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MeeFog TECHNICAL APPLICATION NOTE AN-GT-240

Understanding and Evaluating High Pressure Fogging Systems for Gas Turbine Inlet Cooling

AN-GT- 240

APPLICATION NOTE: AN-GT-240

Date: March 05, 2002, Rev: 03

1. INTRODUCTION

The object of this application note is to examine factors that should be considered during the evaluation of fogging system proposals or when writing specifications and Request for Quotations for inlet fogging systems. The information given here is based on decades of application experience and on lessons learned from 496 MeeFog GT inlet fogging installations to date totaling over 38,000 MW of power.

2. FOGGING SYSTEM EVALUATION CRITERIA

There are several important criteria that should be considered when evaluating a fogging system design in order to ensure that the system will perform as intended and mitigate risk to the gas turbine.

Criteria may be classified in the following categories:

1. Technological Criteria

    - Overall Design Philosophy
    - Fogging Nozzle Technology
    - High-pressure Pump Systems
    - Control Systems & Software
    - Nozzle Manifolds and High-pressure Tubing
    - Quality Control and Testing

2. Commercial Criteria
    - Experience of the Fog System Supplier with Gas Turbine Technology and inlet fogging installations
    - Customer satisfaction track record
    - Turnkey project experience
    - Power augmentation guarantees
    - First cost and operating costs

These issues are discussed in detail below.

3. FOGGING SYSTEM DESIGN PHILOSOPHY

3.1 Climatic Data Analysis

The climatic data available for a particular site is often incomplete and misleading. An experienced fog system supplier will understand how to use the available data to design an optimum system for a particular site.

A common problem is caused by the fact that climatic data often includes the maximum (or average maximum) dry bulb temperature and humidity. Inexperienced engineers sometimes assume that these conditions occur at the same time, but these data points do not generally represent time-coincident data. Typically, the highest humidity occurs during cooler weather conditions and the lowest humidity coincides with the highest dry bulb temperature. In other words, total moisture content is fairly stable for a given season at a given site. Relative humidity is moisture content *relative* to the moisture holding capacity of air. The hotter the air, the more moisture it can hold. Hence, a low relative humidity at a high temperature and a high relative humidity at a low temperature could represent exactly the same absolute moisture content.

Obviously, a design based on the above misconception will result in a Fog system that is not capable of taking advantage of the full evaporative cooling potential for the site.

Mee Industries has detailed climatic information for thousands of sites around the world as well as practical experience in every major climate zone. Mee Industries has also developed proprietary software that can be used to calculate total evaporative-cooling-degree-hours for a site. This information allows the turbine operator to make detailed payback analyses, since it gives hour-by-hour information of the power boost that can be expected at the given site. It also helps the fog system engineer to decide the cooling capacity for which the system should be designed.

3.2 Failure Modes and Criticality Analysis

Any fog system design should be backed up with a detailed Failure Mode and Criticality Analysis (FMECA)[1]. Such an analysis is critical to ensure the safe and effective operation for a system working in conjunction with an expensive gas turbine. Generally, a fog system is a non-critical component in a power plant. The non-availability of a fog system only results in a loss of the incremental power gain. However, since the possibility of damage to a turbine may exist, sound engineering practice dictates that a detailed FMECA be provided. In fact, a review of the various suppliers' FMECAs may be one of the best ways to gain an understanding of the quality of engineering, the depth of experience and the reliability of the proposed designs.

3.3 High-Pressure Pump Skid Design

The pump skid design should be carefully evaluated to ensure that the vendor has adequate experience with the proposed design. Common engineering practice warns against the implementation of complex and untested designs and approaches. One example of this is complex staging arrangements that use many different sizes of pumps and result in the excessive spare inventory.

It is also important to select pump systems that are suitable and reliable for the expected operating conditions. End users should be wary of solutions that utilize high-speed pumps. While this may reduce initial costs, wear and maintenance may be much more severe. Experience at Mee Industries indicates that it is best to keep pump speeds to less than 600 rpm. This ensures long seal life and greatly reduces maintenance problems that arise from the excessive vibrations associated with high speed reciprocating equipment.

3.4 Nozzle Manifold Location and Duct Drainage

One of the most important design factors with inlet-air-fogging systems is the location of nozzle manifolds to avoid excessive water fallout. The location and functionality of duct drains is also critical. This is an area of design where there is no substitute for experience. Inlet fogging systems generate many billions of droplets per second and evaporation and fallout depend on many complex and time variant factors (air temperature, water temperature, humidity, diffusion, droplet dynamics and dispersion,

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[1] see Mee Industries' Application note AN-GT-205

obstructions in the ducts, etc.). Attempts to model such a complex system without being able to refer back to real-world experience are doomed to failure.

Mee Industries has an ongoing research program directed by Dr. M. Chaker, to develop software that will effectively and accurately model fog behavior in inlet air ducts. The current version of this software incorporates Computation Fluid Dynamic (CFD) software with calculations for droplet evaporation rates modified by empirical data collected in a wind tunnel constructed at Mee's R&D lab and with data collected at more than 400 gas turbine inlet fogging installations around the world. With this software, Mee's scientists can perform a detailed study to examine and optimize the location of the nozzles based on the behavior of the fog flow. The software includes the ability to model silencers and trash screens and other features of the inlet-air path as shown in Figure 1.

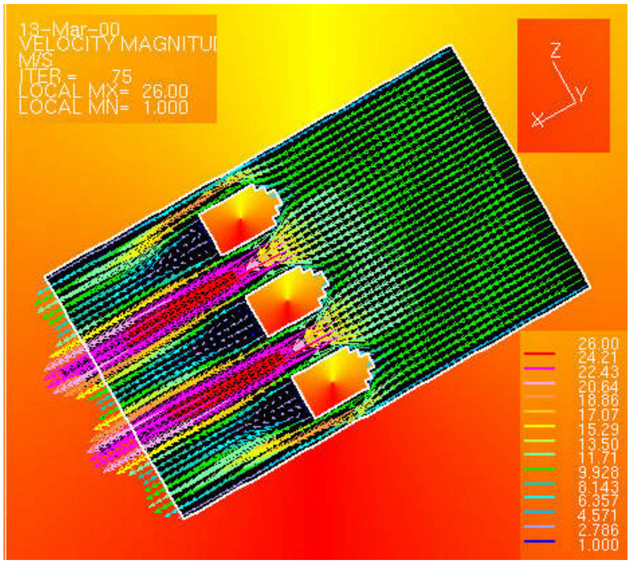

Figure 1. CFD Model of Silencer Section in Gas Turbine Inlet Duct to Evaluate Fog Droplet Trajectory.

Mee Industries also has the capability to experimentally test certain special configurations its in-house wind tunnel. The wind tunnel has a thirty-five foot long duct section that includes a 90-degree bend, is fully instrumented for temperature, humidity and pressure readings, and can operate at air stream velocities of up to 4000 feet per minute. It incorporates a Laser Particle Analysis system for measuring fog droplet sizes.

A good fog nozzle manifold and duct drainage design will include nozzle manifolds located so as to optimize evaporation time and minimize the possibility of fallout when the fog comes into contact with obstructions in the duct. Drains must be designed for continuous operation and must be located and sized so as to remove any accumulated water.

3.5 Estimating and Modeling Power and Efficiency Gains

Inlet fogging systems are installed to affect output and efficiency gains on the gas turbine. The system supplier should have the capability to provide a detailed parametric simulation of the gas turbine and associated equipment so that the effect of fogging (either evaporative cooling or overspray fogging) can be properly estimated. Furthermore, there may be factors which limit the power augmentation available from inlet fogging that are inherent to the specific design of the gas turbine or balance-of-plant equipment. A thorough analysis of the turbine and other equipment, such as the lube-oil, generator and transformer cooling systems, must be performed in order to understand the true capacity improvement available from inlet fogging. Combined cycle plants also need to be studied in detail to understand what impact inlet fogging will have on the bottoming cycle.

Mee Industries has the required modeling tools and an engineering team that is experienced with gas turbines and power plants and can perform detailed parametric simulations of the systems under consideration. A typical analysis of a large combined cycle power plant is provided below. Such analyses are vital engineering tools that allow the turbine operator to select the fog system design that is best suited for their plant configuration, climate and economic situations.

GTPRO SIMULATION RUN FOR LARGE CCPP

Mee Industries Inc, Gas Turbine Division

Date: April 11th, 2001

Project: xxxxxxxxx CCPP

NOTES:
[1] This analysis is intended for information only and does not constitute a guarantee of fog system performance.
[2] Design is for 8 Blocks of GT+ST+HRSG// GT-ST- Single shaft configuration
[3] Gas Turbine Parameters are for each gas turbine
[4] Gas Turbine Model GE Frame 9FA, TIT= 1288°C
[5] OS percentage, relates to water as a % of air mass flow rate
[6] Natural gas fuel.

CASE 1= 33.5C ambient, No fogging
CASE 2 = 33.5C ambient, Fogging to WBT 27C
CASE 3 = 33.5 C ambient, Fogging to WBT 27C + 0.4% Overspray
CASE 4 = 33.5 C ambient, Fogging to WBT 27C + 0.5% Overspray

	Base case	**Fogging**	**Fog+0.4OS**	**Fog +0.5OS**
OVERALL CCPP BLOCK PERFORMANCE	Case 1	Case 2	Case 3	Case 4
Computation Result, Thermoflow - STQUIK	OK	OK	OK	OK
Ambient pressure [bar]	1.013	1.013	1.013	1.013
Ambient temperature [C]	33.5	33.5	33.5	33.5
Ambient Relative Humidity [%]	62	62	62	62
Plant gross output [kW]	2,420,512	2,507,572	2,572,830	2,589,188
Plant net output [kW]	2,360,157	2,445,433	2,509,676	2,525,778
Gross LHV heat rate [kJ/kWh]	6,729	6,722	6,724	6,724
Net LHV heat rate [kJ/kWh]	6,901	6,893	6,893	6,893
Plant gross elec eff [%]	53.5	53.55	53.54	53.54
Plant net elec eff [%]	52.16	52.23	52.23	52.23
GT fuel HHV/LHV ratio	1.11	1.11	1.11	1.11
GAS TURBINE PARAMETERS	Case 1	Case 2	Case 3	Case 4
Computation Result, Thermoflow - STQUIK	OK	OK	OK	OK
GT shaft power [kW]	195,694	205,490	213,191	215,123
GT shaft LHV eff [%]	34.6	35.11	35.49	35.59
GT shaft heat rate [kJ/kWh]	10,404	10,254	10,143	10,116
Compressor inlet massflow [kg/s]	553.1	566.4	566.4	566.4
Compressor inlet temperature [C]	33.5	27.09	27.09	27.09
Turbine inlet massflow [kg/s]	500	512.1	514.4	515
Turbine inlet temperature [C]	1282.6	1282.6	1282.7	1282.7
Turbine exhaust massflow [kg/s]	564.4	578.1	580.7	581.4
Turbine exhaust temperature [C]	613.8	608.4	607.2	606.8
GT fuel HHV input [kWth]	627569	649460	666503	670770
GT fuel LHV input [kWth]	565574	585303	600662	604508
Exhaust gas molecular weight	28.18	28.13	28.06	28.04
Exhaust gas N2+Ar mole percentage [%]	73.83	73.49	72.98	72.85
Exhaust gas O2 mole percentage [%]	12.54	12.39	12.12	12.05
	Base case	**Fogging**	**Fog+0.4OS**	**Fog +0.5OS**
Exhaust gas CO2 mole percentage [%]				
Exhaust gas H2O mole percentage [%]	10.09	10.54	11.26	11.44
GT fuel flow [kg/s]	11.3	11.69	12	12.08
Combustor steam injection [kg/s]	0	0	0	0
Combustor water injection [kg/s]	0	0	0	0
Inlet filter pressure loss [millibar]	10	10	10	10
Total exhaust pressure loss [millibar]	29.98	29.98	29.98	29.98
FOGGING STATUS	NONE	ON	ON + OS	ON +OS
STEAM TURBINE PARAMETERS	Case 1	Case 2	Case 3	Case 4
Computation Result, Thermoflow - STQUIK	OK	OK	OK	OK
Gas temperature reaching HRSG [C]	612.7	607.3	606	605.7
Stack temperature [C]	126.8	128.2	128.5	128.6
Stack massflow [kg/s]	4515	4625	4646	4651
ST shaft power [kW]	883525	893199	897618	898715
Steam cycle gross eff [%]	30.06	29.88	29.84	29.83
HRSG eff [%]	84.07	83.69	83.6	83.58
Total duct burner fuel flow [kg/s]	0	0	0	0
Fuel HHV to duct burner(s) [kWth]	0	0	0	0
Fuel LHV to duct burner(s) [kWth]	0	0	0	0

Mee Industries can also provide aerothermal parameters within the gas turbine to provide users an in-depth analysis of the effect of fogging on the gas turbine operating cycle.

3.6 Fog System Performance Guarantees

It is highly impractical to accurately measure conditions after the inlet fogging system, i.e. at the compressor bell mouth of the gas turbine. Therefore, the only practical performance guarantee is a guarantee of the output of the turbine itself. An experienced fog system supplier will be able and willing to offer a guarantee of power boost from the inlet fogging system.

3.7 Experience with Turnkey Projects

Some gas turbine operators opt for a turnkey project contract when considering inlet-fogging systems. This strategy makes sense as single-point responsibility guarantees the smoothest possible project execution without a lot of complicated negotiations and finger pointing. In the case of turnkey projects, the selected supplier should be able to demonstrate that they have experience with the type of project under consideration. When the supplier is expected to work in an international location, it is important that they have experience with local conditions including business and workforce customs, climate and storage consideration, and knowledge of local availability of material.

Mee Industries has conducted many successful turnkey projects both in the US and other countries. Mee Industries can also provide supervision for the erection (with the plant providing the labor) or if needed, contract with local labor suppliers.

3.8 Fogging Nozzle Technology

The fogging nozzle is the heart of the inlet fogging system and great care should be taken when evaluating different fog nozzles. The fact that no standardized testing procedure exists makes the task somewhat difficult but several fundamental factors can be considered.

The ideal fog nozzle and nozzle arrangement will produce very small fog droplets at low energy consumption and will distribute the droplets evenly in the inlet air stream. The importance of having small droplets cannot be overstated. Small droplets that evaporate faster are less likely to fallout or impact on obstructions in the inlet duct and will not cause compressor damage.

Given the necessity for small fog droplets, and the fact that small droplets follow the flow lines of the inlet air, logic dictates that there must be a relatively large number of fog nozzles installed in the inlet duct. With a few nozzles, large sections of the inlet air stream will be left unfogged. This can have a substantial impact on the overall efficiency of the fog system because if the fog droplets are in concentrated streams, surrounded by untreated air, they will not be able to evaporate before they reach the compressor inlet. The fact that some of the air is cooled and some is not cooled can result in temperature and density stratification and in larger droplets entering the compressor. Fog system efficiency is affected even when we account for the intercooling effect of the ingested droplets because a given mass of water evaporated in the compressor will yield only about half the power boost as it would if it were evaporated in the inlet duct.

Users should be wary of arguments that having fewer nozzles represents a better design. If fewer nozzles are to generate the same flow rate of fog water, than they must individually have higher flow rates. Flow rate and droplet size are directly related to nozzle pressure. At a given operating pressure, if a nozzle is to have a higher flow rate it must have a larger orifice and if it has a larger orifice it will make larger droplets. In the absence of the introduction of some new art to the subject of water atomization for inlet fogging systems, a greater number nozzles in the inlet duct is necessary and beneficial.

3.9 Fog Droplet Sizes

This is an area where much misinformation exists, and where several unsubstantiated claims are often made. At this date, Mee Industries is the only inlet fogging company that actually manufactures their own nozzles in-house. The growing popularity of gas turbine inlet air fogging have made it important to develop a standard for measuring droplet sizes generated by fog systems. Without such a standard, gas turbine operators cannot make informed comparisons of different systems. Fog system manufacturers make various claims based on different testing methods. The result is contradictory information that makes it impossible to make an informed decision as to the relative benefits of competing systems.

The extent of misinformation has prompted Mee Industries to set the Industry Standard for measurement of droplet sizes for Gas Turbine Fogging Applications. A detailed three-part ASME technical paper has been written by Chaker et al of Mee Industries that proposes an Industry Standard. This paper provides actual tests of the various nozzles that are currently being offered for inlet fogging and a full analytical and statistical treatment of the subject. Tests have shown the superiority of the MeeFog Nozzle for gas turbine inlet air fogging.

3.10 Two Types of Fog Nozzles

Two basic types of fog nozzles are used for inlet air fogging; impaction-pin nozzles and swirl-jet nozzles. Both operate on the same general principle; water pressure is converted to velocity when the water is forced through a small orifice. The high velocity water jet is then converted to a conical sheet of water. When the expanding conical sheet becomes too thin it breaks up into small filaments of water and eventually into droplets.

Impaction pin nozzles consist of a smooth, straight-through orifice with an impaction pin located above the orifice. When the water jet hits the impaction pin it is separated into a conical shaped sheet of water. A swirl jet type nozzle has an internal swirl chamber through which liquid flow is directed. The water is forced tangentially out of the exit orifice in a hollow cone pattern. Thus both nozzles form a similar conical sheet but, for a given water pressure and surface tension, impaction-pin nozzles always make smaller droplets than swirl-jet nozzles. This is due to the frictional losses in the internal swirl chamber. In other words, the swirl-jet nozzle uses more energy to form the hollow cone and, therefore, has less energy available for droplet formation. The internal restriction to flow is manifested by the fact that a swirl-jet nozzle always has a lower flow rate than an impaction-pin nozzle with the same orifice size operating at the same pressure. The comparative flow rates and droplet sizes for the two nozzles types at different pressures are shown in the chart below (Figure 2).

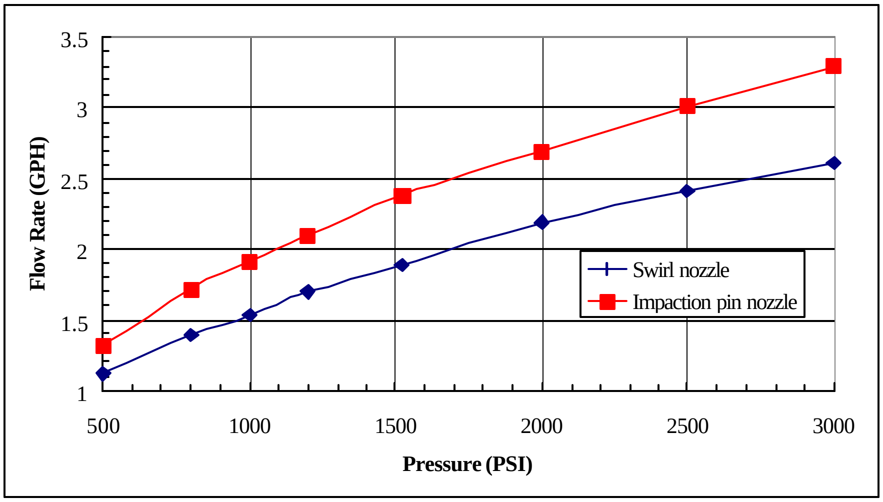

Figure 2. Experimental test data comparing swirl-jet and impaction-nozzles: Swirl jet nozzles with the same orifice size and operating pressure will always produce larger droplets than impaction pin nozzles, as they are less efficient at turning pressure into velocity.

Literature published by various manufacturers of fog systems often indicates that swirl jet nozzles produce droplets as small as or even smaller than impaction-pin nozzles. This seeming inconsistency is due to the fact that there is no standardized method applied to determine the average droplet size of fogging nozzles. Effective evaluation of inlet fogging proposals demands some understanding of droplet-sizing technology. The fact that no standardized method is universally applied makes it difficult to compare droplet size claims from different manufacturers. Differences in the sample location within the nozzle plume can result in different average droplet diameters, even when the same instrument is used for droplet sizing. Statements about droplet size, without a solid analytical description of how the samples were taken and what statistical technique is used are meaningless.

3.11 Measuring and Defining Droplet Sizes and Size Distribution

Direct-pressure water atomization nozzles emit a wide range of droplet sizes. In order to get an accurate representation of droplet sizes, measurements must be taken across the entire spray plume, so that all of the spray is taken into account. Droplets found inside the hollow spray plume are usually the smallest droplets, while the larger droplets are found in the edges of the conical spray plume. This is due to the fact that the smallest droplets can migrate into the center of the spray plume while the momentum of the larger droplets ensures that they remain at the edges. Well over 90% of the mass flow of atomized water occurs at the edges of the spray plume. Obviously, ignoring the bulk of the mass flow will result in incorrect measurements. Furthermore, when sizing droplets, failure to measure a droplet with a diameter of 10 microns is the same as ignoring 1000 droplets of one-micron diameter. Therefore, a measurement technique can fail to detect a relatively large number of *small* droplets without significantly affecting the volume distribution. Conversely, the distribution is drastically altered if one ignores *even a relatively small number of large diameter droplets*. Consequently, droplet tests that measure only smaller droplets will result in average diameter numbers which are highly misleading.

Scientists at Mee Industries have developed a testing method that consists of taking many measurements across the entire spray plume and weighting the results based on the measured percentage of water mass flow in the sample volume of each test. Once droplet size data has been correctly collected, it is important to apply a meaningful statistical method to describe the range of droplets measured. The spray generated by direct-pressure water-atomizing nozzle includes a fairly wide range of sizes of water droplets. There are many statistical methods used for characterizing the average droplet size and size distribution in a given spray. When selecting which spray characterization method to use, it is important to take into account the process to which the fog will be applied. For instance, a characterization method that includes droplet surface area might be most helpful when the process under consideration involves evaporation, while a method based only on diameter might be better for some other process. When considering the various methods for spray characterization it's often helpful to keep in mind that these methods generally refer to a fictitious droplet diameter. For example, the arithmetic average of the diameters of 100 measured droplets might be 12-microns but there may not have been any 12-micron droplets in the measured sample.

There are many mathematical methods used for expressing the average droplet size in a given spray. These approaches are referred to as *characterizing* the spray. One could, for instance, look at the arithmetic average of droplet diameters or of surface area or of volume. For processes that involve evaporation it is helpful to use a characterization method that deals with surface area of the measured droplets. Sauter Mean Diameter (SMD) is one such method. SMD is a number that expresses the average droplet size in terms of the average ratio of volume to surface area of all the measured droplets. Since it deals with surface area, SMD is a good way to describe a spray that is to be used for processes involving evaporation. SMD is defined as the diameter of a hypothetical droplet whose ratio of volume-to-surface-area is equal to the volume-to-surface-area ratio of the entire spray.

Another helpful characterization method is Dv90. As an example, a Dv90 of 30 microns implies that 90% of the mass flow of the spray plume occurs in droplets that are 30 microns and smaller. (When discussing atomization of demineralized water, the terms "volume" and "mass" can be considered interchangeable because the specific gravity of water is constant.) This characterization method is helpful for calculations that involve droplet fallout, agglomeration and impaction on duct obstructions and compressor blading.

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Figure 3. Laser Droplet Measurements being made at Mee Industries R&D laboratories.

In summary, small droplets are critical because they evaporate faster (which ensures high efficiency of the fog system) and are less likely to agglomerate, fallout or impact on duct structures and compressor blading. Comparing droplet size claims from different sources is generally meaningless because different measurement techniques result in very different numbers. Mee Industries can provide test data for essentially all types of nozzles that are currently being offered for inlet fogging. There is no “black magic” involved in water atomization. Nozzles of a particular type and orifice size, operating at a known pressure will produce droplets in a predictable size range. Claims to the contrary are false and are either intended to mislead or a based on bad science.

3.12 Evaluating Droplet Evaporation Time

Over the past several years, Mee Industries has performed extensive theoretical and experimental tests to determine the duration required for droplet evaporation in inlet ducts and the percentage of water that can be expected to fallout with different configurations of inlet ducts and nozzle manifolds. The evaporation process involves the interaction of many billions of fog droplets with the inlet air, with each other and with the duct structures. As droplets evaporate they become smaller, which changes the surface area of the entire spray. As the droplet progresses down the duct, the humidity is constantly increasing and the air temperature is constantly deceasing. A single MeeFog nozzle, operating at 2000 psi (141 bar), generates about five billion droplets *per second*. Needless to say, this is a very complex process that, without the benefit of empirical data, is essentially impossible to model analytically.

As mentioned above, Mee’s R&D scientists have coupled analytical models for droplet evaporation with CFD software and empirical data collected from a test rig (wind tunnel) and from actual inlet fogging installations. The results of one such analysis are given in the following figure.

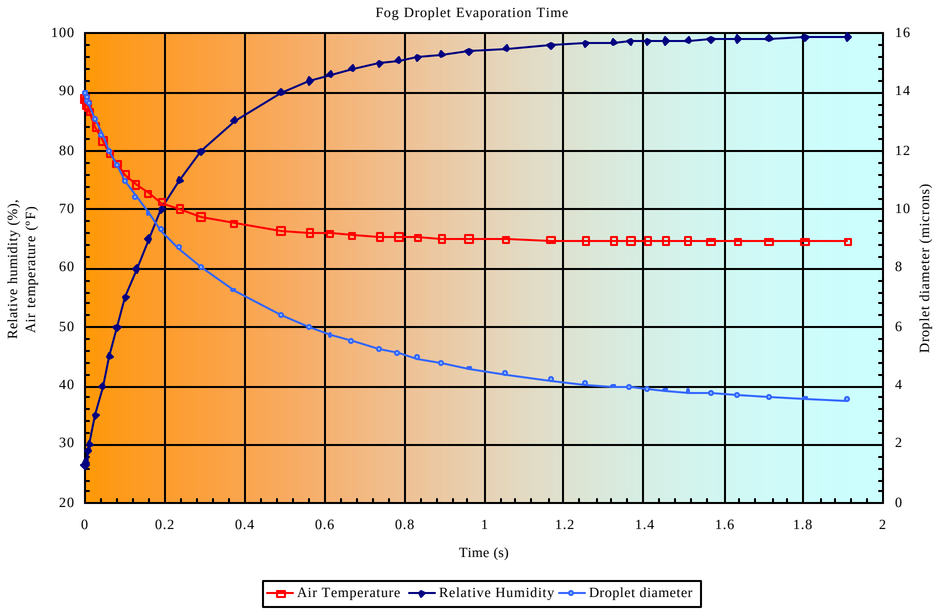

Figure 4. Droplet transient behavior in inlet duct for a heavy-duty gas turbine. Mee Industries can do extensive modeling of this nature to closely define the fog droplet thermodynamics and behavior.

Fog system suppliers who have a thorough and deep understanding of evaporation time and droplet kinetics will be able to design a system that both maximizes evaporation rates (thus ensuring higher fog system efficiency) and minimizes fallout and drainage water (thus minimizing the possibility of damage to compressor balding or blade coating). Evaporating time also plays a key role in the question of fog system staging increments. One theory for fog system design says that staging increments should be of the order of one degree F of cooling. The argument being that it will then be possible to get the maximum amount of cooling without over-saturating the inlet air because over-saturation means that liquid droplets will enter the compressor. Obviously, this theory is rendered meaningless if there is not enough time for all the fog to evaporate. In other words, when evaporation time is short, there will be liquid water entering the turbine, even if fog is injected at a rate that ensures under-saturation. This occurs because there will not be enough time for the droplets to fully evaporate. For this, and other reasons, system designs that include many stages of fog cooling, or increments of less than a few degrees F per stage, are often over-engineered. This subject is discussed in more detail below.

3.13 Fog Cooling Stages- Philosophy of Design

Fog systems differ from media type evaporative coolers in that they can be, and indeed should be, controlled such that the flow of fog water matches the evaporative potential of the ambient climate conditions. Media type coolers are only able to cool the air until about 85% to 90% relative humidity is reached and are incapable of over-saturating the air stream. Fog systems, on the other hand, are capable of meeting and exceeding 100% humidity in the inlet air. Therefore, fog systems must be controlled in stages.

Establishing the size of each increment or stage of fog cooling, generally expressed as it's cooling capacity in degrees Fahrenheit or Celsius, is an important aspect of fog system design. Typically fog systems are designed for a maximum cooling capacity that is capable of making use of all or most of the evaporative cooling potential on the hottest, driest summer day for the site. Climate data must be carefully evaluated to ensure the correct data is being used (see section 3.1.1 above for information on proper evaluation of climatic data).

Once the total cooling capacity has been established, the question of cooling capacity per stage can be addressed. As mentioned above, the typical inlet air duct does not allow enough residence time to affect total evaporation of the fog droplets. This means that trying to make very small cooling stages, in hopes of being able to get very close to saturation (100% humidity) without overshooting the mark, does not make engineering sense. In other words, there will usually always be some unevaporated fog droplets that enter the compressor so there is no point in trying to reach saturation without overshooting or overspraying.

This situation is compounded by the fact that fog system control must be "predictive." The high air velocities and lack of perfect mixing of fog and dry air make it essentially impossible to accurately measure the temperature and humidity downstream of the fog system. Furthermore, since there is always some unevaporated fog in the air stream, a temperature sensor can be inadvertently wetted and will tend to read ambient wet bulb temperature; or a humidity sensor will read 100% relative humidity. This makes it unworkable to use a feedback type control system with an inlet fogging system. Therefore, inlet fog control systems—as developed Mee Industries and as applied by most, if not all, fog system suppliers—typically consist of temperature and humidity sensors, which measure the ambient air (before fogging), and a PLC with software that calculates the evaporative potential of the ambient air and then turns on the required amount of fog. This calculation requires several inputs including; ambient temperature and humidity and air mass flow of the compressor. There are uncertainties in these inputs which effect the calculation and which make it unnecessary, or illogical, to have very small increments of fog cooling stages. These uncertainties are as follows:

3.13.1 Uncertainties in Staging control

The following factors contribute fundamental uncertainties that make the "accuracy" of small cooling stage increments or variable speed pump drives meaningless:

- **Sensitivity of Weather Sensors**. Humidity sensors are typically accurate to ± 2% and temperature sensors are accurate to about ± 0.5°F. If we were to look at a situation where both sensors were at their extreme limits, the algorithm for computing the wet bulb temperature could be in error by ± 1°F. It is possible to utilize redundant sensors or link weather stations together in order to reduce this error but this is not a major area of uncertainty in the overall picture. Gross out of limit conditions are checked by credibility limits in Mee's control software.

- **Gas Turbine airflow variations.** The actual amount of cooling that a given number of fog nozzles will accomplish (the value of one stage of fogging) is a strong function of gas turbine air mass flow rate and this is affected by several factors such as compressor fouling, inlet filter blockage and other factors. Fouling of the axial flow compressor[2] is a major factor affecting turbine airflow and match point of the gas turbine. The situation is further complicated when there are multiple spool gas turbines or variable geometry gas turbines. Fouling of a typical industrial gas turbine compressor blading can result in drop of 5% air mass flow, which results in change

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[2] For details on the causes, effects and control of gas turbine axial compressor fouling, please see Mee Industries Application Note AN-GT-150.

of 5% cooling value per stage. This is the most significant uncertainty factor in inlet fogging.

- **Atmospheric pressure effects**. The evaporative potential algorithm in the control software typically uses a fixed barometric pressure based on the specific site altitude and does not incorporate ambient pressure variations. The affect of this parameter is an uncertainty of about ± 2%.

- **Uncertainty of water flow rate**. While the MeeFog Nozzle has one of the closest tolerances on the market today (each nozzle is individually tested during manufacturing), there is still some degree of flow uncertainty involved the nozzles. The error is slightly biased on the positive side, to ensure there is always enough water to accomplish the required cooling. Each fog pump skid also includes a flow meter but there is some uncertainty in its reading. This factor introduces an uncertainty on the order of ± 2%.

- **Uncertainty in evaporation dynamics in the inlet duct**. Based on our experience, analytical studies and wind tunnel experimental data, we know that this is an extremely complex phenomenon. Mee Industries has examined the issue based on CFD studies and validated its models based on empirical test data. Our conclusion is that typical industrial turbine might have a much as 5%[3] unevaporated water.

Various schemes can be employed to eliminate or at least mitigate the above uncertainties but, in our experience, there will always be at least ± 3% uncertainty in the amount of cooling that a given number of nozzles will accomplish. Obviously, under these conditions, having cooling stage increments of less than 1°F would be irrational as one would have no way of knowing if adding the last stage of fog would reach just below the target temperature or overshoot it.

A simple example will illustrate the significance of these uncertainties with regard to establishing the proper cooling stage increment. Assume an inlet fogging system that is designed to provide 30°F of cooling. The uncertainty in air mass flow, due to compressor fouling would result in an uncertainty of about ± 5% in the amount of cooling that the system would do at any given time. At full cooling capacity, the uncertainty would be as big as ± 1.5°F

One possible control scheme would be to set things up such that one is at least certain that in no case is the target temperature overshoot. This would result in a fog cooling system that always fell short of its full cooling potential by as much as 5°F but this is equivalent to a power boost of about 2.5%, which is a significant amount of power to give up. It is important to remember that in most turbines there will be a significant amount of un-evaporated fog that enters the compressor, due to insufficient evaporation time. Therefore, if the reason for under-shooting the target temperature was to ensure that no water entered the turbine, fixing the uncertainties and undershooting the target temperature, may not be a reasonable proposition.

The above analysis also undermines the reason for using variable speed control of pump units. Variable speed drives adds to system cost and complexity without solving any real engineering problem.

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[3] This can be even higher with certain duct configurations.

3.14 Ability To Work With The End User on Gas Turbine Engineering

Mee Industries has often taken a role in working with the end user to deal with issues such as special coatings for overspray applications, and recommendations relating to gas turbine operation with fogging systems, including duct painting, coatings and materials, special drainage requirements, compressor bleed air issues and other turbine related issues. Mee Industries engineering staff includes several professionals with extensive experience working with gas turbine engines. A list of publications by Mee Industries Inc's engineers is provided in Appendix A.

3.15 Engineering Philosophy for Mee Fog Pump Units

Over the past 30 years that Mee Industries has been in the fogging business, and over the 496 gas turbine inlet fogging installations that if has done, MEE has constantly studied and evaluated alternative technologies including the use of Variable Frequency Drives (VFDs), various high-pressure pump technologies, and low pressure, compressed air atomization systems. In fact, Mee incorporates many of these technologies in project it does for other applications but after extensive analysis found them to be lacking for inlet fogging applications.

MEE has always maintained the philosophy that the simplest design, which will accomplish the intended purpose, will generally prove to be the more reliable and the easiest for the end user to maintain. High reliability and, therefore, simplicity of design must have a higher importance than sophisticated but problematic technical approaches. Mee Industries is an ISO 9001 company and has extensive quality control procedures as well as a policy of continuous improvement. We take great pride in our providing simple, field-proven, rugged and reliable systems.

The engineering justification for some of our basic designs follows.

Use of Reciprocating Pump Units

- MeeFog pump skids include reciprocating pumps that are configured to operate at significantly lower speeds than the manufacturer's maximum speed. This approach results in a higher first cost than other systems but it ensures long-term reliability and reduced maintenance costs. The speed of reciprocating pumps should be taken into account when evaluating competitive bids. Slower speed pumps result in exponentially longer seal life and far less noise and vibration.

- Some fog system suppliers recommend pumps with VFDs as a method for controlling the output of inlet fogging systems. This approach has several fundamental problems. First, reducing the speed of the pumps results in lower flow but also in reduced pressure at the fog nozzles, this means that larger droplets are made, which has a negative affect on both evaporative efficiency and increases both the amount of drainage water and the possibility of compressor blade erosion. Second, VFDs add significant cost. Third, they make it possible to control fog-water output to a very close tolerance but uncertainties in measured parameters and even in the air mass flow of the turbine render such close control meaningless. And last, but not least, VFDs make for a more complex and difficult to maintain system. Mee Industries uses VFDs in commercial humidification projects and has much experience with these fairly temperamental, electronic devices: enough to know that if you don't need it, you don't want it.

A certain fog system supplier claims that variations in operating pressure, within limits, does not affect droplet size. This is true for their particular nozzle, which has a ruby orifice with an excessive pressure drop. This nozzle operates as a choked orifice at pressures in excess of about 2000 psi. While it is correct that droplet size is independent of pressure, the same holds good for the nozzle flow rate. The orifice begins to cavitate at pressures over 2000 psi and both the flow rate and the droplet size go flat. The argument used to justify VFD control is in fact the very reason why it will not work. Changes in pump speed will result in the flow rate remaining constant.

- Reciprocating pumps are positive flow and, therefore, very efficient when compared to centrifugal pumps.

- The standard MeeFog system pump skid design includes multiple, *identical* pumps. Other fog system suppliers often recommend using multiple sizes of pumps in an attempt to lower first-costs. The result is a system that requires stocking many different sizes of spares, seal and valve kits, etc. The Mee design provides built in redundancy and ease of maintenance.

- Some suppliers argue that fewer pumps are inherently better. We would agree with this concept except when it interferes with the ability to have the proper number of stages. (See section on Cooling Stage Design above). It is possible to use larger pump units and automatic, motorized ball valves for stage control. However, economies of scale make certain sizes of pump units very cost effective—because they are used in many different industries. MeeFog systems are designed, wherever possible, to employ pumps that have the lowest cost per gallon per minute.

- MeeFog systems utilize Cat brand, ceramic plunger pumps that have been proven rugged and reliable, when used as designed by Mee Industries, over many years of service. Cat Company offers worldwide availability of parts and service as well as in-the-field support for their pumps. Mee also uses Cat pressure regulators, pulsation dampeners and other pump accessory components, which means that there are not problems associated with improperly matching parts from several suppliers.

3.16 Control System Aspects

The basic function of the control system is to correctly inject the appropriate amount of fog to attain the desired ending temperature near the inlet to the compressor (typically approaching the wet bulb temperature). Mee Industries has evaluated several approaches ranging from the very simple to the very sophisticated and is convinced that its approach of using discrete staging is by far the most practical, sensible and reliable. Other vendors have applied approaches of using infinitely variable speed motors driving pumps in an attempt to reduce the number of pumps and provide “fine control”. While the first objective may be met, the second is fraught with fundamental uncertainties that have been discussed above.

4. EXPERIENCE OF THE FOG SYSTEM SUPPLIER

4.1 Experience in the Gas Turbine Market

It is unfortunately a common misconception that inlet fogging is a low technology art involving just pumps and nozzles that spray water into the inlet duct. Numerous companies who have jumped on the inlet fogging bandwagon have promoted this notion. Nothing could be farther from the truth. A good fogging system has to be carefully designed and engineered considering the gas turbine itself, inlet systems, materials and several other factors pertaining to gas turbine technology.

With fog systems installed on over 38,000 MW of gas turbines, Mee Industries is the acknowledged market leader. Mee has supplied systems on a range of gas turbines from 3 MW to 250 MW, on a total of 496 units and with a combined power boost of nearly 3,000 MW. Fogging of gas turbine engines is both an art and a science, and there are several complexities that only experience can address. Among our several repeat customers is a US utility that has installed MeeFog Systems on nearly 80 of its heavy-duty gas turbines over a four-year period. Mee Industries has worked closely with several utilities world wide in accommodating their special requests, accelerating delivery schedules to meet power crunches and providing responsive after sales support. Our experience covers the full range of heavy duty and aeroderivative units, and includes projects with nearly all Gas Turbine OEMs.

4.2 Research and Development

Mee Industries Inc is committed to a research and development program designed to continuously optimize and enhance its MeeFog Systems. A fully equipped 4,000 square foot research facility is dedicated to gas turbine inlet fogging research. Mee's R&D lab includes a fully instrumented wind tunnel capable of air velocities in excess of 4000 ft/min. This unit was specially designed to analyze fogging flow in gas turbine intake ducts and includes a state of the art laser droplet measurement instrument to monitor droplet behavior as well as other analytical tools and software.

Fundamental and applied research programs are underway for:

- Droplet thermodynamics, kinetics and evaporation rates
- Droplet Collision- Bounce- Coalescence and Shattering dynamics
- Droplet flow and interference dynamics
- CFD studies of gas turbine inlet ducts
- Theoretical and experimental studies on droplet trajectories
- Optimization studies relating to nozzle array placement in ducts.
- R&D on advanced nozzle designs
- Gas Turbine and Combined Cycle thermodynamic studies

Figure 5. Wind tunnel to study droplet kinetics and thermodynamics in inlet ducts. This wind tunnel provides dynamic similarity to gas turbine inlets. Facilities such as these allow Mee Industries Gas Turbine Division to study and measure the practical aspects of droplet behavior in a real life setting

4.3 Expertise in Gas Turbine Engineering

As the fogging system will be applied to a gas turbine it is imperative that the vendor have a background and deep understanding of the aero-thermodynamics of gas turbines and the O&M aspects involved. Having supplied 496 gas turbine fogging systems to date, Mee Industries have acquired considerable expertise in gas turbine engineering. Several members of its engineering staff have long-term experience within the gas turbine and turbomachinery industries.

Mee Industries has a broad base of expertise in the areas of:

- Gas Turbine High Pressure Inlet Fogging
- Fog Droplet Modeling and Analysis
- Gas Turbine Performance and Performance Deterioration
- Gas Turbine Aero-thermodynamics
- Gas turbine Condition Monitoring
- Gas Turbine Blading Vibration and Distress
- Gas Turbine Component Stress Analysis
- Axial Compressor Fouling and Performance Deterioration
- Gas Turbine Operations and Maintenance
- Droplet Thermodynamics and kinetics
- Droplet collision-bounce-coalescence and shattering dynamics
- Meteorological phenomena, climate analysis, etc.

Mee Industries Inc, Gas Turbine Division personnel have over 70 Publications in the area of Fogging, Gas Turbine Engineering and Droplet dynamics. A list of publications is provided in APPENDIX A.

4.4 Quality Assurance

A high level of quality control is very an important aspect of any equipment supplier's qualifications. System suppliers under consideration should be, at a minimum, ISO 9001 qualified and have a detailed quality control manual available for review.

To ensure customers that our quality systems comply with demanding international requirements, Mee Industries Inc. is an ISO 9001 company (Qualified by TUV management an independent worldwide technical services organization). Mee Industries has an extensive quality management system for the design and manufacture of fogging systems - and these documents are available for client review as needed.

Mee Industries quality control efforts include:

- **Continuous quality improvement**- we view ISO certification as an important achievement but also as just a milestone towards our goal of continuous improvement.
- **Measurement of Customer Satisfaction**- As customer satisfaction is an integral part of our mission statement, Mee Industries interviews customers to measure our performance. Several of these customer-contact reports are available for customer review. Our track record shows that Mee Industries has always excelled in customer satisfaction. We have many repeat customers, which, we believe, is a firm indicator of our being on the right track. We are dedicated to continually building on that record because we know that future customer satisfaction depends on continuous improvement of all of our products and services.
- **Empowerment**- Any Mee employee can have a direct input to management regarding quality improvement suggestions.
- **Employee Training** - Mee Industries has an in-house training program for its engineers, installers and other personnel. Included in the training are topics such as gas turbine technology, fogging system design, O&M, startup and troubleshooting.

5. CLOSURE

This application note has covered several factors that should be evaluated in selecting a fogging system supplier. This application note will help in the evaluation of different technology options and capabilities of fogging system suppliers so as to minimize risks in during the design, manufacturing, installation and operation of gas turbine inlet fogging systems.

APPENDIX A

TECHNICAL PAPERS/PUBLICATIONS OF MEE INDUSTRIES GAS TURBINE DIVISION PERSONNEL

SELECTED PUBLICATIONS ARE LISTED BELOW:

1. "***Inlet Fogging of Gas Turbine Engines- Detailed Climatic Analysis of Gas Turbine Evaporative Cooling Potential for International Locations***," to be presented at ASME TurboExpo 2002, Amsterdam, June, 2002, ASME Paper No: 2002-GT-30559.
2. "***Inlet Fogging of Gas Turbine Engines- Part A: Fog Droplet Thermodynamics, Heat Transfer and Practical Considerations***," ***Part B: Fog Droplet Sizing Analysis, Nozzle Types, Measurement and Testing," Part C: Fog Behavior in Inlet Ducts, CFD Analysis, and Wind Tunnel Experiments,"*** to be presented at ASME TurboExpo 2002, Amsterdam, June, 2002, ASME Paper Nos: 2002-GT-30562, 2002-GT-30563, 2002-GT-30564
3. ***"Inlet Fogging of Gas Turbine Engines- Part A: Theory, Psychrometrics, and Fog Generation; Part B: Practical Considerations, Control and O&M Aspects,"*** ASME International Gas Turbine and Aeroengine Congress, Munich, Germany, May 2000, ASME Paper Nos: 2000-GT-307 and 308.
4. "***Compressor Fouling- Causes and Solutions***," Global Gas Turbine News, ASME International Gas Turbine Institute, Volume 40: 2000, No 3.
5. "***Inlet Fogging of Gas Turbine Engines- Detailed Climatic Analysis of Gas Turbine Evaporative Cooling Potential***," ASME TurboExpo 2001, New Orleans, June 4-7, 2001, ASME Paper No: 2001-GT-526. **Also to appear in ASME Transactions for Gas Turbines and Power.**
6. ***"Gas Turbine Performance Deterioration,"*** Proceedings of the 30th Turbomachinery Symposium, Houston, September 18-20, 2001.
7. ***"Gas Turbine Power Augmentation by Fogging of Inlet Air,"*** Proceedings of the 28th Turbomachinery Symposium, Houston Texas, September 1999.
8. ***"Inlet Fogging Augments Power Production***," Power Engineering, February 1999, PennWell Corporation.
9. ***"Inlet Air Cooling- Basic Theory and Practice in the Western States***," Western Energy, Summer 1998.
10. ***"Fog System Selection: It's in the Specs***," Southwestern Energy, August 2000.
11. ***"Peak Capacity Enhancement at Northern States Power's Wheaton and French Island Sttions through Inlet Air Fogging,"*** Electric Power 2000, Cincinnati Ohio, April 4-6, 2000.
12. ***"Turbines in the Mist***," Power Plant Technology, July/August 2000.
13. ***"High Pressure Fogging: The Good, The Bad , and the Ugly***," Western Energy, March 1999.

14. "***A Comparative Guide to Inlet Cooling Technologies Under High Temperature and High Humidity Conditions***," White Paper, Mee Industries Inc, Gas Turbine Division.

15. ***"Disintegration of water drops under the effects of an electric field,"*** 1991 Report of D.E.A. on Energy. University of Nice Sophia-Antipolis.

16. ***"Studies in Electrohydrodynamic Phenomena at the Tip of Capillaries by Digital Image Processing.***" Lebanese Scientific Research Reports, Vol.3, N.3, P.71, 1998.

17. "***New Approaches in ElectrohydrodDynamic Disintegration of Water Droplets***," 6th National Symposium on Visualization and Digital Image Processing In Fluids Mechanics, St. Etienne, France 1995.

18. "***Studies Of Electrohydrodynamics Disintegration of Strongly Charged Drops For Various Geometrical Systems***," Ph.D. Dissertation.. Dr. M. Chaker, University of Nice Sophia-Antipolis, June 1995.

19. "***Study Of The Concentration Of Molecules In A Dielectrophoresis Phenomenon On A Polar Gas And The Formation Of Drops By Condensation***,". Energex, Peking, 1996.

20. ***" Electrohydrodynamic Disintegration Of Water On A Surface And At The Tip Of A Metallic Capillary,"*** Lebanese Scientific Research Reports. vol.3, N.1, P.96, January 1996.

21. " ***Study Of Charged Drops' Trajectories***," Lebanese Scientific Research Reports. Vol.3, N.3, P.84, October 1998.

22. "***Effects Of Structures On Rheology in a Model Magnetorheological Fluid***," MRS spring meeting, San Francisco, April 5-9 1999.

23. " ***Influence On Rheology Of Static And Dynamic Structures In Model Magnetorheological Fluids***, Magnetorheological Suspensions and their applications, Hawaii, 1999.

24. ***"The Fouling of Axial Flow Compressors - Causes Effects Detection & Control,"*** Proceedings of the 18th Turbomachinery Symposium, Dallas, Texas, October 9-12, 1989.

25. "***On-line Condition Monitoring of Two Westinghouse CW-352 Gas Turbine Compressor Sets***", Proceedings of the 8th Symposium on Industrial Applications of Gas Turbines, National Research Council of Canada, Ottawa, Canada, September 24-27, 1989.

26. ***"Gas Turbine Axial Compressor Fouling - A Unified Treatment of its Effects, Detection & Control,"*** ASME Publication IGTI-Volume 5, 1990 ASME Cogeneration Conference, New Orleans, August, 1990. Paper awarded **ASME Best Paper of the Year Award** by the Industrial & Cogeneration Committee. Also in **International Journal of Turbo & Jet Engines**, Vol. 9, No 4.

27. ***"An Approach for the Integration of Condition Monitoring and Multiobjective Optimization for Gas Turbine Maintenance Management,"*** Proceedings of the 3rd International Machinery Monitoring & Diagnostics Conference, Las Vegas, December 9-12, 1991. Also in **International Journal of Turbo & Jet Engines**, Vol. 11, No 1, 1994.

28. ***"Resolution of a Thrust Bearing Overheating Problem in a Large Condensing-Extraction Steam Turbine,"*** Proceedings of the 3rd International Machinery Monitoring Monitoring and Diagnostics, Las Vegas, December 9-12, 1991.

29. ***"Condition Monitoring & Diagnostic Aspects of Gas Turbine Transient Response,"*** ASME Paper No.: 92-GT-100, 1992 ASME Gas Turbine Congress, Cologne, June 1-4, 1992. Also appeared in **International Journal of Turbo & Jet Engines**, Vol. 11, No 1, 1994..

30. ***"Integration of Condition Monitoring Technologies for the Health Monitoring of Gas Turbines,"*** ASME Paper No.: 92-GT-52, 1992 ASME Gas Turbine Congress, Cologne, June 1-4, 1992.

31. ***"Durability Surveillance Program on the GE Frame 7F Advanced Gas Turbine,"*** ASME Paper No.: 92-GT-334, 1992 ASME Gas Turbine Congress, Cologne, June 1-4, 1992. Received 1993 **ASME Best Paper Award** of the Industrial and Cogeneration IGTI Committee.

32. ***"Modeling and Analysis of Gas Turbine Performance Deterioration,"*** 1992 ASME Paper No.: 92-GT-395, ASME Gas Turbine Congress, Cologne, June 1-4, 1992. Paper Published in **ASME Transactions- Journal for Gas Turbine and Power**, Volume 116, January 1994, pp. 46-52.

33. ***"Test Cell Vibration Investigations on the 3 Spool 1500 SHP M1A1 Main Battle Tank Gas Turbine,"*** ASME Publication IGTI-Volume 7, 6th ASME Cogen Turbo Power Congress, Houston, Texas, September 1-4, 1992.

34. ***"Ten Years of Condition Monitoring Experience on Large Mechanical Drive Steam Turbines in an Ethylene Plant,"*** ASME Publication IGTI-Volume 7, 6th ASME Cogen Turbo Power Congress, Houston, Texas, September 1-4, 1992.

35. ***"Durability Surveillance of Advanced Gas Turbines-Performance and Mechanical Baseline Establishment for the GE Frame 7F,",***ASME Paper No: 93-GT-276, 1993 ASME Gas Turbine and Aeroengine Congress, Cincinnati, May 24-27.

36. "***Case Studies on Turbomachinery Operation and Maintenance using Condition Monitoring***," Proceedings of the 22nd Turbomachinery Symposium, Dallas, September 14-16, 1993.

37. ***"Design, Installation and Experience with a Comprehensive Condition Monitoring System for a 500 MW Thermal Power Plant,"*** International Joint Power Generation Conference, Kansas City, Kansas, October 17-22, 1993, ASME Paper No: 93-JPGC-PWR-15.

38. ***"Condition Monitoring and Diagnostic Approaches for Advanced Gas Turbines,"*** 1993 ASME COGEN TURBO POWER, Bournemouth, UK, September 21-23, 1993, IGTI-Volume 8, pp. 347-350

39. ***"Gas Turbine and Combined Cycle Technologies for Power and Efficiency Enhancement in Power Plants,"*** ASME International Gas Turbine and Aeroengine Congress, The Hague, 1994, ASME Paper No: 94-GT-435.

40. ***"Condition Monitoring and Optimization of a 340 MW Combined Cycle Power Plant, Part 1: Design***," ASME Joint International Power Generation Conference, Phoenix, Arizona, October 2-6, 1994.

41. "***Advanced On-Line Condition Monitoring to Optimize Operation and Maintenance of Combined Cycle Power Plants***," Proceedings of the Seminar on O&M of Gas Based Power Plants, New Delhi, India, April 27-29, 1994, Volume II.

42. ***"Compromise: An Effective Approach for Condition Based Maintenance Management of Gas Turbines," Journal of Engineering Optimization***, 1994, Vol. 22, pp. 185-201.

43. ***"<u>Blading Vibration and Failures in Gas Turbines</u>"***

Part A: Blading Dynamics and the Operating Environment
Part B: Compressor and Turbine Airfoil Distress
Part C: Detection and Troubleshooting
Part D: Case Studies

ASME International Gas Turbine and Aeroengine Congress, Houston, TX, June 5-8, 1995, ASME Paper Nos: 95-GT-418, 95-GT-419, 95-GT-419, 95-GT-420.

44. ***"<u>Detect, Troubleshoot Gas Turbine Blade Failures,</u>"*** POWER, December 1995

45. ***"<u>The Development of the Junkers Jumo 004B- The World's First Production Turbojet</u>***," ASME International Gas Turbine and Aeroengine Congress, Birmingham, UK, June 10-13, 1996. ASME Paper No: 96-GT-457. Presentation at the Aircraft Engine Theme Session. Paper to appear in **ASME Transactions for Gas Turbines and Power. Also published by ASME in *MECHANICAL ENGINEERING* Magazine, September 1997.**

46. "***<u>The Development of the Whittle Turbojet</u>***", ASME International Gas Turbine and Aeroengine Congress, Orlando, Florida 2-5, 1997. ASME Paper No: 97-GT-528. Presented at the Aircraft Engine Theme Session. Also in **ASME Transactions for Gas Turbines and Power, April 1988, Vol 120. Paper received ASME Best Paper award by the Aircraft Engine Committee**

47. "***<u>Gas Turbine Blade Failures- Causes, Avoidance, and Troubleshooting</u>***," Proceedings of the 27th Turbomachinery Symposium, Turbomachinery Laboratories, Texas A&M University , Houston, Texas, September 22-24, 1998.

48. ***"<u>The Design and Development of an Externally Fired Injected Gas Turbine for Cogeneration</u>,"*** Proceedings of the Industrial Energy Conservation Conference, April 26-29, 1981, Houston, Texas.

49. ***"<u>Aerothermal and Mechanical Health Monitoring and Diagnostics of Turbo-Compressor Sets,</u>"*** Proceedings of the 11th Turbomachinery Symposium, Turbomachinery Laboratories, Texas A&M University, Houston, Texas, 1982.

50. "***<u>Life Cycle Cost Reduction for High Speed Turbomachinery Utilizing Aerothermal-Mechanical Condition Monitoring</u>***", Proceedings of the 1982 IECT Conference, Houston, Texas.

51. "***<u>On-line Monitoring and Diagnostics of Power Plants</u>***", Proceedings of EPRI Workshop on Incipient Failure Detection of Power Plants Components, Hartford, Connecticut, August 25-27, 1982.

52. "***<u>Aerothermodynamic Gas Path Analysis For Health Diagnostics of Combustion of Gas Turbines</u>***", Proceedings of the 36th Meeting of the Mechanical Failure Prevention Group - Conference on Technology Advances and Their Impact on Detection, Diagnosis and Prognosis Methods, Cambridge University Press, 1983.

53. ***"<u>Combustion Gas Turbine Power Enhancement by Refrigeration Of Inlet Air,</u>"*** Proceedings of the 1983 Industrial Energy Conservation Technology Conference, Houston, Texas, April 17-20, 1983.

54. "***<u>Application of Integration Logistics Support Concepts In Energy Project Planning</u>***", Proceedings of the 1983 Industrial Energy Conservation Technology conference, April 17-20, 1983.

55. ***"<u>Reliability Improvement by Aerothermal Analysis of High Speed Rotating Machinery,</u>"*** 5th ASME Failure Prevention and Reliability Conference, Dearborn, Michigan, September, 1983.

56. ***"The Development and Implementation of Advanced On-line Monitoring and Diagnostic Systems for Gas Turbines,"*** Tokyo International Gas Turbine Conference, October, 1983, Paper No. 83-IGTC-94.

57. ***"Operating Experience with Health Monitoring and Diagnostics of Large M.D. Steam Turbines,"*** 1983 ASME Joint Power Generation Conference, September, 1983, ASME Paper No: 83-JPGC-PWR 28.

58. ***"Practical Approach to Surge and Surge Control,"*** Proceedings of the 12th Turbomachinery Symposium, Turbomachinery Laboratories, Texas A&M University, Houston, Texas, November 15-17, 1983.

59. ***"Reliability, Maintainability and Availability Considerations for Cogeneration Systems,"*** Proceedings of the 6th Industrial Energy Conservation Technology Conference, April 15-18, 1984.

60. ***"An Overview of Cogeneration Technology- Design, Operations and Maintenance,"*** Proceedings of the 13th Turbomachinery Symposium, Houston, Texas, November 13-15, 1984.

61. ***"Feasibility Study on the Application of Artificial Intelligence Techniques for Turbomachinery Diagnostics,"*** ASME International Gas Turbine Conference, Houston, Texas, 1985, ASME Paper No.: 85-GT-102. Also published in **International Journal of Turbo and Jet Engines**, Volume 5, No. 1-4, 1988.

62. ***"Detection of Turbomachine Blading Problems Using On-line and Off-line Analysis",*** Proceedings of the EPRI Workshop on Incipient Failure Detection of Power Plants, Florida, October 10-12, 1984, EPRI Publication CS-2920.

63. "***Energy Efficient Operation of Gas Turbine Compressor Sets***", ASME International Gas Turbine Conference, Houston, Texas, 1985, ASME Paper No. 85-GT-78.

64. ***"Reasoning Foundations for Machinery Diagnostics- Thought Processes and Expert Systems***," 40th Meeting of the Mechanical Failure Prevention Group (NBS) Symposium on New Technology to Improve Mechanical Readiness, Reliability and Maintainability, April 16-18, 1985.

65. ***"Compressor and Hot Section Fouling in Gas Turbines Causes and Effects,***" Proceedings of the 1987 Industrial Energy Technology Conference, Houston, Texas, Texas A&M University, October, 1987.

66. "***Advanced Maintenance Management System Design for the LM 2500 Gas Turbine,***" SAE Paper No.: 881171, Society of Automotive Engineers, Conference on Future Transportation Technology, San Francisco, August, 1988. Paper also in Transaction **Journal of the Society of Automotive Engineers.**

67. ***"Diagnose Causes and Effects of Fouling, then Prescribe Cure,"*** Article in **POWER**, August, 1988.

68. "***On-line Condition Monitoring Systems for Off-shore Turbomachinery System Design and Operating Experience***", Proceedings of the 43rd meeting of the Mechanical Failure Prevention Group, Symposium on Advanced Technology in Failure Prevention, October, 1988.

69. "***Condition Monitoring of Aeroderivative Gas Turbines***", 34th ASME International Gas Turbine Conference, Toronto, Canada, June, 1989, ASME Paper 89-GT-36.

70. "***A Diagnostic Methodology for Condition Monitoring of High Speed Turbomachinery***", Society of Tribology and Lubrication Engineers Annual Meeting on Condition Monitoring and Preventive Maintenance, Atlanta, Georgia, May, 1989.

71. ***"Vibration & Debris Analysis for Gear Box Condition Monitoring - An Integrated Approach,"*** Proceedings of the 1st International Machinery Monitoring & Diagnostic Conference, Las Vegas, September, 1989.

72. ***"Pioneering Turbojet Developments of Dr. Hans von Ohain- from the HeS1 to the HeS001,"*** ASME Gas turbine and Aeroengine Conference, Indianapolis, ASME Paper No: 99-GT-228 Also in **ASME Transactions for Gas Turbines and Power, April 1988, Vol 122, Issue 2, April 2000.**

73. ***"The Historical Evolution of Turbomachinery,"*** Proceedings of the 29th Turbomachinery Symposium, Houston, Texas, September 2000.

74. ***"Gas Turbine Technology - Part A: Overview, Cycles and Thermodynamic Performance. Part B: Components, Operations and Maintenance".*** Published in Industrial Cogeneration Applications. Ed. D.L. Limaye, Fairmont Press Inc., 1986.

75. "***Condition Monitoring of Power Plants***," Handbook of Condition Monitoring and Maintenance Management in Industry, Elsevier Publishing, Ed. Dr. B.K.N. Rao, 1996.