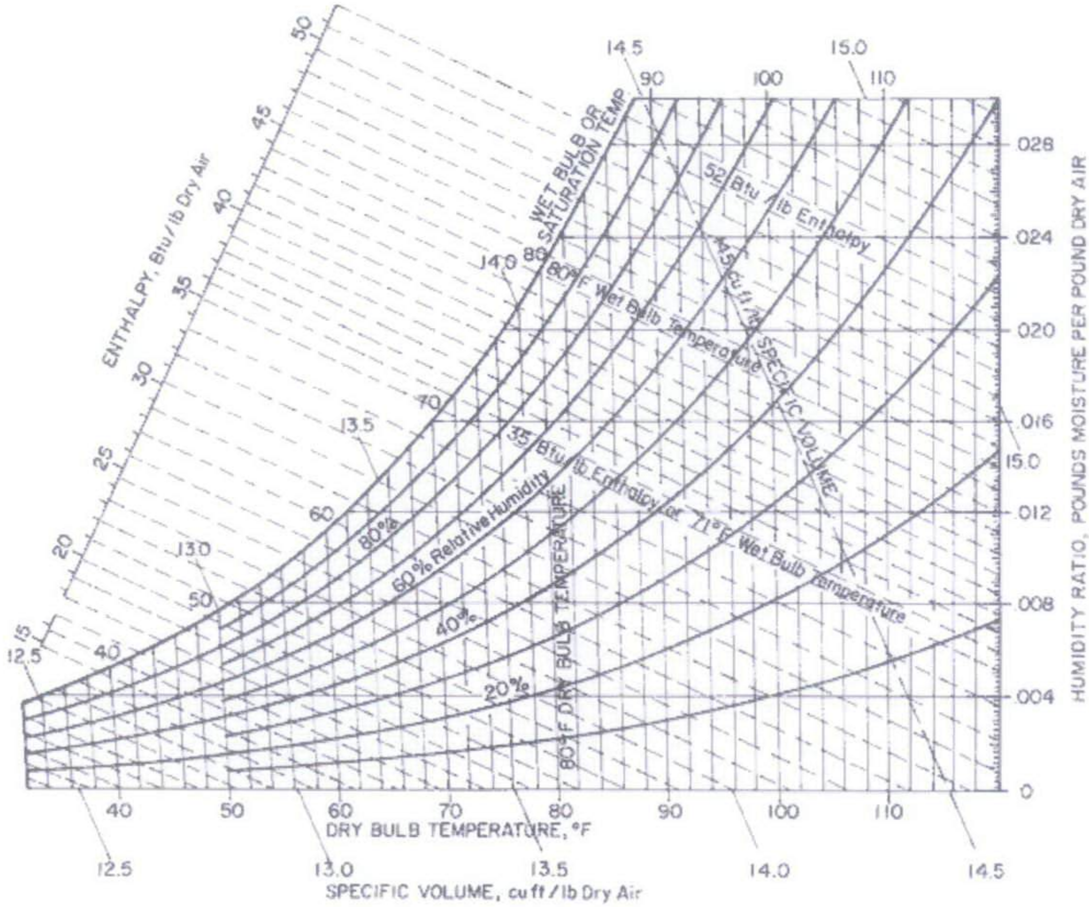


Figure 4.1: Psychrometric Chart

A psychrometric chart contains a lot of information packed into an odd-shaped graph. If we dissect the components piece by piece, the usefulness of the chart will be clearer. Boundaries of the psychrometric chart are a dry-bulb temperature scale on the horizontal axis, a humidity ratio (moisture content) scale on the vertical axis, and an upper curved boundary which represents saturated air or 100 percent moisture holding capacity. The chart shows other important moist air properties as diagrammed in Figure 4.2: wet-bulb temperature; enthalpy; dewpoint or saturation temperature; relative humidity; and specific volume.

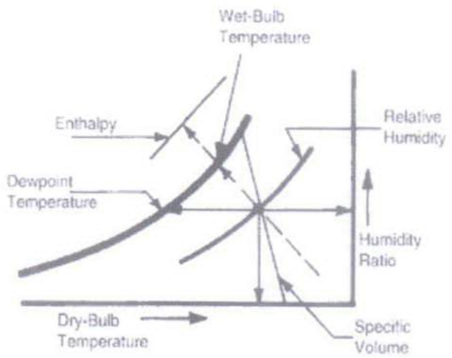


Figure 4.2: Properties of moist air on a psychrometric chart.

4.3 Effectiveness Measurement

The design controls the effectiveness of the cooler, defined as follows:

$$\textbf{Cooler Effectiveness} = (T_{1DB} - T_{2DB})/(T_{1DB} - T_{2WB})$$

Where: T_{1DB} = *dry bulb temperature upstream of the cooler*

T_{2DB} = *dry bulb temperature downstream of the cooler*

T_{2WB} = *wet bulb temperature downstream of the cooler*

This equation can only be used if the dry bulb temperature upstream of the cooler and the relative humidity value are known. It will determine how effective the evaporative cooler in the specified condition. For further understanding, example of calculation for cooler effectiveness;

Given that:

RH = 80%

T_{1DB} = 90°F

T_{2DB} = 85°F

Using the Psychometric chart the wet bulb temperature is determined. Enter the bottom of the chart at 90°F and proceed upward to intersect the 80% RH line. Then follow the diagonal line to the wet bulb and dew point temperature lines and go down to read about 86°F for T_{WB}. From the equation above the cooler effectiveness is about 12.5%.

4.4 Experiment

Previously, the author mentioned about the experimental set up for the test rig. The purpose of this experiment was to analyze the evaporative cooler on how much temperature will be dropped hence increase the power output of the gas turbine. Basic theory of the cooler pad is actually the heat transfer. Heat transfer due to the temperature difference between air and water. The heat from the air is absorbed by the water and evaporates it to the air again. This will result cool air through the cooler pad. The experiment was performed in the ambient temperature. As mentioned earlier, there were 3 main systems which are suction system, water distribution systems and cooler pad/media. The water was distributed to the cooler pad evenly using water pump and circulate the water that trapped in the reservoir. Below is the schematic diagram of the water distribution system:

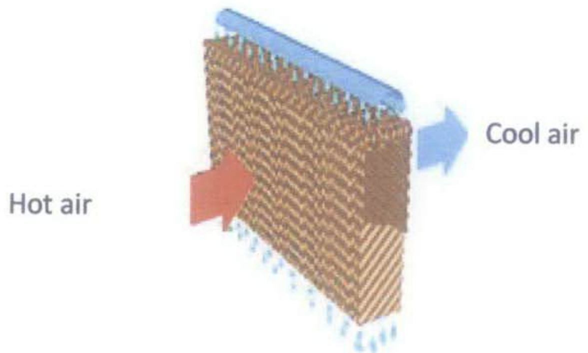


Figure 4.3: Schematic diagram how water is distributed to the cooler pad

Parameters of the experiment

Parameters of the experiment
Relative humidity,(%RH)
T_{1DB} ,dry bulb temperature upstream of the cooler (°C)
T_{2DB} ,dry bulb temperature downstream of the cooler(°C)
T_{2WB} ,wet bulb temperature downstream of the cooler (°C)
Velocity of air (m/s)
Cooler effectiveness (*e*)
Temperature gradient (ΔT)

4.5 Results

The results obtained from the experiment after measured the relative humidity (%RH) and the velocity of the air as follow:

RH = 77.4%

Velocity of air: 3.8 m/s

The wet bulb temperatures were obtained from a psychrometric chart and the result as follow:

time (t)	T_{1DB} (°F)	T_{1DB} (°C)	T_{2DB} (°F)	T_{2DB} (°C)	T_{2WB} (°F)	T_{2WB} (°C)
0	93.2	34	89.6	32	82.7	28.17
5	93.2	34	87.8	31	82.7	28.17
10	93.2	34	87.8	31	82.7	28.17
15	95	35	89.6	32	85.4	29.67
20	95	35	88.7	31.5	85.4	29.67
25	95	35	87.8	31	85.4	29.67

Table 4.5: The Wet Bulb Temperature

Using the equation, the cooler effectiveness were measured and tabulated in the table below. The table also show the temperature gradient for each different upstream dry bulb temperature and downstream dry bulb temperature.

time (t)	T_{1DB} (°F)	T_{1DB} (°C)	T_{2DB} (°F)	T_{2DB} (°C)	ΔT (°F)	Cooler Effectiveness(*e*)
0	93.2	34	89.6	32	3.6	34.29
5	93.2	34	87.8	31	5.4	51.43
10	93.2	34	87.8	31	5.4	51.43
15	95	35	89.6	32	5.4	56.25
20	95	35	88.7	31.5	6.3	65.63
25	95	35	87.8	31	7.2	75

Table 4.6: Temperature gradient and cooler effectiveness

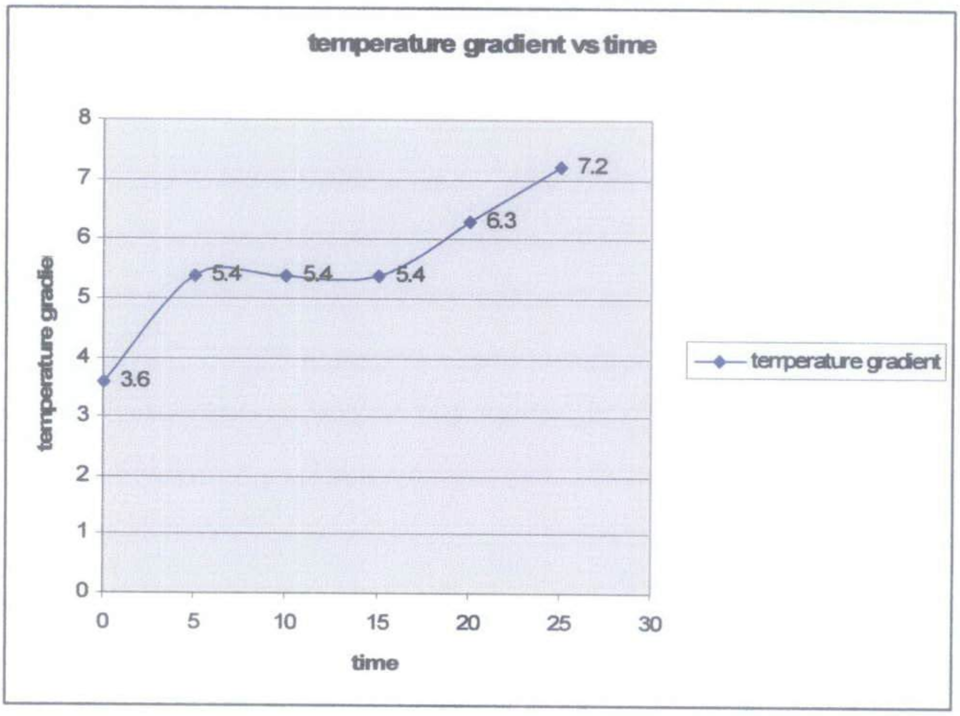


Figure 4.4.: Relationship between temperature and time

Figure 4.5 show the relationship of cooler effectiveness with the temperature gradient. It is clearly defined that every single value of temperature drop the cooler effectiveness raises hence the power output of gas turbine increases.

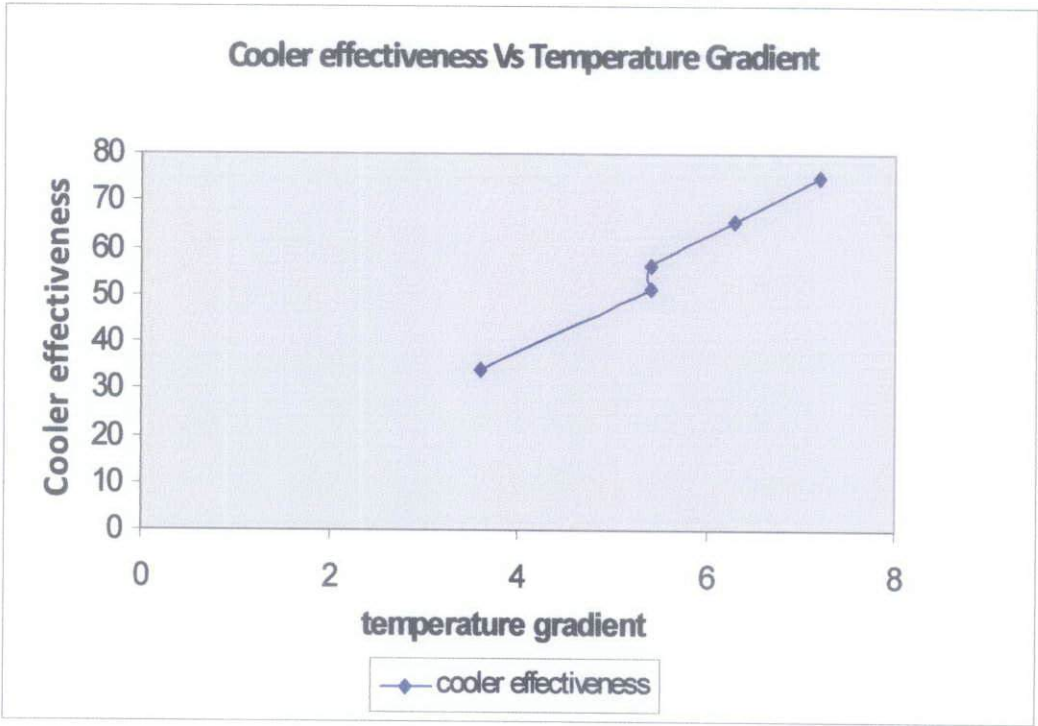


Figure 4.5: Cooler effectiveness and temperature gradient relationship

4.6 Evaporation rate

Evaporation rate also was taken into consideration in this experiment. This will show how much in kg/min water has been evaporated. The calculation involved the basic equation of density which:

Density = mass/volume

Where,

Density = density of water (kg/m^3)

Mass = mass of water (kq)

Volume = volume of water (m^3)

Volume of the water was obtained from the cross section of the reservoir tank. Before taking any reading, the system was freely operated within 15-20 min to achieve the steady state. After steady state achieved, the reading was taken as follows:

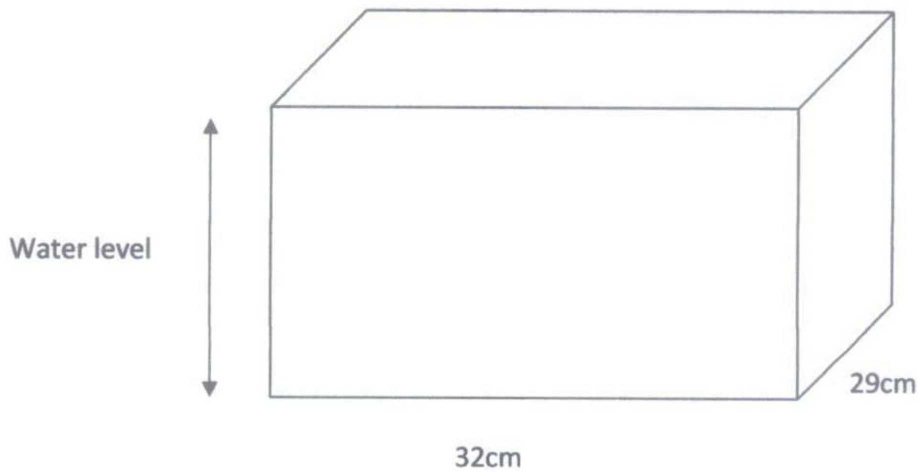


Figure 4.6: Reservoir tank dimension

Time - t	Water level -m	Volume-m^3
After 15-20mins (steady state):	0.073	0.0067744
After 100mins	0.072	0.0066816

The table shows that after 60mins,the water loss was 0.0000928 m^3. So the water evaporated per min was:

Water evaporated per min = 0.0000928 m^3 / 60 min

= 1.5467 x 10^{-6} m^3/min

So using the density equation, provided density of water is 1000 kg/ m^3 the value of evaporation rate in kg/min could be determined.

Mass of water evaporated = density x volume

= 1000 x 1.5467 x 10^{-6}

= 1.5467 x 10^{-3} kg/min

4.7 Output Recovery

Normally, the gas turbine will drop the power output by 0.54% - 90% for every 1°C rises in ambient temperature [12]. Should every 1°C drop in ambient temperature which means power output increase by 0.54% - 90%. So assuming that the recovery was 0.74% and the evaporative cooler is the real application for gas turbine, the power output recovery is:

Actual power output = 34 MW
Design power output = 36 MW
Output recovery = 0.74% / 1°C

Gas turbine power output recovery = (ΔT x 0.74/100) x 34 MW

For different temperature gradient, the gas turbine power output were calculated and tabulated in the table below:

time (t)	ΔT°C	Power output recovery (MW)
0	2	0.5032
5	3	0.7548
10	3	0.7548
15	3	0.7548
20	3.5	0.8806
25	4	1.0064

Table 4.7: Power output recovery

From the result above, the average gas turbine power output recovery was 0.7758MW. So the expected power output with the cooling system was:

Expected power output = 34 + 0.7758
= 34.7758 MW

4.8 Discussion

Referring to the result mentioned before, the system managed to decrease the air outlet temperature maximum 7.2°F. The power output can be achieved about 34.7758 MW after cooling system. Based on the literature review, in hot and humid region evaporative cooler can actually results more than that. It can decrease the temperature up to 10-15°F. Actually, there were some reasons which cause the performance of the system. It involves the weather condition, surface area of the cooler pad, water flow rate and so on.

4.8.1 Weather condition

Weather condition plays important role for evaporative cooler performance. For hot and dry climate condition, the evaporative cooler performs well as its application in the Middle East country. For the high relative humidity region, usually there is another technology to help evaporative cooler perform well. It is called dessicant-based evaporative cooling system. it can be used to absorb the air humidity before the air is passed to the evaporative cooler. Absorption of water by dessicant causes the dry bulb temperature of the air to increase. Then, the air is cooled by using and evaporation based system. Addition of dessicant-based system improves capabilities of the evaporative cooler making it suitable even for hot and humid climate. Dessicant wheels are normally made of adsorptive material such as silica gel, activated alumina, lithium chloride, lithium bromide, etc.

The Figure 4.7 shows the evaporative cooler performance forecast chart. It shows the conditions to the evaporative cooler whether works well, not ideal and inefficient. This forecast varies with the temperature and dew point changes.

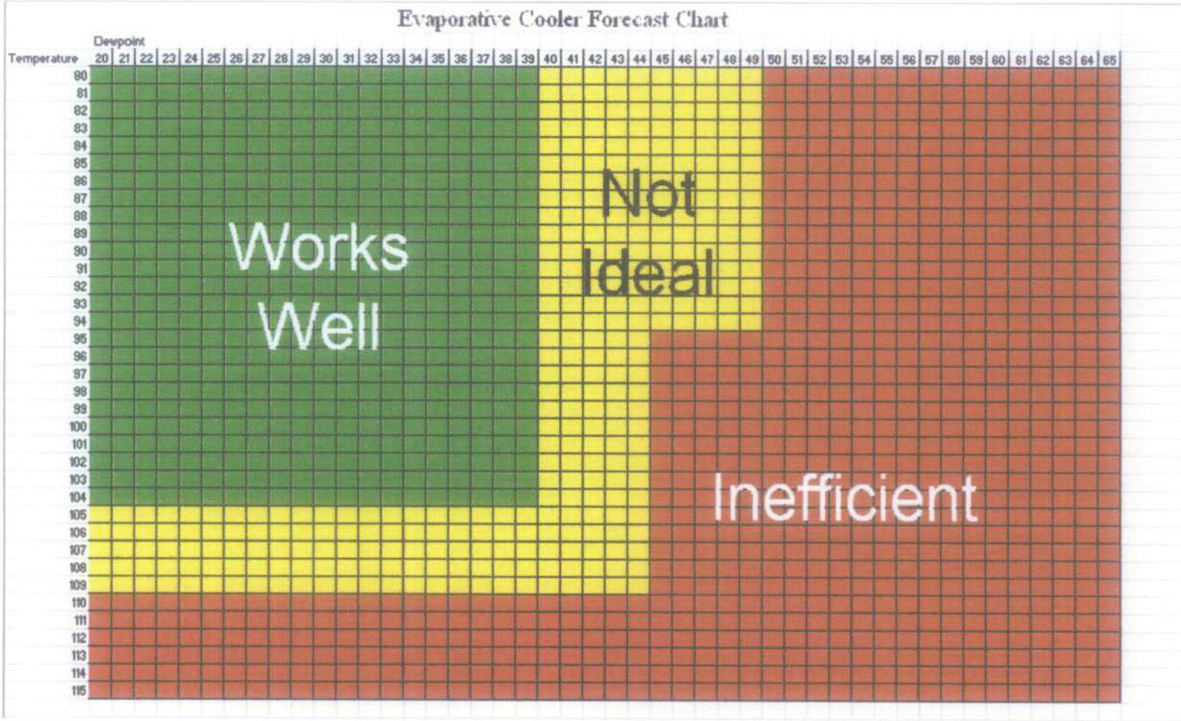


Figure 4.7: The evaporative cooler forecast chart [13]

4.8.2 Surface area

Since the evaporative involve heat transfer principle, surface area is the major contributor for the heat to be transferred. More surface area is exposed to the air, more heat will be transfer. So the media/cooler pad has to be made with the larger surface area. This project only uses wood wool which is not arranging accordingly. For the actual cooler pad, the wood wool or corrugated papers are arranged with specific condition so that the surface area will be greater.

CHAPTER 5
CONCLUSION & RECOMMENDATIONS

5.1 CONCLUSIONS

Gas turbine generator performance varies significantly with the different weather condition. With high hot and dry climate region, the performance decrease. Hence the power output of the gas turbine decline. The most common solution is cooling the air intake temperature. This application widely used in the industrial nowadays. The application such as fogging, evaporative cooler and chillers are the most common one applied in any industry in the world. All those applications have their advantages and limitations which were discussed in this project. Based on design parameter and economic consideration, evaporative cooler is the best option. From this project it shows that, the evaporative cooler works slightly well whereas it can reduce the temperature up to 7.2°F. Besides the cooler effectiveness increase when temperature gradient rises. So, all of this actually can increase the power output of the gas turbine. From the calculation conducted, assuming the prototype is the real application, the power output is improved to 34.7758 MW. The objective of this project finally achieved.

5.2 RECOMMENDATIONS

1. Analyse the effect of different types of cooler pad such as sponge and cloth and different type of wood.
2. Analyse the effect of the orientation of the cooler pad placement, because the technology available placed the cooler pad perpendicular to the air flow.
3. Try to increase the surface area of the cooler pad contact to the air.
4. Calculation amount of evaporated / °C drop in temperature.

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