Gas Turbine Efficiency Improvement at Centralised Utility Facilities (CUF) Kertih, Terengganu

by

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
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Approved by,

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(Mr Rahmat Iskandar Shaarani)

UNIVERSITI TEKNOLOGI PETRONAS

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.

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MUHAMAD AFIQ BIN AHMAD

ABSTRACT

This paper project concerns an improvement of the efficiency of gas turbines at Centralised Utility Facilities (CUF) Kertih, Terengganu. It involves the selection and application of the air inlet treatment. The existing gas turbine does not achieve the expected output as designed by the manufacturer. It is due to the different temperature and pressure range of the environment. Centralised Utility Facilities is located in coastal area of Kertih, Terengganu. High humidity and temperature, tropical rain and sunny conditions are the limitations of the environment. Inlet air cooling is increasingly being recognised as one of the most cost effective means of increasing turbine efficiency and capacity. 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 reduction in turbine output. In this project, the available inlet air cooling systems are discussed as a treatment method to increase gas turbine efficiency. Evaluation and comparison are studied in order to analyse the best possible option to be selected and applied. The factor of selecting includes technical parameters and also general economical study. Experiment is done using fogging cooling system prototype in order to prove the temperature drops and efficiency of the cooler. The results show that by using fogging cooling method, the reduction of temperature is significant; hence increasing the mass flow of the air into compressor. Thus, the efficiency of gas turbine can be improved.

ACKNOWLEDGEMENT

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MUHAMAD AFIQ AHMAD

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CHAPTER 1

INTRODUCTION

1.1 Background Of Gas Turbine

Gas turbine is one of the most significant equipment nowadays especially for the industrial practitioners and widely used in various purposes. It extracts energy from a flow of hot gas produced by combustion of gas or fuel oil in a stream of compressed air. It has an upstream air compressor (radial or axial flow) mechanically coupled to a downstream turbine and a combustion chamber in between. Gas turbines offer a high-powered engine in a very small and light package. However, they are not as responsive and efficient as piston engines over the wide range of rotation per minute (rpm) and powers for the purpose vehicle applications [1].

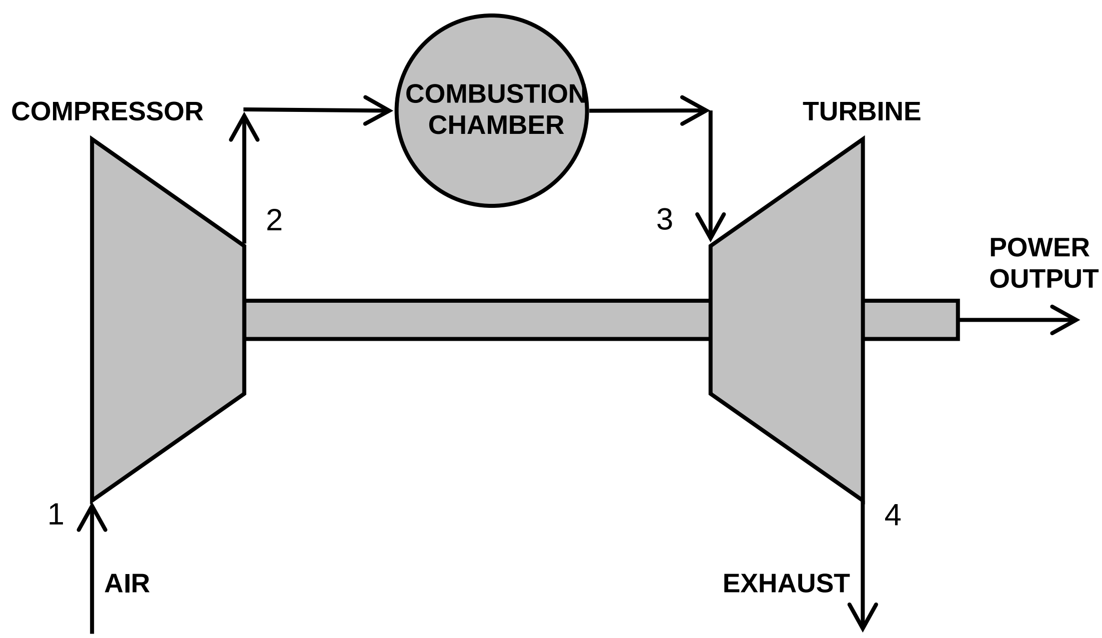


Figure 1.1: Gas turbine cycle

Gas turbines are described thermodynamically by the Brayton cycle, in which air is compressed isentropically, combustion occurs at constant pressure, and expansion over the turbine occurs isentropically back to the starting pressure [2].

In practice, friction, and turbulence cause:

1. Non-isentropic compression; for a given overall pressure ratio, the compressor delivery temperature is higher than ideal.
2. Non-isentropic expansion; although the turbine temperature drop necessary to drive the compressor is unaffected, the associated pressure ratio is greater, which decreases the expansion available to provide useful work.
3. Pressure losses in the air intake, combustor and exhaust: reduces the expansion available to provide useful work.
4.

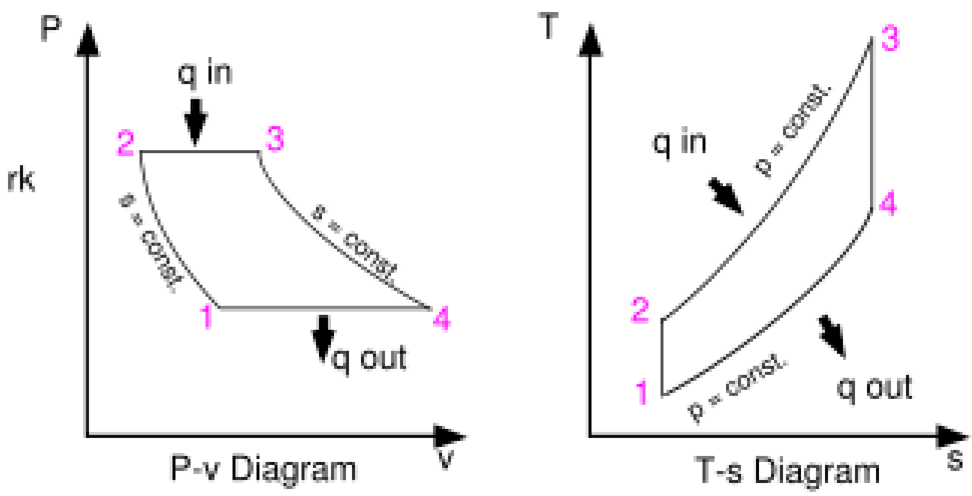


Figure 1.2: Idealized Brayton cycle [2]

As with all cyclic heat engines, higher combustion temperature means greater efficiency. The limiting factor is the ability of the steel, nickel, ceramic, or other materials that make up the engine to withstand heat and pressure. Considerable engineering goes into keeping the turbine parts cool. Most turbines also try to recover exhaust heat, which otherwise is wasted energy. Mechanically, gas turbines can be considerably less complex than internal combustion piston engines. Simple turbines might have one moving part; the shaft, compressor, turbine and alternative rotor assembly, not counting the fuel system.

More sophisticated turbines may have multiple shafts, hundreds of turbine blades, movable stator blades, and a vast system of complex piping, combustors and heat exchangers. As a general rule, the smaller the engine the higher the rotation rate of the shaft needs to be to maintain speed.

Turbine blade tip speed determines the maximum pressure that can be gained, independent of the size of the engine. Jet engines operate around 10,000 rpm and micro turbines around 100,000 rpm. Thrust bearings and journal bearings are a critical part of design. Traditionally, they have been hydrodynamic oil bearings, or oil-cooled ball bearings. This is giving way to foil bearings, which have been successfully used in micro turbines and auxiliary power units.

The advantages of gas turbine engines are very high power-to-weight ratio, smaller than most reciprocating engines of the same power rating, moves in one direction only with far less vibration than a reciprocating engine, very reliable and simpler in design. The disadvantages of gas turbine engines are the cost is much greater compared to a similar size reciprocating engine, consume more fuel when idling compared to reciprocating engines and less efficient unless in continual operation. It explain why road vehicles, which are smaller, cheaper and follow a less regular pattern of use than tanks, helicopters, large boats and so on, do not use gas turbine engines, regardless of the size and power advantages imminently available [3].

1.2 Industrial Gas Turbine

Industrial gas turbines range in size from truck-mounted mobile plants to very complex systems. They can be particularly efficient up to 60% when waste heat from the gas turbine is recovered by a heat recovery steam generator to power a conventional steam turbine in a combined cycle configuration. They can also be run in a cogeneration configuration where the exhaust is used for water heating, or drives an absorption chiller for cooling or refrigeration.

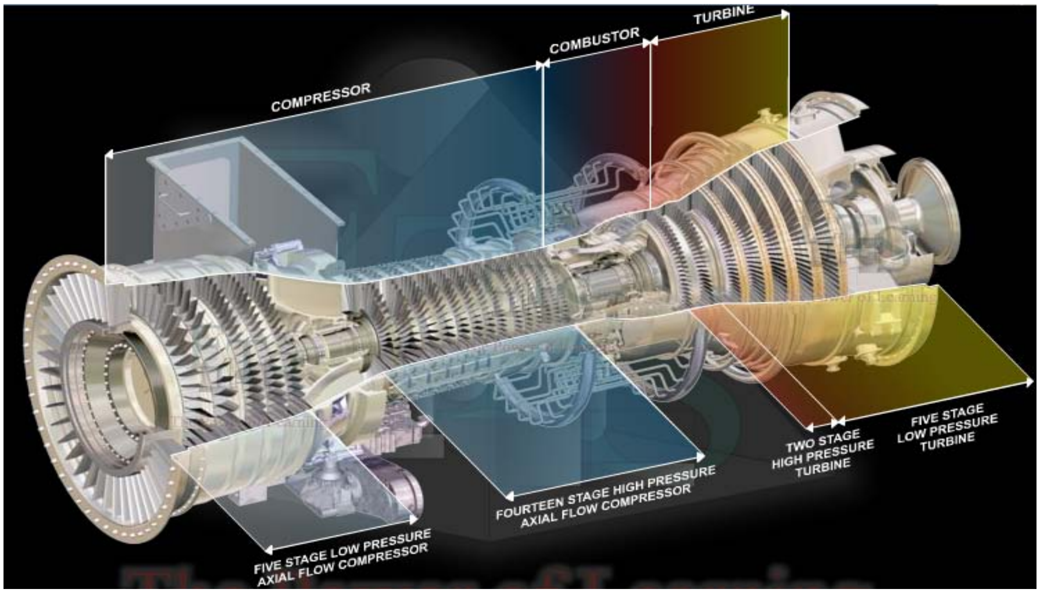


Figure 1.3: Industrial gas turbine layout [4]

Simple cycle gas turbines in the power industry require smaller capital investment than either coal or nuclear power plants and can be scaled to generate small or large amounts of power. Their other main advantage is the ability to be turned on and off within minutes, supplying power during peak demand. Since they are less efficient than combined cycle plants, they are usually used as peaking power plants, which operate anywhere from several hours per day to a couple dozen hours per year, depending on the electricity demand and the generating capacity of the region.

In areas with a shortage of base load and load following power plant capacity, a gas turbine power plant may regularly operate during most hours of the day and even into the evening. A typical large simple cycle gas turbine may produce 100 to 300 megawatts of power and have 35 to 40% thermal efficiency. The most efficient turbines have reached 46% efficiency [4].

1.3 Problem Statement

Gas turbines are installed in many environments from desert to coastal, tropical, arctic, agricultural and oil fields. The weather conditions, temperature and pressure range differ. International Standards Organization (ISO) condition of gas turbine is defined as 15°C of inlet temperature, 14.7 psia of inlet pressure and 60% of relative humidity. But in Malaysia, specifically at Centralised Utility Facilities (CUF) Kertih; due to the tropical and coastal environment, the temperature reaches as high as 37°C and 80% of relative humidity. Due to this, the gas turbines cannot achieve the expected power output as it only manage to produce maximum 34 megawatts of electricity instead of design output 36 megawatts.

1.4 Objectives and Scope of Work

The main objective of this project is to improve gas turbine efficiency at Centralised Utility Facilities (CUF) Kertih by applying air inlet cooling treatment. There are a few possible methods for this kind of treatments such as evaporative media system, fogging system and chillers system.

The scopes of work involved in the project are:

1) To study and gather data about the inefficiency of existing gas turbine performance at CUF.
2) To identify possible and available solutions to the problem.
3) To discuss various methods of cooling the air inlet, the major factors that influence its general economic factor and the selection of design conditions.
4) To study the application of the selected methods and test the system in real application obtains results.

CHAPTER 2
LITERATURE REVIEW

2.1 Turbine Air Inlet Cooling Systems

There are several options available for increasing the performance of a gas turbine based power plant. These options include steam/water injection, turbine air inlet cooling, fuel preheating, multi-pressure Heat Recovery Steam Generator (HRSG), HRSG duct burner firing, etc. Out of these performance enhancing alternatives, air inlet cooling is a highly effective means of increasing the performance during hot ambient and high humidity conditions [5].

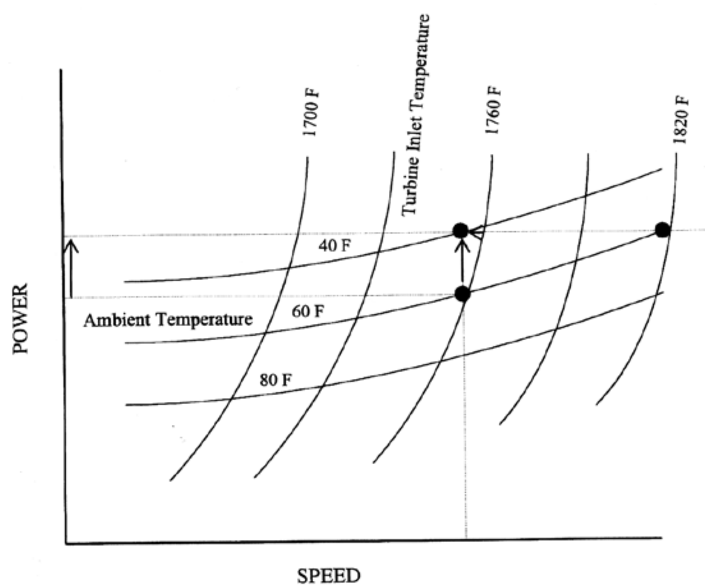


Figure 2.1: Temperature-power-speed interrelationships [5]

Figure 2.1 shows the effects of increasing ambient temperature on gas turbine output. It clearly indicates the advantages of cooling the compressor air inlet, especially in hot climates. The performance of a gas turbine varies significantly with ambient air temperature. As the air temperature reduced, its density increases, resulting higher mass flow rates through the compressor and turbine, thereby increasing turbine output and its thermal efficiency. Gas turbine power output increased by 0.54% - 0.90% for every 1°C reduction in ambient temperature [6].

The work required to compress air is directly proportional to the temperature of air. By reducing the air inlet temperatures, work of compression can be reduced. As a result, more work available at the turbine output shaft. Besides, by cooling the air inlet into compressor, the effect of weather on turbine performance also reduced. Gas turbine performance becomes more consistent and predictable thus helping power producers to meet contractual obligations.

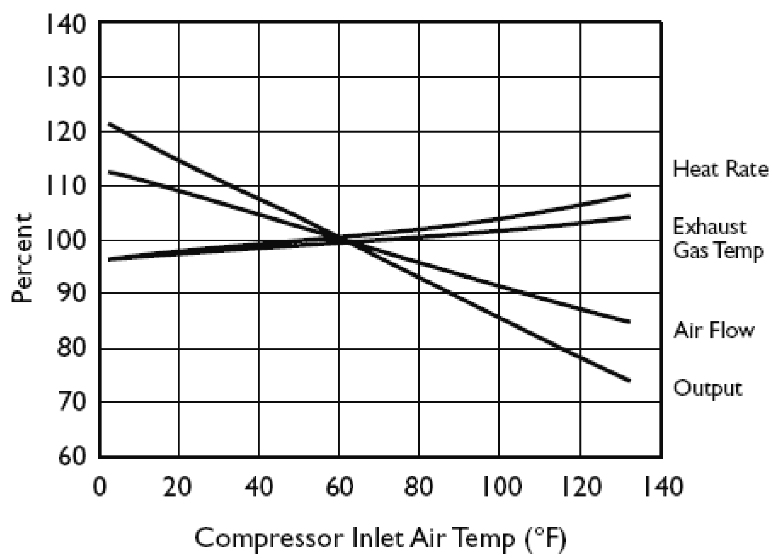


Figure 2.2: Effect of compressor air inlet temperature on gas turbine performance [6]

Figure 2.2 indicates the effect of ambient temperature on turbine output, heat rate, airflow and turbine exhaust temperature. Lowering the compressor air inlet temperature can be accomplished either by the installation of evaporative media system, fogging system or chiller system in the inlet ducting.

The design controls the efficiency of the cooling system; defined as follows:

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

where: T_{1DB} = *inlet dry bulb temperature of the cooler*

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

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

2.2 Fogging System

Fogging system is used with gas turbines to increase the density of the combustion air, thereby increasing power output. The air density increase is accomplished by evaporating water into the inlet air, which decreases its temperature and correspondingly increases its density. It consists of water flow nozzles placed across the face of the gas turbine inlet and coalescer stage. These nozzles distribute the fine mist of water into the air stream and the coalescer stage eliminates non-evaporated water carry over. The quantity of fogger nozzles is a function of nozzle orifice size, spray angle, cross sectional area of the gas turbine inlet and air flow velocity. Fogger-type nozzles can be placed either upstream or downstream the air filters.

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. These systems work well in drier climates because they cool the air inlet to near wet bulb temperature. For regions with high humidity, they provide less cooling because the presence of high moisture content in the ambient air limits its ability to absorb additional moisture. However, treated water is preferred for this type of cooling at high humidity region to prevent deposits, should water droplets be carried to the compressor. Mist eliminators may or may not be required depending upon the air velocity at the water interface spray location, distance from the interface location to the turbine inlet and the amount of water used for cooling. This type of cooling is relatively inexpensive to install.

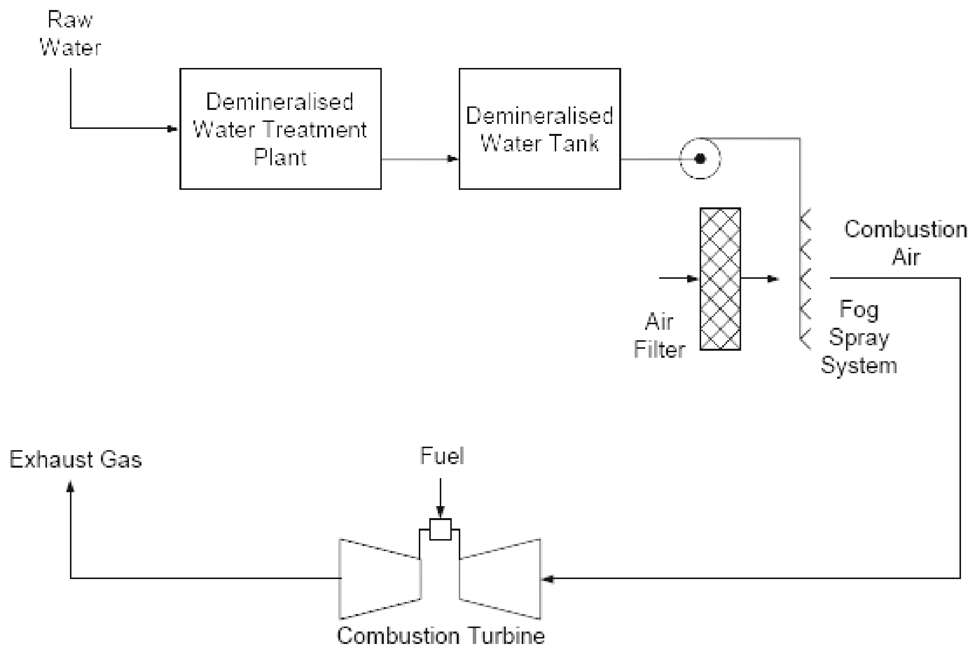


Figure 2.4: Schematic diagram for fogging system [7]

When foggers are used, water is sprayed into the air stream through nozzles placed at the cross-section of the incoming air. The orifice of these nozzles is only a few thousandths of an inch. Therefore demineralised water is often required to prevent clogging of nozzle opening. When demineralised water is used, stainless steel tubing and nozzle arrays are normally required to protect the tubes from corrosion. The size of the water droplets is a function of nozzle dimensions and water pressure. The main advantage of foggers is that the air side pressure drop, when fogging is not operational, is negligible. In addition, a more precise control over the humidity level of the cooled air is possible when foggers are used instead of evaporative media.

2.3 Evaporative Media System

The evaporative cooler is the effective way to recover capacity during periods of high temperature and low or moderate relative humidity. The biggest gains are realized in hot, low humidity climates. However, evaporative cooler effectiveness is limited to ambient temperature of 16 °C and above. The effectiveness of evaporative cooler is a measure of how close the cooler exit temperature approaches the ambient wet bulb temperature. The actual temperature drop realized is a function of both the equipment design and atmospheric conditions.

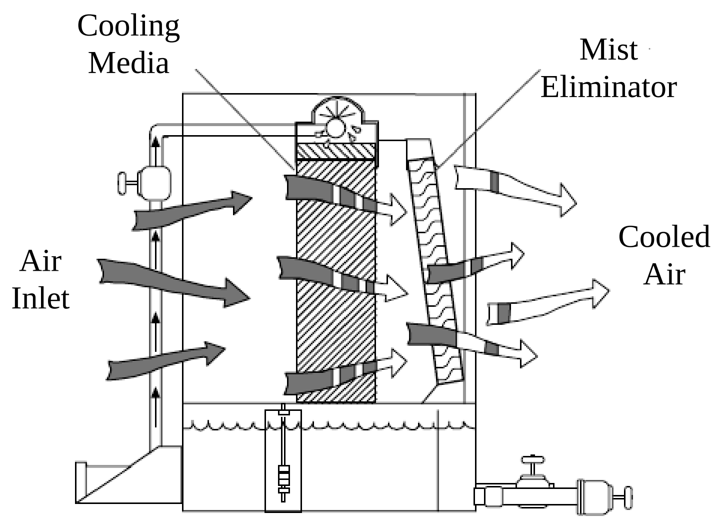


Figure 2.5: Evaporative media cooling mechanism [7]

Evaporative cooling using media requires a large surface area to allow for sufficient contact time between air and the water. This may raise a concern for retrofits if sufficient space at the inlet duct is not available for media installation. The media imposes an additional pressure drop during colder ambient conditions when cooling is not required.

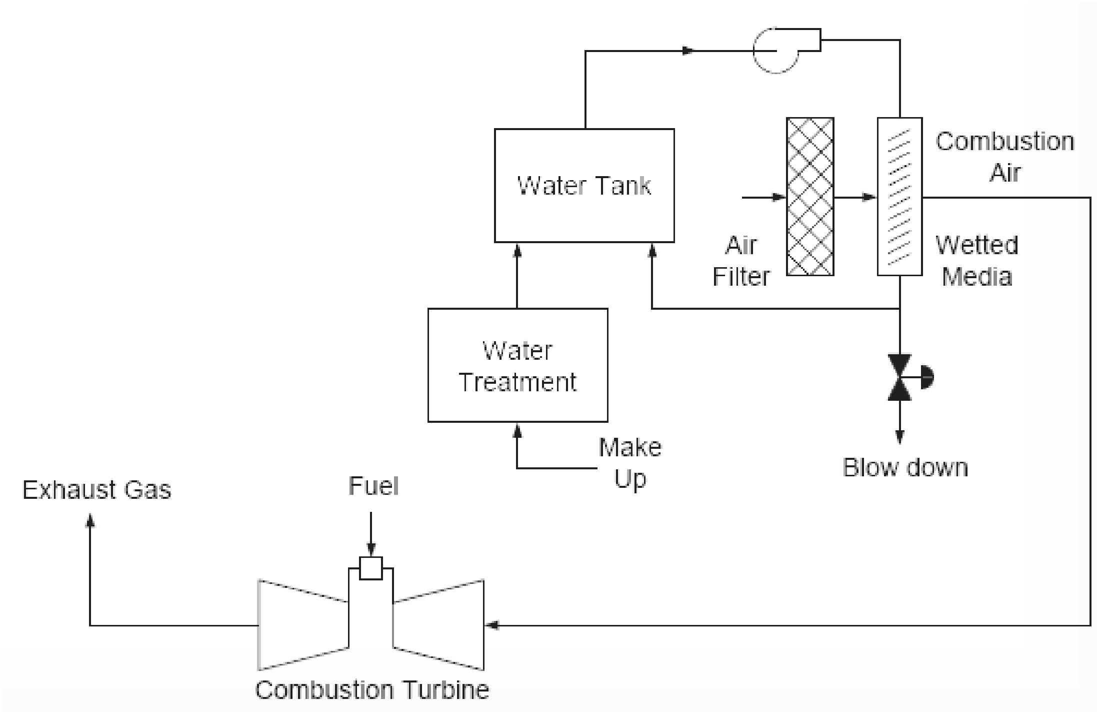


Figure 2.6: Schematic of evaporative media cooling [7]

2.4 Chiller System

As airflow passes through the chilled coils, the air is cooled through an indirect heat exchange with the cooling fluid. The air then passes through drift eliminator media to eliminate excess droplets and then into the turbine. The coils are cold and therefore condensation is created. Condensate droplets are directed downward and collected in pans, then directed out of the system. Typically, all condensation is eliminated this way, but to ensure air dryness, mist eliminator panels are in place to remove any stray condensate droplets.

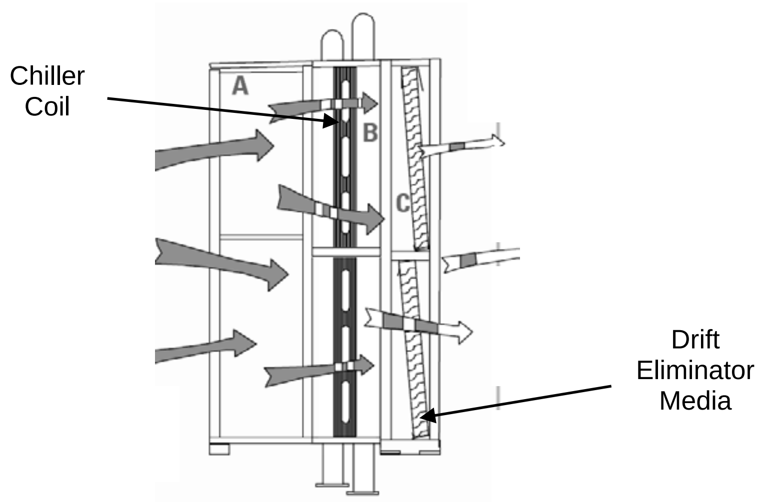


Figure 2.7: Chiller system mechanism [7]

Chillers are not limited by the ambient wet bulb temperature. The power increase achievable is limited by the machine, capacity of chilling device and ability of coils to transfer heat. Cooling initially follows a line of specific humidity. As saturation is approached, water begins to condense from the air. Further heat transfer cools the condensate and air, and causes more condensation. Because of the relative high heat of vaporization of water, most of the cooling energy goes to condensation and little to temperature reduction. Therefore, chillers should be designed to avoid forming excessive condensate [7].

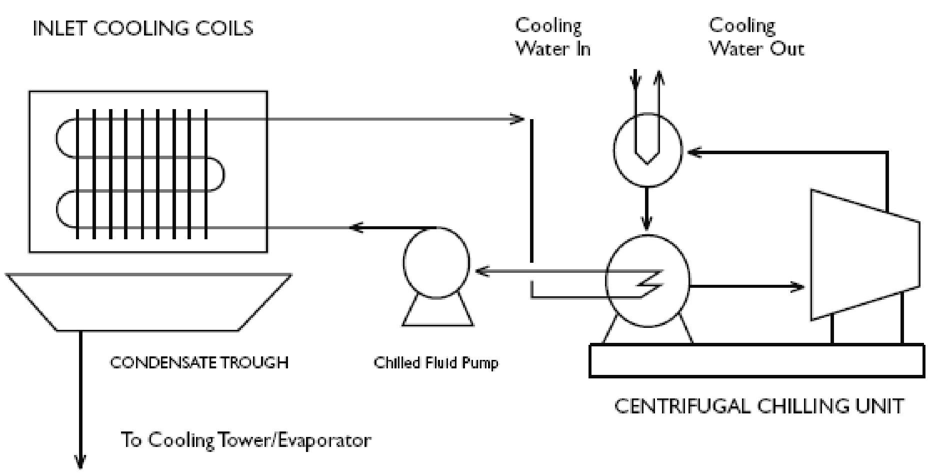


Figure 2.8: Schematic diagram of a chiller system [7]

2.5 Application of Fogging Cooling System

In fogging system, air density increase is accomplished by evaporating water into the inlet air. It consists of water flow nozzles placed across the face of the gas turbine inlet by distributing the fine mist of water into the air stream. The quantity of fogger nozzles is a function of nozzle orifice size, spray angle, cross sectional area of the gas turbine inlet and air flow velocity. Water is brought in contact with the incoming air. As it absorbs heat from the air and is evaporated, the air stream is cooled [8].

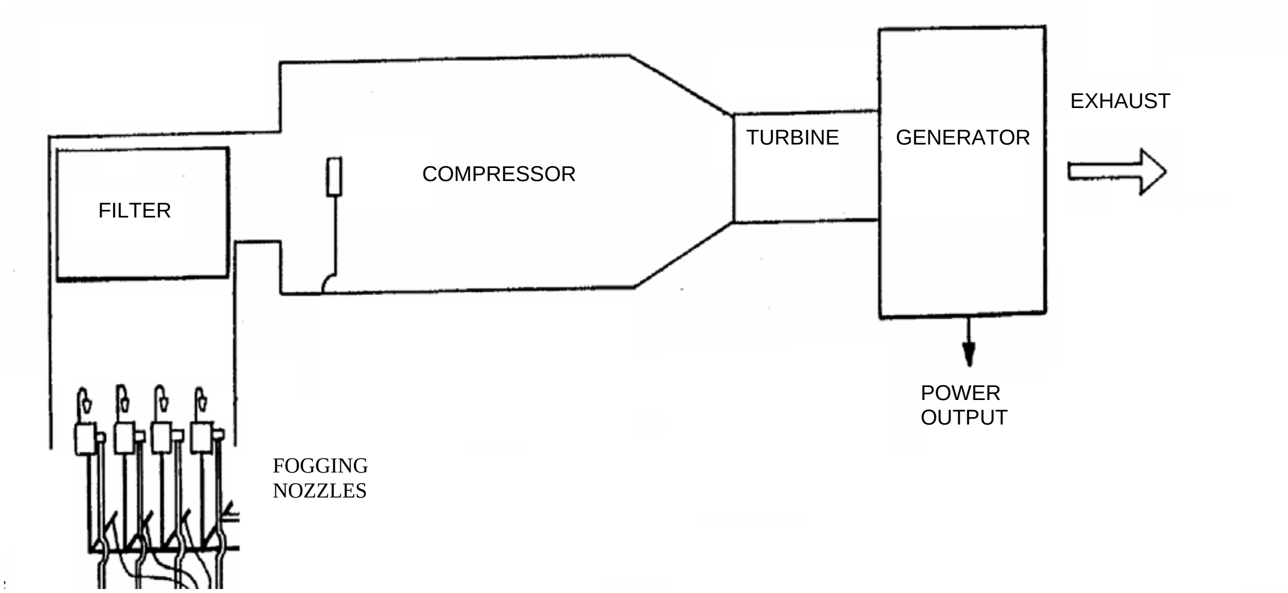


Figure 2.9: Application of fogging system in gas turbine [8]

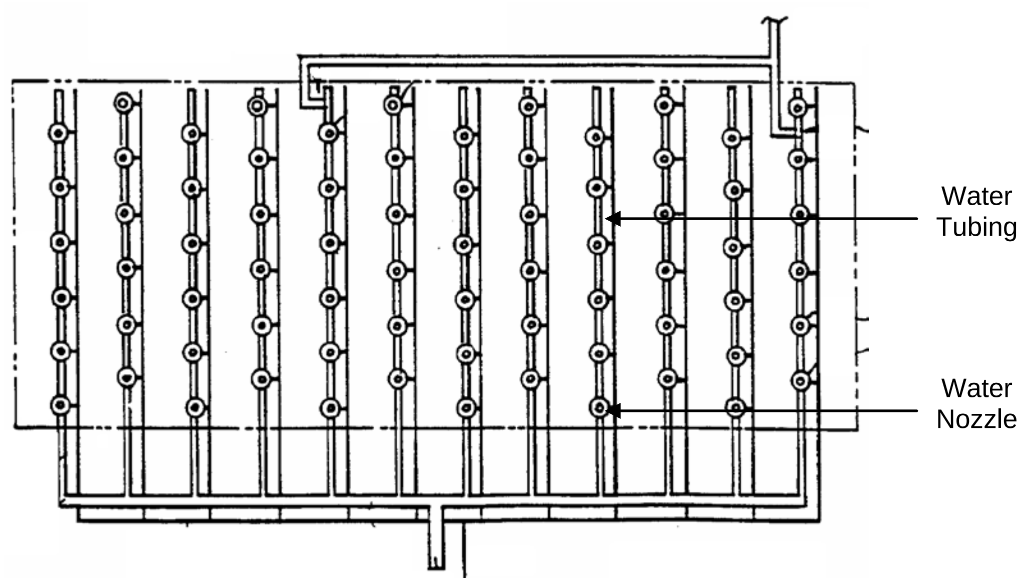


Figure 2.10: Plan View of an array of fogging system [8]

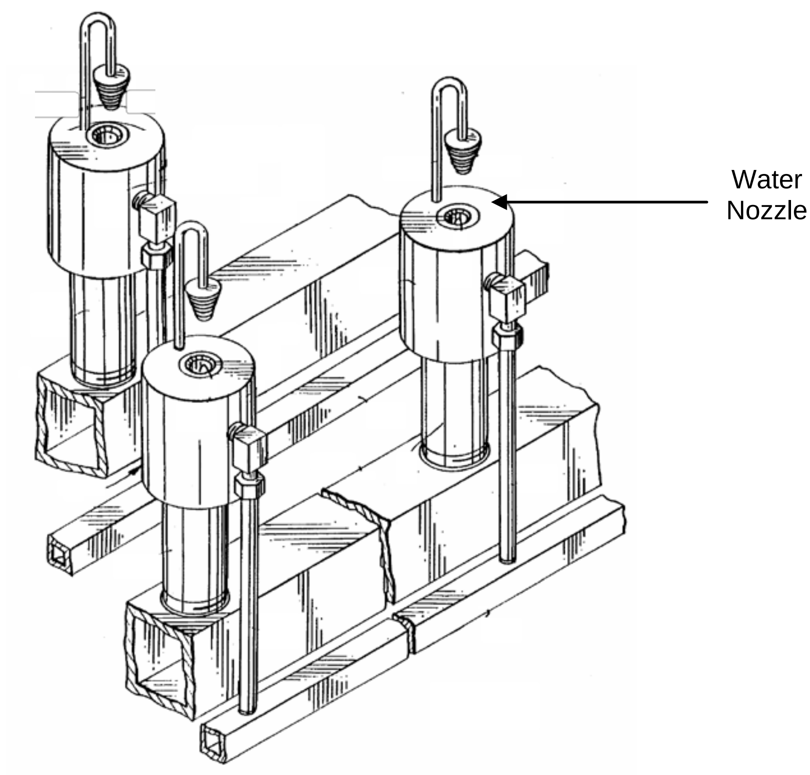


Figure 2.11: Nozzles of fogging system [8]

Figure 2.12: Mist of water form fogger nozzles [8]

The equipments involved in the fogging system are fogger nozzles, high pressure pump and controller. All of these contribute to the effectiveness of the cooling system and can be manipulated to suit with the applied condition in order to get the maximum effect to the inlet temperature reduction.

2.6 Atomization Concept

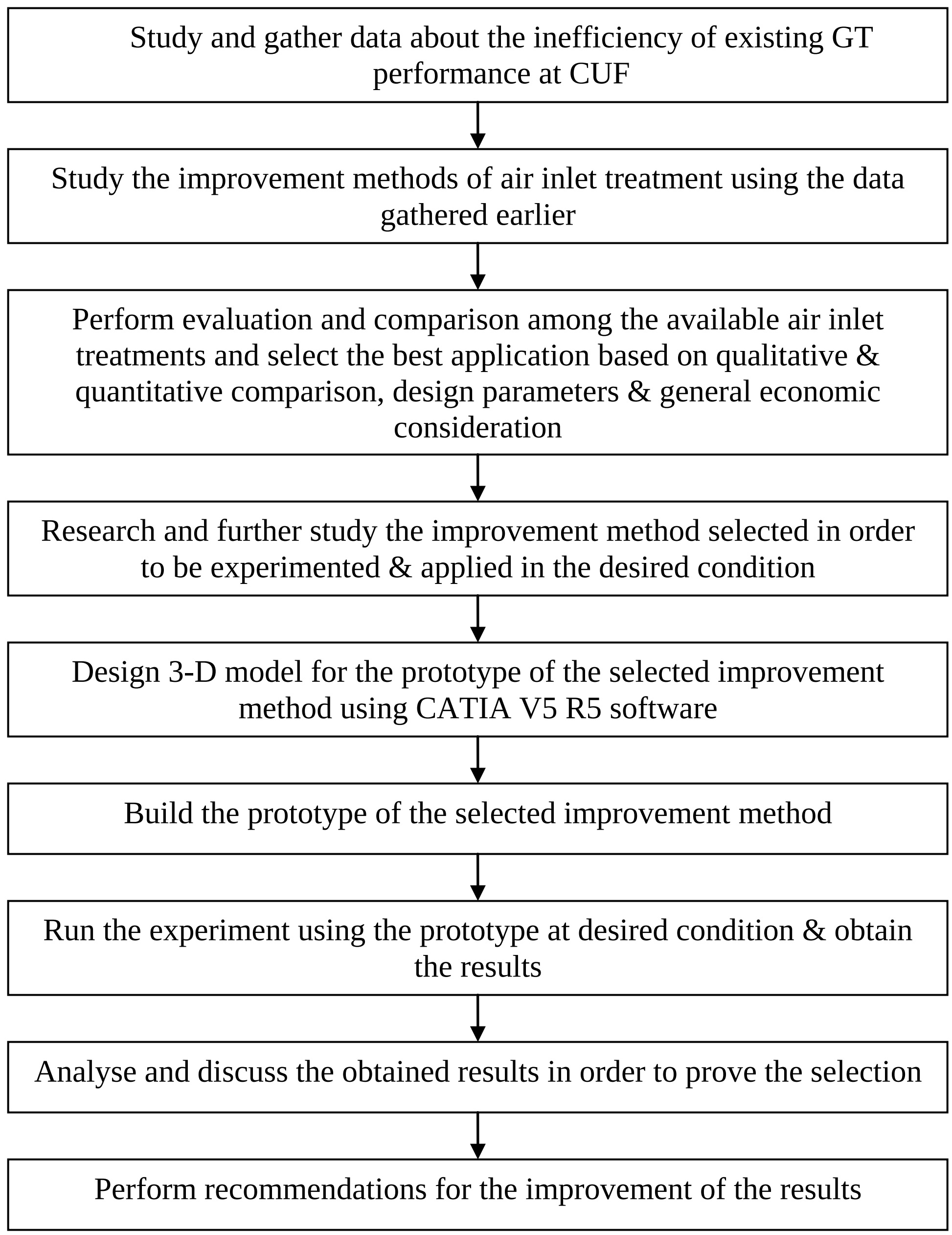
In atomic spectroscopy, atomization stands for the conversion of a vaporized sample into atomic components. Liquid samples are first nebulized, the fine mist is transported into the atomization source (flame or plasma), where the solvent evaporates and the analyte is vaporized, then atomized. The term atomization is sometimes improperly used instead of nebulization for the conversion of bulk liquid into a spray or mist (i.e. collection of drops), often by passing the liquid through a nozzle. But for the common usage, atomization is accepted. [9].

In fogging system, particularly for the purpose of gas turbine, a complete understanding of atomization process is important. This ensures the water droplets produced by nozzles able to produce cooling effect for the air inlet of compressor. Several parameters are critical such as velocity of air stream in which the nozzle is located, the properties of water itself, pressure applied on the liquid and consequently the spray angle [10].

CHAPTER 3

METHODOLOGY

3.1 Flowchart



3.2 Experimental Set-Up

The objectives of the experiment are to determine the temperature drop and efficiency of fogging cooling method. Evaporative cooling is a process that reduces air temperature by evaporation of water into the air stream. As water evaporates, energy is lost from the air causing its temperature to drop. Two temperatures are important when dealing with evaporative cooling systems - dry bulb temperature and wet bulb temperature. Dry bulb temperature is the temperature that we usually think of as air temperature. It is the temperature measured by a regular thermometer exposed to the air stream. Wet bulb temperature is the lowest temperature that can be reached by the evaporation of water only. It is the temperature you feel when your skin is wet and is exposed to moving air. Unlike dry bulb temperature, wet bulb temperature is an indication of the amount of moisture in the air. Wet bulb temperatures can be determined by checking with local weather station or by investing in an aspirated psychrometer, an electronic humidity meter or investigating Psychrometric Chart.

3.3 Parameters of the Experiment

Table 3.1: Parameters of experiment

No	Parameters
1.	Inlet Dry-bulb temperature, T_{1DB} (°C)
2.	Outlet Dry-bulb temperature, T_{2DB} (°C)
3.	Wet-bulb temperature, T_{WB} (°C)
4.	Relative humidity, RH (%)
5.	Water temperature, T_w (°C)
6.	Velocity of air, V (m/s)
7.	Water flowrate, m (cm^3/s)
8.	Temperature gradient, ΔT (°C)
9.	Cooler effectiveness, ***e*** (%)

3.4 Engineering Drawing

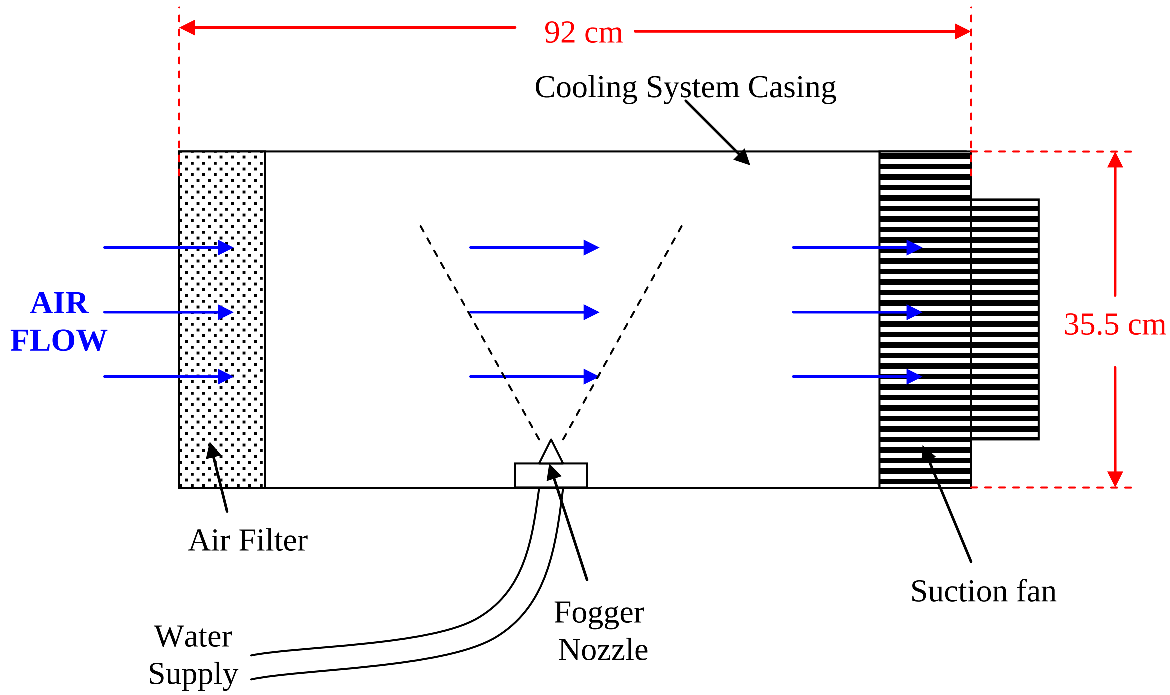


Figure 3.1: 2-D model of the prototype

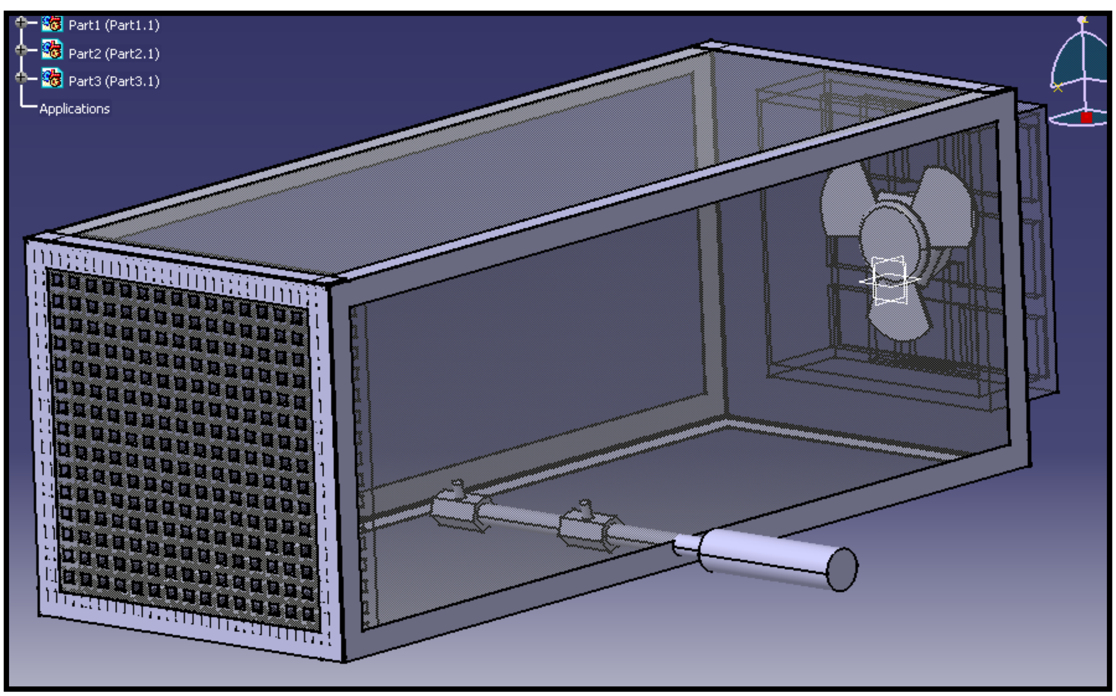


Figure 3.2: 3-D model of the prototype

3.5 Apparatus of the experiment

Table 3.2: Apparatus of experiment

No.	Apparatus	Quantity
1.	Suction Fan	1
2.	Water Nozzles + Fittings	2
3.	Air Filter	1
4.	Water Tubing	1
5.	Cooler casing	1
6.	Anemometer	1
7.	Beaker 300 ml	2

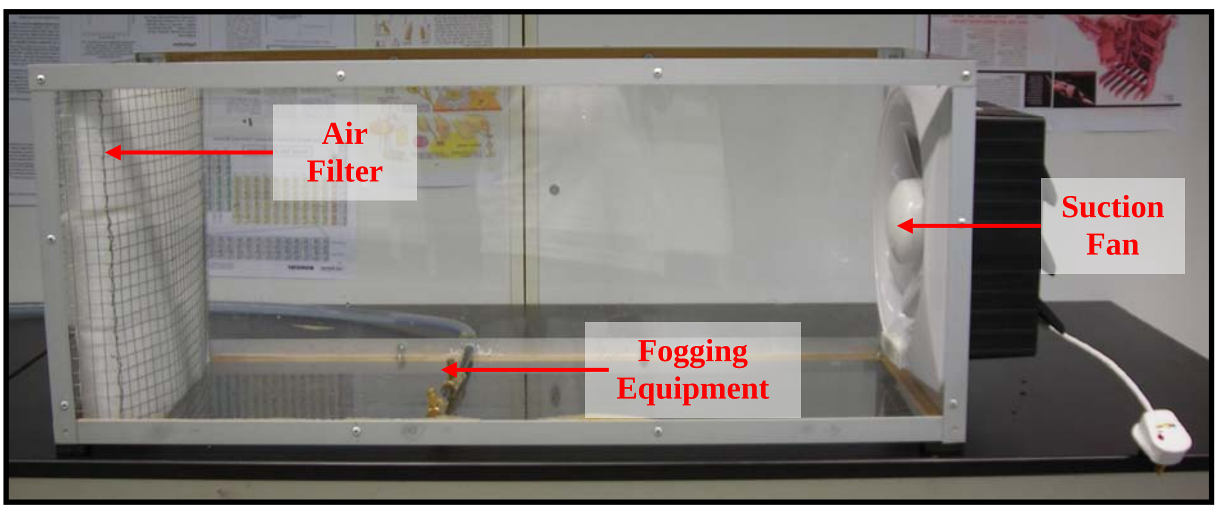


Figure 3.3: Prototype of the cooler system

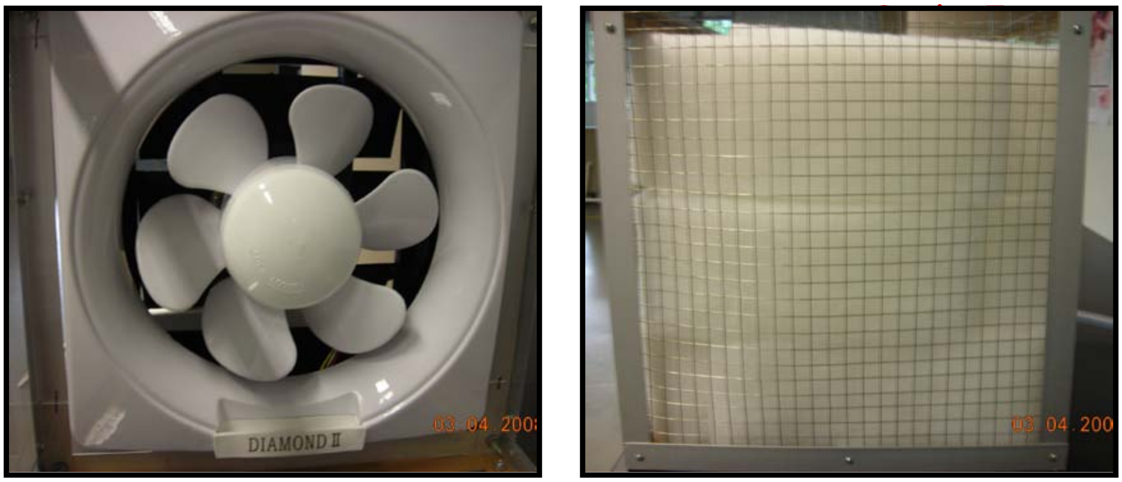


Figure 3.4: Suction fan and air filter

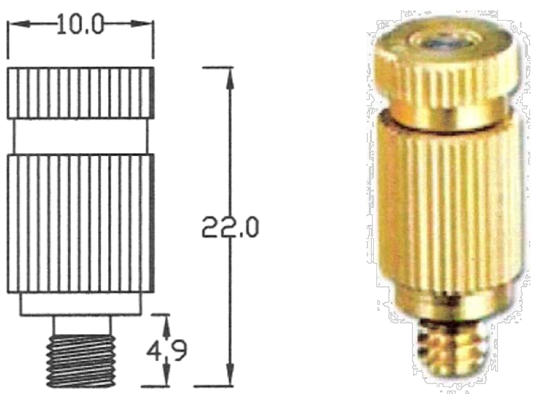


Figure 3.5: Water fogger nozzle

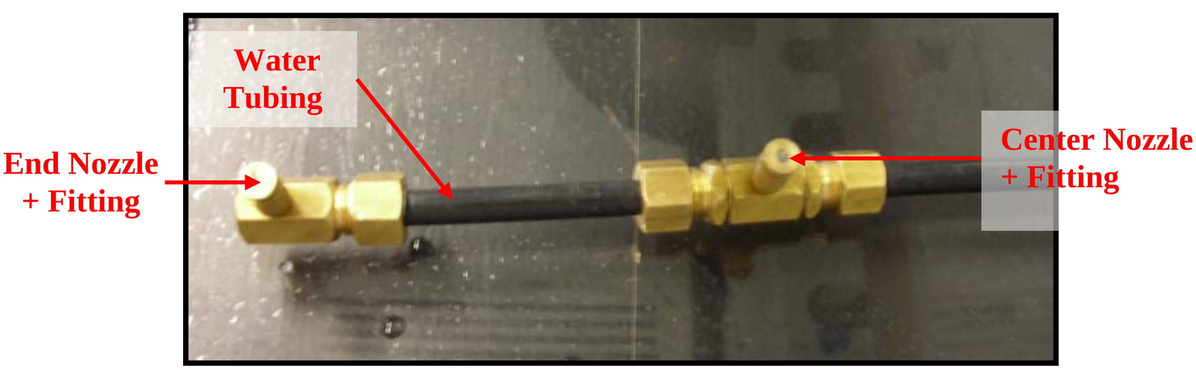


Figure 3.6: Fogging equipment

Table 3.3: Specification of nozzle

Specification of the Nozzle	
Model	SIM 1-BR
Orifice (mm)	0.15
Orifice (in)	0.006
Material	Brass
Angle (degree)	50-65
Length (mm)	22
Diameter (mm)	10
Thread	10/W24

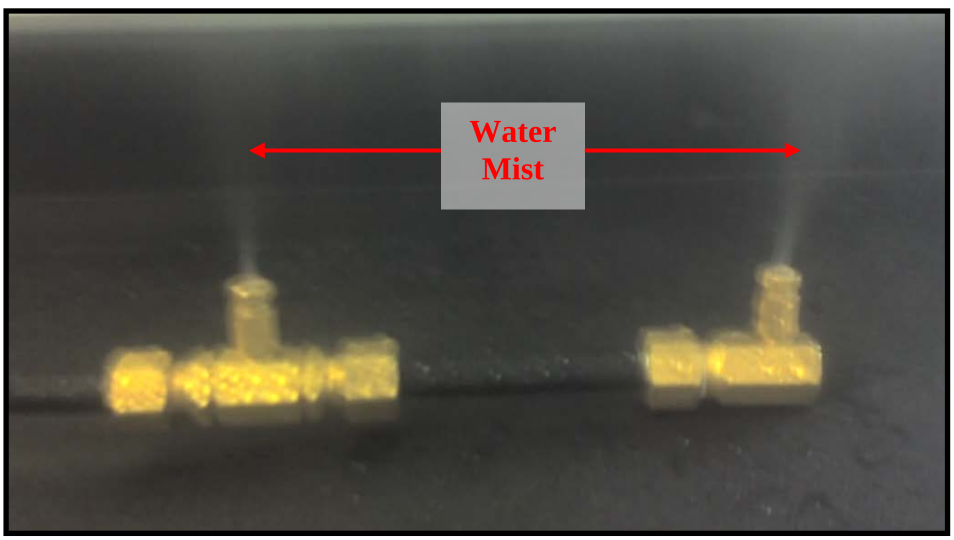


Figure 3.7: Atomization of nozzles

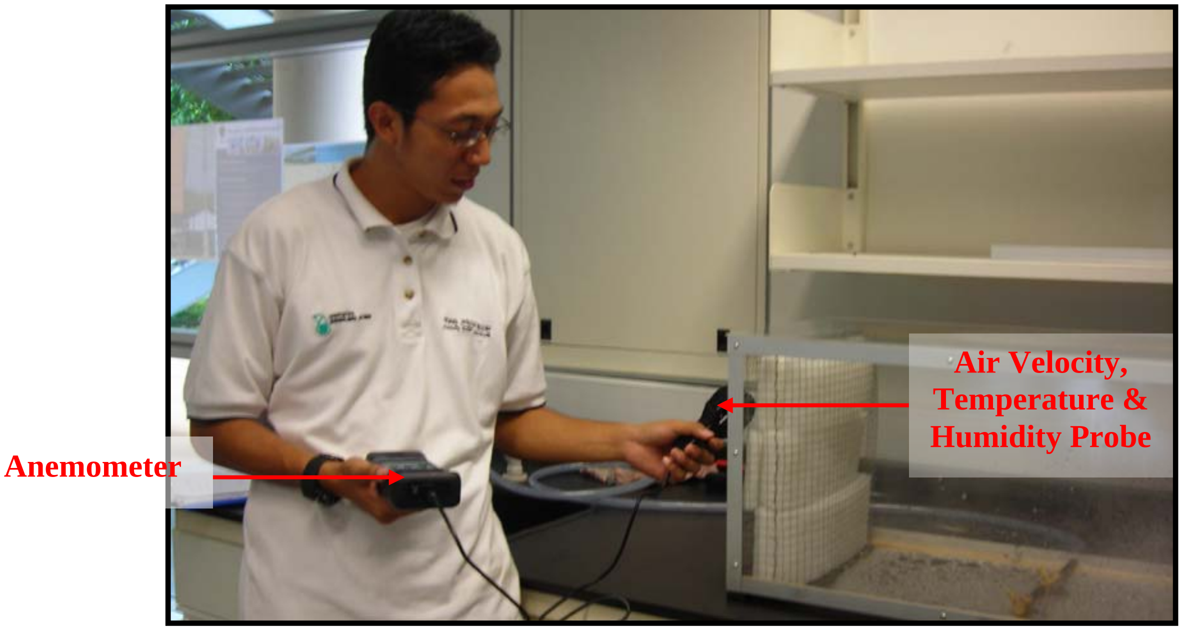


Figure 3.8: Measurement taken during experiment

Table 3.4: Specification of Anemometer

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

3.6 Experimental Procedures

a) All of the equipments are arranged accordingly.

b) Using Anemometer, relative humidity of the surrounding is measured.

c) Volumetric flow rate of the inlet and outlet of the fogging system is determined

d) Suction fan is turned on and suck the air from atmosphere into the cooling system casing.

e) Water supply to the fogger is turned on.
f) Air inlet is filtered through air filter at the opening of the system casing.
g) Air stream flowing through evaporative cooling section undergone evaporation of water, hence reducing the air temperature.
h) Using Anemometer, inlet and outlet dry bulb temperature is measured at 2, 4, 6, 8 and 10^{th} minutes. Data are recorded in the table.
i) Using Anemometer also, air velocity is measured.
j) Steps (c) until (i) are repeated with other two values of volumetric flow rates. All the data are recorded in the table with different values of volumetric flow rate.
k) Graph temperature gradient versus time is plotted for different values of volumetric flow rate.

CHAPTER 4
RESULT AND DISCUSSION

4.1 Design Parameters

The major design factors that influence the suitability of a gas turbine inlet air cooling systems are as follows:

4.1.1 Ambient Temperature

The ambient wet bulb temperature has a significant impact on the size and cost of the system since most of the cooling load consists of the latent load. Often the design conditions are specified in terms of dry bulb temperature and relative humidity (RH). The design conditions could also be specified in terms of dry and wet bulb temperature to avoid confusion

4.1.2 Ratio of Air Flow to Turbine Output

The other important criterion is the air flow, lb/hr, to kW ratio. The cooling load is directly proportional to the air flow. The lower the ratio, the more effective inlet cooling is. For a ratio less than 30, the cooling option is very cost effective; for a ratio between 30 and 35, the cost effectiveness diminishes. The newer more efficient gas turbines have low ratios and therefore provide considerable capacity enhancement at lower inlet air temperatures. Another important point to remember while looking at the air flow to kW ratio is the size of the turbine. The cost/ton of cooling capacity goes down as the size of the unit goes up. Therefore, it is possible that larger units with a higher ratio may prove to be as cost effective as smaller units with a lower ratio.

4.1.3 Slope of Turbine Performance Curve

The slope of the turbine performance curve as a function of its compressor's inlet air temperature determines the capacity enhancement by cooling inlet air. The steeper the curve, the more benefits that can be realized from cooling inlet air.

4.1.4 Hours of Operation

If more than 6 hours of cooling is needed, continuous cooling is the most cost effective way unless excess refrigeration equipment is already available at the site which is not used to its full capacity. This is because the size of the cooling system is directly proportional to the hours of cooling required and as the number of hours increase, the size and cost of the system required increases correspondingly.

4.2 General Economic Consideration

The cost of an inlet cooling system is often evaluated in terms of profit/kW. This can be misleading because the output enhancement as a result of inlet air cooling varies with the ambient temperature. A better way of evaluating the economic feasibility of a cooling system is through cost benefit analysis. All these factors contribute to total revenues and should be properly accounted for in economic evaluation. Major factors that influence the economics of a project are as follows:

i. Installation costs
ii. Maintenance cost
iii. Operation cost
iv. Fuel costs
v. Effectiveness
vi. Revenues

4.3 CUF Gas Turbine

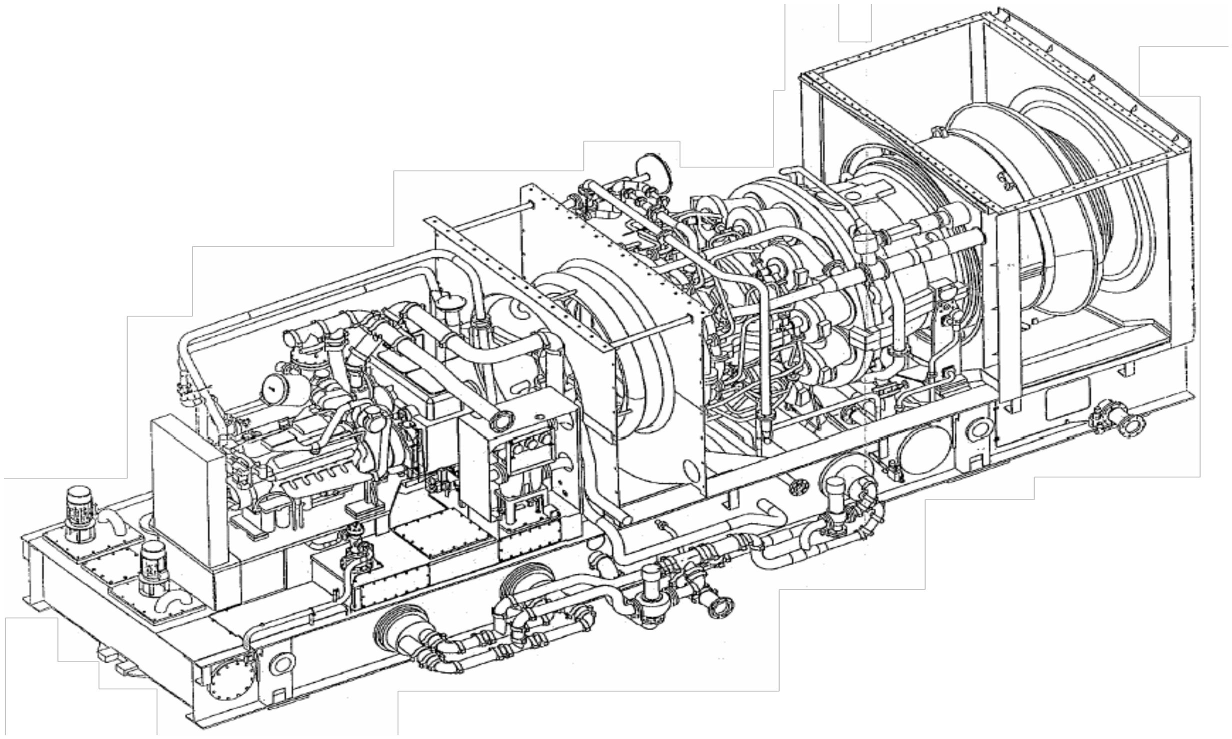


Figure 4.1: Layout of GE MS6001B gas turbine used at CUF

Table 4.1: General Electric (GE) MS6001B gas turbine data

Simple Cycle Performance 50/60Hz Power Generation	
Model Designation	GE MS6001B
Output	36 MW
Heat Rate	10642 Btu/kWh (11227 kJ/kWh)
Mass Flow	311 lb/sec (141.1 kg/sec)
Turbine Speed	5163 rpm
Pressure Ratio	12.2:1
Exhaust Temperature	1018°F (548°C)

Source: Centralised Utility Facility Mechanical Catalogue

4.4 Evaluation Of Air Inlet Cooling System

Table 4.2: Qualitative Comparison of inlet cooling system

CRITERIA OF EVALUATION	IMPROVEMENT METHODS		
	Fogging System	**Evaporative Media**	**Chillers System**
Ambient temperature (DB = 35°C)	Significant temperature reduction	Low temperature reduction	Significant temperature reduction
Relative humidity (RH = 80%)	Less suitable for high humidity but can be improve by water treatment	Not suitable for high humidity region	Suitable for high humidity region
Hours of operation	Suitable if less than 6 hours of operation per day	Suitable if less than 6 hours of operation per day	Not suitable if less than 6 hours of operation per day
Installation	Low installation cost and less installation time	Low installation cost and less installation time	High installation cost and complex design
Operation and maintenance cost	Low O&M cost and do not require expertise	Low O&M cost and do not require expertise	High O&M cost and need expertise to handle it
Effect when cooling system not operated	No effect to the air inlet pressure	The media imposes additional pressure	The cooling coil imposes additional pressure
Space required in inlet duct	Less space required	Large space required	Large space required
Control	Precise control over humidity level of cooled air	Less control over humidity level of cooled air	Significant control over temperature level of cooled air

Table 4.3: Quantitative comparison of inlet cooling system

CRITERIA OF EVALUATION	WEIGHTAGE	IMPROVEMENT METHODS		
		Fogging System	**Evaporative Media**	**Chiller System**
High temperature reduction	3	2	1	3
High humidity condition	2	1	0	2
Low power consumption	3	3	3	1
Simplicity of installation	2	3	3	1
Low operation and maintenance cost	3	3	3	1
Low effect cooling system not operated	2	3	0	1
Less space required in inlet duct	1	3	2	0
Controllable	2	3	0	3
TOTAL		**47**	**29**	**29**

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

4.5 Principle of Calculation

Two parameters are important when dealing with evaporative cooling systems; dry bulb temperature and wet bulb temperature. Dry bulb temperature is the temperature that we usually think of as air temperature. It is the temperature measured by a regular thermometer exposed to the air stream. Wet bulb temperature is an indication of the amount of moisture in the air. Wet bulb temperatures can be determined by investing Psychrometric Chart.

4.5.1 Water Flow rate

The volumetric flow rate of the experiment is determined by measuring the difference between input and output water flow rates of nozzles.

$$\textbf{Water Flowrate, } m = m_1 - m_2$$

where: *m_1 = input water flow rate*

m_2 = output water flow rate

4.5.2 Temperature Gradient

The temperature drop of dry bulb temperature is determined by measuring the difference between inlet dry bulb temperature and outlet dry bulb temperature.

$$\textbf{Temperature gradient } (\Delta T) = T_{1DB} - T_{2DB}$$

where: *T_{1DB} = inlet dry bulb temperature*

T_{2DB} = outlet dry bulb temperature

4.5.3 Cooler Efficiency

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

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

where: T_{1DB} = *inlet dry bulb temperature*

T_{2DB} = *outlet dry bulb temperature*

T_{WB} = *wet bulb temperature*

Using Psychrometric chart, downstream wet-bulb temperature (T_{WB}) is determined based on relative humidity (RH) and inlet dry-bulb temperature (T_{1DB}). By applying the correlation above, efficiency of the cooler system is calculated.

4.5.4 Psychrometric Chart and Air Characteristics

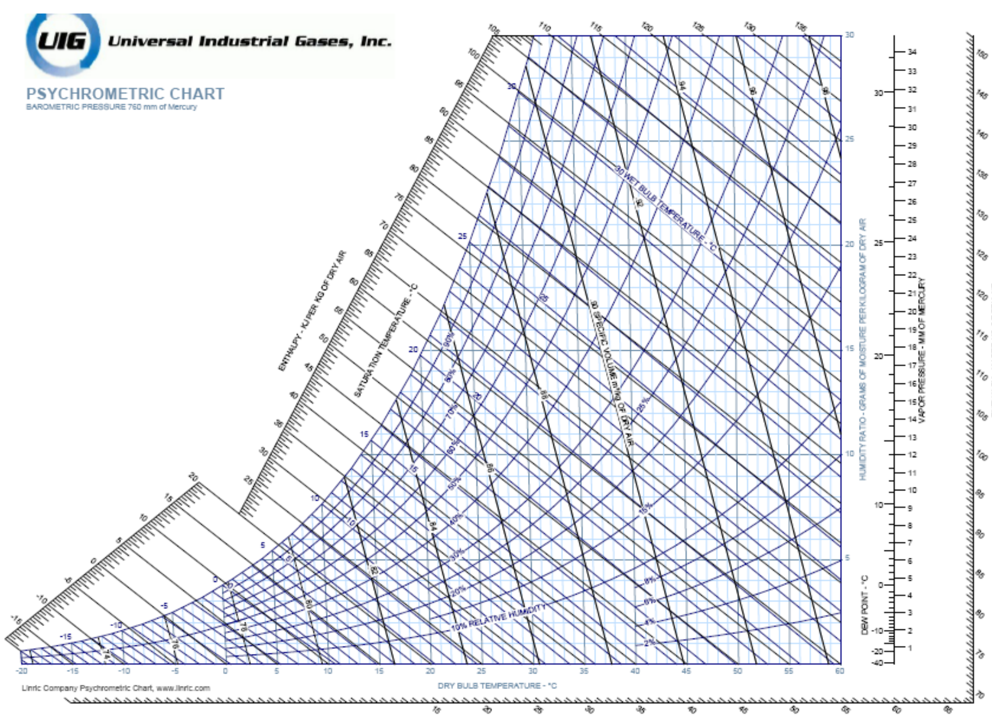


Figure 4.2: Psychrometric Chart (SI Unit)

A psychrometric chart presents physical and thermal properties of moist air in a graphical form as diagrammed in Figure 4.2. 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. 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 4.3: wet-bulb temperature; enthalpy; dewpoint or saturation temperature; relative humidity; and specific volume [8].

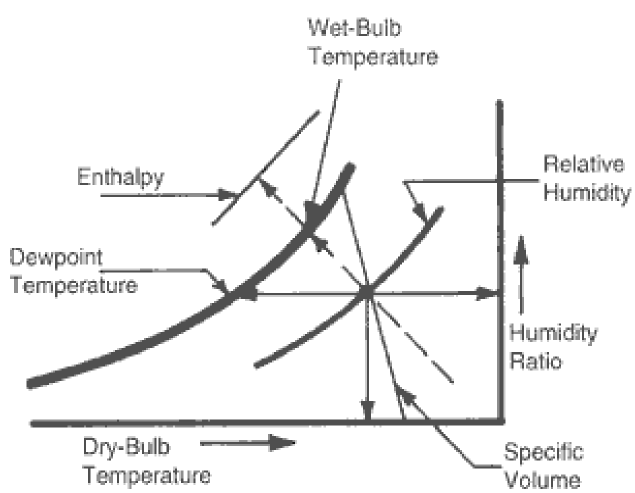


Figure 4.3: Properties of moist air on a psychrometric chart

4.5.5 Power Recovery

According to the literature, gas turbine power output recovery is between 0.54 % - 0.90 % for every 1°C reduction in ambient temperature. Assume the recovery is 0.7 %.

Actual power output at CUF = 34 MW
Design power output at CUF = 36 MW
Output recovery = 0.70 % / 1°C

Power output recovery = (ΔT °C x 0.7/100) x 34 MW

4.6 Result Analysis and Discussion

From the experiment using fogging cooling prototype, measurements taken are as follows;

Water Temperature, T_W = 23 °C
Relative Humidity, RH = 77.4 %
Velocity of air = 3.3 m/s
Pressure = Atmospheric pressure

Experiment is done with three different values of water flowrate of nozzles. Each flowrate produced different values of inlet dry-bulb temperature, outlet dry-bulb temperature and web-bulb temperature. The values tabulated in the table as below:-

i) For the water flowrate = 150.8 cm^3/s

Table 4.4: Time and temperature relation for water flowrate = 150.8 cm^3/s

Water Flowrate = 150.8 cm^3/s				
t (minutes)	**T_{1DB} (°C)**	**T_{2DB} (°C)**	**T_{WB} (°C)**	**ΔT (°C)**
2	24.7	21.8	20.7	2.9
4	24.5	21.5	20.5	3.0
6	24.4	21.3	20.5	3.1
8	24.5	21.3	20.5	3.2
10	24.4	21.3	20.5	3.1
TOTAL	122.5	107.2	102.7	15.3

T_{1DB} average $= \sum T_{1DB} / 5$

$= 24.50$ °C

T_{2DB} average $= \sum T_{2DB} / 5$

$= 21.44$ °C

T_{WB} average $= \sum T_{WB} / 5$

$= 20.54$ °C

Cooler efficiency, *e* **$= (T_{1DB} - T_{2DB}) / (T_{1DB} - T_{WB})$**

= 77.27 %

ΔT average $= \sum \Delta T / 5$

$= 3.06$ °C

Output recovery **= (ΔT °C x 0.7/100) x 34 MW**

= (3.06 °C x 0.7/100) x 34 MW

= <u>0.73 MW</u>

ii) For the water flow rate = 125.9 cm^3/s

Table 4.5: Time and temperature relation for water flowrate = 125.9 cm^3/s

Water Flowrate = 125.9 cm^3/s				
t (minutes)	**T_{1DB}**	**T_{2DB}**	**T_{WB}**	**ΔT (°C)**
2	24.6	22.2	20.6	2.4
4	24.7	22.1	20.7	2.6
6	24.5	21.9	20.5	2.6
8	24.5	21.9	20.5	2.6
10	24.6	22.0	20.6	2.6
TOTAL	122.9	110.1	102.9	12.8

T_{1DB} average $= \sum T_{1DB} / 5$

$= 24.58$ °C

T_{2DB} average $= \sum T_{2DB} / 5$

$= 22.02$ °C

T_{WB} average $= \sum T_{WB} / 5$

$= 20.58$ °C

Cooler efficiency, *e* (%) $= (T_{1DB} - T_{2DB}) / (T_{1DB} - T_{WB})$

= 64.00 %

ΔT average $= \sum \Delta T / 5$

$= 2.56$ °C

Output recovery **= (ΔT °C x 0.7/100) x 34 MW**

= (2.56 °C x 0.7/100) x 34 MW

= <u>0.61 MW</u>

iii) For the volumetric flow rate = 111.2 cm^3/s

Table 4.6: Time and temperature relation for water flowrate = 11.2 cm^3/s

Water Flowrate = 111.2 cm^3/s				
t (minutes)	**T_{1DB}**	**T_{2DB}**	**T_{WB}**	**ΔT (°C)**
2	24.7	22.4	20.7	2.3
4	24.8	22.5	20.8	2.3
6	24.6	22.5	20.6	2.1
8	24.7	22.6	20.7	2.1
10	24.5	22.4	20.5	2.1
TOTAL	123.3	112.4	103.3	10.9

T_{1DB} average $= \sum T_{1DB} / 5$

$= 24.66$ °C

T_{2DB} average $= \sum T_{2DB} / 5$

$= 22.48$ °C

T_{WB} average $= \sum T_{WB} / 5$

$= 20.66$ °C

Cooler efficiency, *e* (%) **= ($T_{1DB} - T_{2DB}$) / ($T_{1DB} - T_{WB}$)**

= 54.50 %

ΔT average $= \sum \Delta T / 5$

$= 2.18$ °C

Output recovery **= (ΔT °C x 0.7/100) x 34 MW**

= (2.18 °C x 0.7/100) x 34 MW

= 0.52 MW

iv) Relationship between Water Flow rate and Temperature Gradient

Table below shows the relationship between water flow rate and temperature gradient based on experiment done.

Table 4.7: Relationship between water flowrate and temperature gradient

t (minutes)	ΔT (°C)		
	For Water Flow rate = 150.8 cm^3/s	**For Water Flow rate = 125.9 cm^3/s**	**For Water Flow rate = 111.2 cm^3/s**
2	2.9	2.4	2.3
4	3.0	2.6	2.3
6	3.1	2.6	2.1
8	3.2	2.6	2.1
10	3.1	2.6	2.1

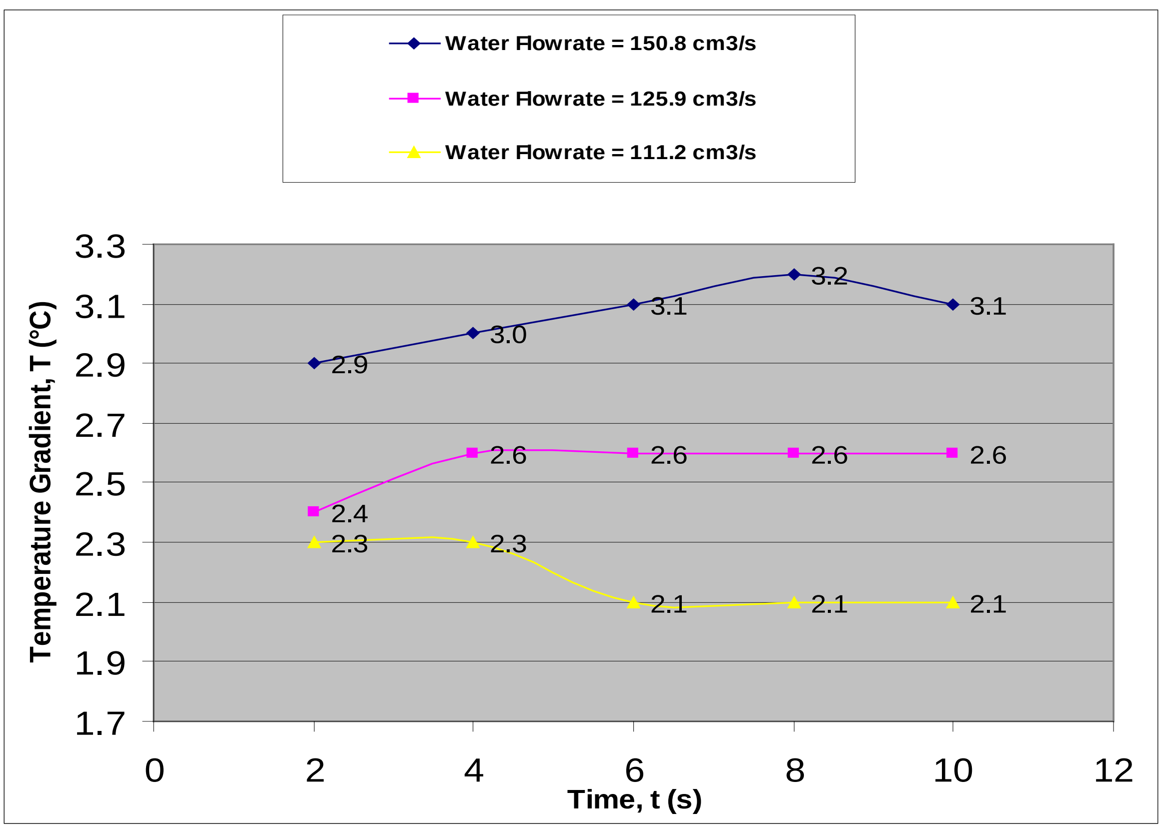


Figure 4.4: Graph temperature gradient vs. time with different water flowrate

According to the graph plotted, the relationship between water flow rate and temperature gradient is clearly defined. It is directly proportional to each other. The higher the water flow rate of water, the higher temperature gradient will be. Hence, more recovery output can be produced.

When flow rate of the water supplied to fogger nozzle increased, the volume of water contacts to the inlet air is increased. Hence, the evaporation of the water increases. Thus the temperature drops rises.

CHAPTER 5
CONCLUSION AND RECOMMENDATIONS

Various air inlet treatments of gas turbine are studied. Based on the evaluation done, fogging cooling system is the best application for the condition at CUF as far as design and economic consideration are concern. By applying the system at air inlet, the power output recovery of gas turbine is clearly significant.

By measuring the dry bulb temperature inlet and outlet of the fogging cooling system, the efficiency of the cooling can be proved by calculation. There are a few factors that lead to the effect of cooling, including relative humidity (RH), wet-bulb and dry-bulb temperature.

The efficiency of the fogging cooling system is directly proportional to the water flow rate of the water supply to the system. By increasing the water flow rate, the efficiency of fogging cooling method rises.

For further improvement, I would like to suggest a few recommendations:-

1. The efficiency of the cooler can be improved by reducing the water droplets size by using smaller orifice size of the nozzles.

2. Besides, it can be further improved by increasing the water supply pressure to the nozzles in order to produce higher flowrates.

3. In addition, by applying treatment to the water used in fogging system, the cooling effect can be increased.

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