

INLET FOGGING OF GAS TURBINE ENGINES PART B: PRACTICAL CONSIDERATIONS, CONTROL, AND O&M ASPECTS.

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ABSTRACT

The severe dependence of gas turbine output on ambient temperature has created the need for inlet cooling technologies. This paper focuses on the practical aspects of direct evaporative cooling by fogging of the inlet air to a gas turbine compressor. This paper covers several of the practical considerations relating to the location of nozzles, water quality and operations and maintenance issues that relate to implementation of such systems. A design and implementation checklist is provided to assist users in ensuring a reliable installation.

1. INTRODUCTION

The need for low cost power augmentation techniques that are applicable during periods when the ambient temperatures are high has fostered the use of high pressure inlet fogging. In this technology, very fine droplets of fog are created in the inlet duct of the gas turbine by means of special nozzles and the use of high-pressure pumps which operate at pressures of 1000-2000 psi. Part A of this paper (Meher-Homji and Mee, 2000) has covered the theoretical aspects of direct fog evaporation, the psychrometrics involved and hardware to generate fog. In this paper, several practical control and operations and maintenance aspects are covered to help users implement such systems. A discussion is also made of installations on a variety of gas turbines.

2. LOCATION OF FOG NOZZLES IN THE GAS TURBINE INLET

Direct high pressure inlet fogging systems can be retrofitted with minimal effort compared to the incorporation of a media based evaporative cooler. To incorporate fog cooling very little modification of the inlet system is normally needed. However, it may be desirable to install access doors to allow for service of fog nozzles and drains to remove any excess water which may accumulate in the ducts. There are two main options for installing the inlet fogging

system locating them either upstream or downstream of the filters as depicted in Figure 1.

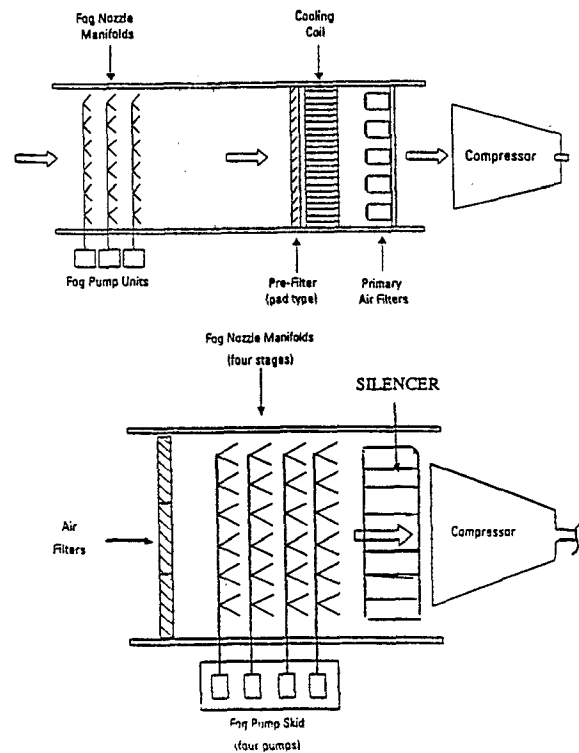


Figure 1. Location Options for the Inlet Fog Nozzles. For Fog Intercooling, Nozzles can be downstream of Silencer.

2.1 Fog Nozzles Located Upstream of Inlet Filters.

An advantage to positioning the fog nozzle manifold upstream of the air filters is that the installation can often be accomplished without outage time. In this case, a fog droplet filter must be added downstream of the fog nozzle manifold to remove any unevaporated

fog. By definition the droplet filter would not allow any fog intercooling¹. Typically about half of the water output by the fog nozzles is captured by the droplet filter and drained away. This type of system, while used on some early installations, is rarely applied to gas turbine installations today. It requires more fog nozzles, and more water and is generally more expensive to operate and install. However, turbine operators who have experienced excessive loading of the inlet air filters, could use this as a “fog scrubber” and in several cases this has been shown to dramatically increase air filter life. A system installed prior to the airfilters is shown in Figure 2.



Figure 2. Fog Nozzles in operation upstream of Filters.

2.2 Fog Nozzles Located Downstream of the Inlet Filters.

The most common location for the high-pressure fog nozzle manifold is downstream of the air filters and upstream of silencers and trash screens. Installation in this location requires an outage of one to two days and calls for only minor modifications to the turbine inlet structure. This type of installation allows fog intercooling. While the fog nozzle manifolds can be also installed downstream of the silencers, it is generally considered best to locate them upstream of the silencers as this would allow more residence time for the fog droplets to evaporate. However, one fog system user reported excessive compressor fouling when nozzle manifolds were located upstream of dirty silencer panels. The fog washed dirt off the silencer panels and deposited it on the axial compressor blades. The problem was resolved when the nozzle manifolds were relocated to a position downstream of the silencer panels. During the reinstallation of the nozzle manifolds, the silencer panels were inspected and were found to be much cleaner than the panels in other turbines located at the same site. Presumably the compressor fouling problem would have gone away once the fog had washed all the dirt from the silencer panels. Fog nozzle manifolds are almost always installed upstream of the trash screens to avoid any possibility of FOD. For application downstream of the filters, nozzle location is important (to avoid wetting the duct floor, etc.). In general if the primary purpose of the fog system is

evaporative cooling, the nozzles should be installed before the silencers to allow as much time as possible for evaporation. If the primary purpose of fogging is fog intercooling, the nozzle manifolds should be installed just upstream of the trash screen, to minimize wetting of the duct and silencers. In certain installations involving large heavy duty gas turbines, two nozzle manifolds may be installed, one before the silencers for evaporative cooling and one after the silencers for fog intercooling. Nozzle orientation is also an important factor. Pointing the fog nozzles into the airstream gives more residence time and evaporation in a high velocity airstream.

2.3 Importance Of Nozzle Location With Respect To The Duct To Avoid Water In Ducts.

Fog systems can create water in the inlet ducts and this occurs with the non-optimal location of the inlet nozzles. Some water is normal as droplets will impact some parts of the inlet structure in the duct and will fail to evaporate. In most cases drains have to be located in the inlet duct to ensure that no excessive water accumulates. It is also important to ensure that the system is properly designed and the water flow rates must be metered to avoid delivery of more water than can be evaporated in the air stream.

3. FOREIGN OBJECT DAMAGE [FOD] CONSIDERATIONS AND DESIGN FOR SAFETY

3.1 FOD Considerations.

With the presence of a large number of nozzles in the airstream as is shown in Figure 3, FOD is naturally a concern. This is more of a problem when the nozzles are located downstream of the airfilters which is the most common location. The danger comes from loosening of the nozzles or damage of the grid structure due to flow induced vibration. Both of these problems can be eliminated by careful and conservative design. Lock wiring of the nozzles (see Figure 4) also provide a line of defense in the case of nozzle loosening however no positive restraint can be provided. To date there have not been any cases of FOD damage.

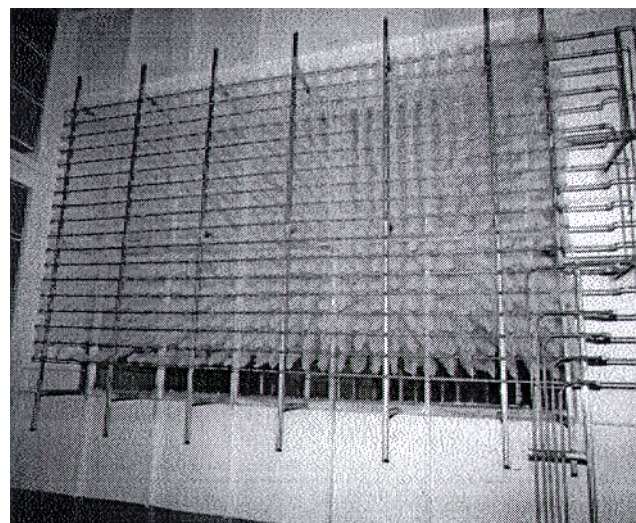


Figure 3. Fog Nozzle Manifold in operation.

¹ The ingestion of unevaporated fog into the axial compressor.

3.2 Flow Induced Vibrations.

As the entire grid measuring several feet made of tubing is located in the gas turbine airflow, there is always a possibility of flow induced vibration causing a failure. Again, the natural frequencies can be computed analytically and by conservative design, this risk can be mitigated.

Vortex shedding frequencies can be calculated by means of the equation:

$$f_v = (SN) V / d * 12 \quad (1)$$

Where,

- f_v = Vortex Shedding Frequency, Hz
- SN = Strouhal No.
- V = Velocity, fps
- D = Tube diameter, in.

The natural frequency of the grid structure tubes can be determined by the dimensional information, using standard formulae.

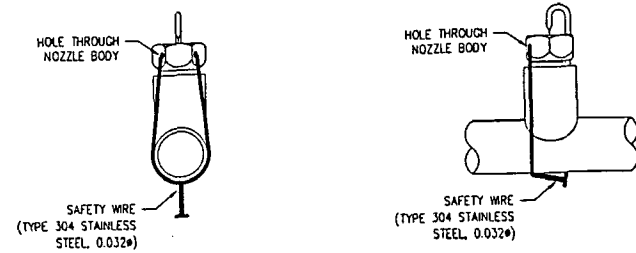


Figure 4. Lock-wiring of Nozzles for FOD prevention.

4. FOG WATER QUANTITY AND QUALITY

The importance of water quality cannot be overstated especially when fog intercooling is desired. Experience has shown that demineralized water often requires additional treatment, if it is to be used for gas turbine inlet-air cooling. Demineralization generally removes ionic material (minerals that are dissolved in the water in ion form) but does not remove colloidal material. Surface waters, such as river or lake-water, and even some well waters often contain Silica in colloidal form (i.e., in particles that are small enough that they do not readily settle out of the water). As silica is a very hard element, its presence can damage fog nozzles and possibly even compressor blading. The fog pump skids or water treatment plant should include sub-micron water filters to remove the silica from the fog supply water.

The amount of water required depends on the degree of cooling required, ambient conditions and the turbine mass flow rate. While preliminary computations have been provided in Meher-Homji and Mee, (2000), there are several practical considerations that have also to be accounted for. A feel for the amount of water required for different mass flow rate machines for defined degrees of cooling is presented in Table 1

Mass flow rate, Kg/sec	Litre/hr for 1°C cooling	Liter/hr for 5°C cooling	Litre/hr for 10°C cooling
202	299	1495	2990
227	336	1682	3364
370	458	2738	5476
420	621	3107	6213
459	679	3397	6793

Table 1. Water requirements (approx) for direct evap cooling.

5. GAS TURBINE AXIAL COMPRESSOR EROSION AND FOULING CONSIDERATIONS

5.1 Erosion Considerations.

An area of primary concern in the earlier years for the application of fogging systems was the possibility of blading erosion. With the small droplet diameters being generated and use of demineralized water, erosion related to inlet air fogging and fog intercooling has been shown not to be a problem. This has been documented in several references including Sexton et al (1998) and Utamura et al (1999). There is no detrimental effect on the blading from an erosion standpoint when high pressure fogging is employed and indeed some earlier studies have indicated that even higher droplet sizes do not have any detrimental erosion effect. Figure 4 (Bechtel and Rumbaugh, 1973) shows a guideline for erosion showing that even with dust, erosion problems will only exist when more than 5 % by weight exceed 10 microns. Clearly, the situation with water droplets is less severe.

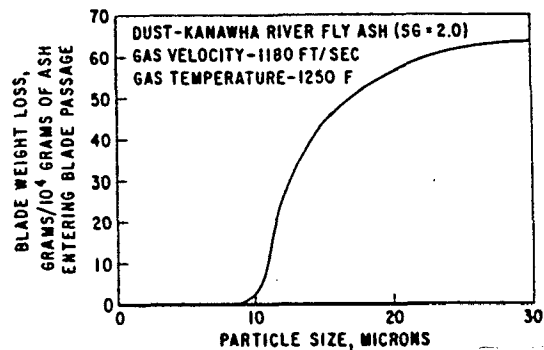


Figure 4. Erosion Rates and Particle Size for Dust (Bechtel et al, 1973).

It is indeed interesting to note that compressor water injection has actually been suggested to improve performance of an eroded axial flow compressor (Tabakoff et al, 1990). This can be done because the

water injection increases the total pressure ratio, thus recovering some erosion-related deterioration.

5.2 Fouling Considerations.

The area of compressor fouling deterioration is indeed one of importance. When good quality DM water is used and inlet ducts and silencers are clean, no problems of deposits have been noted. In fact, operator experience indicates that there is a washing effect from the fog itself. It is possible that using fog on a nearly continuous basis for power augmentation, results in a continuous washing effect. When fog is in use, the likelihood of dirt in the air stream becoming attached to the compressor blades is greatly reduced. This effect may result in savings of on-line wash costs and washing chemicals. The use of fogging may reduce power losses due to compressor fouling between washes.

High pressure fog systems have also been successfully applied as air scrubbing systems. In this application the fogging nozzles are installed up-stream of the air filters and a droplet eliminator is employed to remove the fog from the air stream before it reaches the main barrier filters. Dust in the ambient air is captured by the fog droplets, which, in turn, are captured by the droplet eliminator. On installations where this method has been employed, a considerable reduction in the frequency of replacement of barrier filters has been attained.

The area of compressor fouling and control is complex and site dependent. However, a general comment can be made that inlet fogging will not have a detrimental effect, but could indeed help. Details relating to axial compressor fouling may be found in Meher-Homji (1990).

6. CONTROL ASPECTS

The control system incorporates a programmable logic controller (PLC), which is typically mounted on the high pressure pump skid. Sensors are provided to measure relative humidity and dry bulb temperature. Programming codes within the PLC use these measured parameters to compute the ambient wet bulb temperature and the wet bulb depression (i.e., the difference between the dry bulb and wet bulb temperature) to quantify and control the amount of evaporative cooling that is possible with the ambient conditions. The system turns on or off fog cooling stages to match the ability of the ambient air conditions to absorb water vapor. Typically the system should have a user editable parameter that gives the operator the ability to inject a controlled amount of excess fog for compressor intercooling. The control system also monitors pump skid operating parameters such as water flow rates and operating pressures and provides alarms when these parameters are outside acceptable ranges. For applications where the fog system will be employed through a range of turbine loads it is advisable to input turbine load to the PLC. The software would then be configured to adjust the amount of fog injected in proportion to the inlet air mass flow.

The staging method for fogging operation is shown in Table 2. In this example, the second and third columns represent the dry bulb and wet bulb temperatures as the day progresses. Additional stages are activated as the day warms up and cooling requirements are increased. In this control scheme, each stage is activated for 5°F cooling.

Time	DB °F	WB, °F	DB-WB °F	Stage on	Cooling °F
9:00	70	68	2	None	-
10:00	75	69	6	1	5
11:00	80	70	10	2	10
12:00	86	70	16	3	15

Table 2. Fog Cooling Stage Control (4 stages of 5°F each)

Table 3 indicates the situation when an intercooling effect is desired. In this control scheme, a user-defined parameter "max overcool" is utilized which controls the amount of excess water injection. In intercooling mode, the parameter "Max overcool" is set to a positive number and the controller tries to always inject more fog than will evaporate.

Time	DB °F	WB, °F	DB-WB °F	Stage on	Cooling °F
9:00	70	68	2	1	3
10:00	75	69	6	2	4
11:00	80	70	10	3	5
12:00	86	70	16	4	4

Table 3. Fog Intercooling Stage Control (4 stages, 5 F each, max overcool set at +5°F)

By choosing pump displacements (gpm) it is possible to derive multiple cooling stages by the utilization of different pump combinations. A configuration of nine cooling stages with the use of five pumps, one rated at 2.5gpm and four at 5 gpm is indicated in Table 4. This allows considerable flexibility with the minimal number of pumps and minimizes spare part requirements.

Cooling Stage	PUMP UNIT "ON"					Flow gpm	Cooling, Deg F
	1	2	3	4	5		
1	•					2.5	3
2		•				5	6
3	•	•				7.5	9
4		•	•			10	12
5	•	•	•			12.5	15
6		•	•	•		15	18
7	•	•	•	•		17.5	21
8		•	•	•	•	20	24
9	•	•	•	•	•	22.5	27

Table 4. Nine Cooling Stages utilizing one pump at 2.5 gpm and four at 5 gpm.

The stage control process is represented in Figure 6 which shows a situation where no fog intercooling is done. The abscissa represents the time of the day and the ordinate the wet

bulb depression. In this case, each “stage” is designed for 2°F of cooling. Between 2 to 4 PM, all 9 stages are utilized. The fog intercooling control schedule is depicted in Figure 7. In this case, the control parameter is set at 2°F of “overcooling” i.e., the control system will spray a greater quantity of water than can be evaporated prior to the compressor inlet implying that some fog intercooling will occur.

7. OPERATIONS AND MAINTENANCE

A typical fog system used for cooling inlet air for a gas turbine requires 15 to 20 hours per year of maintenance. Items requiring maintenance include:

- Inspection of the nozzle manifolds and cleaning or replacement of any damaged fog nozzles.
- Changing crankcase oil for the high-pressure pumps--- Replacing inlet water filter cartridges-
- Performance of extended shutdown procedures for the pump skids and nozzle manifolds when they are not to be used.
- Seasonal start up procedures (installing new filters, etc.)
- Inspection of water treatment facilities and periodic testing of water quality

8. SYSTEM IMPLEMENTATION AND OPERATING EXPERIENCES.

8.1 Application of Inlet Fogging on Frame 7FA Gas Turbine.

Fogging on a Frame 7 FA advanced gas turbine was implemented at a combined cycle power plant in 1997 in Oregon. The utility investigated several cooling options and determined that the most cost effective was an inlet fogging system. The analysis included operating and maintenance costs and also the need for structural modifications required for the inlet system to incorporate traditional evaporative cooling.

In this installation the location of the fogging manifold is downstream of the air filters and upstream of the silencers and trash screens. A total of 1,120 nozzles are arranged in eight stages with each stage providing 3.75 °F of cooling. Operation of all eight stages would result in cooling of upto 30°F. The system operating pressure is 2000 psi and the total fogging water flow is 50 gpm. In this application, the pump skid has four 20 HP high pressure pumps. Shutdown time required for installation was less than one week.

The facility has reported an output increase of approximately 2 MW per cooling stage (3.75°F per stage). A problem that was noted at this facility was the accumulation of water on the floor of the clean air plenum. A water drain was installed just downstream of the fog nozzle manifolds which eliminated this problem.

8.2 Inlet Fogging Application To Frame 7 EA Cogen Plant- Hybrid Application.

A cogeneration facility in California operates a large Frame turbine, which generates a total of 120 MW of Power and also provides steam to a nearby food processing plant. This plant utilizes chillers to cool the gas turbine inlet air. However, the high running costs of the chiller plant made it economically feasible to add some form of evaporative cooling, for use during off-peak periods. In 1994, the company decided to install a high-pressure inlet fogging system. This installation was one of the earlier fogging systems installed and there were several teething problems.

[1] Due to the use of high-speed positive displacement pumps, excessive vibration was noted on the high-pressure lines. The installation of pulsation dampers resolved this problem. While pulsation dampers are recommended for any positive displacement pumping application, running pumps at slower speeds inherently reduce vibration and greatly increases the usable life of pump valves and seals.

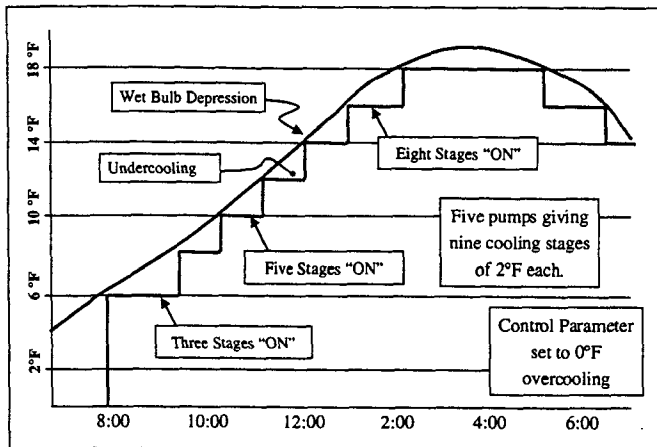


Figure 6. Fog Staging- Pure Evaporative cooling. “Overcooling” Control parameter set to 0°F. (Five pumps configured in nine stages giving 2°F cooling per stage).

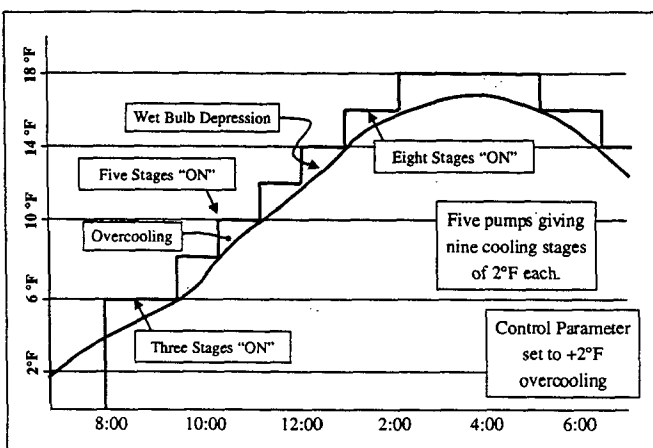


Figure 7. Fog Staging- for Fog intercooling. “Overcooling” Control parameter set to +2°F. (Five pumps configured in nine stages giving 2°F cooling per stage).

[2] The water supply stagnated and allowed the growth of bacteria, which caused plugging of the fogging nozzles and clogging of water filters. This problem was resolved by implementing a maintenance schedule for draining the system during periods of non-use.

[3] Some fog nozzle manifold failures were experienced possibly due to excessive vibration from the high-pressure pumps or to maintenance people climbing on them during air filter maintenance. The problem was resolved by strengthening the attachment of the nozzle manifolds to the structure.

Currently, the chillers are utilized only during the hottest part of the day, when the high running costs are economically justifiable. The fogging system, which is far less expensive to operate, is used during off peak hours. This is a good example of a hybrid system wherein both cooling technologies are integrated and result in an optimal solution.

8.3 Inlet Fogging Applied to- LM 6000 Gas Turbine- Hybrid Application.

Another application that uses a hybrid approach is an LM 6000 installation located in a peaking plant in Las Vegas that starts up 560 times a year. This installation has a 1040-ton capacity absorption chiller but, as the plant is located in a very hot region, the chillers are not able to cool to the ambient dew point temperature. A high-pressure inlet fogging system is used to augment the chiller plant and to provide instant cooling during start up, as the chillers take some time to come online. The fog system is used exclusively when the ambient temperature is less than 70 °F. When temperatures exceed 70°F, the absorption chilling system is also brought online.

In this application, the fogging system is installed upstream of the inlet filters and chiller coils. Results have shown that the final barrier filters remain dry and that the filters stay cleaner due to the scrubbing effect of the fog. This system consisted of 240 nozzles installed in 3 stages of cooling and operates at 2000-psi water pressure with a water flow rate of 10.8 gpm. Three 5 HP high-pressure pump units are installed, one for each cooling stage.

8.4 Inlet Fog Application (upstream of filters) for Frame 7EA Turbine.

A Cogeneration plant operates a Frame 7 EA turbine with a fog system installed upstream of the air filters. The inlet fogging system was designed to include six stages of cooling with 30 gpm of water pumped through a total of 912 nozzles by two high-pressure (1000 psi discharge) pumps. A coalescing type fog droplet filter was installed to remove the fog from the air stream prior to the air filters. This system as installed in 1989 and is also one of the earliest applications of inlet fogging.

The main problem experienced by this cogen facility resulted from its adjacency to a coke plant and the effectiveness of high pressure fogging as a scrubbing or prefiltering system. Large quantities of airborne coke fines were scrubbed out of the inlet air and captured in the fog water. In the original design, the water that was collected on the fog droplet filters was returned to the fog system. This recycled water contained a large number of sub-micron coke particles, which overwhelmed the water filtration system and caused plugging of the filters located in each nozzle. Several fixes were attempted including using larger orifice nozzles that would allow the

coke fines to pass through. While this solved the plugging problems, the larger droplet size generated by the large orifice nozzles did not evaporate quickly and failed to provide adequate evaporative cooling. The final solution was to reinstall the smaller orifice nozzles and abandon the water recycling system. Fresh demineralized water was used and the wastewater was filtered then burned off by the plant's stream host. The plant continues to use the fog system for gas turbine power augmentation.

9. DESIGN AND IMPLEMENTATION CHECKLIST

A checklist is provided here to ensure trouble free operation of an inlet fogging system. While not totally exhaustive, it contains several elements of importance from design to maintenance.

9.1 Application Engineering Checklist.

- Has a detailed climatic study been conducted?
- Has economic analysis been conducted to check NPV of system over its life cycle?
- What are the economic parameters that are subject to change that might make the project marginal?
- Has impact on emissions been considered?

9.2 Design Review Checklist.

- Check all the vendors design calculations with regards to flow requirements, off design conditions, and evaluate the design under different climatic conditions.
- Evaluate amount of overspray required (i.e., intercooling effect) and ensure that the compressor can accommodate this .
- If overspray is being considered, review generator capability, LO cooler capability
- Insist on all SS piping.
- If a high pressure system is being used, have pulsation dampers been provided ?
- In the event of a problem, does the design permit rapid isolation so operation can proceed without the fogging system?
- Optimize location of the fogging manifold with respect to air filters and inlet system
- Check that sequential fogging capability (cooling stages) is adequate to meet your demand profile and turndown profile.
- What design features has the vendor provided to avoid potential FOD?
- Check rigidity of the manifolds to avoid flow induced vibration due to gas turbine airflow.
- Review vendors proposed manifold design for structural rigidity and strength.
- Review possible tie-in of skid PLC with plant DCS.
- Ensure that design does not impose a large pressure drop
- Evaluate proposed installation in duct for maintainability and accessibility.
- Ensure that appropriate drain lines will be installed in the inlet system

9.3 Vendor Selection Checklist.

- Has vendor proven experience with application of fogging to gas turbines? Check track record.
- What is vendor experience with the size/type of gas turbine that you are considering.
- Talk to users of the proposed system
- Evaluate long term service capability of vendor
- Evaluate after sale support by asking for user experience.
- Has vendor supplied systems that can be used as hybrid systems should this need arise in the future.
- Check track record of installation and debugging time with different users.
- What tests has the vendor done to quantify droplet size for his system?
- What studies (CFD, lab testing, installation tests etc.) has the vendor done to address droplet evaporation time, optimum location and orientation of fog nozzles in the airstrip?

9.4 Production and QA Checklist.

- Review Vendors Quality Plan and set up inspection points for the skid and other equip.
- Does vendor exhaustively check each fog nozzle?
- What in house tests are conducted?

9.5 Installation Checklist.

- Ensure that the appropriate outage has been planned and that the details of the installation and Division of Responsibility has been clearly defined with the vendor.
- Has thought been given to maintainability of the system – access doors, viewing windows and drains.

9.6 Testing Checklist.

- Has a test plan been clearly defined and guarantee qualifications made. This should be carefully looked at to avoid problems especially if there is a turbine overhaul instituted.

9.7 Operations Checklist.

- What testing program has been instituted to ensure quality demin water is always being supplied?
- What sensors and interlocks have been provided to ensure quality water?

9.8 Maintenance Checklist.

- Has vendor provided a detailed manual including PLC logic and code?
- Has some training been scheduled for your operators? Are operators aware of the importance of only demin water being used and of avoiding stagnant water in the fog sysem etc.?
- Review maintenance of the demin water system
- Nozzle inspection and refurbishment schedule.

10. CLOSURE

The severe dependency of gas turbine output and heat rate to ambient temperature has fostered a wide range of inlet cooling technologies. This paper has covered several practical issues relating to high pressure inlet fogging implementation. As with any system the user must understand the system, the features and the limitations. The paper has included several lessons learned and provides a design and installation checklist to facilitate implementation.

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