NUMERICAL INVESTIGATION OF IMPACT OF RELATIVE HUMIDITY ON DROPLET ACCUMULATION AND FILM COOLING ON COMPRESSOR BLADES

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by

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THESIS

Presented to the Faculty of the Graduate School of

The University of Texas at El Paso

in Partial Fulfillment

of the Requirements

for the Degree of

MASTER OF SCIENCE

Department of Mechanical Engineering

THE UNIVERSITY OF TEXAS AT EL PASO

August 2014

Acknowledgements

I would like to first and foremost thank my family for all of their love and for supporting me throughout my school years. Without them I would not be where I am now.

I would also like thank Dr. Shaolin Mao for all his guidance, support and especially his patience while this work was completed.

Lastly I would like to thank my co-workers in the cSETR Computational Lab at the University of Texas at El Paso, especially Luis Varela, Diego Delfin, Alejandra Castellanos, and Antara Badhan for always bringing a great attitude to work and making my working environment very enjoyable every day.

Abstract

During the summer, high inlet temperatures affect the power output of gas turbine systems. Evaporative coolers have gained popularity as an inlet cooling method for these systems. Wet compression has been one of the common evaporative cooling methods implemented to increase power output of gas turbine systems due to its simple installation and low cost. This process involves injection of water droplets into the continuous phase of compressor to reduce the temperature of the flow entering the compressor and in turn increase the power output of the whole gas turbine system. This study focused on a single stage rotor-stator compressor model with varying inlet temperature between 300K and 320K, as well as relative humidity between 0% and 100%. The simulations are carried out using the commercial CFD tool ANSYS: FLUENT. The study modeled the interaction between the two phases including mass and heat transfer, given different inlet relative humidity (RH) and temperature conditions. The Reynolds Averaged Navier-Stokes (RANS) equations with k-epsilon turbulence model were applied as well as the droplet coalescence and droplet breakup model considered in the simulation. Sliding mesh theory was implemented to simulate the compressor movement in 2-D. The interaction between the blade and droplets were modeled to address all possible interactions; which include: stick spread, splash, or rebound and compared to an interaction of only reflect. The goal of this study is to quantify the relation between RH, inlet temperature, overall heat transfer coefficient, and the heat transferred from the droplets to the blades surface. The result of this study lead to further proof that wet compression yields higher pressure ratios and lower temperatures in the domain under all of the cases. Additionally, droplet-wall interaction has an interesting effect on the heat transfer coefficient at the compressor blades.

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Chapter 1: Introduction

A variety of power systems are used worldwide to provide power; one of these is the gas Turbine (GT) system. A gas turbine system generated power by compressing ambient air to a high pressure, then adding heat to it in a combustion chamber and sent into a turbine where useful work is generated. As with any other machine, a GT system has ideal operating conditions. These ideal, or often referred as optimal conditions, are conditions at which the system will work at its highest efficiency and generate the highest power possible. Some properties and that can cause an effect in the efficiency of a GT system and cannot be easily controlled, including ambient temperature and ambient relative humidity (RH).

It is known that increasing the temperature at the inlet of a gas turbine system will cause a series of issues with a GT system. Initially a decrease in the density of fluid due to elevated temperatures is experienced; which reduces power output of the system. In past years, to counteract this effect; a variety of cooling methods have been implemented in GT systems.

Methods used for cooling the ambient air include evaporative coolers and chillers. These are installed at some distance prior to reaching the compressor. Evaporative coolers use droplets to help lower the ambient inlet air temperature through their evaporation. Chillers use the refrigerant cycle to cool the inlet air, typically with vapor or refrigerant. Essentially pipes with cooler fluid flows normal to the flow direction and will cool the ambient air as it comes in contact with the cooler pipes.

Evaporative cooling methods such as fogging and wet compression have been implemented into systems to reduce the inlet temperature at the compressor [1]. Fog cooling is the process of cooling the inlet of the compressor with evaporation of atomized water in which the continuous phase is cooled until it reaches a 100% relative humidity [1]. Similarly, wet

compression is the process in which atomized water is directly injected into the continuous flow [1]. However, more water is injected in the domain than required to reach 100% relative humidity, this cooling method is often referred to overspray [1]. Other methods have been implemented into GT systems; however, due to low costs and easy installation evaporative coolers are favored [1].

Previous researchers [1-6] have investigated the effects that droplets have on the compression process. Wang and Khan have did extensive research with wet compression and inlet fogging. In [1] the thermodynamic parameters were established to more closely predict the effects of wet compression and fogging. Tomita [2] investigated the relationship between the small changed in relative humidity and found that pressure ratio in increased as well as reduced the stagnation temperature. With Tomita and research done by with [1, 4, 7], power generated by the GT system will increase after the implementation of evaporative cooling.

In those numerical investigations, the blades and droplets have only contained one interaction; stick, film generation, or rebound. However, the transient feature of droplet motion on the blade has not been studied in stick or rebound interaction. The expansion of a droplet after impinging on the blade may have an important effect on mass exchange between droplets and continuous phase air as well as the blade temperature.

In this study, wet compression will be further studied using high fidelity computational fluid dynamics (CFD) software: ANSYS (FLUENT). Initially uniform droplet size is assumed neat the inlet. Inlet temperature is varied and mole fraction of water is presumed at the inlet condition to satisfy the relative humidity (RH) value. A variety of RH were assumed, ranging from 0% to 100%; inlet temperature conditions were varied between 300K and 320K. These simulations will aid in the analysis and investigation of the relationship between RH, inlet

temperature, pressure ratio (P.R) and heat transfer coefficient (HTC) and the overall heat transfer coefficient (OHTC) of the domain.

The three main objectives for this study are as follows:

1. To generate a two dimensional domain that will generate feasible results for a single stage compressor.
2. To evaluate the effects that wet compression has at different relative humidity and inlet temperature.
3. To compare the effects that wall – droplet interaction has on the overall heat transfer coefficient.

With these three objectives HTC will be evaluated for the rotor and stator blades and the HTC between the droplets and continuous phase, as well as the OHTC of the domain. In the following sections, additional background information on the GT system, on inlet cooling methods and the thermodynamic properties will be covered in detail. Numerical methods will be discussed as well as boundary conditions applied to the model. The results will include the contours of pressure, temperature, relative humidity, and entropy and plots were generated to see the effects that relative humidity has on the other properties. HTC and OHTC values were calculated and compared between the different generated cases.

Chapter 2: Literature Review

The following sections will go into detail on the thermodynamics behind the gas turbine (GT) system and the importance of the compressor and the impact operating conditions have on the system. Additionally, detailed explanations of different methods which have been used to lower the temperature at the compressor inlet will be discussed and compared.

2.1 Thermodynamics

A thermodynamic cycle is a process which utilizes a fluid to transform energy stored in the fluid into a useful energy. A gas turbine cycle is composed of four main components: compressor, combustor, turbine and a generator. As seen in Figure 2.1 air at ambient conditions flows into the compressor, depicted by point 1, in which the air is compressed in to a high pressure and, ideally, no heat is added. Next the compressed air is send into the combustor, point 2 in Figure 2.1, where air is mixed with fuel and burned at a high temperature. Then the high temperature, high pressure fluid exits the combustor and enters the turbine, depicted in Figure 2.1 labeled as point 3. In the turbine the hot fluid produces work. The useful work produced by the system is the difference between the work produced by the turbine and the work consumed by the compressor. Usually the amount of work consumed by the compressor is more than 50% of the work produced by the turbine [7].

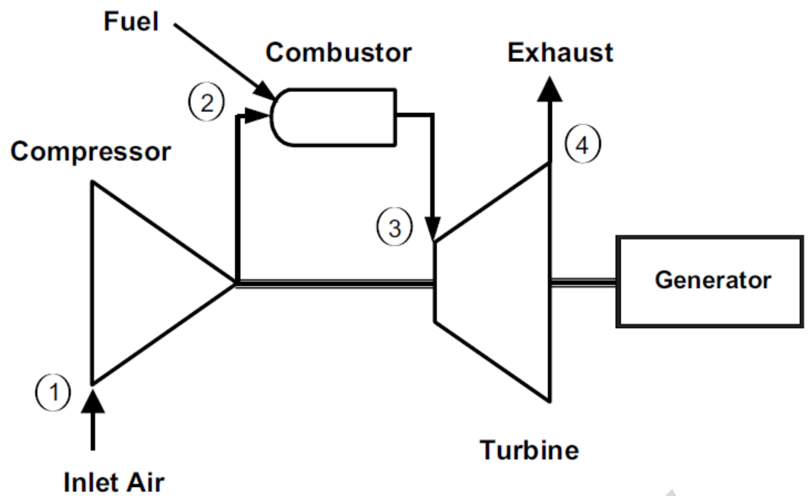

Figure 2.1: Gas turbine system components and fluid flow [7]

2.1.1 Brayton Cycle

The Brayton cycle is the thermodynamic cycle in which the GT turbine operates. In Figure 2.2 are the Pressure-specific volume (P-v) and Temperature-entropy (T-s) diagrams for the cycle. The process described above is depicted in the P-v and T-s diagrams; Figure 2.2. From point 1-2 there is a pressure increase and temperature increase due to the compression process [7]. The connection between points 2-3 depicts the heat addition process experienced in the combustor at a constant pressure [7]. The path from point 3-4 describes pressure drop to that of the inlet and temperature decrease experienced within the turbine [7]. The diagrams themselves depict a "closed cycle" in which the fluid leaving the turbine is cooled and send back into the compressor [7]. However, in reality the cycle is an "open" system, where the fluid leaving the turbine is not directly send back to the compressor; instead the atmosphere does the actual cooling and provides cool air to the compressor [7].

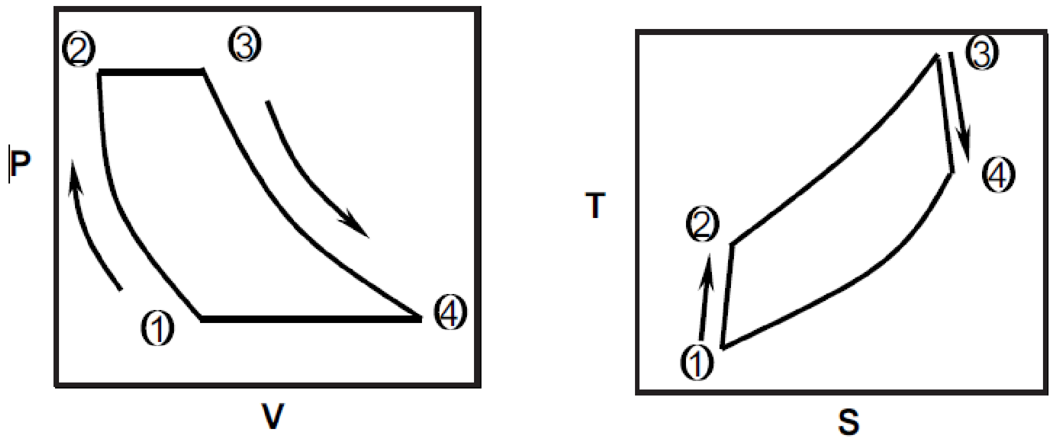

Figure 2.2 - P-v and T-s diagrams from [7]

2.1.2 Performance characteristics

Common characteristics that evaluate the performance of a GT system include but are not limited to pressure ratio, firing temperature specific output, and thermal efficiency. Firing temperature is the hottest temperature obtained in the system. GE defined the firing temperature as the 'mass-flow mean total temperature' in the first stage of trailing side of the nozzle [7]. A stage is one rotor/stator pair; the amount of stages in a compressor varies with the compressor used in the GT system.

A series of equations, described below can be used to calculate the thermal efficiency, work generated, work consumed, pressure ratio, and work net of the GT system. It is required to quantify the amount of heat transferred to the working fluid in the system. This can be evaluated by enthalpy or change in temperature as seen in the formula below. The variable q_{in} quantifies the heat transferred into the GT system through the combustor and q_{out} quantifies the heat that is leaving the system between the inlet of the compressor and the outlet of the turbine, no losses are made, i.e. ideal Brayton cycle [8].

$$q_{in} = h_3 - h_2 = C_p(T_3 - T_2) \tag{1}$$

$$q_{out} = h_4 - h_1 = C_p(T_4 - T_1) \quad (2)$$

In GT system we find components that produce and consume work, it is important to verify that the system as a whole will produce more work that what is consumes, essentially a positive work net; as seen in the following equation [8].

$$W_{net} = W_{out} - W_{in} \quad (3)$$

Work In and Work out of a GT system can be also computed by the change in entropy in an ideal Brayton cycle [8].

$$W_{out} = h_2 - h_1 \quad (4)$$

$$W_{in} = h_3 - h_4 \quad (5)$$

Pressure ratio is the ratio of pressures that are entering and leaving the compressor, P2 being the pressure that leaves the compressor and P_1 being the pressure at which the fluid enters the compressor [8].

$$P.R. = r_p = \frac{P_2}{P_1} \quad (6)$$

Thermal efficiency is another parameter that can be used in a system to quantify how well a GT system works converting thermal energy into work [8]. It is expressed by evaluating the ratio of net-work obtained to the total heat input, also this can be written in terms of pressure ratio and specific heat ratio (k) for the Brayton Cycle [8].

$$\eta_{th} = \frac{W_{net}}{Q_{in}} = 1 - \frac{1}{r_p^{(k-1)/k}} \quad (7)$$

Figure 2.3 shows the effects that pressure ratio and firing temperature has on the specific output and thermal efficiency in a simple GT cycle. With an increase in pressure ratio, thermal efficiency sees an increase and small variation in the specific output. Also seen in Figure 2.3, it is visible that an increase in firing temperature has a positive effect in specific output.

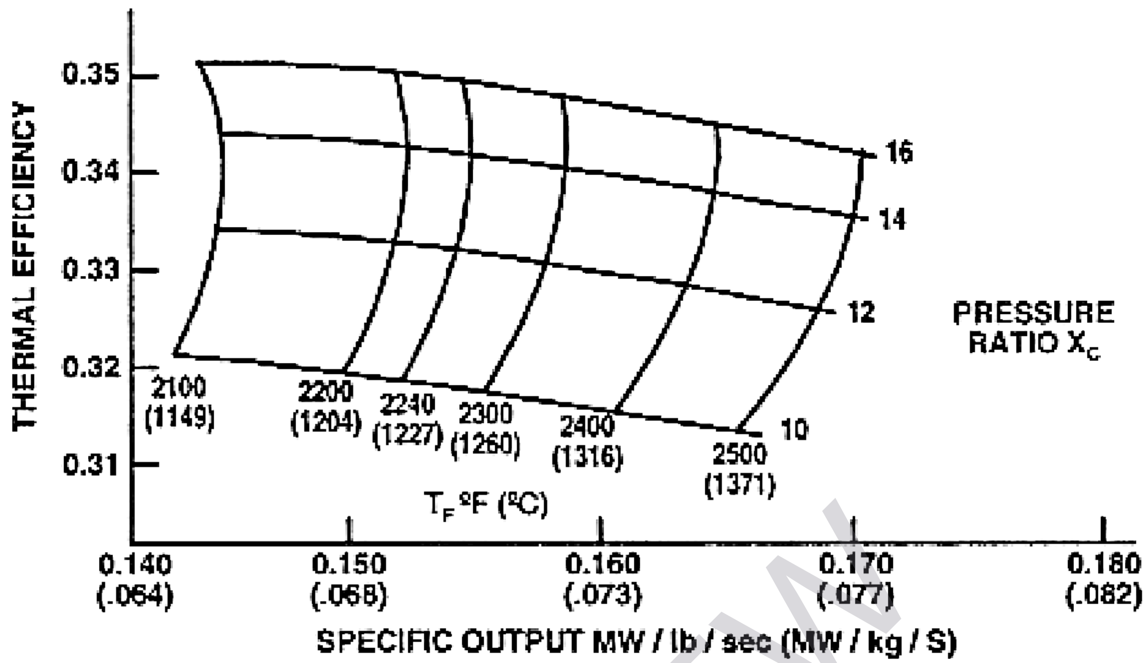

Figure 2.3 Thermal efficiency versus Specific output [7]

Factors that affect the GT system

Every gas turbine system is created with ideal operating conditions; operating a system at any other operating conditions will affect efficiency, power output and possibly life of a system component. According to [1, 7], factors that affect the performance of a GT system include air temperature, site elevation, humidity, inlet and exhaust losses, fuels, and fuel heating.

Ambient Temperature

The gas turbine system utilizes ambient air directly into the ambient air, any changes in mass flow rate and/or density will modify the inlet properties of the compressor. In Figure 2.4 the P-v and T- s diagrams show the effects that a higher inlet temperate has on the GT cycle.

The Figure 2.4 has two graphs which depict two system diagrams with different operating conditions; one with ideal operating conditions and the other is a system with elevated inlet temperature. In both graphs (A and B) the system with ideal operating conditions is represented

by the path that intersects points 1-2-3-4. The path enclosed by points 1'-2'-3-4 represents a system with elevated inlet temperature.

Figure 2.4 shows the effects that temperature has on pressure and specific volume. Required compressor work can be represented by the area that is enclosed by a-1-2-b. It is easily seen that the area enclosed by 1'-2'-3-4 (higher inlet temperature) is larger than that enclosed by 1-2-3-4 (ideal inlet temperature). This means that the compressor of a GT system running at higher inlet temperatures will require a larger amount power to compress the hotter air to the same pressure. This increase in power required will decrease the specific power output of the system [1].

(a) (b)

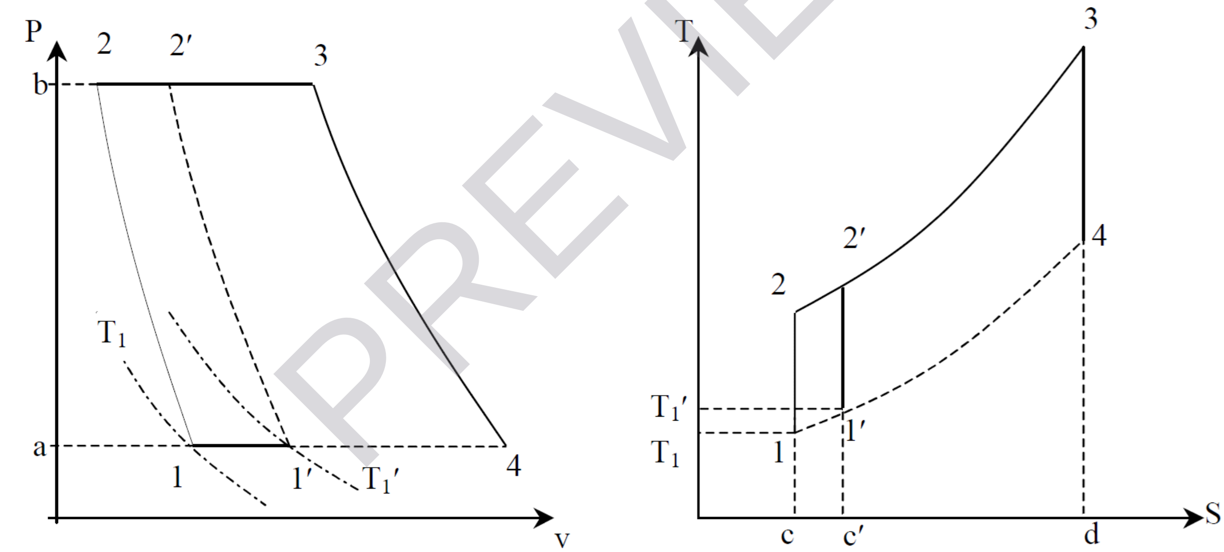

Figure 2.4: Thermodynamic Properties: (a) P-v and (b) T-s [1]

The graph on the right, Figure 2.4 (b), depicts how change in inlet temperature affects entropy. Previously on this paper, it was explained that from point 2-3 serves as a representation of the amount of useful energy generated by the system. From Figure 2.4 (b) it is clearly visible

that the system running at ideal conditions (1-2-3-4) will produce more useful energy in the combustion chamber that the system at elevated inlet temperature [1].

Figure 2.5 shows the influence that ambient temperature has on exhaust flow, heat consumption, output, and heat rate. The figure depicts the effects caused to a single shaft MS7001 system. It is visible that the system as a whole will work at 100 percent at ISO conditions; when the temperature is increased, power output and heat consumption in the combustion chamber is decreased [7].

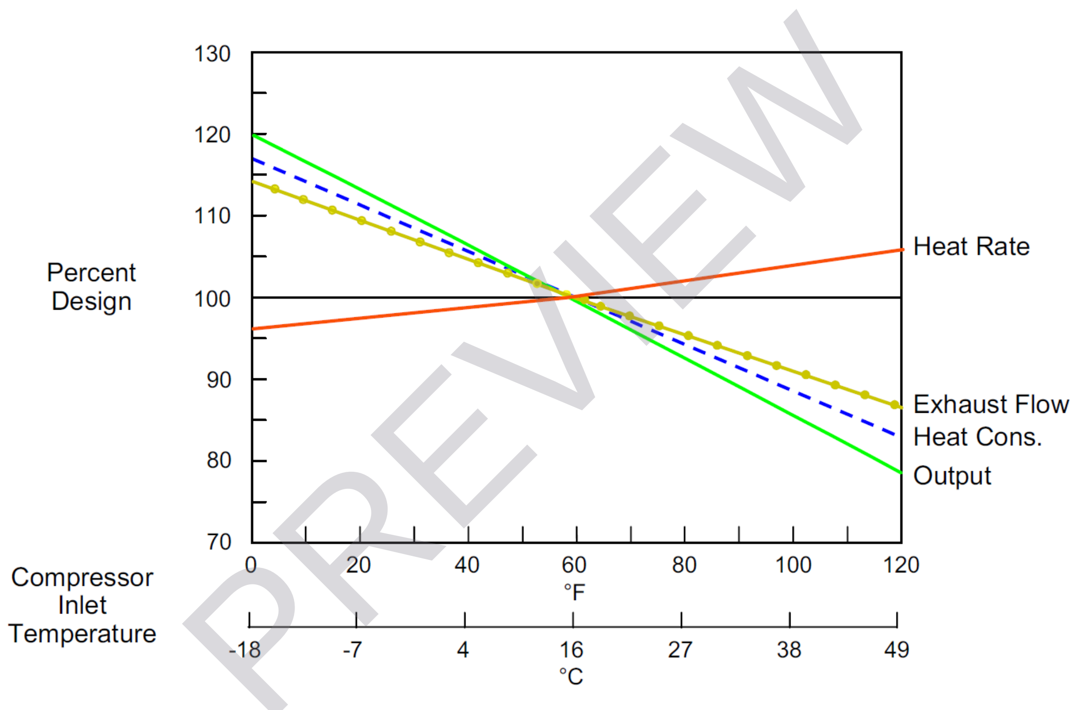

Figure 2.5: Effects of Ambient temperature on GT system [7]

Humidity

Humidity of the ambient air also has an effect on the GT performance. Humid air is less dense than dry air which also affects the heat rate and the power output of a system. This can be seen in Figure 2.6 where a correction factor is generated while varying specific humidity. As the specific humidity moves away from the ISO specific humidity the power output is reduced.

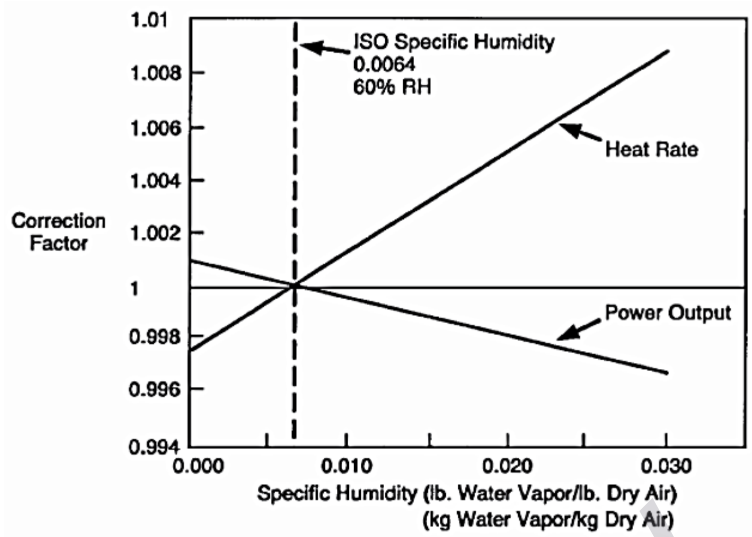

Figure 2.6: Humidity and its effects on heat rate and power output [7]

Pressure losses

Pressure losses in a GT system can be caused by inserting air filtration, silencing, and evaporative coolers/chillers. The magnitudes of the losses vary with the design. One example of these losses for the MS7001EA system can be seen in the Figure 2.7 below.

Table 2.1: Effects of Pressure drop in the in MS7001EA system [7]

4 Inches (10 mbar) H_2O Inlet Drop Produces:	*4 Inches (10mbar) H_2O Exhaust Drop Produces:*
1.42% Power Output Loss	*0.42% Power Output Loss*
0.45% Heat Rate Increase	*0.42% Heat rate Increase*
1.9 °F (1.1 °C) Exhaust Temperature Increase	*1.9 °F (1.1 °C) Exhaust Temperature Increase*

Fuels

When addressing fuel and its effects on the GT system, usually affects the turbine generated by the turbine. The work of the turbine, as previously described depends on the mass flow rate, the temperature difference between the inlet and outlet of the turbine and the heat

energy in the combusted gas (C_p). An example given by [7] is that methane will produce a greater 2% output than distillate oil, due to the specific heat properties.

On Figure 2.7 Some of the effects of evaporative cooling have on the GT system. Increase in relative humidity will decrease the increase in percent output.

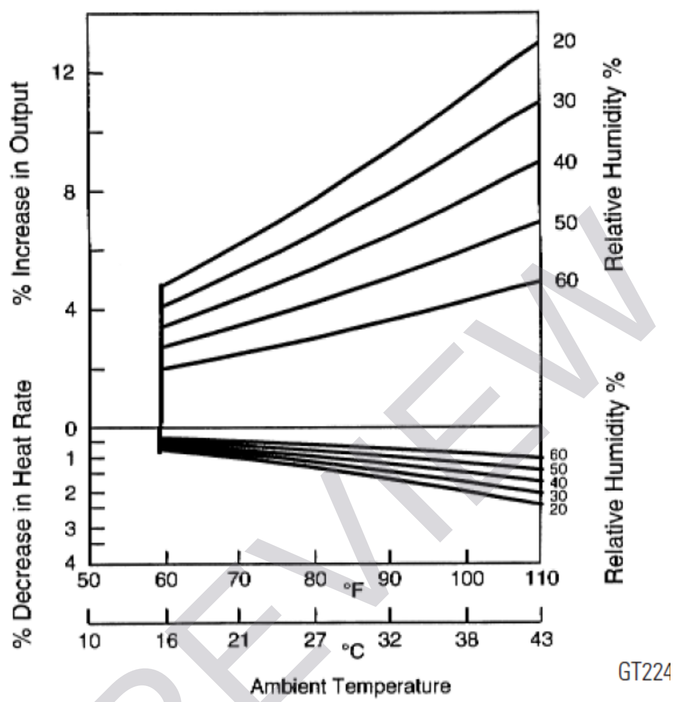

Figure 2.7: Effect evaporative cooling on output and heat rate [7]

Fouling

Fouling in the compressor has also been attributed to reduced pressure ratio, air flow, and efficiency [9]. Two methods highly used methods to counteract fouling are offline and online washing. Online washing is one while the system is still on; which will maintain the compressor clean and will extend the time between offline washing [9]. Offline washing is done while the machine is shut down and cleaned extensively [9].