DISSERTATION

Development of a System for Cooling Inlet Air for Gas Turbine using Fogging System

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CERTIFICATION OF APPROVAL

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Approved by,

____

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MAY 2011

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.

(Nurfanizan Binti Mohd Afandi)

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ABSTRACT

This report discusses the Development of a system for Cooling Inlet Air for Gas Turbine using Fogging system. Fogging system is one of the methods to cool inlet air for increasing the power output of gas turbines. During hot weather, power plant can produce less amount of power compared to cold condition. This is due to the decreases in air density hence less mass flow rate. The objective of this project is to study the gas turbine operating parameters when using the inlet fogging and calculating the mass flow rate of water needed to cool down the air inlet temperature near to the wet bulb temperature. Moreover, this project focuses on finding the best way to reduce the ambient temperature to the predicting compressor air inlet temperature. However, the overspray fogging or wet compression is not cover in this report. It needs some extensive studies. In this study, the temperature of air inlet is about 360 K and the air outlet is about 297 K. With the total amount of water is about 2.048 kg/s, it succeeded to cool down the airflow until 297 K. The operating parameters that used in this report were chosen based on research done through journals especially from MeeFog Industries. Then, this airflow was validated by using Computational Fluid Dynamics (CFD). This is to show the differences in air temperature during fogging process.

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND OF THE STUDY

In the field of power generation, gas turbine is broadly used since it is relatively less polluting due to the use of gas fuel than other fuel alternatives such as coal or oil. This is further boosted by the increasing activity in gas exploration which in turn, would cushion the impact of growing gas-powered electricity demand. However, gas turbine is less efficient and numerous modifications are applied to improve the efficiency of the gas turbine. The power output of a gas turbine (GT) is highly affected by ambient temperature with power output dropping by 0.54%-0.90% for every 1°C rise in ambient temperature [1]. High ambient temperature causes decreases of air density, hence limits the air mass intake to the compressor. Less combustion occurrs and this causes a drop in power output. One way to counter this limitation is to implement a system to cool the inlet air to the possible lowest temperature of air.

The basic idea of this project is to cool down the inlet air temperature by using fogging system. The inlet fogging of gas turbine engines for power augmentation has been commenced as a method of air inlet cooling for increasing the power output in gas turbine and combined cycle power plants. Over the past 5 years this method has become increasingly popular and is estimated that approximately 700 gas turbines have been fitted with fogging systems at this time [1].

Fog cooling is an evaporative cooling method that is becoming increasingly popular for gas turbine power augmentation. A series of nozzle distribute the demineralized water under high pressure which in turn atomizes the water into fine droplets in the form of fog. Due to its small size and distribution over a large area, the water droplets evaporate quickly and effectively cool the air. Fogging can achieves 100% saturation of air and can cool it down to the wet bulb temperature [2].

This project focuses on the feasibility of installing a fog cooling system to the gas turbine GT13E2 of a co-generation power plant in Sitiawan. The design of inlet fogging system is the main keyword for this study to determine the parameters needed for cooling ambient air to the lowest temperature and validate the result by using software. This type of inlet cooling system was considered due to ease of installation and the relatively low first cost compared to the other inlet cooling methods [3].

1.2 PROBLEM STATEMENT

Malaysia has tropical climate which is hot and humid weather conditions throughout the years. It warms in the days and fairly cool at night. The ambient temperatures during day time are around 29 °C to 35 °C. During hot days the air conditioner has to work pretty hard to keep the people cool and comfort. Indeed an air conditioner used most of the energy supplied to run its process for providing comfort to human being. Moreover, many people are using electricity throughout days to run the process and their activities. These cause demanding in power output during daytime. In turn, power plants need to produce more power to meet the demand and to make sure activities can be done smoothly.

Meanwhile, on the plant side, the power output is dropping due to the hot weather condition and this situation cause gas turbine to operate at its limit in order to achieve demands target from consumers. The decreases in power output is due to the drop off in density of air, hence limits the mass flow rate of air into the compressor. It caused less combustion and dropped in power output. In addition, high ambient temperature will increase the compressor work and lowers the thermal efficiency [2]. There are 3 main factors that control the power outputs of gas turbine which are temperature, pressure and relative humidity of ambient air. Changes in the humidity ratio have a negligible effect on the power output [4, 5].

This creates inducement to overcome this problem during high ambient temperature. Many ideas were proposed and one of them was cooling the air inlet by using fogging system. The fogging system will operate during high demand periods in daytime. Power plant needs to aim minimum capital cost for the incremental power generated. Therefore this project will aim to increase the power outputs generated by gas turbine during high ambient temperature and to minimize capital lost for the incremental power generated by using inlet fogging system.

1.3 OBJECTIVES

The main objectives of this research are:

- To determine the application of the inlet fogging system to the gas turbine.
- To study the effects of ambient conditions on gas turbine loads.
- To design the fogging system for cooling ambient air of GT13E2 installed in Sitiawan to the lowest possible temperature.
- To validate result of air flow by using software.

1.4 SCOPES OF STUDY

The scope of works for semester one final year project are to research about fogging system including the nozzles, operating parameters like operating pressure, temperature, mass flow rate and so on. Moreover research about the effect of gas turbine towards gas turbine without fogging system and with fogging system. Mathematical modeling was used to solve the problem regarding designing the fogging system. Later, familiarizations of the entire components that are involved in the gas turbine system were pursued.

During the second semester of this final year project, the results were proved by using computational fluid dynamics (CFD) to verify the drop in air temperature while installing fogging system. Mostly the results used in CFD were calculated earlier by making several assumptions.

CHAPTER 2

LITERATURE REVIEW

2.1 OVERALL FOGGING SYSTEM

Chaker and Maher [3] reported that gas turbine power output drop by 0.54 to 0.90 % for every 1°C increase in ambient temperature. Direct inlet fogging is a method of cooling the inlet air where demineralized water is converted into a fog and provides cooling when it evaporates at the air inlet duct. This system can obtained closely 100% relative humidity at the gas turbine inlet and gives the lowest temperature possible without refrigeration. Since it cause very small pressure drop and relatively inexpensive to install, they have been successfully installed in areas with high summer time humidity.

Gajjar et. Al [6] stated that evaporative cooling offered low initial cost and was purposely used to maintain the inlet air temperature below 30°C. However it limitation is based on the ambient humidity condition. It has two types of evaporative cooling which are fog type and media type evaporative cooling.

Schurmann, et al. [7] investigation showed that, depending on ambient condition, power boost of 5% per 1% of injected water for fogging applications can be achieved. Droplet size distribution is required to be within 20 – 30 μm in order to have quick evaporation process. The location of the system can vary along the air intake's ducting.

Brooks [8] stated that the standard conditions used by gas turbine industry which give optimum power performance of gas turbine are at 15°C, 1.013 bar and 60 % relative humidity. This condition is established by International Standard Organization (ISO).

2.1.1 Inlet Fogging System

This system used direct evaporation effect which generates a fog by high pressure pumps and atomizing nozzles. The fog evaporates in the inlet duct and cools the air down to the wet bulb temperature [1, 9]. The reason for injecting water droplets is to increase the density of the air flow and the evaporation process leads to a decrease in the temperature resulting in an increase in the air mass flow. This result in decreasing compressor power consumption and increased the gas turbine net power output. There are several others factor that define the success and efficiency of the fogging process which are:

- Droplet size
- Nozzle flow rate
- Operating pressure
- Type of nozzle

A typical high pressure fogging system consists of [1]

- A high pressure pump skid with associated pumps and controls
- A set of fog nozzles located in the intake duct after filters
- A PLC-based control system

Figure 2.1 shows the MeeFog inlet fogging system.

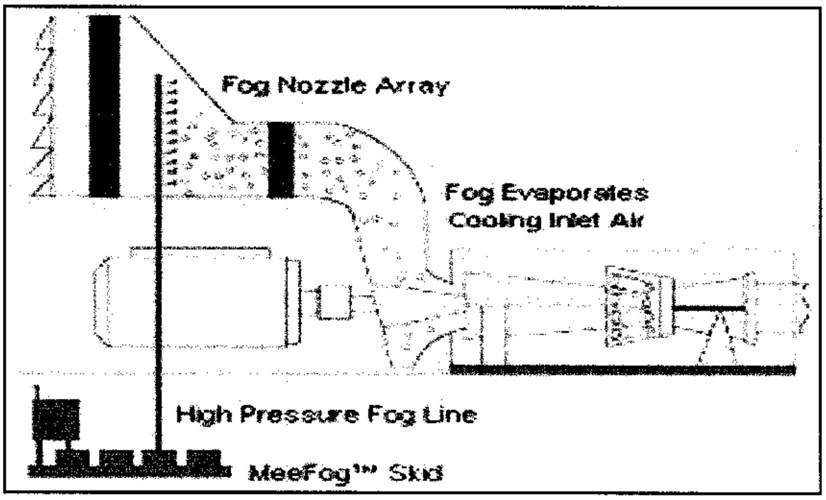


Figure 2.1: MeeFog inlet fogging system [10]

2.1.2 Assumptions in Inlet fogging system

Bhargava et al. [11] researched that inlet fogging is considered to be adiabatic process which means the thermal energy loss from a nonsaturated air ($\dot{Q}_{air}$) stream with the injection of water may be expressed as the sum of energy, per unit time, consumed for water evaporation ($\dot{Q}_{ev}$) and energy stored in the water droplets ($\dot{Q}_{d}$) not yet evaporated.

$$\dot{Q}_{air} = \dot{Q}_{ev} + \dot{Q}_{d} \quad \text{.......................................} \quad (1)$$

By using the subscript a and ac to distinguish the air before and after cooling, rewriting Eq (1) as;

$$\dot{Q}_{air} = c_{pa}\dot{m}_a T_a - c_{pac}\dot{m}_{ac}T_{ac} \quad \text{...............................} \quad (2)$$

Where c_p is specific heat capacity.

Equation is valid if the temperature of ac is greater than wet bulb temperature.

$$\dot{Q}_{ev} = \dot{m}_{ev}(\Delta h_{lat} + \Delta h_{lat}) \text{..................................} \quad (3)$$

Where, $\Delta h_{lat} = 2501.7 - 2.3704T_d$ and $\dot{Q}_d$ can be neglected due to assumptions that T_d is constant during evaporation process.

$$c_p\dot{m}_a(T_a - T_{ac}) = \dot{m}_{ev}(\Delta h_{lat} + \Delta h_{lat}) \text{.........................} \quad (4)$$

For the inlet evaporative fogging it is assumes that $\dot{m}_{inj} - \dot{m}_{ev} = 0$

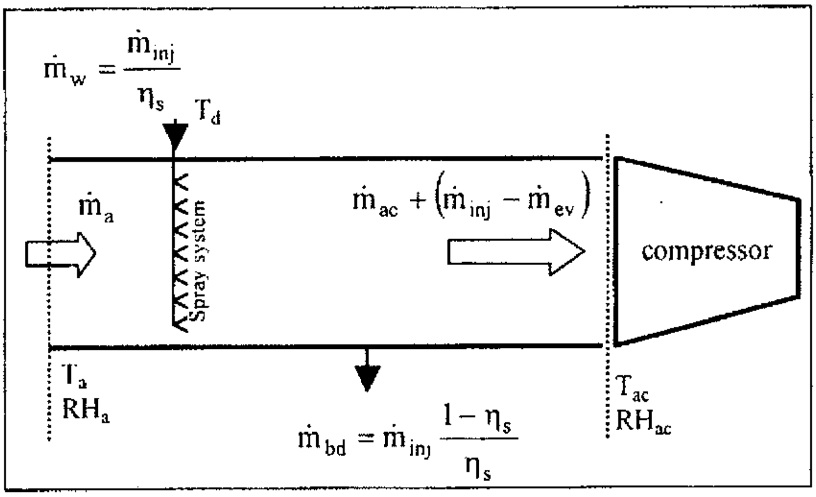


Figure 2.2: A schematic nomenclatures at the compressor inlet with fogging [11]

Where $\dot{m}_{inj}$= water mass flow rate injected

$\dot{m}_{inj} = \dot{m}_{ev}$ but $\dot{m}_{w} \gg \dot{m}_{inj}$. It is because of water loss that may occur inside the ducting.

From the above hypothesis, it can be assumed that inlet evaporative fogging can cool down the air inlet temperature to wet bulb temperature with 100% relative humidity.

In this study, it is assumed that there is no pressure drop occurred inside the silencer while the temperature and pressure of air flow through fog nozzles manifolds are at ambient condition.

2.2 FACTORS AFFECTING GAS TURBINE

There are many factors that affect the performance of gas turbine which are fuel, fuel heating, air temperature and site elevation, inlet air cooling, humidity, inlet and exhaust losses, air extraction, performance degradation, diluents injection and steam and water injection for power augmentation [12]. Only 3 factors will be cover in this report since these factors have significant relation with the inlet fogging system. These are:

- Inlet air cooling

  The performance of gas turbine is affected by changes of density and mass flow of the air intake to the compressor. The graph in Figure 2.2 clearly shows the effect of ambient temperature towards the power output of gas turbine. It is evidence that the power output decreases about 15% where the compressor inlet temperature increases from 15°C to 40°C.

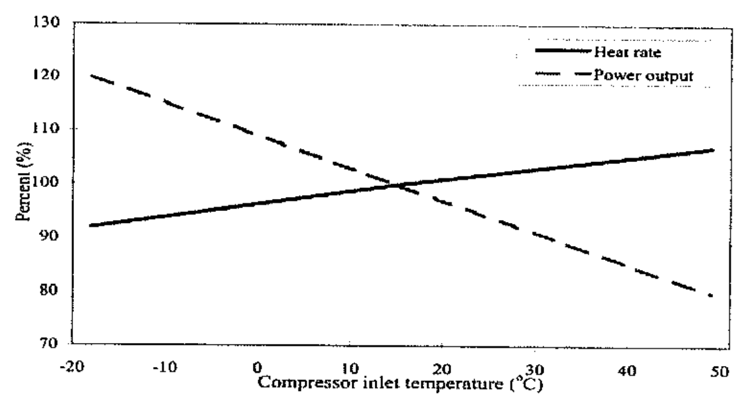


Figure 2.3: Effect of ambient temperature [12]

However, each gas turbine model has its own ambient temperature effect curve, as it depends on the cycle parameters and component efficiencies as will as air mass flow.

- Specific humidity

Humidity need to be considered if the size of the gas turbine is big enough. Or else, this effect would be negligible because the value is too small. Figure 2.3 shows the humidity effect curve.

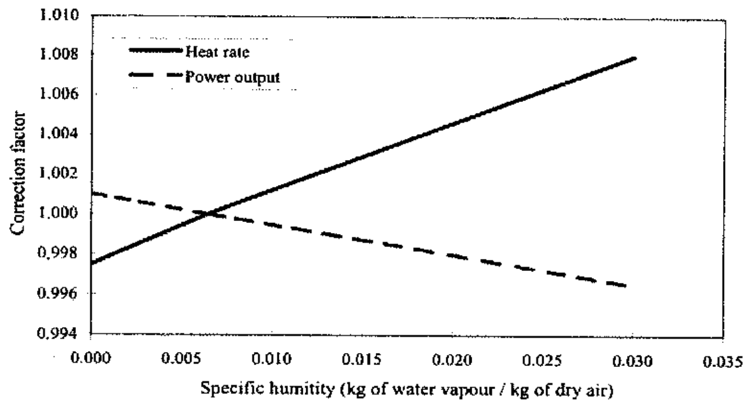


Figure 2.4: humidity effect curve [12]

- Pressure Drop

There are many modifications done to the inlet system since pressure drop across the inlet structure affect gas turbine performances. Increases in pressure drop means decreases in gas turbine performances although the air inlet temperature had been reduced. Robb [13] mentioned that Watson Cogeneration which is one of the companies in Carson had modified the inlet structure to reduce the pressure drop. The silencer panels, for example, came with rectangular leading and trailing edges. These were reconfigured with rounded inlets and aerodynamically profiled tail sections. A larger filter element was installed and Venturi tubes for "Huff and Puff" self-cleaning intake air filters were eliminated. Since inlet air fogging systems cause a very small pressure drop in the inlet air stream, and are relatively inexpensive to install, they have been successfully applied in areas with very high humidity areas. It is been described by Chaker [3].

2.3 PSYCHOMETRIC CHART

Cengel [14] reported that the state of the atmospheric air at specified pressure is completely specified by two independent intensive properties. The rest of properties can be calculated easily from mathematical equation. Psychometric chart is a graphical presentation of air properties under a variety of condition. When two properties are known, others properties can be obtain directly from psychometric charts. Psychometric chart shows air properties such as wet bulb temperature, dry bulb temperature, relative humidity, Humidity ratio, specific volume and enthalpy. Figure 2.4 is one of example of psychometric chart.

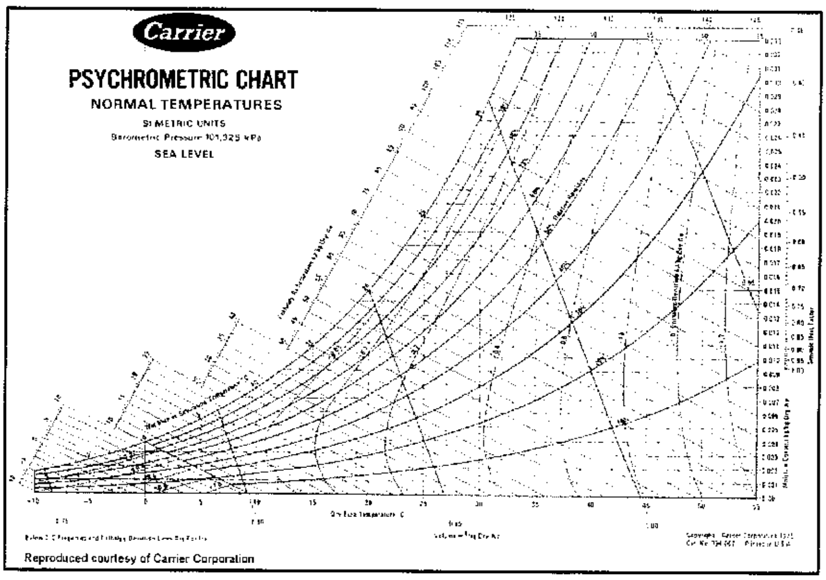


Figure 2.5: Psychometric Chart [25]

Based on Cengel [14], wet bulb temperature is a temperature that measured by using thermometer whose bulb is covered with a cotton wick saturated with water and to blow air over the wick. When unsaturated water passes over the wet wick, some of the water in the wick evaporates. It results in temperature difference between air and water and drive the heat transfer from hot region to cold region. After a while, the heat loss from the water evaporates equals to the heat gain from the air and the water temperature stabilizes.

Relative humidity is the ratio between the amounts of air can holds divided by maximum amount of moisture the air can hold at the same temperature. Usually it will be expressed in terms of percentage. Meanwhile adiabatic saturation process happens when the system contains a long insulated channel and in the middle of the channel there is nozzle that sprays water to the unsaturated air coming from inlet. If the channel is long enough, the air stream exits as saturated air (RH = 100%) at temperature outlet. This is due to the moisture content of air increases during this process and its temperature decreases since part of the latent heat of vaporization of the water that evaporates comes from the air. Figure 2.5 shows the example of an adiabatic saturation process.

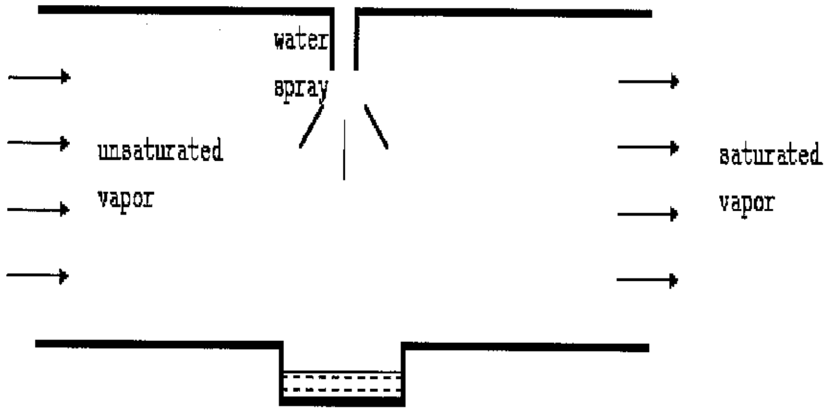


Figure 2.6: Adiabatic Saturation Process [26]

All gases employed as the working fluid in gas turbine engines, except for water vapor may be considered as perfect gases without compromising calculation accuracy. When the mass fraction of water vapor is less than 10%, the performance calculations the gas mixture may still be considered perfect [4]. The formula for ideal gas equation is given below.

$$PV = mRT \quad \ldots\ldots (5)$$

Where P = absolute pressure, V = volume of air, m = mass of air, R = ideal gas constant and T = absolute temperature

From the ideal gas equation, density is a proportional to the mass flow rate since

$$\rho = \frac{m}{V} \quad \ldots\ldots (6)$$

Then, the atmospheric air can be treated as an ideal gas-mixture whose pressure is the sum of the partial pressure of dry air P_a and that of water vapour, P_v.

$$P = P_a + P_v \quad \text{.......} (7)$$

Since water vapor is an ideal gas, the enthalpy of water vapor is a function of temperature only. The enthalpy of water vapor can be determined approximately from

$$h_g(T) \cong 2500.09 + 1.82T \qquad where, T\ in\ °C \quad \text{.......} (8)$$

Humidity ratio or specific humidity or absolute humidity is the proportion of mass of water vapor, m_v present in a unit mass of dry air, m_a. It is denoted by ω and can be expressed as:

$$\omega = \frac{m_v}{m_a} = 0.622\frac{P_v}{P_a} = 0.622\frac{P_v}{P-P_v} \quad \text{.......} (9)$$

Moreover, the ratio of amount of moisture the air holds to the maximum amount of moisture the air can hold at the same temperature (m_g) is called relative humidity ratio and denoted by $\emptyset$. The specific humidity can be expressed as

$$\emptyset = \frac{m_v}{m_g} = \frac{P_v}{P_g} = \frac{\omega P}{(0.622+\omega)P_g} \quad \text{.......} (10)$$

Based on ElAwad et al.[2], the turbine power output and heat rate of the gas turbine at a given inlet-air temperature (T) can be calculated from:

$$Power\ Output, P_o = \gamma P_{o_s} \quad \text{.......} (11)$$

$$Heat\ Rate, HR = HR_s/\eta \quad \text{.......} (12)$$

Where P_{o_s} and HR_s are respectively the power output and heat rate of the gas turbine at the standard temperature of 15.6°C. The relative power (γ) and relative thermal efficiency (η) at the desired temperature are calculated using the formulae :

$$\gamma = 1.1007953 - 0.0068486514T - 9.6865641T^2/10^7 \quad \text{.......} (13)$$

$$\eta = 1.0276476 - 0.0018092128T - 1.105712T^2/10^5 \quad \text{.......} (14)$$

The above equations are based on the performance characteristic curves of the ABB GT13 gas turbine. Lumut Power Plant used GT13E2 for gas turbine model and this equation shows the relationship between the ambient air temperatures with the power output.

ElAwad et al. [2] also said that the temperature of air after fog cooling can be obtained from the energy balance equation. Assuming adiabatic mixing, the energy gained by the sprayed water is balanced by the energy lost by the dry air, and the original air-borne moisture, after cooling such that:

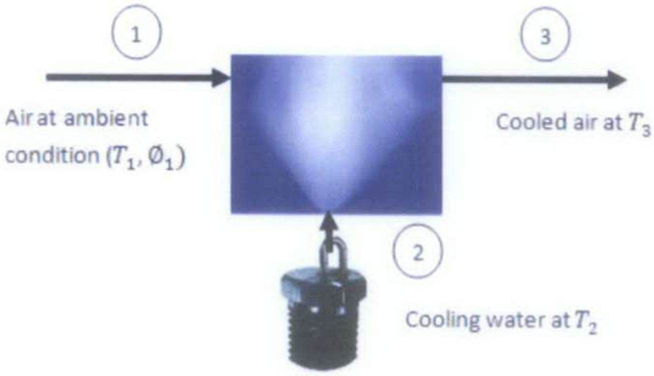


Figure 2.7: Principle of fog cooling system

$$m_w(h_{v3} - h_{w2}) = m_a(h_{a1} - h_{a3}) + \omega_1 m_a(h_{v1} - h_{v3}) \quad (15)$$

Where m_w is the mass flow rate of cooling water and h_{w2} its enthalpy, m_a is the mass flow rate of dry air, $(h_{a3} - h_{a1})$ is the enthalpy change of dry air, ω_1 is the humidity ratio and $(h_{v1} - h_{v3})$ is the enthalpy change of water vapour after cooling [2]. From conservation of mass, the amount of water sprayed is equal to the mass of water vapour at point 3 minus the water vapour originally in the air at point 1:

$$m_w = (\omega_3 - \omega_1)\, m_a \quad (16)$$

Density of the humid air can get from this formula:

$$\rho_{humid\ air} = \frac{P_d}{R_d T} + \frac{P_v}{R_v T} \quad (17)$$

Where P_d is a partial pressure of dry air, P_v is a partial pressure of water vapour, R_d is a specific gas constant for dry air, 287.07 (J/kg.K) and R_v is a specific gas constant for water vapour, 461.495 (J/kg.K).

2.4 NOZZLE DESIGN

There are many factors that need to be considered in the design of nozzle such as the pressure, flow rate and surface tension. High pressure will produce small droplets while high flow nozzles will produces larger droplets. The droplet sizes of the water must be as small as possible, in order to maximize the surface area so as to increase the heat transfer between the droplet surface area and the air. The underlying principle of any pressure-atomizing nozzle is to convert the applied pressure into kinetic energy by the use of a small orifice [15]. The most important factors for nozzle selection are droplet and the distribution of fog in the duct cross-section.

2.4.1 Types of Nozzles

There are many types of nozzle but typically there are two types of nozzles that generally use in gas turbine applications which are impaction-pin nozzles and swirl-jet nozzles [15]. Impaction pin nozzle produce full cone nozzles while swirl jet nozzle create hollow cone pattern.

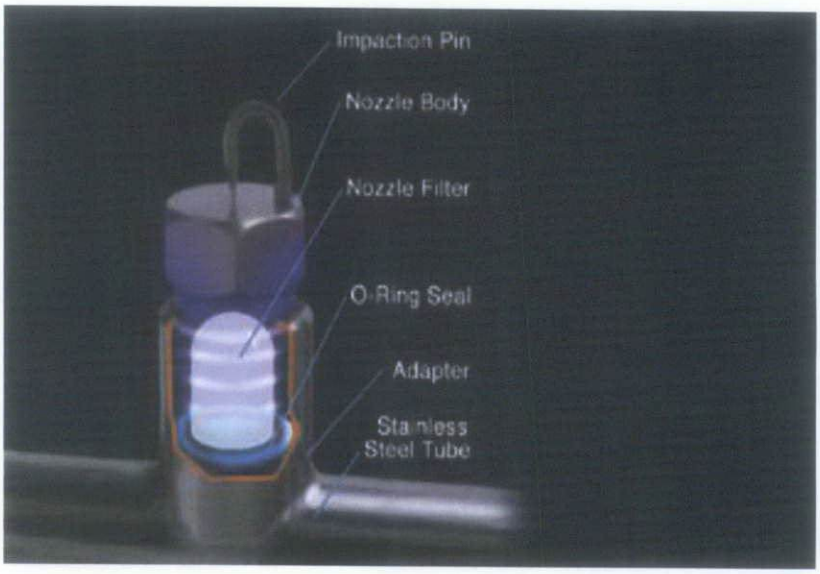


Figure 2.8: impaction pin nozzles [28]

Figure 2.9: swirl-jet nozzles [29]

Impaction-pin nozzles

Impaction-pin nozzles consists of smooth orifice that water is forced through it and the high velocity jet is directed at an impaction pin which is located above the orifice. The size of the droplets produced and the velocity of the jet depends on the applied pressure. When the pressure increased, the velocity of water also increases causing the decrease in droplet size because of low frictional losses. Low frictional losses cause the conversion of energy of the applied pressure to axial velocity becomes more efficient [5]. Due to high velocity of the droplets very close to the nozzle tip, the Weber number is high and this leads to an important secondary break up of the larger droplets. The result of the collision between the droplets in this area is a shattering due to the high Weber number. The secondary breakup because of high Weber number occurs if the surface tension force which acts to keep the droplet spherical is no longer able to balance the opposing aerodynamic forces. The Weber number is given by:

$$We = \frac{\rho_a . v_{rel}^2 . D_d}{\gamma_w} \quad \text{...} \quad (18)$$

Weber number effect applies to both nozzles but it is more significant when using impaction-pin nozzles because it has higher relative velocities of droplets under similar operating conditions.

Swirl-jet nozzles

The fluid is forced to enter tangentially into the swirl chamber taking a helical path before discharging through a cylindrical hole concentric to the swirl chamber. This leads to the formation of an air core with a large diameter in the swirl chamber, as compared to the one in orifice. Swirling jet involved axial and radial forces since it is nature flow [5]. When the operating pressure increased, the axial and radial forces also increased until at some point the axial velocity dominates and radial forces drop causing the nozzles to operate as an "open orifice" nozzle.

2.4.2 Nozzle Orientation

Nozzles break the water into droplets and form the spray pattern. This will propel the droplets in the proper direction. Arrangement of nozzles is important because it affect the spray pattern. The spray pattern will be uneven if nozzles are not aligned properly on the spray boom. Bad alignment leads longer evaporation time and time distortion at compressor inlet [17]. The nozzle angle with respect to the inlet airflow may vary from 0 degree to 90 degree. Normally, 90 degree (perpendicular to air flow) is not recommended even though it gives a marginally longer residence time as compared to the co-flow arrangement. However, due to practical considerations, 90 deg is rarely used. The plume diameter stays relatively constant in the axial length and it provides a homogenous pattern across the duct when the distance between nozzles is not too large. In cases there is large spacing between nozzles, the 90 deg orientation may be advantageous. It produces large plume diameter and can covers more of the duct cross section.

2.4.3 Nozzle Materials

The most common material for nozzle is brass, nylon, stainless steel, hardened stainless steel, tungsten carbide and ceramic [18]. Ceramic and tungsten carbide nozzles are very long-wearing and extremely corrosion resistant. Stainless steel nozzles last longer than brass or nylon and generally produce a more uniform pattern over an extended time period. Nylon nozzles with stainless steel or hardened stainless steel inserts offer an alternative to solid stainless steel nozzles at a reduced cost. Thermoplastic nozzles have good abrasion resistance, but swelling can occur with some chemicals, and they are easily damaged when cleaned. Nozzles made from hard materials cost more initially, but in the long run, they pay for themselves because of long-lasting properties. The nozzles must be in the same materials, types, spray angles or spray volumes on the same spray boom. All of these factors will affect the spray pattern.

2.4.4 Location of nozzles

There are 2 options that can be considered to install fog nozzle manifold either upstream or downstream of the air filters [19]. For the upstream part, installation can be done without outage time. However, the fog droplet filter needs to be installed to remove any unevaporated fog. Since this method is very expensive and consumes a lot of water, fog scrubber is being used as an alternative to encounter this problem.

Meanwhile, to install fog nozzles manifold at downstream of air filters, the outage needs to be done. In this case, there are 2 ways to install the nozzles either upstream of silencers or downstream of the silencers. The advantage of installation at upstream of silencers is the fog will have more residence time to evaporate but one user said it can cause compressor fouling. Fog washed dirt off the silencer panels and deposited it on the axial compressor blade. The location of nozzles are depends on the purpose why to install the fog nozzle manifolds. If the purpose is for evaporative cooling, it is appropriate to install before the silencer if it is for fog intercooling, it is more suitable to install after silencer [19].

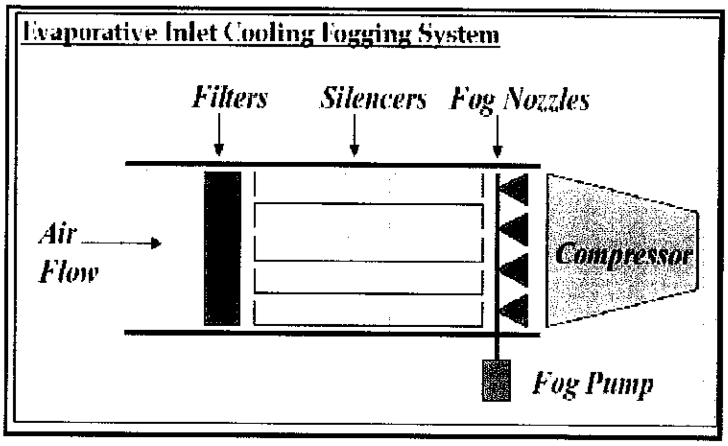


Figure 2.10: Evaporative Inlet Cooling Fogging System [27]

2.4.5 Duct Drainage

This is the most important needs to be considered in designing fogging system. Drains should be strategically located near the nozzle manifolds. Chaker et al. [1, 17] said that number of drains depends on configuration of duct and obstructions that might result in water collection. Basically, it is based on experience. Drains should be either P trap designs or flapper style check valves. All drains need to be operated during periods of inlet fogging. P trap arrangements are not preferred because of the risk of the water seal evaporating causing the trap to run dry and allowing ingestion of untreated air into the engine.

2.4.6 Number of nozzles

The number of nozzles should be appropriately designed so they provide uniform fogging of the gas turbine inlet duct. Having a fewer number of higher flow rate nozzles can results in larger spaces between the plumes and less homogeneity of the fog distribution [17].

2.4.7 Cooling potential pump stage

Cooling stage is used to identify the pumps that need to be operated during fogging process. The equation for pump stages on is stated as below.

$$\text{Pump stages ON} = \frac{\text{cooling stages}}{3.05°\text{F}} \quad \text{.................................} \quad (19)$$

It is stated that 1 stage can cool down to 3.05°F of airflow [19].

CHAPTER 3
METHODOLOGY

3.1 PROCEDURE IDENTIFICATION

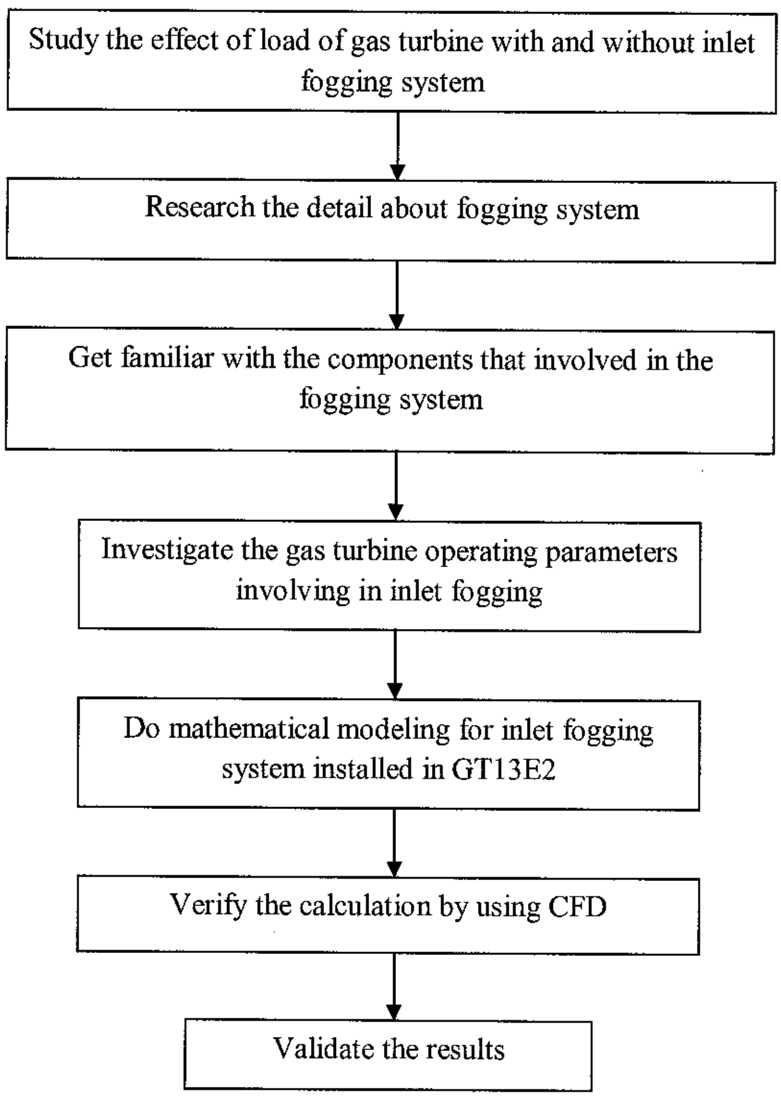


Figure 3.1: Process flow chat

The procedure involved in designing fogging system are basically based on the flow chart of the below figure. The procedures are identified to ensure the project accomplishment within time frame provided. The procedure had been divided into two parts which the first part is the target work to be done for final year project 1 and the second part is the target for final year project 2.

Figure 3.1 shows the process flow for this project. Firstly, it focused more on understanding about the behavior of gas turbine when installing the cooling system and affect towards its load. In this period, a lot of research works were required in order to obtain the accurate data. Then this project focuses on research the basic idea of inlet fogging system and the important of several issues regarding it. The purpose of this task was to develop a better understanding about fogging system in order to design in the next task. There are several issues that were considered before this system can be developed such as the ambient condition of the air before entering the compressor. Moreover, many formulae and chart were used for calculating the operating parameters. Before, the inlet fogging system can be designed, several components that relates to fogging system were studied such as mass flow rate of water, no of nozzles requires, cooling potential, the size of pipe needed and so on.

For Final Year Project II, the continuation of mathematical modeling had been done and gives the properties like number of nozzles, mass flow rate of water and so on. Before the mathematical modeling was formulated the analysis of weather data was gathered to define the cooling potential needed for cooling the ambient air. As in this project, Sitiawan has been chosen as a location and the weather data in the result was taken on 24^{th} June 2011. The weather data was taken at meteorological sites. After identify the cooling potential the calculation of mass flow rate of water and number of nozzles can be done by using those equations in literature review. After identifying the parameters by using mathematical modeling, the last step was to validate the result data from the studies by using Computational Fluid Dynamics (CFD) likes Gambit and Fluent and varies the data to get an optimum result.

In Gambit, the 2D drawing was plotted and the boundary conditions were specified before meshing it. After meshing process, the drawing in Gambit was exported to Fluent to verify the flow. For the present setting more than 5 000 iterations which took about 2 hours to complete the iteration. When the result was not acceptable, the iteration was repeated again and again. After getting the acceptable result, it was plotted to graph.

Together with this result, the conceptual design of inlet fogging system inside the ducting need was drew to show the exact location of nozzle that been installed in GT13E2. This conceptual design was sketched by using CATIA software. In CFD, examination of flow and temperature in intake duct was extensively studied. Furthermore, the flow of air to the gas turbine was been verified in CFD by examining the decreases in air inlet temperature.

3.2 INVESTIGATING GAS TURBINE OPERATING PARAMETERS

Before determining the type of nozzle, an operating pressure, nozzle capacity and other several parameters, the compressor air inlet temperature had been decided. During the fogging process, the air inlet can be cool down until wet bulb temperature only. Wet bulb temperature is a temperature when air is saturates with the water and the relative humidity of air is 100%. At first, the ambient conditions of air like temperature, relative humidity and pressure were getting from metrological department of Sitiawan, Perak. Then, the value of specific volume, enthalpy and humidity ratio was determined directly by using psychometric chart. After all the value being obtained by psychometric chart, the mass flow rate of water needed to cool down the air inlet been calculated by using equation 16. From the mass flow rate of water required, the number of nozzle was determined. The nozzle flow rate is 0.17 liter/minute for each nozzle. Figure 3.2 shows a diagram of fog-cooling system. It is assumed to be an adiabatic mixture. Point 1 is an ambient temperature while point 3 represents air after it undergoes cooling. Pressurized liquid had been sprayed into the air at point 2.

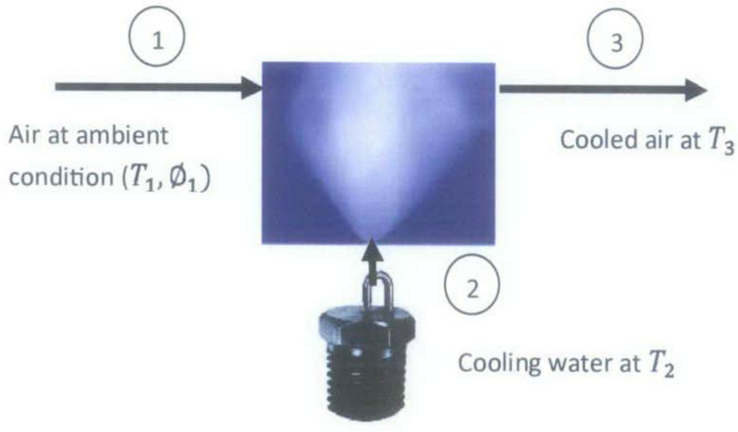


Figure 3.2: Fog cooling system

The temperature at point 2 was set at 25°C and the temperature at point 3 can be obtained from the psychometric chart. Once the temperature after fog cooling is obtained, the power and heat rate of the gas turbine characteristic performance curves can be developed.

3.2.1 Location of nozzle

Before designing fogging system, location of installation of nozzles had been considered in order to have longer evaporative time. In this project, the fog nozzles manifolds have been installed after the silencers. It is to avoid from compressor fouling.

3.2.2 Type of Nozzle

As stated before, there are two (2) types of nozzles which are impaction-pin nozzles and swirl-jet nozzles. Research about these two types of nozzle can give a clear thought about the preferred nozzle. Pros and cons of these nozzles need to be taken account before can select the best type of nozzle because this nozzle can affect the diameter of the droplet of fog spray and hence can decrease the efficiency of this system. In addition, these two types of nozzles can produce different result in droplet sizes. In this study, impaction pin nozzle had been chosen since it gives small droplet diameter as well as full cone sprays.

3.2.3 Operating Pressure

Chaker [20] determined the significant of operating pressure on the droplet size for different air flow velocities. It is stated that when there is increased in operating pressure, the diameter of droplet sizes decreases. Then, the diameter of the droplet can be discovered since the operating pressure proportional to the diameter based to empirical formulae. Based on reference of MeeFog Industries, 2000 psi had been chosen for the operating pressure of water outlet.

3.2.4 Air Flow velocity

The air flow velocity also can affect the diameter of the droplet as stated by Chaker [20]. The droplet sizes will decrease when air flow velocity increases and can increase the efficiency of the heat transfer.

3.2.5 Features of nozzles

In this study, impaction pin nozzles had been chosen and the features of impaction pin nozzles as below [20].

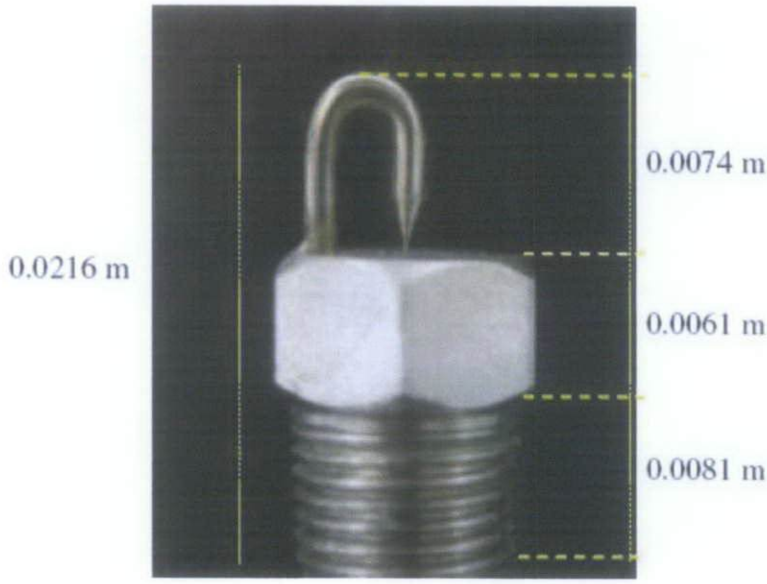


Figure 3.3: Dimensions of impaction pin nozzles [24]

The lock wiring needs to be installed at this nozzle in order to avoid the loose nozzles from flow to the compressor or fall down along the ducting.

3.2.5 Mass Flow rate of water

After getting mass flow rate of air and the specific humidity at both side, mass flow rate of water can be calculated. This parameter is important to calculate because it affects the temperature of airstream exits since fogging system used adiabatic saturation process.

3.2.6 Number of nozzle

It provides the efficiency of cooling potential to become a saturated air. Decreases in number of nozzles will lead to insufficient amount of water to spray for cooling the air inlet. So the cooling cannot be done effectively. In this study, there are 688 nozzles that being installed at 33°C with 40% RH. Numbers of nozzles are defined as volume flow rate of water needed to be sprayed divided by nozzle flow rate. All of this calculations been shown in chapter 4.

3.2.7 Distance from nozzle to nozzle

Apart from above, the distance from nozzle to nozzle was considered for improving the efficiency of water distribution during fogging. So, the power output will be optimum and give profit to the company.

3.2.8 Operating Parameters

By using data that get from the MeeFog industries [16], there is difference in the value of droplet size between those nozzles. The experiment is done by maintaining the operating pressure at 2000 psi. The results from their research are shown below:

Table 3.1: Differences in droplet diameter between two types of nozzles

Nozzle Type (D32)	Center	Edge
Impaction pin nozzle (2000 psi)	6.5	8.0
Swirl Jet nozzle (2000 psi)	15	28

The standard of impaction pin nozzles using by MeeFog Industries shown below.

Material = high grade stainless steel
Orifice diameter = 0.006 in (150 micrometer)
Operating Pressure = 2000 psi (138 bar)
Volume flow rate = 1500000 m^3/hr
Height of nozzle = 0.0216 m (Impaction Pin nozzle)
Nozzle flow rate = 0.17 Lit/ min per nozzle

At this operating pressure, the nozzle can produce the droplets size below than 10 microns (SMD) or less 20 microns (Dv90).

Every cooling stage has been set to spray maximum of 3.42 gpm of water to the channel. Furthermore the total coverage area for GT13E2 is about 34.44 m^2.

3.3 CONCEPTUAL DESIGN

For better understanding about this project, the design of fogging system had been shown towards the end of chapter 4. This conceptual design using software called CATIA. This design illustrate clear picture about the measurement between the nozzles and so on. AutoCAD also can be used to design this project but CATIA is more preferable because it is easy and reliable than AutoCAD. After that, this design was transferred into CFD (Computational Fluid Dynamics) for verifying the result. In this part, the drawing was illustrated in 2D to simplify the work done by using Gambit and verifies the flow in Fluent. Fluent was used to simulate the air flow into the compressor after installing the fogging system. This software verified the calculation that been done by using mathematical modeling and make sure the calculation is approved.

3.3.1 Gambit

In Gambit, the design was created before can evaluated the flow by using Fluent. This software is related to each other. In this process, the ducting and nozzles were in 2D. The steps below shows the process happened in Gambit:

1. Vertexes were created based on coordinates that been provided in appendixes.
2. Lines were created to connect the vertexes to visualize ducting and nozzles.

Properties	Length (m)
Outside diameter pipe	0.002667
Thickness of pipe	0.00039116
Internal diameter of pipe	0.0018847

Table 3.2: Dimensions of pipe

The properties of pipe were taken based on stainless steel pipe standard.

3. Two faces had been formed which were channel and nozzles. Then, the nozzles were subtracted from the channel leaving the channel alone. In this study, it focused on the flow of air only. That is why nozzles need to be subtracted from channel. After that, groups were constructed.
4. Later, boundary conditions were specified before meshing process can be done at last steps.

Groups/edges	Boundary conditions
Top wall, Bottom wall	Wall
Nozzle wall	Wall
Air inlet	Velocity inlet
Air outlet	Pressure outlet
Water Outlet	Velocity inlet

Table 3.3: Types of boundary Conditions

5. During meshing process, interval size had been set to 0.0009467 until 0.09467 which had a step size of 1.1.

3.3.2 Fluent

1. After gambit had been exported to fluent, the grid was checked in order to examine the error that may occur during meshing.
2. The default segregated model had been accepted and the standard k-epsilon was turned on in define menu.
3. Models were defined in discrete phase. Water-liquid was chosen as the material.
4. At material type, water liquid, air, and stainless steel were chosen.
5. For boundary condition, the value of below had been entered inside the box provided.

Properties	Value	Unit
Mass flow rate of air	494.9	Kg/s
Mass flow rate of water	0.1218	Kg/s
Velocity of water	10.815	m/s
Velocity of air	12.098	m/s
Diameter for water outlet	0.0037868	m
Nozzle wall	Stainless steel	-

Table 3.4: Value of properties in boundary condition

6. Flow field had been initialized using conditions at all zones.
7. Iteration had been done up to 10 000.

3.4 GANTT CHART (FYP I)

No	Details	Week														
		1	2	3	4	5	6	7		8	9	10	11	12	13	14
1	Selection of Project Topic	■							MID SEMESTER BREAK							
2	First meeting with my supervisor		■													
3	Preliminary Research work															
	a) Research the detail about inlet fogging			■	■	■	■									
	b) Research about the application of inlet fogging with gas turbine					■	■	■								
4	Preliminary Report preparation			■												
5	Submission of Preliminary Report (20 August 2010)							■								
6	Seminar 1										■					
7	Progress report preparation							■		■						
8	Submission of Progress Report										■					
9	Research and investigating the gas turbine operating parameters							■		■	■	■	■	■		
13	Submission of Interim Report Final Draft															■
14	Oral Presentation (During study week)															

GANTT CHART (FYP II)

	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Week 11	Week 12	Week 13	Week 14
eters of fogging Flow rate, temperature of air and water, etc	•	•	•	•										
sheet form Psychometric chart Graph of typical daily weather trends			•	•										
air inlet system Overall design of air flow Location of nozzle Using CATIA			•	•	•									
oy using Fluent Set boundary condition in GAMBIT Mesh the drawing in GAMBIT Iteration in FLUENT				•	•	•	•							
ss Report								•						
'Pre EDX									•	•	•			
eport									•	•	•	•		
eport													•	
resentation														•

CHAPTER 4
RESULTS AND DISCUSSIONS

This section discusses about the findings of parameters in the gas turbine fogging application that have been made during this project. There are a lot of factors that need to be considered in order to get those parameters since they relate to each other. As stated before, the diameter of the droplet sizes of water must be as smallest as possible to increase the effectiveness of heat transfer in between droplet sizes with the air. The purpose of this process is to get the lowest air inlet temperature for obtaining high power output.

4.1 DATA ANALYSIS

Fogging system is similar to evaporative media coolers since both cool the inlet air except that compressor inlet air can not reach saturated state. It is assumed that inlet fogging is adiabatic humidifying process, the capacity is designed large enough and the fog drop diameter is small enough and heat exchange efficiency of fogging approximates 100%. In this research, many journals were referred through to acquire parameters of gas turbine fogging applications.

In Malaysia, the ambient temperature can vary and every increase or drop in ambient temperature affects the wet bulb temperature since it relates to each other. During the fogging process, inlet air temperature can be cooled to wet bulb temperature. Further cooling can lead to the condensation process. This condition can led to finding the operating parameters that can cool down the ambient temperature to the wet bulb temperature. In this project, the location of the installation of fogging system of GT13E2 is in Sitiawan. The weather data shown in Figure 4.1 was taken on 24^{th} June 2011.

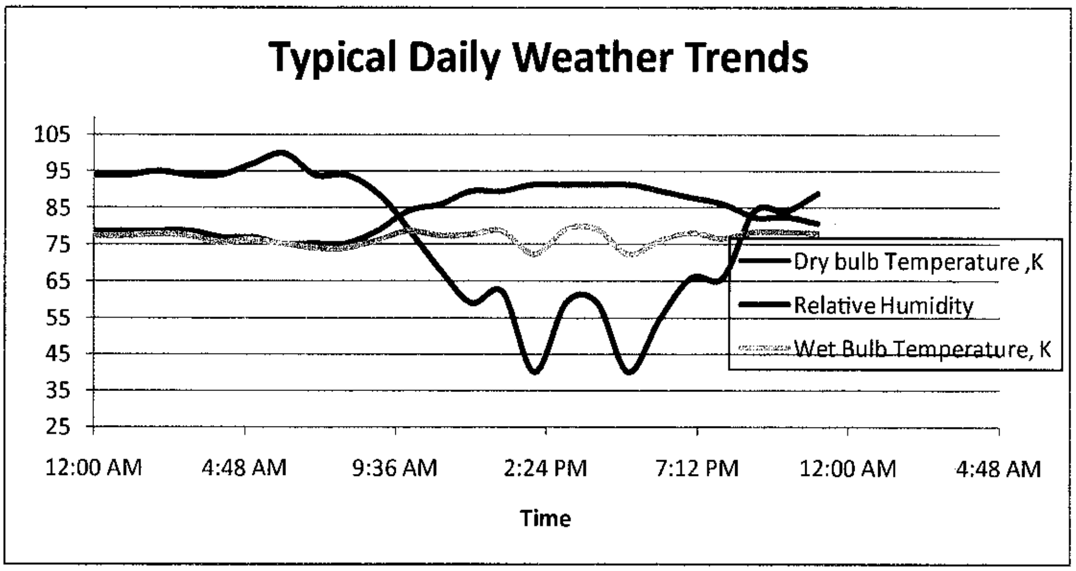


Figure 4.1: Typical Daily Weather Trends

This graph shows the highest ambient temperature occurred during noon and evening. The relative humidity also falls down near 40%. Meanwhile in early morning, the ambient temperature is almost equal to wet bulb temperature since the relative humidity nearly 100%. On average this weather data is almost the same throughout the months but is exceptional during rainy time. These ambient conditions were taken into account for the next step because it affects the gas turbine performance. The next graph in Figure 4.2 shows cooling potential needed for this day.

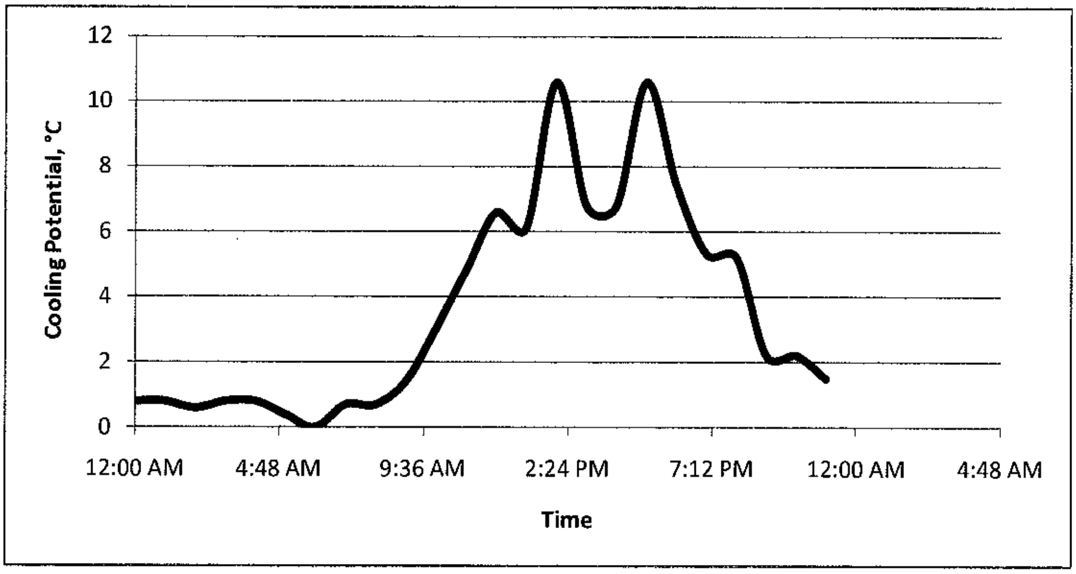


Figure 4.2: Cooling Potential on 24th June 2011

The cooling potential is a difference between dry bulb temperature and wet bulb temperature. This shows a requirement temperature needed to be cool down and the operation for fogging system.

Cooling potential = dry bulb temperature, T_{db} – wet bulb temperature, T_{wb}

Table below shows calculation for cooling potential on 24th June 2011.

Time	Dry Bulb temperature	Relative humidity	Wet bulb temperature	cooling potential
12:00 AM	26	94	25.2	0.8
1:00 AM	26	94	25.2	0.8
2:00 AM	26	95	25.4	0.6
3:00 AM	26	94	25.2	0.8
4:00 AM	25	94	24.2	0.8
5:00 AM	25	97	24.6	0.4
6:00 AM	24	100	24	0
7:00 AM	24	94	23.3	0.7
8:00 AM	24	94	23.3	0.7
9:00 AM	26	89	24.6	1.4
10:00 AM	29	79	26	3
11:00 AM	30	68	25.2	4.8

12:00 PM	32	59	25.4	6.6
1:00 PM	32	62	25.9	6.1
2:00 PM	33	40	22.4	10.6
3:00 PM	33	59	26.2	6.8
4:00 PM	33	59	26.2	6.8
5:00 PM	33	40	22.4	10.6
6:00 PM	32	55	24.6	7.4
7:00 PM	31	66	25.7	5.3
8:00 PM	30	66	24.8	5.2
9:00 PM	28	84	25.8	2.2
10:00 PM	28	84	25.8	2.2
11:00 PM	27	89	25.5	1.5

The fogging system can be actively operated during days and during high demand load. In figure 4.2, it showed that at 1 pm and 3 pm have the highest cooling potential. During this time, the power plant needs to produce more loads and it can simply to be done by using fogging system.

The graph also shows the cooling stage that need to be operated during this process. By using equation 19, it affirmed that 7 stages of pump needs to be ON in order to cool down the ambient temperature close to wet bulb temperature.

Cooling stages $= \frac{(91.4-72.32\ K)+2\ F}{3.05} = 7$ stages ON

In this study, I took the ambient conditions as 33°C as ambient temperature with 40% relative humidity. From psychometric chart, the parameters below were obtained.

Table 4.1: Value of properties from psychometric chart

Properties	Value	Unit
Wet bulb temperature	22.4	°C
Specific humidity, 1	12.50	g/kg dry air
Specific humidity, 3	16.64	g/kg dry air
Volume flow rate	1 500 000	m^3/hr

Later than cooling potential had been determined, the mass flow rate of water can be calculated by using equation 16. After acquired mass flow rate of water, the number of nozzles can be obtained. In this study there are 688 nozzles which have 43 nodes at horizontal line and 16 nodes at vertical line.

<u>Calculations</u>

$\dot{V}_a = 1\,500\,000\, m^3/hr$ $\rho_a = 1.18776\, kg/m^3$

$V_a = \frac{1\,500\,000\, m^3/hr}{(4.2 \times 8.2) m^2}$ = 43 554 m/hr or 12.098 m/s

$\dot{m}_a = 1\,500\,000 \frac{m^3}{hr} \times 1.18776\, kg/m^3$ = 1 696 200 kg/hr @ 494.9 kg/s

$\dot{m}_w = \dot{m}_a(\omega_3 - \omega_1) = 494.9\,(0.00414) = 2.048\, kg/s$

$\dot{V}_{ev} = \frac{7\,014.2\, kg/hr}{1000\, kg/m^3} = 7.0142 \frac{m^3}{hr}$ @ $1.95e^{-3}\, m^3/s$ = 116.903 lit/min

Number of nozzles = $\frac{116.903\, lit/min}{0.17\, lit/min} = 687.67 \approx 688\, nozzles$

Figure 4.3 shows the mass flow rate of water needed to be sprayed at particular time.

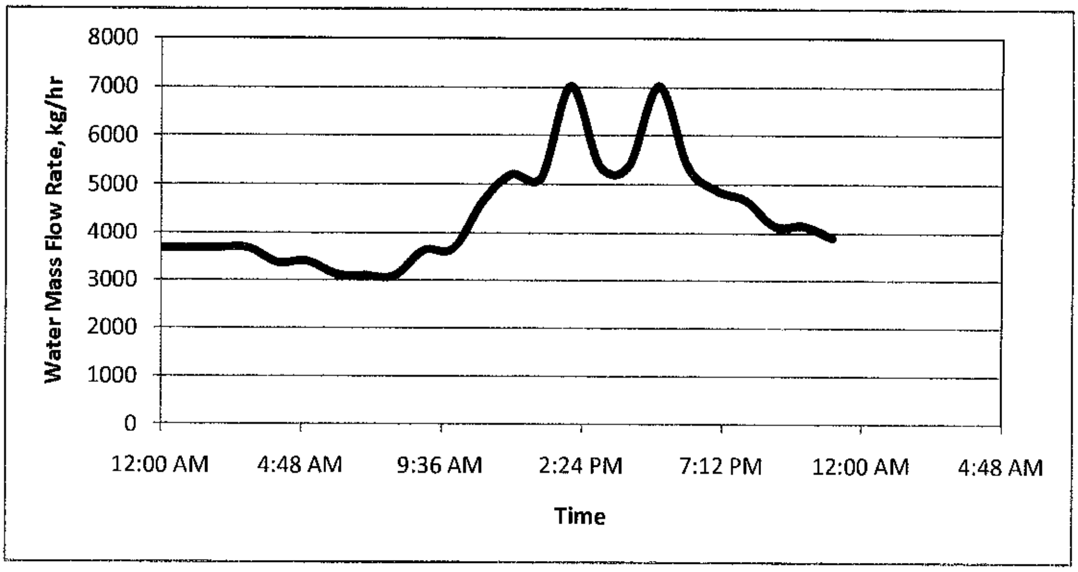


Figure 4.3: Mass Flow rate of water at particular time

This flow rate determines the number of nozzles and pumps needed to be operated at particular time. Mass flow rate of water is highest during highest cooling potential needed. This is due to increasing in ambient temperature and decreases in density whilst mass flow rate of air into the compressor. By spraying the water, it will increase the density of air into the compressor and increases also the mass flow rate of air. So the power output will be increase.

After all this parameters being obtained, the conceptual design can be visualized in the next section. There were three (3) software uses in this study. It consists of:

1. CATIA – for visualizing the overall design.
2. Gambit – designed in 2D.
3. Fluent – evaluate the air flow.

4.2 DESIGN OF FOGGING SYSTEM

4.2.1. CATIA

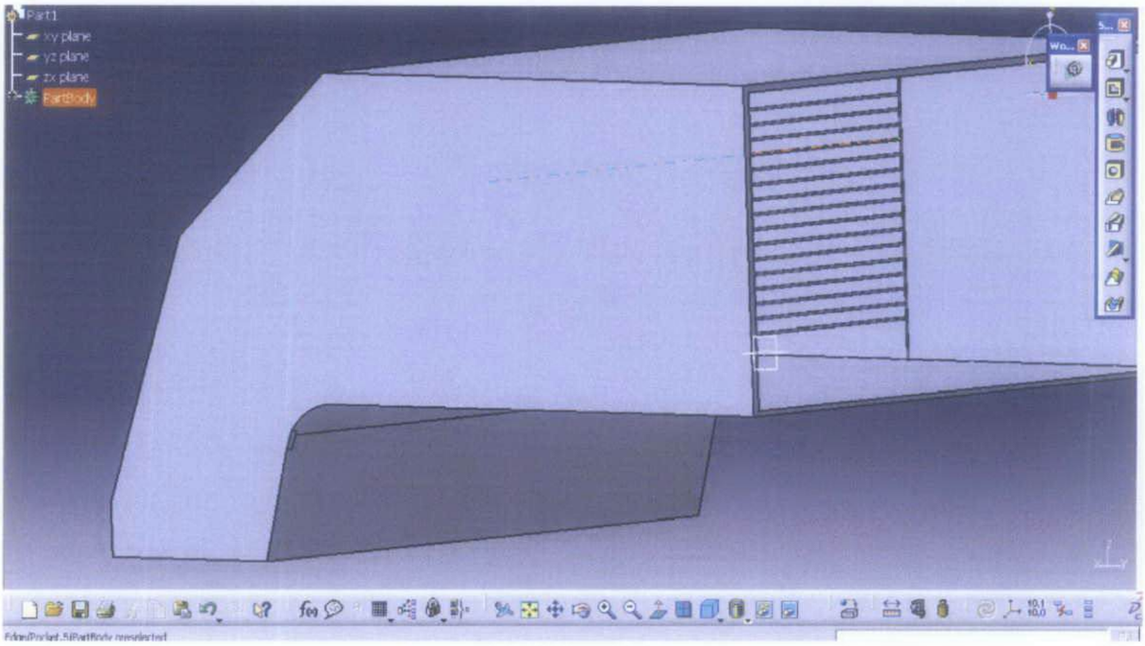
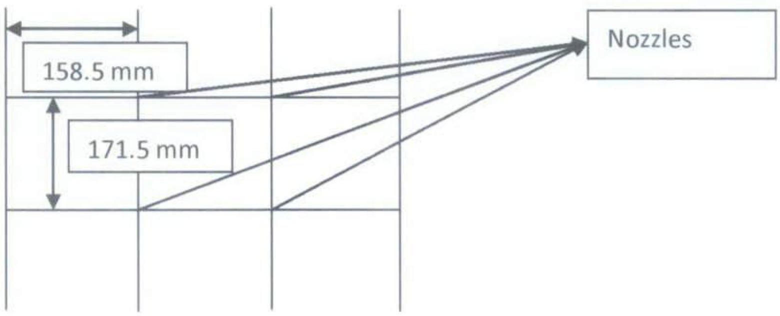


Figure 4.4: Overall Design

Nozzles are installed after the silencer to reduce pressure loss inside the ducting. Moreover, this is too preventing any compressor fouling. There are 688 nozzles in the drawing. There are 43 nodes on horizontal part and 16 nodes on vertical part for installing the nozzles. For the horizontal part, the distance between each nozzle is 158.5 mm meanwhile vertical part is 171.5 mm. The material for piping is stainless steel that has 26.67 mm in diameter based on standard piping. Air flow inside the channel had been evaluated by Fluent.



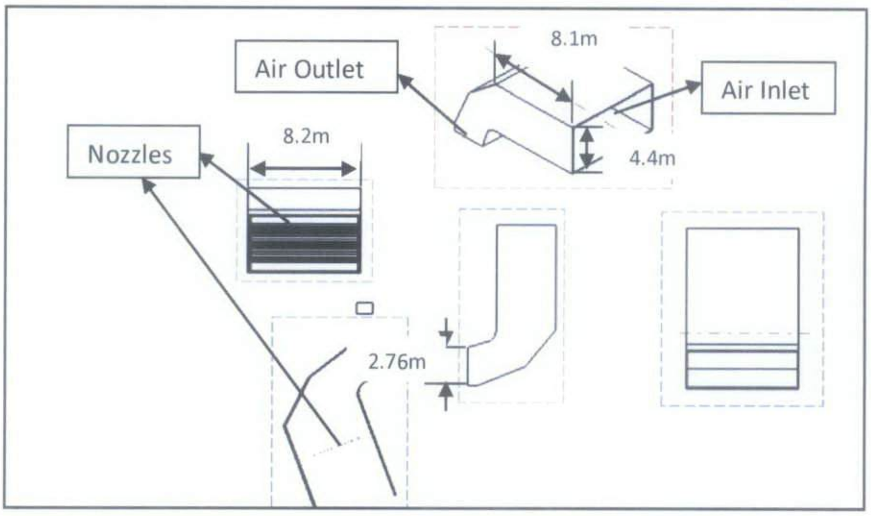


Figure 4.5: Isometric, front and side view of inlet ducting

4.2.2 Gambit

Before the flow inside the channel can be evaluated, the boundary condition and meshing needs to be done. These tasks can be done in Gambit. While draw and set the boundary condition, this channel had been divided into 2 parts which are nozzles and channel. For the boundary condition, the velocity inlet, pressure outlet and wall had been chosen in this project. The steps to produce this design had been explained in the methodology section. Figure 4.6, shows the meshing for all part.

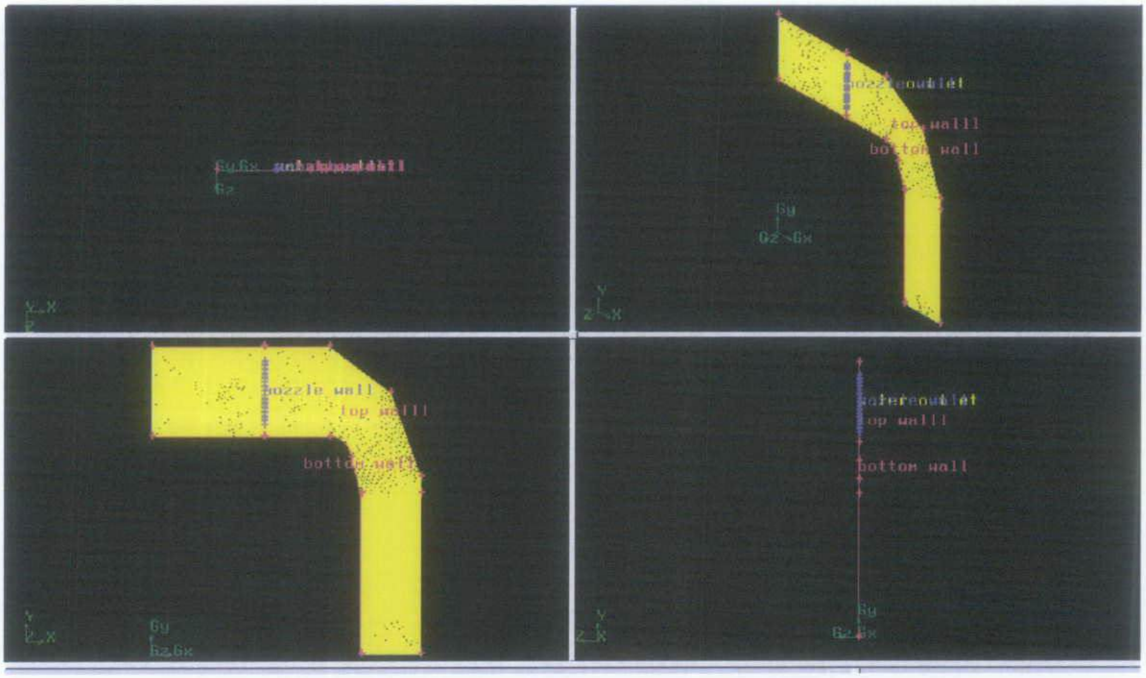


Figure 4.6: 4 view of ducting system in Gambit

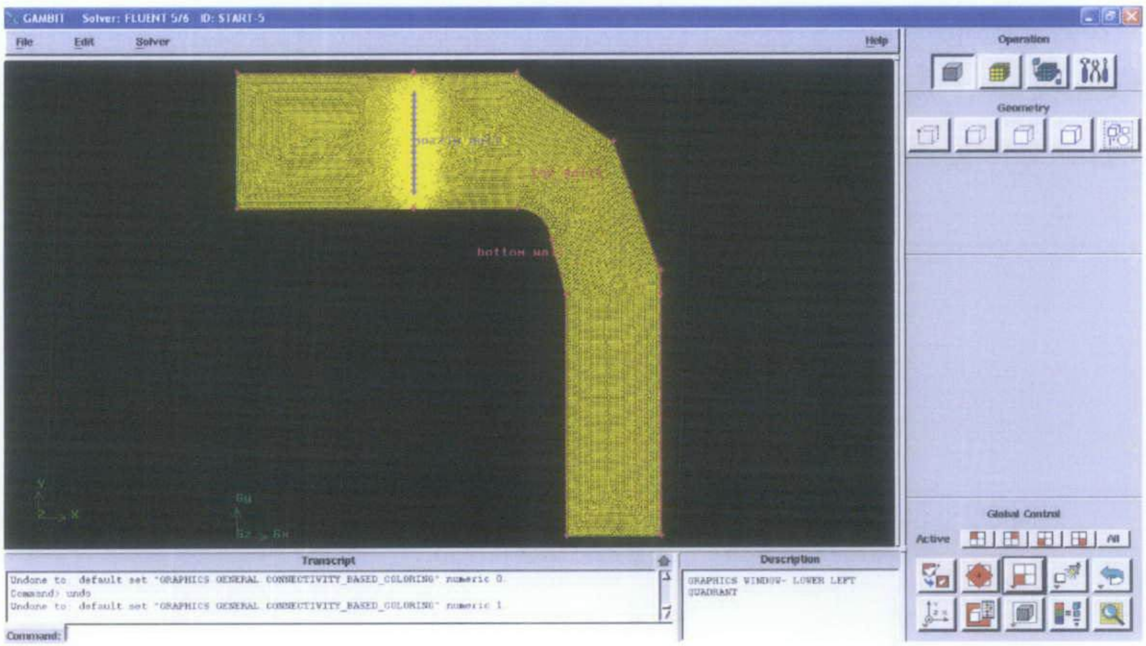


Figure 4.7: Overall 2D view in Gambit

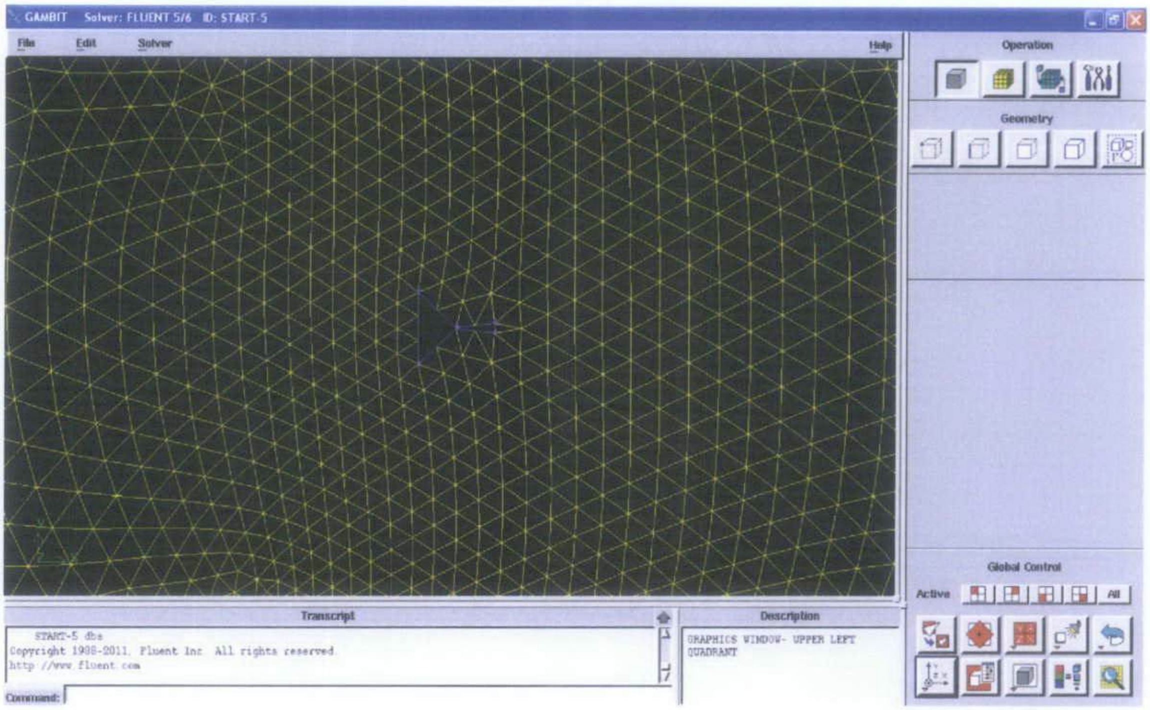


Figure 4.8: Meshing part near nozzles

In Gambit, there is no 3D view because it consume a lot of time to mesh and iterate it in Fluent. This study only consists of 2D view. To simplify the drawing, silencer was not introduced at the inlet part. Based on the above assumptions, there was no pressure drop occurred in this study which it is impossible in real situation. The nozzles that was drawn in Gambit was to picture the real nozzles during fogging process. In this case, there are 16 nozzles. One nozzle corresponds to 43 nozzles. Later, the flow rate of this nozzle is equal to 43 nozzles. The design of nozzles is to portrait the process flow of water sprayed inside the nozzle.

After meshing part was done, this drawing was exported to mesh to Fluent.

4.2.3 Fluent

In this software, velocity and temperature of air were studied and the differences of these parameters are shown in this drawing.

Figure 4.9: Velocity vectors of airflow

This figure shows the velocity vectors near the nozzle during fogging system. The velocity vectors show airflow is nearly constant along the ducting. While the airflow passes through the nozzles, the velocity is decreases. But this velocity starts to increase back when the airflow is flowing far away from the nozzles.

The magnitude of velocity occurred inside the ducting is shown in figure 4.10. The velocity is high at elbow of ducting. As the air flow to the compressor its velocity slightly increases. It is due to the dimensions of ducting. Dimensions of ducting become smaller at the end of ducting which located before the air enters into the compressor.

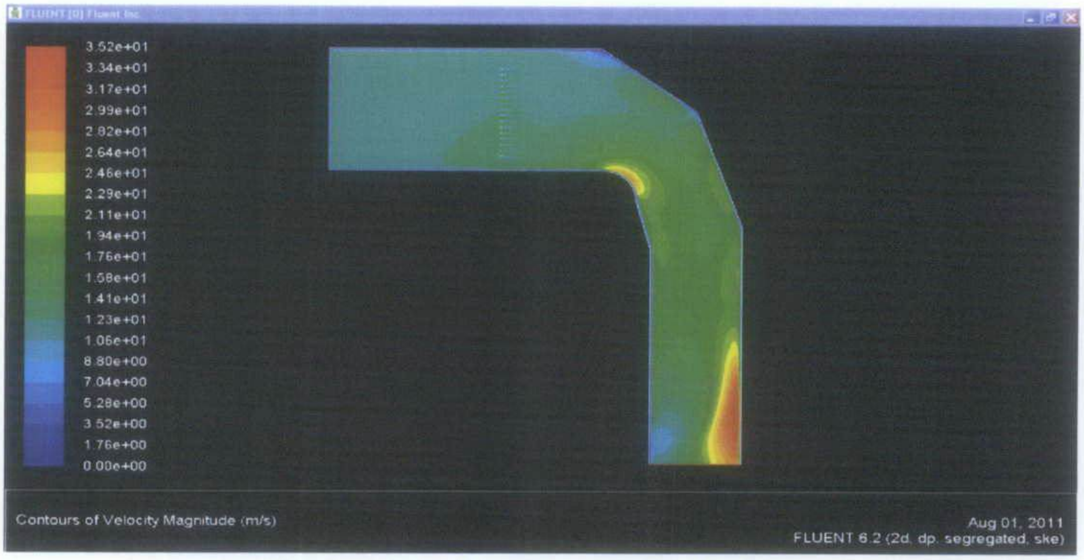


Figure 4.10: Velocity magnitude of airflow

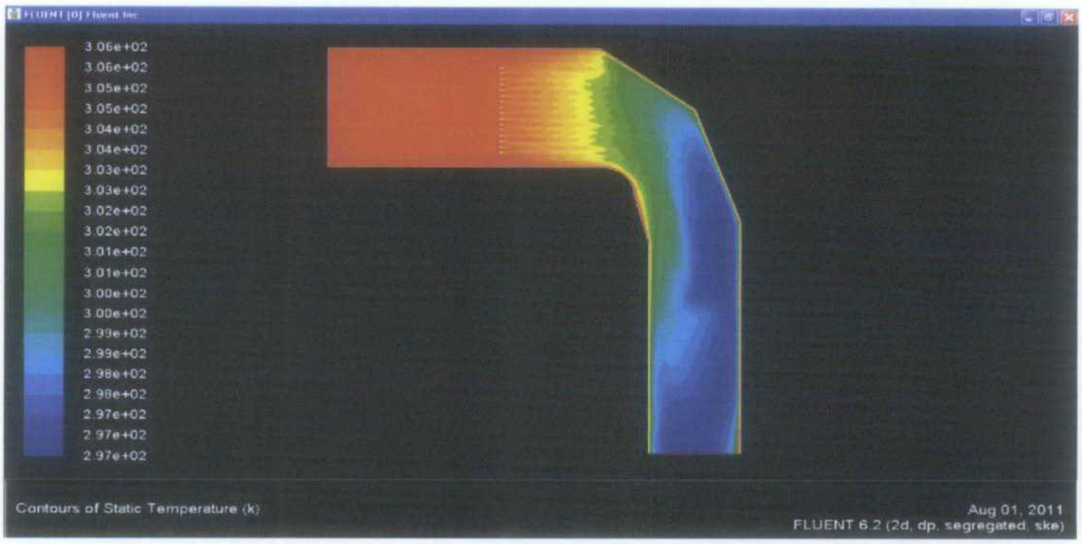


Figure 4.11: Static Temperature of airflow

In this figure, it shows that during fogging system the air had been cool down to certain temperature. At first, the temperature of airflow is nearly constant. It is about 360 K. When the airflow is passing through the nozzle, the temperature of airflow starts to decrease. The nozzles spray the water to bring down the temperature of airflow. The temperature of air inlet is about 306 K and the air outlet is about 297 K. With the total amount of water is about 2.048 kg/s, it succeeded to cool down the temperature until 297 K.

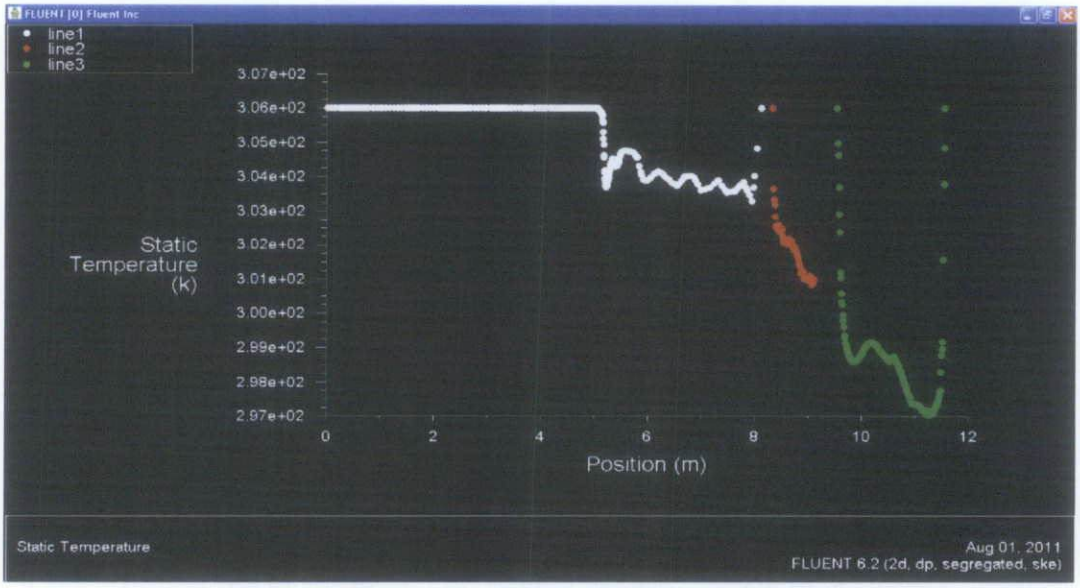


Figure 4.12: Graph of static temperature of airflow

This graph shows the dropping in air temperature and briefly explains about Figure 4.11. This graph clearly stated that at position 9m to 11 m, the temperature of air flow was dropping until 297 K. Because of the ducting's design which is 90°, the graph cannot be plotted properly.

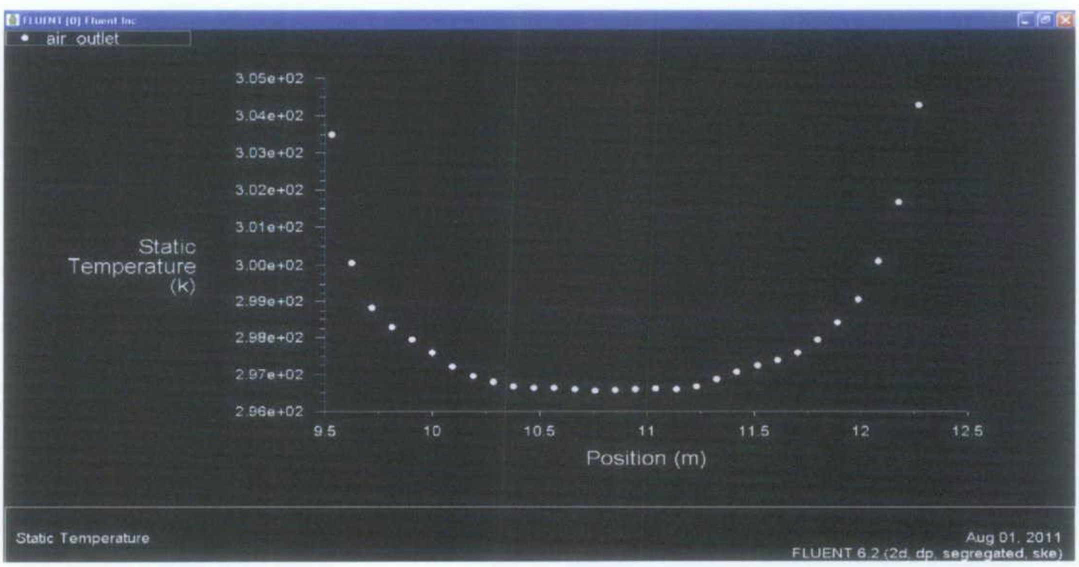


Figure 4.13: Graph of static temperature at air outlet

Figure 4.13 explains the static temperature at air outlet. At the end of the position, the temperature of air is increases because of the temperature of ducting's wall. It was assumed that the temperature of ducting's wall is nearly constant. This value was entered at the boundary condition of wall.

CHAPTER 5
CONCLUSION

As a conclusion, inlet fogging is one of the methods for cooling air inlet to increase the efficiency of gas turbine due to the increasing of air mass flow inside the compressor so that the injection of fuel will be increased. Small changes in gas turbine operating parameters can result in significant differences to other parameters and care has to be taken while studying this project. The gas turbine operating parameters such a nozzle design, measurement of droplet size, and compressor inlet fogging system had been established. It can be the best method to cool down the air inlet temperature because it is easy to install and less expensive than other methods. The fogging system that was implemented can bring benefit to power plant to increase their profit without being influenced by ambient condition. From this study, it is well said that the temperature of air flow can be cool down close to wet bulb temperature.

In this project, the temperature of air inlet is about 306 K and the air outlet is about 297 K. With the total amount of water is about 2.048 kg/s, it succeeded to cool down the temperature until 297 K.

For getting better result, this project can be extensively study in wet compression system. It is to increase the efficiency of gas turbine even more. Moreover, the drainage system needs to be designed carefully because it can affect the gas turbine performance. It is because water can be clogged inside the ducting and increases the pressure loss of air flow. So, the performance of gas turbine will be decreases.

Last but not least, to get accurate result, monthly or yearly weather data can be taking into account instead of daily weather data.

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APPENDIXES

Vertex

Coordinates

A (0, 10.175)

B (5.1, 10.175)

C (5.12667, 10.175)

D (8.1, 10.175)

E (8.1, 9.175)

F (9.1, 9.175)

G (9.53, 7.5)

H (9.53, 0)

I (12.27, 0)

J (12.27, 7.5)

K (12.27, 8.25)

L (10.9, 12.233)

M (8.1, 14.375)

N (5.12667, 14.375)

O (5.1, 14.375)

P (0, 14.375)