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APPLICATION OF INLET FOGGING FOR POWER AUGMENTATION OF MECHANICAL DRIVE TURBINES IN THE OIL AND GAS SECTOR

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ABSTRACT

The use of inlet fogging systems to boost the power for gas turbine engines is well known and extensively applied in the power generation field. In this paper the application of inlet fogging of gas turbine engines utilized in the oil and gas sector for mechanical drive applications is covered. Extracting oil from a well is often limited by the rate of gas extraction, and consequently by the gas turbine power and efficiency. In hot and dry air climates, such as desert areas of the gulf countries, gas turbine engine power output is dramatically reduced because of the reduction in gas turbine air mass flow. This effect is even more predominant with aeroderivative units that are commonly used in this sector. Cooling the air to the wet bulb temperature, will increase the density of the air, increase the air mass flow, and boost the power and efficiency. Consequently the amount of extracted gas, and therefore oil, will be substantially increased. With such a cooling potential, and the current trend in oil prices, inlet fogging can have a very rapid payback. In this paper, the behavior of gas turbines with and without fog injection will be analyzed in detail based on actual field data. Critical parameters such as the power turbine inlet temperature, exhaust temperatures, compressor discharge pressure, the gas generator and power turbine speeds, as increasing stages of fogging are applied are covered. Furthermore, specific issues relating to the design and control of fogging as applied to aeroderivative engines will be discussed.

NOMENCLATURE

DBT = Dry Bulb Temperature
ΔT = Static Temperature Depression
ECDH = Equivalent Cooling Degrees Hours
CDP = Compressor Discharge Pressure
GG = Gas Generator
HPT = High Pressure Turbine
LP = Low Pressure
MWBT = Minimum Wet Bulb Temperature
PGF = Process Gas Flow
PT = Power Turbine
PTET = Power Turbine Entry Temperature
RH = Relative Humidity
RPM = Revolutions Per Minute
TIT = Turbine Inlet Temperature
T = Temperature
T_a = Ambient Temperature
U/C = Blade Mach Number
WBT = Wet-Bulb Temperature
WBD = Wet Bulb Depression (DBT- coincident WBT)

1.0 INTRODUCTION

Gas turbine output and efficiency are reduced during periods of high ambient temperature. On several heavy frame gas turbines, power output drops of around 20% can be experienced when ambient temperature reach 104 °F (40 °C), coupled with a heat rate increase of about 5%. Moreover, aeroderivative gas turbines exhibit even a greater sensitivity to ambient temperature. In the oil and gas, petrochemical and process industries, the reduction in output of mechanical drive gas turbines curtails plant output or thruput. The sensitivity of an aeroderivative engine compared to a typical heavy-duty engine is depicted in Figure 1.

While inlet fogging has been extensively applied in the power generation sector and much has been published regarding this, the application of fogging to mechanical drive units has received minimal attention in the literature. This paper will cover some of the special considerations relating to its application to multispool gas turbines in mechanical drive service.

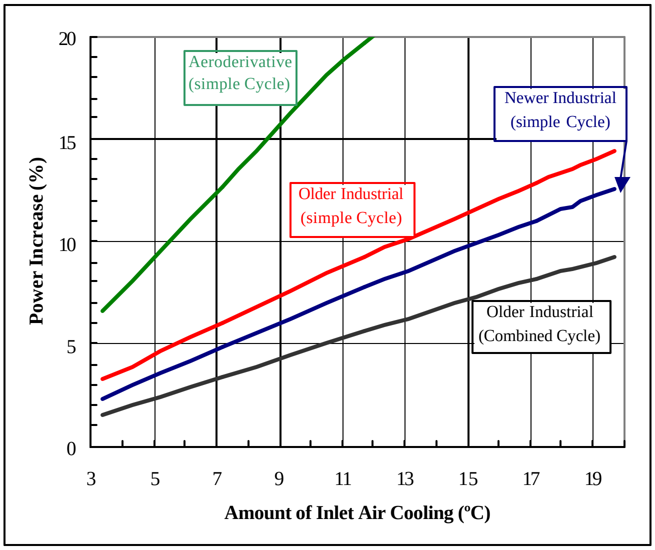

Fig 1. Power boost versus amount of inlet air-cooling

2.0 OVERVIEW OF GAS TURBINE FOGGING

Fogging is a method of inlet cooling where demineralized water is converted into fine fog droplets by means of specially designed atomizing nozzles operating at pressures between, 69 to 207 barg (approximately, 1,000 to 3,000 psig). As the fog evaporates in the intake duct, it cools the air. This technique can achieve close to 100% evaporative cooling effectiveness in terms of attaining the wet-bulb temperature at the compressor inlet under design conditions.

A typical high pressure fogging system consists of series of high pressure reciprocating pumps providing demineralized water to an array of fogging nozzles located downstream of the inlet air filter elements. High pressure water is required as droplet size is proportional, to a limit, to the (applied pressure)^{a}. Where, value of exponent 'a' varies between –0.5 to –0.2 depending on the nozzle type, nozzle geometry, liquid characteristics and droplet diameter definition. The fog nozzles create a large number of small droplets of varying size (< 50 microns in diameter), which evaporate as they flow through the gas turbine intake system. A large gas turbine can have an array of several hundred nozzles. Demineralized water is necessary to minimize the potential for compressor blade fouling and hot gas path corrosion that can result from minerals naturally present in untreated water. A typical fogging nozzle array is shown in Figure 2. A review of fogging technology may be found in Bhargava et al [1, 2] and Meher-Homji and Mee [3]. Details relating to operations and maintenance are provided in Meher-Homji and Mee [4]. Chaker et al [5, 6, 7] have provided the first detailed analysis of the subject matter specifically dealing with the physics and details of droplets, experimental studies and other relevant practical matters. More information related to this subject can be found in [8, 9, 10, 11].

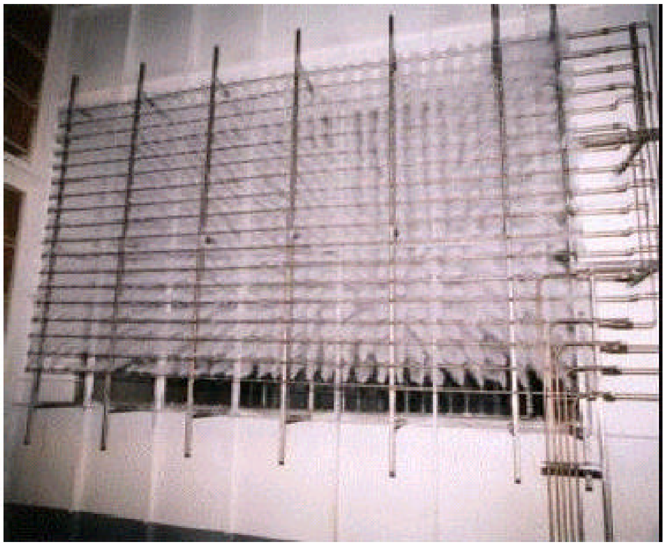

Fig 2. Fogging nozzle array showing nozzles in operation

3.0 AEROTHERMODYNAMIC CHARACTERESTICS OF MECHANICAL DRIVE TWO SHAFT GAS TURBINES.

A schematic of a typical two-shaft gas turbine is shown in Figure 3. This configuration is commonly utilized by several mechanical drive gas turbines in the oil and gas industry and include units such as the Frame 5D, and aeroderivative engines such as the LM2500+, the RB211, the Avon etc. A variation of this configuration are some of the higher pressure ratio engines on the market such as the Rolls Royce Trent and the GE LM6000 which are different in that there is no free power turbine. For example the LM6000 has a LP and HP compressor driven by a LP and HP turbine, with the power output being derived from the LP shaft.

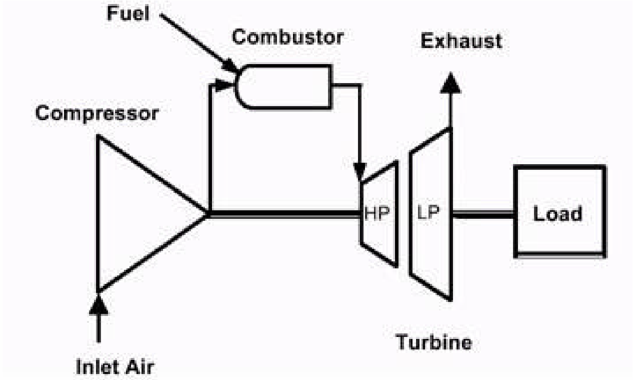

Fig 3. Typical configuration of a two shaft mechanical drive gas turbine. The HP turbine is often called the gas generator turbine while the LPT is often called the power turbine or "free turbine"

The operation of a two-shaft gas turbine is described in detail in Saravanamuttoo et al [12]. In a gas turbine engine, the operating point is defined by the match between the compressor and the turbine. In essence, a match point is simply a set of operating conditions (pressures, temperatures and flows) where the compressor and turbine can work in unison and in equilibrium. In addition, matching is based on the compatibilities of flow, work and speed. Essentially, the following compatibility conditions are required for equilibrium operation.

[a] Speed compatibility: The speeds of the compressor and driving turbine must be the same by definition. In multiple spool engines, the free spools must be in equilibrium.

[b] Mass Flow Compatibility: The flow rates must be compatible because gas turbines are continuous flow machines. Air bleeds and fuel flow must be taken into account.

[c] Power compatibility: The compressor work must match the work output of the turbine that drives it. In aeroderivative engines, the gas generator turbine drives the compressor. In the case of a 3 spool engine, the LP turbine work must match the LP compressor work while the HP turbine must much the HP compressor work. In a single shaft gas turbine, the turbine work must equal the sum of the output and the compressor work. Of course, this would have to take into account mechanical losses.

In mechanical drive split shaft gas turbines there is an optimal power turbine speed (optimal U/C ratio). Operating away from this speed will result in a loss in terms of power and efficiency. What is more, the power turbine optimal speed is a function of ambient temperature. Assuming the design is for ISO conditions, as the ambient temperature increases the power turbine optimal speed drops. If adjustment of turbine geometry is available (through variable PT inlet vanes) then the effect can be mitigated resulting in a flatter efficiency curve. It worth noting that some engines such as the Frame 5D have variable vanes between the gas generator and power turbines.

3.1 Influence of Ambient Temperature

As the density of air increases with a drop in inlet temperature, the airflow rate will be inversely proportional to the ambient temperature. In practice, the mass flow at a given rpm and inlet guide vane (IGV) setting will be proportional to the inverse of the temperature raised to an exponent between 0.5 and 1.0 based on the operating Mach number sustained by the machine. At colder temperatures, the increase in mass flow causes the power to increase. As the nozzle runs choked, the increased mass flow causes an increase in the pressure ratio of the machine assuming that the TIT was held constant. Further, the compressor specific work drops as the inlet temperature drops compared to the turbine specific work (which is essentially governed by TIT).

With aeroderivative gas turbines, the speed of the gas generator spool accelerates while the power developed by the turbine remains the same. However, the specific work of the compressor will consequently drop. Thus, the spool speed would attain equilibrium with a higher mass flow rate and pressure ratio. Usually there is a limit to the extent that power can increase with cooler inlet temperatures. This limitation can be a mechanical speed, compressor discharge pressure or excessive air inlet Mach number presence at the compressor inlet. It is important to note that because turbine blade cooling air is derived from compressor bleed, turbine blades will tend to run hotter during higher ambient temperatures. Several aeroderivative engines will actually exhibit flattening of the power versus. ambient temperature curve as colder temperatures are derived, and in some cases, the power may actually drop below a defined knee point. As a practical guide, however, the power will drop as ambient temperature increases when considering a typical range of temperature values.

3.2 Impact of Power loss in Oil and Gas Applications.

Depending on the specific application, power limits in terms of the gas turbine driver can reduce plant output. In re-injection applications for example, power limits at high ambient temperatures often result in a curtailment of production. Alternatively, the gas turbines may have to be operated in a peaking level of power (above base load operation) which has a detrimental effect on the time between overhauls. Under severe conditions, maintenance intervals can be shortened by as much as 20%. In applications where the mechanical drive gas turbine is operating a refrigeration cycle such as an LNG facility, lost production due to high ambient temperatures can be modulated by fog power augmentation.

As an example, the variation in process gas flow for a plant gas compressor driven by an aeroderivative gas turbine is shown in Figure 4. The drop in process gas flow with increasing ambient temperature (due to the loss of the driver gas turbine power) can be easily seen.

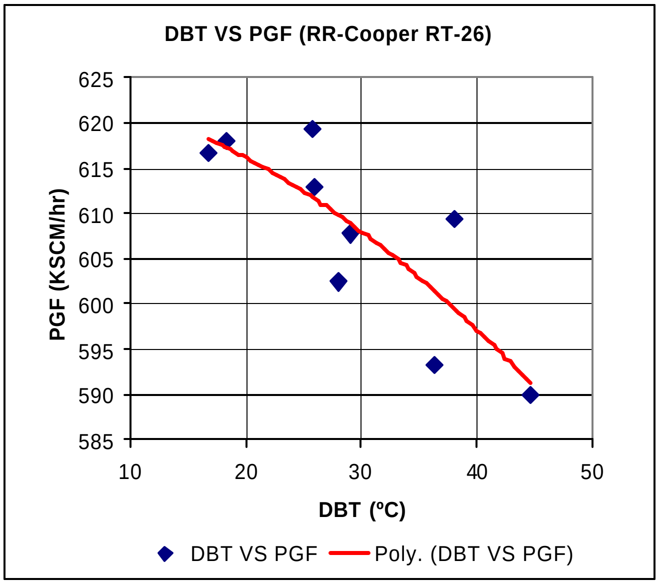

Fig 4. Variation in process flow with ambient temperature

The variation in power turbine inlet temperature (also known as jet pipe temperature) with changing ambient temperatures can be seen in Figure 5.

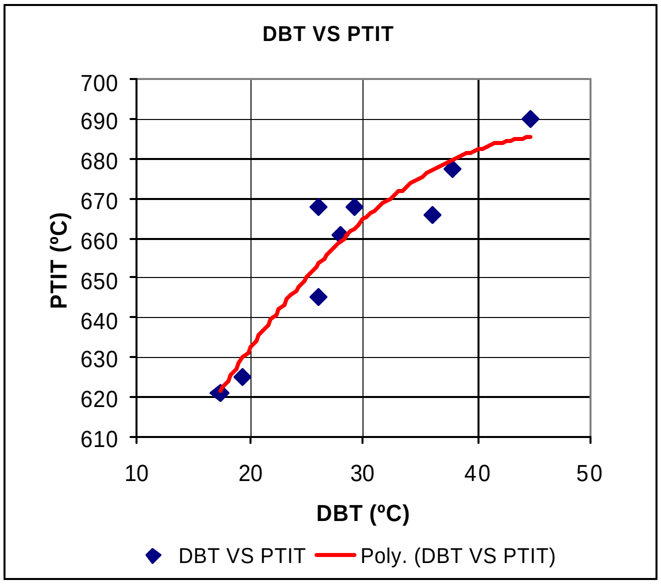

Fig 5. Variation in PTIT with ambient temperature

4.0 PRACTICAL CONSIDERATIONS

There are several practical engineering considerations which need to be addressed during the design of inlet fogging systems and are discussed below.

Foreign Object Damage (FOD): As the nozzle manifolds are mounted in the air stream, care must be taken to avoid any chance of foreign object damage resulting from the nozzles or nozzle array components themselves. Normally for evaporative fogging, nozzles are located in a low velocity area after the air filtration system. Extensive safety wiring of nozzles and analysis of the fog nozzle array for airflow-induced vibration should be done to ensure that the structure is strong and cannot break.

Gas Turbine Inlet Icing: The fog control system should automatically terminate fogging whenever there is any chance of inlet icing due to the static temperature depression that occurs in the bell-mouth due to the acceleration of the air.

Duct Drainage: This is an important subject matter and there are a lot of practical issues involved. Drains should be strategically located both near the silencers and also in the intake bell-mouth region. These should be carefully designed as continuous drains and the number of drains should be determined based on experience, configuration of the duct and obstructions that might result in water collection. Special shaped channel sections may be located on the floor and duct sections to channel water collected to the drains. Further some silencer designs can have drainage systems built into them.

Drain flow should be monitored and logged as a function of ambient conditions and the number of fog stages in operation. Figure 6 shows the proximity of the floor to the inlet of a gas turbine. In such cases, a special arrangement may have to be made to prevent pooling.

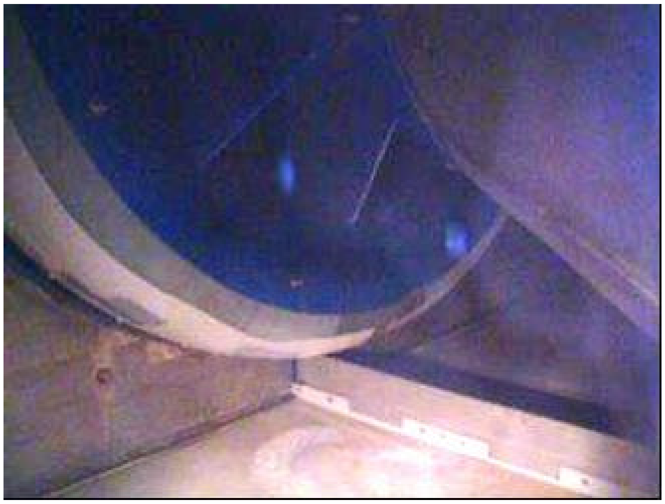

Fig 6. Proximity of the intake to the floor of a gas turbine

Compressor Surge: This is of greater concern on systems that are implemented with overspray (or fog inter-cooled). In most cases, the extent of the overspray is a little over the amount that is allowed for compressor on-line water washing. The effect of overspray is to cause the operating points on the compressor map to move towards the surge line. Also, with overspray, there is a movement of the engine operating line and surge line normally, on-line water wash rates are themselves in the range of 0.4-0.5 % on most heavy-duty gas turbines. Even with evaporative fogging, compressor inlet temperature distortion and rate of change has to be considered carefully in the design of the fogging system and the control system. The issue of surge margin must be evaluated for each specific engine type. The evaluation should also look at factors that would impact the surge margin including blade condition, and the presence of severe compressor fouling.

Compressor Intake Temperature Uniformity: Axial compressors have stringent intake temperature and pressure uniformity criteria. Issues relate to blading vibration that can be induced due to extensive distortions. Details of blading issues may be found in Meher-Homji [13]. Fogging systems are designed in multiple stages and each stage has manifolds distributed within the inlet duct to provide a relatively uniform intake temperature. This is an important consideration as the susceptibility of the compressor to stall or surge could be affected by severe temperature distortion.

The location of gas turbine compressor inlet temperature (CIT) sensors, typically do not provide a means to evaluate temperature distortion. In several engines with complicated ducts, considerable temperature and pressure distortions exist even without fogging and it is not uncommon to find temperature difference of the CIT sensors of 2°C. A common problem faced is that as the CIT sensors become wet, they tend to read lower temperatures than the bulk inlet temperature. To avoid this problem, special shielded sensors should be used.

Axial Compressor Fouling: It is important to distinguish between the problems of natural climatic fog and the fog generated by the fogging system. High natural humidity and climatic fog that often occurs during the nights and early mornings can cause high filter differential pressure trips and sometimes the heavily fouled filters tend to unload and leach contaminants through the filter causing compressor fouling. However, if the air filtration system is appropriately designed and working well, the increased humidity caused by the fogging system does not inherently increase fouling. Fouling is a situation that is so site specific that it is very difficult to predict the behavior. At times, if the No.1 bearing is leaking oil then this may combine with the high humidity (caused by inlet fogging) to create some fouling. An important issue is to wash the silencers thoroughly to avoid dirt that has been accumulated here being washed into the compressor by the fogging system during startup. This is particularly importance when fogging is being retrofitted on older machines. On retrofit applications, it may be necessary to perform several crank washes before the problem resolves. More details on compressor fouling may be found in Meher-Homji [14] and Meher-Homji et al [15].

Compressor Blade Erosion: In evaporative fogging systems the control system can be adjusted to maintain a margin between the compressor inlet temperature and the wet-bulb temperature, thus ensuring (in theory) that no water enters the compressor. Yet, it is possible that some droplets do enter the compressor. For relatively small size (less than 15-20 microns) droplet, CFD studies have shown that the flow will tend to follow the air stream. There is an issue of larger water particles forming on the trash screen and inlet cone of the gas turbine but with proper design and drainage approaches this can be minimized. It is important to note that the operational experience with overspray systems has not resulted in excessive erosion problems and several OEMs are offering this technology currently

Corrosion in the Inlet Duct: The use of demineralized water can deteriorate inlet ducts that are already in a deteriorated state- the increased humidity is clearly a corrosion factor. With proper maintenance and painting this problem can be mitigated. The use of SS 316L as the duct material is gaining in popularity as life cycle studies have indicated that while the first cost is a little higher, the life cycle costs are significantly lower.

Electrostatic Build-up and Bearing Distress with Overspray: Similar to the electrostatic charges that occur in the LP section of a steam turbine where condensed particles induce an electrostatic charge, machines that are operated with wet compression need to have superior shaft grounding brush systems utilized. Several installations have used Sohre [16] Turbomachinery grounding brush systems very successfully.

Multi-spool Gas Turbines for Mechanical Drive or Power Generation Service: In the case of multi-spool gas turbine such as commonly found in mechanical drive service, the changes in the gas generator speed result in modified airflow through the machine. It is important, therefore, that this be taken into account during the fogging system design to ensure that the injected water is appropriate with respect to the gas turbine airflow. If two-shaft gas turbines are used for power generation applications as is commonly done in the case of aeroderivative gas turbines, the same considerations should apply.

5.0 SITE CLIMATIC CONDITIONS

The underlying reason for the applicability of inlet fogging in varied climatic conditions is the inverse relationship that exists between the dry bulb temperature and the relative humidity. Even in so-called "high humidity" regions, the relative humidity drops as the dry bulb temperature increases. Figure 7 shows the relationship of data from the site under consideration in the United Arabic Emirates (UAE). Table 1 provides an idea of the hours that are available at different wet bulb depressions. For example, at this site, there are 1375 hours a year when cooling of between 18 and 24°C is possible. The table also provides the equivalent cooling degree hours in °C-hrs.

WBD (°C)	**0-6**	**6-12**	**12-18**	**18-24**	**>24**
Occurrence (Hours)	1685	2424	2098	1375	207
ECDH (°C-hr)	6415	21763	30611	28217	5169

Table 1. Occurrence in hours and ECDH for ranges of Wet Bulb Depressions.

At this site, temperatures have been known to have peaked at 52°C.

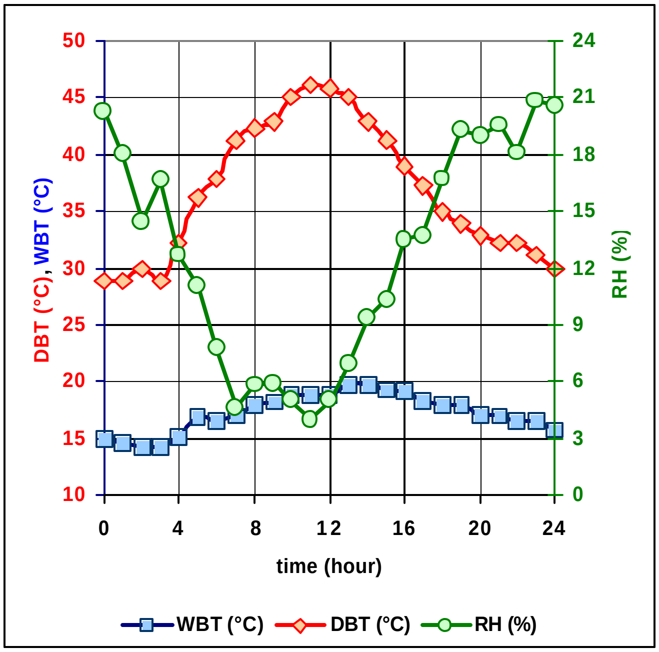

Fig 7. Variation of Dry Bulb Temperature, Wet Bulb Temperature, and Relative Humidity during the course of 22 of May 2002. It can be seen that there is a significant cooling potential (between 13°C -25°C)

The relationship between the dry bulb temperature and wet bulb temperature averaged over the year is shown in Figure 8. In examining the minimum wet bulb temperature, the deviation from the wet bulb temperature as the dry bulb temperatures increase is visible. This graph shows that cooling potentials of approximately 25°C are available.

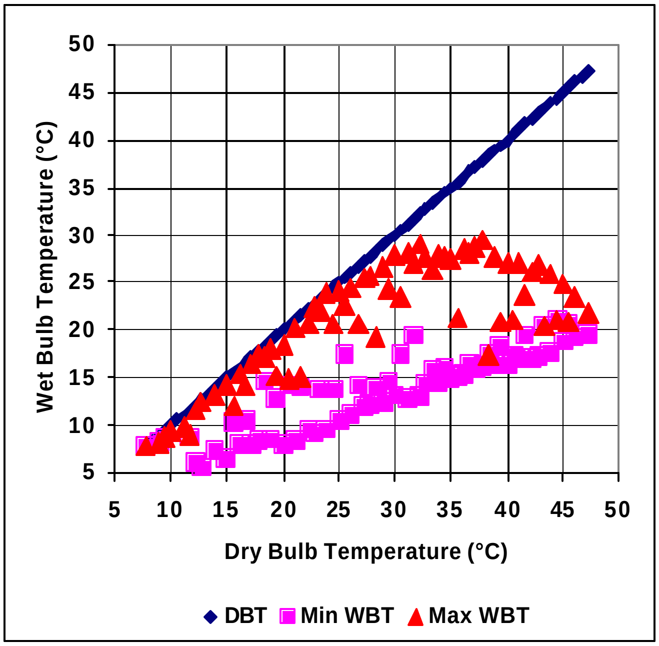

Fig 8. Relationship between Dry Bulb Temp (DBT) and Wet Bulb Temperature (WBT)

The equivalent cooling degree hours available for the 12 months of the year is shown in Figure 9. The individual bars in the bar chart are also split up to show different ranges of wet bulb depressions available. The cumulative ECDH is also shown on the graph. In this graph, the minimum wet bulb temperature has been taken at 12.8°C.

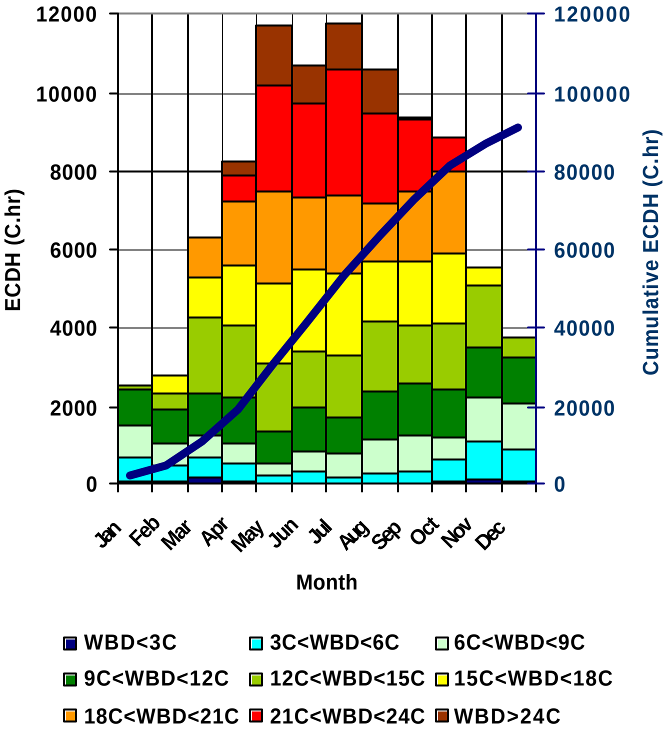

Fig 9. Representation of Equivalent Cooling Degree Hours over a period of 12 months of the year

A detailed description of climatic aspects as they relate to the fogging of gas turbine engines has been provided by Al-Amiri and Zamzam [17] and Chaker and Meher-Homji [18]

6.0 PERFORMANCE WITH FOGGING ON AERODERIVATIVE GAS TURBINES

Data is now presented from two types of turbines in mechanical drive service driving re-injection compressors. The first turbine is a two shaft aeroderivative, and the second is a three spool aeroderivative engine. Key operating parameters as additional stages of fogging are added are shown in Table 2. In this table, the cooling metric is provided in % and represents the amount of cooling attained divided by the available wet bulb depression. Similarly, the water flow metric is provided in % and shows the actual flow divided by the theoretical water flow that would attain wet bulb conditions. The table also shows the power turbine inlet temperature and the axial compressor discharge pressure. The effect of the fogging on the GG inlet temperature and GG and PT speeds is shown in Table 3, for 3 identical gas turbines installed in the same site. The drop in GG speed as the compressor inlet temperature drops due to fogging can be clearly seen. The impact of fogging on the load compressor process flow and other inlet air temperature is shown graphically in Figure 10.

Turbine 1	Turbine 1		
Ambient Temperature (C)	42.5	42.9	43.3
Relative Humidity (%)	24.1	22	18.1
Wet Bulb Temperature (C)	25.2	24.8	23.3
Wet Bulb Depression (C)	17.3	18.1	20
Compressor Inlet Temperature (C)	52	45	38
Number of operating stages/Temperature (C)	0	8	10
Cooling Metric		88.4	100
total injected water from flow meter (lpm)	0	29.1	36.3
Amount of water to reach saturation (lpm)	34.5	36.0	38.6
Flow Metric	0.0	80.9	94.0
Compressor Outlet Pressure (PSI)	204	206	206
Turbine Inlet Temperature (C)	850	793	778
Turbine Exhaust Temperature (C)	566	531	515

Table 2. Performance effects as fogging is added

	Turbine 1			Turbine 2			Turbine 3		
	Before	After	Diff.	Before	After	Diff.	Before	After	Diff.
GG Inlet Air Temperature (C)	52	36	16	51	31	20	44	25	19
PT Inlet Temperature (C)	837	777	60	840	830	10	753	688	65
GG Speed (rpm)	9161	8905	256	9303	9135	168	8963	8758	205
PT Speed (rpm)	5716	5727	-11	5728	5790	-62	5702	5709	-7

Table 3. Change in turbine operating parameters as fogging is applied

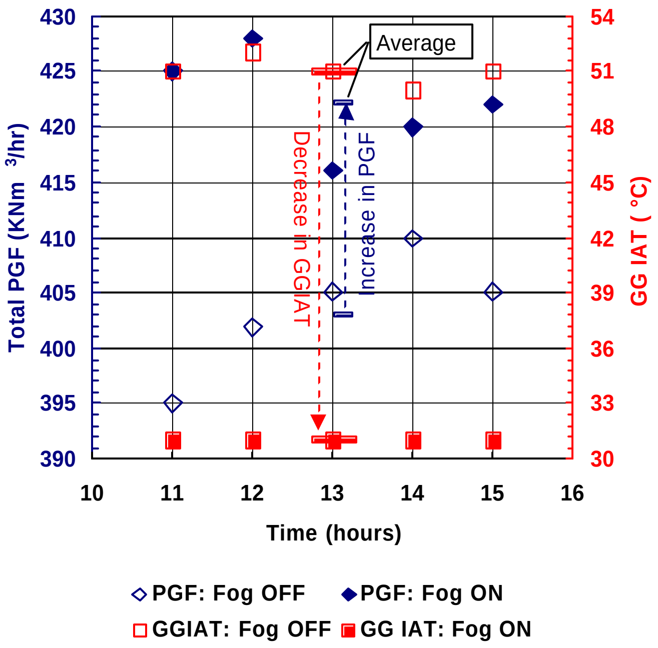

Fig 10. **Graphical results of increase in process gas flow rate (PGF) as fogging is applied. Data over 4 hours**

A graphical representation of the changes in GG speed and PT speed as fogging is applied is shown in Figure 11.

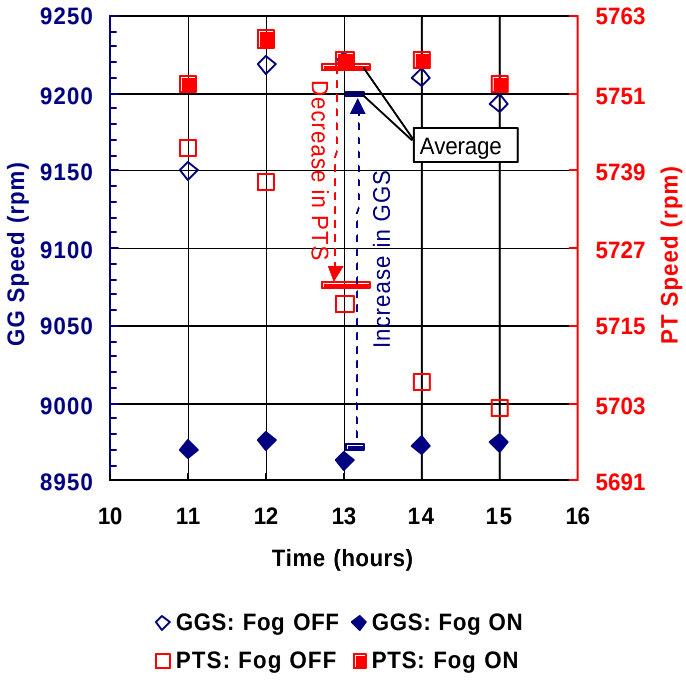

Fig 11. Representation of behavior of GG and PT Speed with and without fogging. Data over 4 hours

A graphical representation of the change in parameters over ten minutes as successive fog stages are deployed is shown in Figure 12. As can be seen in this figure, as the fogging is increased (moving from left to right), the compressor inlet temperature drops from an initial value of 52°C to36°C, representing a 16°C drop.

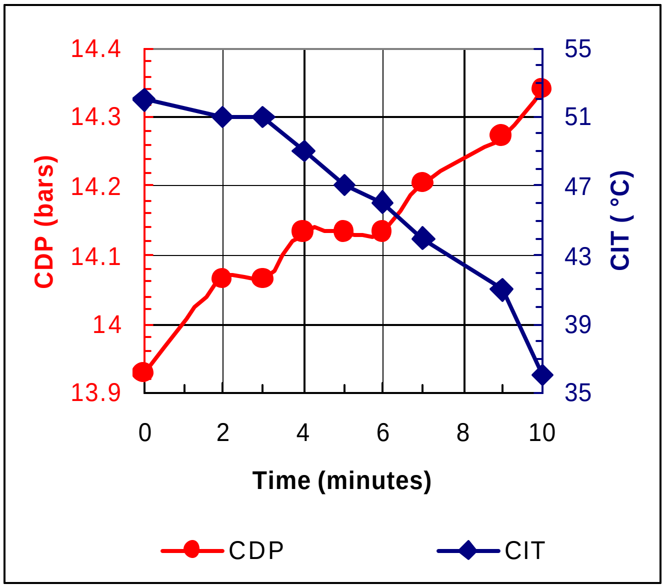

Fig 12. Variation of Compressor discharge Pressure (CDP) and Compressor inlet temperature (CIT) as fog stages are deployed over 10 minutes

The variation of the GG speed and Power turbine speed as fog stages are deployed is shown in Figure 13. The GG speed steadily drops, and the power turbine speed increases initially as more power is developed and finally settles as the control system set point matches the desired flow rate.

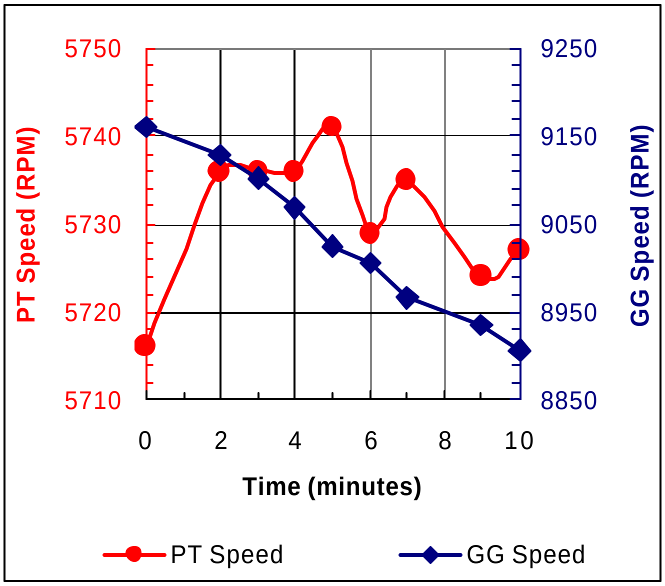

Fig 13.Variation of GG and PT speed as fog stages are deployed over 10 minutes.

The drop in the power turbine entry temperature and corresponding drop in the exhaust temperature as fogging stages are deployed are shown in Figure 14. As the mass flow through the machine increases, this allows for a backing off in firing temperature.

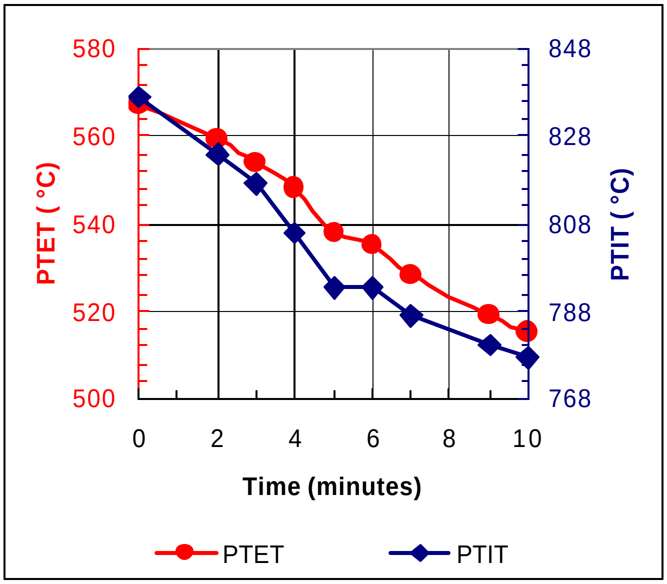

Fig 14. Variation of Power turbine inlet temperature (PTIT) and Power turbine exit temperature (PTET) as fog stages are deployed over 10 minutes. Note that the temperature scales are not the same

The behavior of a different aeroderivative engine (two compressor shafts and a free power turbine) as fog stages are turned off, are depicted in Figures 15 and 16. Figure 15 shows that the compressor discharges pressure (CDP) and the PT speed start to drop as the fog is turned off (and ambient temperature starts to go up. The corresponding growth of ambient temperature is shown in Figure 16. The time scale on the abscissa for these two graphs is the same i.e., 10 minutes.

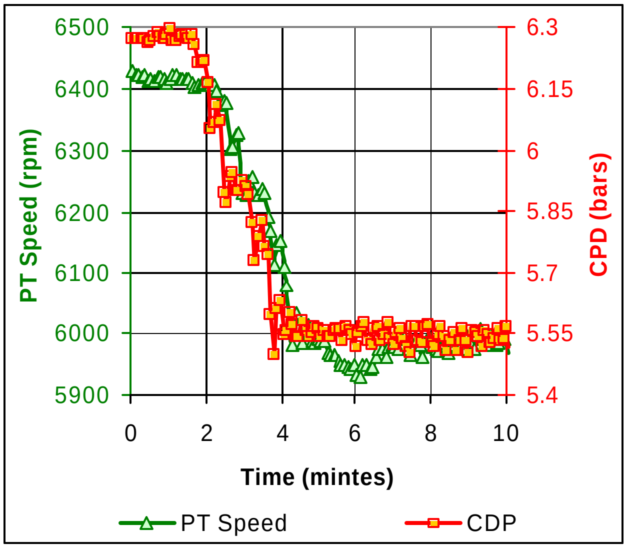

Fig 15. Measured decay in power turbine speed and compressor discharge pressure (LPC) as fog stages are sequentially turned off over 10 minutes

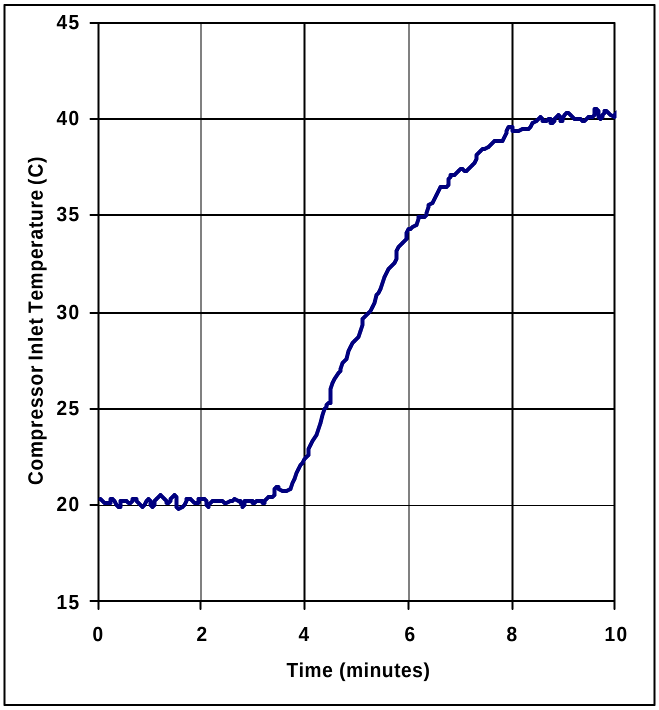

Fig 16. Measured growth in compressor inlet temperature measured at the bellmouth as fog stages are sequentially turned off over 10 minutes

7.0 CONCLUSIONS

The applicability of inlet fogging to mechanical drive gas turbines is discussed in this paper. Most mechanical drive applications are power limited during the hot afternoons or during the hot ambient temperatures. Inlet fogging can be applied as a retrofit to alleviate this situation. There are several aspects related to the fogging of multishaft gas turbines. For example the control of the fogging system must have some ability to modulate water flow as a function of axial compressor airflow. The paper has provided results of some applications where fogging has been applied to mechanical drive turbines. It is important that the practical aspects of the installation also be considered for a successful installation.

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