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INLET FOGGING OF GAS TURBINE ENGINES DETAILED CLIMATIC ANALYSIS OF GAS TURBINE EVAPORATIVE COOLING POTENTIAL

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ABSTRACT: Inlet fogging of gas turbine engines has attained considerable popularity due to the ease of installation and the relatively low first cost compared to other inlet cooling methods. With increasing demand for power and with shortages envisioned especially during the peak load times during the summers, there is a need to boost gas turbine power. There is a sizable evaporative cooling potential throughout the world when the climatic data is evaluated based on an analysis of coincident wet bulb and dry bulb information. This data is not readily available to plant users. In this paper, a detailed climatic analysis is made of 122 locations in the US to provide the hours of cooling that can be obtained by direct evaporative cooling. This data will allow gas turbine operators to easily make an assessment of the economics of evaporative cooling. The paper also covers an introduction to direct evaporative cooling and the methodology and data analysis used to derive the cooling potential in different regions of the US. Simulation runs have been made for gas turbine simple cycles using a reference plant based on a GE Frame 7111EA gas turbine at the 122 locations studied in the US to provide a feel for the sensitivity of operation with inlet fogging.

NOMENCLATURE

ECDH	Equivalent Cooling Degree Hours
GPM	Gallons/minute
DB	Dry Bulb Temp
WB	Wet Bulb Temp
WG	Water Gauge

I. INTRODUCTION

Gas Turbine output is a strong function of the ambient air temperature with power output dropping by 0.3-0.5 % for every 1°F rise in ambient temperature. On several heavy frame gas turbines, power output drops of around 20% can be experienced when ambients reach 95°F (35°C), coupled with a heat rate increase of about 5%. Aeroderivative gas turbines exhibit even a greater sensitivity to ambient conditions. Figure derived by examining several turbines provides a representation of the power boost capability for different types of gas turbines. This was derived using GTPRO software over a range of turbines. This loss in output presents a significant problem to utilities, cogenerators and IPPs when electric demands are high during the hot summer months. Inthe petrochemical and process industries, the reduction in output of mechanical drive gas turbines often curtails plant output. For example, at some LNG plants, production may have to be curtailed during the hot afternoons when the refrigeration capacity is limited by gas turbine driver power. One way to counter this drop is to cool the inlet air. While there are several cooling technologies available, fogging has seen large-scale application because of the advantage of low first cost when compared to other techniques including media evaporative cooling and refrigeration technologies.

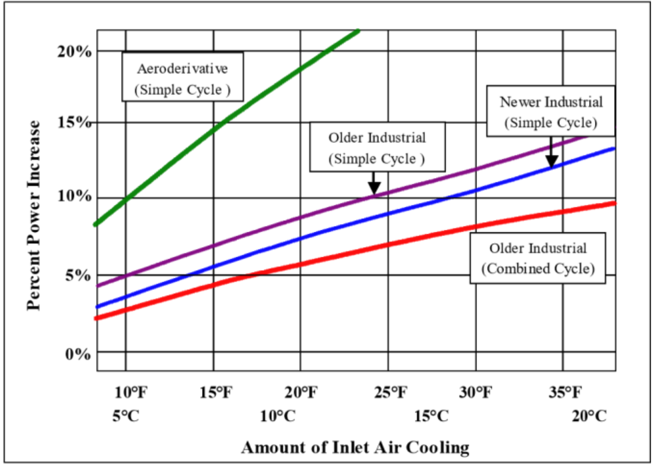

Figure 1. Representation of power boost possible by inlet cooling.

One obstacle faced by gas turbine users in analyzing the potential for fog evaporative cooling is that there is sparse climatic data available in a form that users can make a decision on the benefits of evaporative cooling. The obstacle may bebroken into two factors:

Operators cannot easily locate the appropriate weather data for their site. Much of the data is available at a plant site may be based on average data points with no representation of the values of coincident dry and wet bulb temperatures. This data is invaluable when evaluating any evaporative cooling solution. Even when some appropriate data is available through web sites or other sources, the data tables and information are not in a format to enables an operator to rapidly access the potential of evaporative cooling. The data has often to be considerably massaged and collated before any meaningful estimate can be made of cooling potential at the site. This paper will provide a detailed analysis of multiple locations in the US providing useful climatic data which allows users to evaluate the power augmentation potential available. To our knowledge, this is the first attempt to consolidate this data in a form that users can use easily. It is planned to extend this analysis in a later paper, to sites located at several locations in the world. McNeilly

(2000) has provided an excellent study on the importance of accurate climatic data when evaluating gas turbine inlet cooling projects. The relative potential of different gas turbines to capacity increase due to inlet cooling has been evaluated by Kitchen et al (1995). A psychometric chart can be used to obtain the values. The exact power increase depends on the particular machine type, site altitude and ambient conditions.

II. OVERVIEW OF EVAPORATIVE COOLING TECHNOLOGY

2.1 Traditional Evaporative Cooling

Traditional media based evaporative coolers have been widely used in the gas turbine industry especially in hot arid areas. The basic principle of evaporative cooling is that as water evaporates, it consumes 1,160 BTUs of heat (latent heat of vaporization) and in doing so reduces the ambient air temperature. Traditional Evaporative Coolers are described in detail by Johnson, (1988).

Evaporative cooler effectiveness is given by:

$$E = \frac{T_{1DB} - T_{2DB}}{T_{1DB} - T_{2WB}} \qquad (1)$$

The presence of a media type evaporative cooler inherently creates a pressure drop which results in a drop in turbine output. As a rough rule of thumb, a 1” WG increase in inlet duct losses will result in a 0.48% drop in power and a 0.12% increase in heat rate. These numbers would be somewhat higher for an aeroderivative machine. Increases in inlet duct differential pressure will cause a reduction of compressor mass flow and engine operating pressure. Increase in inlet differential pressure results in a reduction of the turbine expansion ratio. The inherent loss of efficiency and increased inlet pressure loss in a traditional evaporative cooling system never allows for the maximum cooling effect to be attained. Water quality requirements are, however, less stringent than those required for direct fog cooling systems and this may be an important factor in some site locations when demineralized water is not easily available or is expensive.

2.2 Inlet Fogging

Direct inlet fogging is a method of cooling where demineralized water is converted into a fog by means of special atomizing nozzles operating at 2000 psi. This fog provides cooling when it evaporates in the air inlet duct of the gas turbine. This technique allows 100% effectiveness in terms of attaining 100 percent relative humidity at the gas turbine inlet and thereby gives the lowest temperature possible without refrigeration (the wet bulb temperature). Direct high boosting the power output considerably. In this paper, consideration pressure inlet fogging can also be used to create a compressor intercooling effect by allowing excess fog into the compressor, thus

Where,

T1 = inlet temperature

T2 = exit temperature of evaporative cooler

DB = dry bulb

WB = wet bulb

A typical value for effectiveness is 85-90% which means that the Wet bulb temperature can never be attained.

The temperature drop is given by:

$$\Delta T_{DB} = 0.9(T_{1DB} - T_{2WB}) \qquad (2)$$

is only made of evaporative fogging alone, with no discussion of fog intercooling being considered. A photograph showing a typical high pressure fogging skid is shown in Figure 2.

Figure 2. Typical high pressure fogging skid. The feed lines from the high pressure pumps to the inlet system can be seen here.

This consists of a series of high pressure reciprocating pumps providing demineralized water to an array of high pressure fogging nozzles located after the air filter elements. The nozzles create a large number of micron size droplets which evaporate cooling the inlet air to wet bulb conditions. A photo of a nozzle array fogging an inlet duct for a large frame machine is shown in Figure 3.

Figure 3. High pressure fogging skid in operation for a heavy-duty gas turbine.

2.2.1 Control of Inlet Fogging Systems and the Importance of Climatic Data. The control system incorporates a programmable logic controller (PLC), which is mounted on the high-pressure pump skid. Sensors are provided to measure relative humidity and dry bulb temperature. Programming algorithms within the PLC use these measured parameters to compute the ambient wet bulb temperature and the wet bulb depression (i.e., the difference between the dry bulb and wet bulb temperature) to quantify and control the amount of evaporative cooling that is possible at the prevailing ambient conditions. The system turns on (or off) fog cooling stages to match the ability of the ambient air conditions to absorb water vapor. The software would then be configured to adjust the amount of fog injected in proportion to the inlet air mass flow. By choosing pump displacements (i.e., flow in gpm) it is possible to derive multiple cooling stages with the utilization of different pump combinations. Obviously, the control of the skid is based on climatic conditions and so the overall utilization of the fogging system at any location, is a strong function of the climatic conditions. It is thisreason that makes an accurate understanding of the variations inclimatic conditions an imperative.

III. CLIMATIC AND PSYCHROMETRIC ASPECTS OF INLET FOGGING

3.1 Modeling of Climatic Data

There are numerous problems and traps when modeling climatic data- several of which derive from the concept of “averaging” of data. One example of this is using data such as shown in Figure 4. This figure provides a correlation of dry bulb and wet bulb averages at a certain site. The graph shows that the linear behavior may lead one to conclude that at a dry bulb temperature of 25°C, the expected wet bulb is 20°C allowing a wet bulb depression of 5°C. (i.e., a measure of evaporative cooling potential). This is totally erroneous as the data was derived by taking the average WB temperature and the average DB temperature and plotting the curve. Consequently, the graph does not reflect coincident WB and DB conditions and will therefore indicate a much reduced cooling potential. This sort of error is very common. There is also a tendency of engineers to specify operating conditions that represent the “worst case” in terms of temperature and humidity. This is done in an attempt to derive an installation that will provide required capacity under the most stringent conditions, but in most cases, these extreme conditions can never exist in nature. The result is that plants may end up more expensive than they need to be.

This philosophy also pervades the definition of site conditions for power generation and mechanical drive applications. More than often the capacity conditions are defined at a very high temperature in combination with a high or average relative humidity. This often leads to more expensive plant construction than is needed (McNeilly, 2000). It is advisable that the site’s temperature profile for a full year of hourly data with the 20-30 year average wet and dry bulb coincident temperatures be considered in the analysis. These data can be used to generate “evaporative cooling degree hour” (ECDH) numbers for each hour of the year and allow a turbine operator to make a very detailed and accurate analysis of potential power gain from inlet fogging.

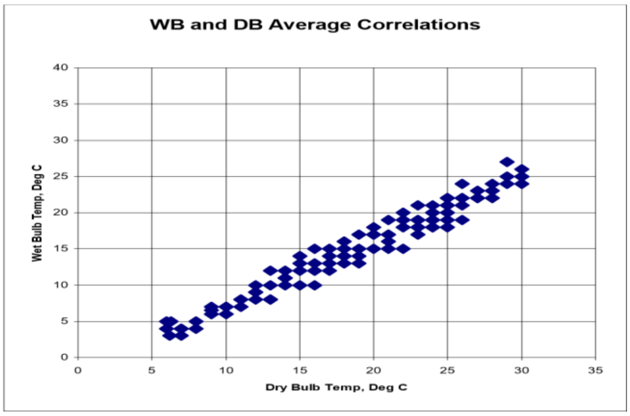

Figure 4. Correlation of WB and DB temperatures- averaged data.

High relative humidity conditions do not occur with high dry bulb temperatures. A typical pattern of variation of dry bulb and wet bulb temperature over a day is depicted in Figure 5. As can be seen, during the afternoon hours, there is a considerable difference between the wet bulb and dry bulb temperatures. It is this spread that allows the use of fog evaporative cooling. A common mistake made by potential users is to take the reported high relative humidity and temperature for a given month and base the design on these. The problem is that the high relative humidity generally occurs time-coincident with the lowest temperature and the lowest relative humidity occurs with the highest temperature. This mistake results in the erroneous conclusion that very little evaporative cooling can be accomplished and has historically been the underlying cause of the maxim that evaporative cooling is not possible in “high humidity regions”.

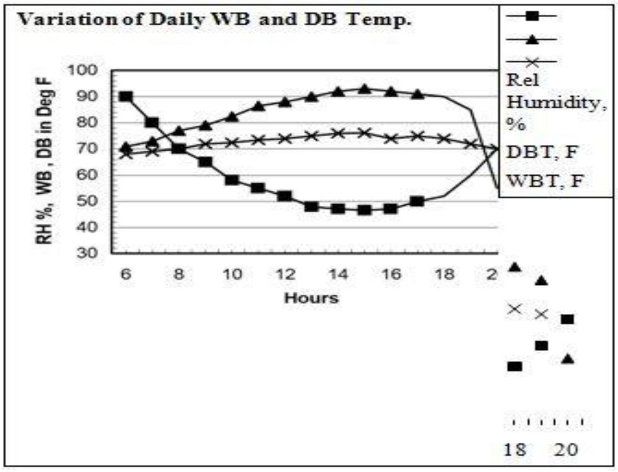

Figure 5. Daily variation of dry bulb and wet bulb temperatures.

Table 1 shows a sample calculation that computes degrees F of evaporative cooling potential for a site based on DOE climatic data. This table provides one months worth of data and a summary for the year’s operation. The total indicated is the total annual degree F – hours of cooling potential by the use of fog. A bar chart showing composite data considering all the months of the year from another site

(Orlando, Florida) is depicted in Figure 6.

DB [F]	Hrs	Avg Coincident WB [F]	WB Depression [F]	Evap Cool Potential F-hrs
110-86	0	0	0	0
85	1	71	14	14
84	1	70	14	14
83	0	0	0	0
82	2	72	11	21
81	7	73	8	55
80	9	73	7	61
79	9	73	6	55
78	13	72	6	73
77	10	72	5	53
76	22	69	7	154
75	29	69	6	163
74	37	70	4	140
73	41	68	5	203
72	38	66	6	221
71	62	66	5	281
70	76	66	4	286
			TOTAL:-	1794

Table 1. Data taken for a typical month .

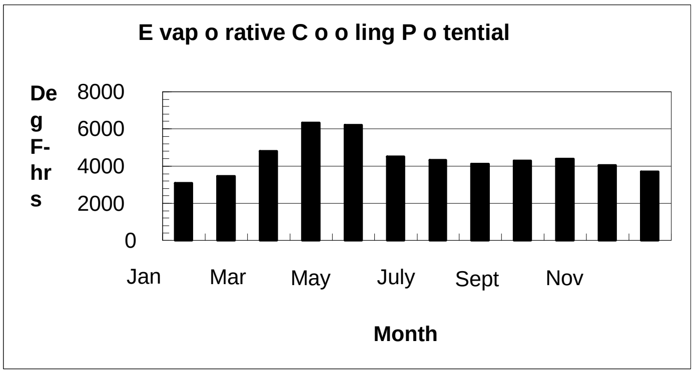

Figure 6. Evaporative Cooling Potential for a year.

3.2 Fog Evaporative Cooling in High Humidity Regions.

Even the most humid environments allow for up to 15°F of evaporative cooling during the hotter part of the day. The term “Relative Humidity” refers to the moisture content in the air “relative” to what the air could hold at that temperature. In contrast “Absolute Humidity,” is the absolute amount of water vapor in the air (normally expressed in unit mass of water vapor per unit mass of air). The moisture-holding capacity of air depends on its temperature. Warmer air can hold more moisture than cooler air. Consequently, relative humidity is highest during the cool morning and evening hours and lowest in the hot afternoon hours. 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 summer time humidity such as the Texas Gulf Coast region in the USA.

IV. METHODOLOGY AND ANALYSIS TO CREATE THE US DATABASE FOR EVAPORATIVE COOLING DEGREEHOURS.

Data was obtained from a DOE climatic database. The climatic data was primarily obtained from both National Climatic Data Center and the California Energy Commission. The goal of the analysis was to determine the Equivalent Cooling Degree Hours (ECDH) for a variety of locations in the USA. The ECDH is defined as a number that provides the total amount of cooling that can be derived for a given time period. The total ECDH is arrived at by summing the ECDHs derived for the 12 months at a location. For example, in the tabulation in Appendix C, the total ECDH for Atlanta GA, is derived by summing the numbers in that row, from January to December.

The database consists of two types of files:

TMY Files- These are typical meteorological year data generated by selecting long-term data gathered over approximately 20 years. The Typical year is a combination of twelve typical months chosen form the entire long-term database. Consequently, the typical year can be composed of 12 months from up to 12 different years. This data includes DB and WB temperature, barometric pressure, and other climatic data. TMY files were used for the analysis in this paper as they represent the most typical conditions and would provide the best estimate of future trends. TRY Files- This is a Test Reference Year by selecting data from a long term database by a process of elimination wherein years that have months with extreme temperatures are eliminated until only one year remains. The final remaining year becomes the Test Reference year. After data was collated from the above data files, a cross check was performed with ASHRE data. Finally, the data was placed in a spread sheet and then a tabulation provided in the Appendix was derived. The ECDH was chosen with a lower limit of 45°F (7.2 °C). This was considered a prudent number to avoid any possibility of inlet icing. A Map of the USA provided in Appendix B, provides a pictorial depiction of the available cooling degree hours in major US cities. A detailed list of 122 cities covering all the states of the USA has been provided in Appendix C with a month by month calculation of the cooling hours (ECDH) available. If the ECDH number is used to compute MW-hr boost over the year, it is important to note that this would imply that fogging is employed whenever there is even a 1°F depression. In reality there may be a delay set in the control system to trigger the first stage of cooling and also the cooling degrees per stage, would have to be larger than the depression.

Typical stage cooling is 2-3°F.

4.1 Use of the Table

Any gas turbine operator can immediately see the potential for evaporative cooling per month in his or her location based on a long term historical database The results can be directly read off the tabulation and it is relatively easy to compute the MW-hours of capacity available by the use of evaporative fogging. In order to do this the ECDH number would be multiplied by the turbine specific MW/°F cooling number. This can be obtained from the gas turbine OEM's curves. An economic evaluation can then be developed on a month-by-month basis knowing the site-specific economic criteria. ECDH data can also be looked at more closely to account for differences in energy market values at different times of the year. For example, examination of data could provide an estimate of the revenue stream during the hot summer months alone.

V. GAS TURBINE SIMULATION

In order to put the entire situation into perspective, a GTPRO simulation was made using a Frame 7111EA gas turbine in simple cycle configuration (fueled by natural gas) as a reference plant. Salient particulars of this gas turbine are provided in Table 2. A schematic showing the thermodynamic parameters is shown in Figure 7 in Appendix A.

ENGINE MODEL	GE 7111EA
RPM	3600
Power	84920 kWe
Pressure Ratio	12.4:1
TIT	2020 F
EGT	981 F
Mass flow rate of air	646 lbs/sec
Heat Rate	10,212 BTU/kWhr
Thermal Eff	32%

Table 2. Salient features of gas turbine engine used for simulation.

The procedure used followed the following steps: [1] GTPRO was used to define the MW vs. temperature relationship for the particular engine. This was done by assuming three different wet bulb depressions of approx 35F, 21F and 6F, and then by simulating the engine output for the different wet bulb conditions using GTPRO. From this the MW/Deg F sensitivity for the engine could be determined for the different extents of cooling. (as opposed to just taking a linear relationship or utilizing a rule of thumb) In the case of the Frame 7111EA the relationship was found to be linear and so a value of 0.28MW/Deg F was used

[2] Using the tabulated ECDH data, the MW-hrs that can be augmented on a Frame 7 EA gas turbine is provided in the last column. (See tabulation of Appendix C).

VI. ECONOMIC CRITERIA FOR INLET COOLING

The specific decision to utilize inlet evaporative fogging technology is an economic one and the total project cost must be evaluated over the life cycle. Because of the varying economic situation in different parts of the country, no economic analysis is presented here. Dominating factors which should be taken into account in doing a study are:

- Climatic Profile (discussed above)
- Installed cost of the cooling system in terms of $ /incremental power increase
- Amount of power gained by means of inlet air cooling. This should take into account parasitic power used, and the effect of increased inlet pressure drop. With fogging systems, the maximum parasitic power is in 50-80 kW for larger turbines when the maximum wet bulb depression has to be derived. The inlet pressure drop is almost nil due to the configuration and design of the nozzle array.
- Fuel and demin water costs, and costs of incremental power- i.e., what benefit is attained by the power boost.
- Projected O&M costs for the system
- Environmental impact
- For cogeneration applications, the time of use electric rates and the PPA have to be carefully considered
- Potential impact on existing emission licenses

Economic analysis for inlet cooling systems may be found in In this paper, the emphasis is more on the climatological aspects as opposed to the economic analysis due to the fact that the economic conditions are very site specific in terms of a deregulating market that exists at this time in the US market.

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