Proceedings of ASME Turbo Expo 2003
Power for Land, Sea, and Air
June 16-19, 2003, Atlanta, Georgia USA

2003-GT-38757

INLET FOGGING FOR A 655 MW COMBINED CYCLE POWER PLANT- DESIGN, IMPLEMENTATION AND OPERATING EXPERIENCE

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ABSTRACT

The design, installation, commissioning and operation of a fogging system for a large 655 MW combined cycle power plant is described. Technical details and practical installation issues are discussed. Special considerations as to how the fogging system could help in the augmentation of power during high temperature and low frequency operation of the gas turbine is discussed. Finally a discussion is made regarding the importance of inlet filtration and the proper selection of blade coatings.

NOMENCLATURE

DBT	Dry bulb temperature, C
WBT	Wet bulb temperature, C
EOH	Equivalent Operating Hours
CFD	Computational Fluid Dynamics
IGV	Inlet Guide Vane
FOD	Foreign Object Damage
Lpm	Litre per Minute
Hz	Line Frequency, Hertz

INTRODUCTION

Gujarat Paguthan Energy Corporation Pvt. Ltd.'s (GPEC) genesis can be traced to the year 1991, when Govt. of India liberalized different sectors of economy and invited the private sector to participate in increasing the power generating capacity of the country. The project took off with laying of the foundation stone on 24th January1996. The ambitious 655 MW gas based Dual Fuel Combined Cycle Power Plant is located near Bharuch in the State of Gujarat, India. The first gas turbine was commissioned in October 1997, twenty one months after laying the foundation stone. Combined cycle operation commenced in October 1998. GPEC was the first IPP of a power project of this size in India and was the first project in the country to go on stream with Naphtha as a major fuel.

GPEC's plant comprises of :

- Three Siemens type V94.2 Gas Turbine Generators each rated at 138 MW.
- Three Waste Heat Recovery Steam Generators (HRSG) supplied by Deutsche Babcock producing 275 tonnes/hr
- One Siemens Steam Turbine Generator rated at 241 MW.

The Gas Turbines are capable of firing Gas and Naphtha independently as well as simultaneously in dual fuel mode. Gas is received by a pipeline from nearby Gandhar Gas fields. Naphtha is received by Rail Wagons at a Railway Siding, stored and then pumped via a 10" diameter 7 km long pipeline to the site storage facilities. Electrical power produced is evacuated through 220 KV and 400 KV switchyards to Gujarat Electricity Board for further distribution.

The plant Water supply is derived by drawing water from the Narmada River and pumping it via a 36" diameter 24 km long pipeline to the reservoirs at site. Water is then treated in a pre-treatment plant and Demineralization plant for further use.

UNDERLYING NEED FOR GAS TURBINE INLET COOLING

The climatic conditions in Gujarat include a very hot summer season where the ambient temperatures can reach temperatures of 45 C. During this period, gas turbine[1] and combined cycle output dramatically drop causing a reduction in plant output during a period when maximum power is needed. In addition to the normal temperature sensitivity of the gas turbine, there was a problem of under frequency of the grid the impact of which is described below.

Special Considerations For IGV Control at High Temperatures And Underfrequency Operation

After commissioning the combined cycle, plant operation stabilised and started running for long duration remaining connected with the electricity grid. It was observed that the plant output was adversely affected due to the changing grid frequency.

There are situations in India which cause operation for extended durations in the 48-50 Hz ranges. This under frequency operation has serious implications to the power output as there is a dramatic drop-off in output when the frequency drops. Figure 1 shows a graph of the drop in output with under frequency operation. To compound this, this gas turbine has a control aspect that calls for the shutting of the Inlet Guide Vanes during conditions when the ambient temperature exceeds 38 C and the frequency is less than 48.5 Hz

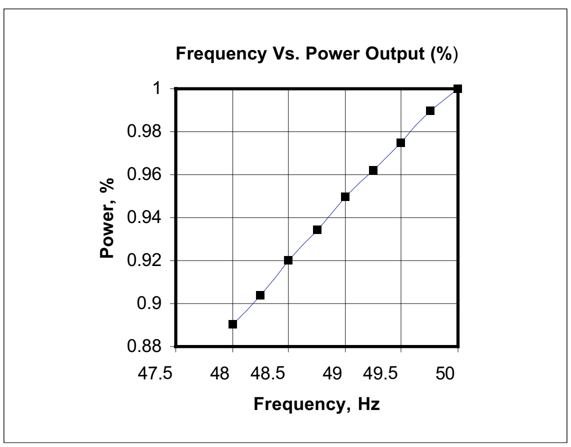

Figure 1. Effect of Under frequency Operation on Gas Turbine Power output at 45 C ambient temperature. Note that the effect under 48.5 Hz is even more severe than shown due to partial closing of the IGVs which is not shown in this Figure.

In particular, during the times when the grid frequency was less than 48.5 Hz and ambient temperature higher than 30 C the gas turbine Inlet Guide Vanes, as per design, closed to a pre-set degree to avoid compressor front end rotating stall. Due to the closing of guide vanes the Gas Turbines unloaded and resulted in a load reduction of as much as 45 MW across the combined cycle (3GTs+1ST). As the peak demand is during high ambient temperature periods this represented a problem that had to be resolved.

[1] The drop in output for the gas turbine is approximately 0.7% per C rise in ambient temperature. Higher temperatures also worsen the gas turbine heat rate.

As the Grid Frequency was not in the control of GPEC, the only way to overcome the problem was to examine a method to reduce the Gas Turbine Inlet Air Temperature to a point where the IGVs would not close.

EVALUATION OF INLET COOLING TECHNOLOGIES

Various methods of cooling the inlet air were looked into. For this, necessary site data including history of ambient air parameters were collected and analysed. The cost effective analysis was done considering the gain in power due to inlet air cooling. The main advantage of cooling came from reducing the ambient temperature just below 30 C to overcome the effect of GT deloading at greater than 30 C ambient coupled with frequency below 48.5 Hz. It was also imperative that full potential of cooling can not be realized as the Generator design with respect to its cooling potential would not permit the output to reach base load with high temperature ambient air cooled to 15 C or lower temperature.

Two types of inlet cooling systems were available. Evaporative Cooling and Refrigeration Cooling. On preliminary assessment, refrigeration cooling was not considered due to:

- High initial cost and can be as high as 5 to 8 times that of evaporative cooling. O&M costs were also significantly higher
- High parasitic power consumption and the scheme resulted into poor cost effectiveness.
- Requirement of major modifications in the existing filter house.
- Long installation time resulting in downtime for the gas turines.

Evaporative cooling, on the other hand, offered the following advantages ;

- Low initial cost.
- Evaporative cooling cost effectively fulfilled the GPEC requirement which was mainly to maintain the inlet air temperature below 30 C to overcome the effect of GT deloading under high ambient temperature and low frequency conditions.
- Short delivery and installation time enabling rapid realization of the benefits.

Evaporative cooling, however has limitations based on the ambient humidity conditions. This was not an issue at GPEC as the cooling envisaged was to achieve just less than 30 C temperature and during high ambient conditions the humidity remained low enough to allow required cooling.

Once Evaporative cooling was decided upon, two types of systems were evaluated:

- Fog Type Evaporative cooling
- Media type evaporative cooling

In the fog type evaporative cooling, water is atomized by fog nozzles and introduced directly into the inlet air flow passage of the GT Inlet Air Ducting. These fine water droplets, in the form of a fog, evaporate quickly in the air stream and produce an evaporative cooling effect. The issues in favor of spray system were:

Cost approximately half that of Media type.

Payback period of 1 to 2 yrs.

No filter house modifications necessary.

With fogging systems, excessive droplet carryover to the compressor can pose a problem and corrosion of air intake duct should be considered due to the use of demineralized water. Compared to media type systems the auxiliary load requirement are higher and the control is more complex. Details regarding inlet fogging are provided in Chaker et al [1,2,3]. An evaluation of climatic aspects as they impact inlet fogging is provided in Chaker et al [4].

In the <u>Media Type Cooling</u>, water travels down along a specially designed screen or media. The air passes perpendicular to the media and gets cooled in the process. The water, collected at the bottom, is recirculated with a certain percentage blow down done to maintain the water quality. A water droplet eliminator is introduced to reduce droplet carry over. Media type cooling advantages ;

Less probability of water droplet carry over

Lower auxiliary load requirement.

And its disadvantages ;

First Cost twice that of fogging systems.

Payback period of 2 to 3 yrs.

Need for filter house modification if fitted after air inlet filters.

Extra inlet pressure drop. This pressure drop occurs throughout the year, regardless of whether the media cooler is used or not. Typical pressure drops would be approximately 25.4mm (1 inch) water gauge.

Ongoing costs of Media replacement every 3 years or so.

Comparing the two systems on experience basis, it was observed that the Media type cooling system started to be used in the 1970's and there are over 1000 in use world side. Fog systems, on the other hand introduced later and approximately 300 were in use at that time[2].

Considering the merits and de-merits of the two types of evaporative cooling, GPEC decided to float an enquiry with specifications drawn keeping the following things in mind:

Temperature to be achieved below 30 C at an ambient of 45 C i.e. a cooling potential of 15 C.

No overspray or oversaturation.

Fast track delivery to take advantage of outages and start getting early benefit of the system.

Bidder was to suggest the type of evaporative cooler – Media or Fog.

Bidder to suggest the location of cooler, i.e. before or after the GT inlet air filters.

Provide proper justification and if required CFD analysis towards addressing the problem of droplet carry over.

[2] It is estimated that there are currently 700-800 system in use.

On evaluation of various offers received and available options, GPEC selected a Fogging system based on:

Lower cost and payback period.

Timely supply and installation.

Experience.

Justification regarding droplet size, droplet carryover and its impact.

No filter house modification required.

The fogging system supplier located the fogging nozzles after the inlet filters as was their normal procedure. Due to the air quality around GPEC plant, problem of high filter differential already existed during foggy weather and installation of fogging system before the filters would have made it worse.

CFD STUDIES OF THE INLET DUCT

Detailed CFD studies of the flow within the inlet duct were conducted by the fog system supplier. The study indicated the velocity and flow profiles that were to be expected. The aim of this study is to show the impact of possible collision between droplets, as a function of the size, dispersion and velocities of the droplets in the gas turbine inlet air duct. This was done by actually simulating the flow with CFD to provide a dispersed multiphase flow modeling.

The flow consists of the air as continuous phase, and the water droplets as dispersed phase. The motion of the droplets is influenced by the motion of the air and vice versa via displacement and inter-phase momentum, mass and heat transfer. The strength of the interactions depends on the size and density of the droplets.

The interaction between the droplets and the air can lead to mass transfer accompanied by inter-phase heat transfer. The consequence is a decrease both in the temperature of the air and the size of the droplets. Depending on the droplets' density and the fluid dynamic forces acting on the droplets, collision between droplets may occur. The outcome of this collision may lead to breakup into smaller droplets or coalescence into bigger droplet sizes. Additionally, some droplets can strike the wall. The result may be bouncing, shattering or accumulation and emission of bigger droplets depending on the impact conditions. This problem has been addressed using CFD software.

An example of one of the CFD plots is shown in Figure 2 and 3.

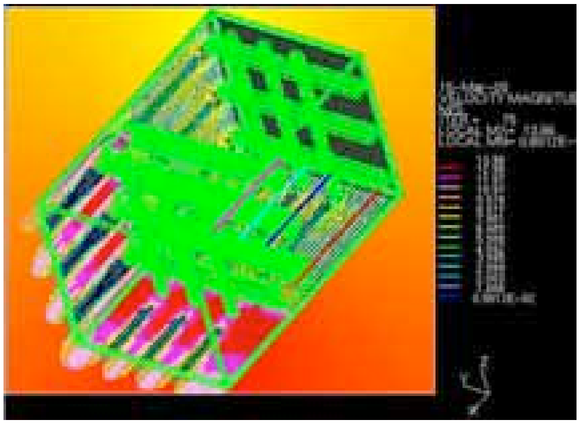

Figure 2. CFD representation of the nozzles (on right) and silencer section.

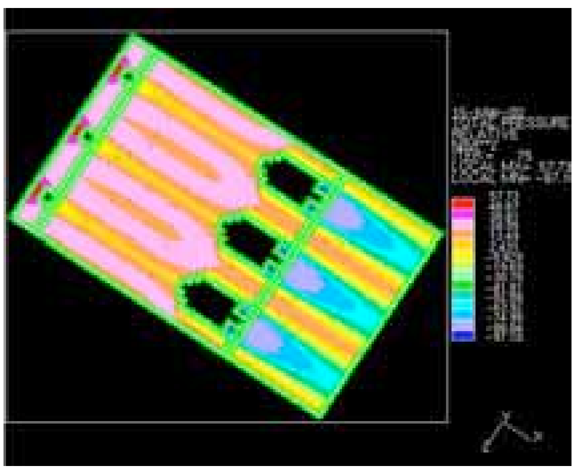

Figure 3. Pressure representation over a section of the silencer.

DESCRIPTION OF FOGGING SYSTEM

Each GT has a fogging system comprising of:

Pump skids containing triplex reciprocating pumps providing high pressure water at 138 Bar (2000 psi). The skids are self contained and provide all the required controls and piping. Two skids were provided per gas turbine with a total of 8 pumps. The skids were shipped by the supplier and located on foundation pads that were constructed by GPEC. Figure 4 shows the fog skids.

A high pressure nozzle manifold located in the gas turbine inlet duct after the filter system. Each gas turbine has a total of 16 manifolds and a total of 1248 high pressure fog nozzles. The nozzle manifolds are shown in Figure 5. A close up of the nozzle is shown in Figure 6.

Interconnecting piping between the skids and the inlet ducts. Figure 7 shows the stainless steel high pressure piping routed to the gas turbine inlet. The inlet filter is shown in Figure 8 where the interconnecting piping can be seen below the walkway.

Each pump puts water into two manifolds out of which one manifold has a valve provided whereby on/off control is achieved on individual manifolds. Each manifold supplies water equivalent to achieve 1 C of cooling. The system uses demineralized water supplied from the already existing DM water plant of GPEC. The water requirement is 11.94 lpm per degC of cooling. Total water flow for maximum cooling of 16 C was 191 lpm.

The system is controlled by a PLC located on the skid which runs in automatic mode based on the dry bulb and wet bulb temperature measurements provided on each of the skid. Start/stop combination of the pumps and manifolds ensures that proper cooling is achieved. The system can be controlled by varying the temp set point to under-fog (i.e. maintain the humidity below 100 %) or over-fog. The saturation control can be achieved within the tolerance of 1 C is sufficient for the application.

INSTALLATION AND COMMISSIONING FOGGING SYSTEM

The system was ordered in January 2000 and commissioning of all three fogging systems were completed one after another within a span of four months. The installation sequence was such that all the work external to the Air Intake Plenum which required GT shutdown was completed beforehand. After arrival of the fog skids, the erection and connected piping upto the filter house for one GT took a minimum of 15 days as the location of the skids was a long distance away from the inlet duct.

Figure 4. High pressure fogging skids

Figure 5. Fog Nozzle Manifold after the inlet filters

Figure 6. Individual nozzle line showing fog nozzles.

Figure 7. Interconnecting Piping from the skids to the gas turbine.

Figure 8. Inlet duct of the gas turbine. The interconnecting pipes can be seen under the walkway.

Once the external work was over, work of installing nozzle manifolds inside the clean air plenum was taken up during the minor inspection shutdown of the GT. In the first unit, the installation and testing took 72 hours. In subsequent units the work was completed within 48 hours. During the initial pressurization tests, some compression fittings that were leaking were replaced. The installation procedures included several measures to ensure cleanliness and the avoidance of FOD.

The fog skids had to be supplied with demineralised water and a three phase electrical connection. Additionally a control connection was made to the plant Siemens control system. For supply of demineralised water, a Tee-off was taken from the main DM water supply line and extended to the pumping skids.

The tie in to the Control room allowed the fogging system to be switched on or off manually from the central control room. The system is automatically switched off if the GT trips and other permissives are provided to ensure safety.

Several drains were installed in the clean air plenum. These drains, with a u-tube water seal, ensured that the water which accumulated on the floor effectively drains out. Three drains are provided along the clean air plenum just before the silencer.

Two viewing windows with lights were provided for each GT. One is located on the side wall of the clean air plenum so that the fog and most of the nozzles can be viewed while in operation. The other viewing window and light is also provided at the compressor inlet bellmouth area so that the condition of air entering the compressor can be viewed and also compressor blades can be observed with the help of a strobe light. The viewing window located at the manifold location in the clean air plenum after the filter system is shown in Figure 9 and a view from the viewing window at the compressor inlet is shown in Figure 10.

The testing and commissioning of the system involved:

- Functional tests of the control system.
- Functional tests of the pumps and testing of its safety relief valves.
- Functional tests of the manifold motorised valves.
- Leakage checks and rectification.
- Fogging of each manifold one by one and checks for uniformity of fog. This also involved relocation of some nozzles where the spray was impinging on the support frame-work leading to condensation and droplet formation.

Figure 9. Penetration of high pressure fogging tubing into the inlet duct for the multiple cooling stages. The viewing window can be seen to the left. The upper window is to provide lighting.

Figure 10. View from compressor inlet plenum viewing window.

OPERATION AND MAINTENANCE OF THE FOGGING SYSTEM

After successful commissioning, the fogging system was put into regular operation with the following philosophy of operation:

- Use mainly when required to overcome the effect of low frequency and high ambient conditions.
- Temperature of inlet air to be brought below 30 C

During the initial operation of the system, regular visual observations from the viewing windows were made. It was observed that considerable condensation took place on the support frame-work which trickled down and drained out. Also some of the nozzles were located such that condensation took place on the cross support beams in the plenum. Subsequently, during a short shutdown, the nozzle orientation was changed such that they were inclined away from the filters. Some of the nozzles were relocated to avoid condensation on the support beams.

As such, the operation of the system has not posed any problems except minor failure of two to three safety relief valves and two pumps failing out of the total 24 installed. One PLC failure has been faced during the operation. The supplier has provided services and replacement promptly. Maintenance of the system mainly involves regular checks on the pumps.

EFFECTS OF FOGGING AND FUTURE STRATEGY

For four months after commissioning, the fogging system was operated for an equivalent of 2.5 months on two GTs and an equivalent of 3 weeks on one GT. Fogging helped the station maintain maximum output during the peak demand months of summer. Subsequently, the system has remained in use for short periods due to low electrical demand and part load operation of the power station. The station availability increased by approximately 2% over the year.

Due to varying grid frequency, it was difficult to determine the power gain under steady conditions. Table 1 shows some data recorded. It was observed that the power gain was as expected and as per the performance curves of Siemens. The main power & hence availability gain came from avoidance of GT deloading during low frequency high ambient conditions.

During initial operation, power loss was observed after running fogging for a short period. Off line compressor washing was then done which resulted into recovery of the power lost. This initial compressor fouling was attributed to the fact that the fog has a tendency to carry with it the dust which has previously accumulated in the clean air plenum, silencer and ducting.

After four months of operation, units were inspected during the scheduled outage. At first look it was observed that the leading edge of the inlet guide vane and the first stage blades had erosion and it was thought to be normal. Also the easily visible suction side of the blades was normal. However, when the pressure side the first stage blade was observed with the help of a mirror, considerable coating wear was found (See Figure 11). The maximum wear in one of

Figure 11. Compressor blade coating wear.

the GT on 1st stage blade extended to approximately 60-70 mm along the blade width from the leading edge. The pattern of wear was same on all the GTs. The inlet guide vanes were found to be unaffected. The first six coated stages of blades were replaced during a routine overhaul.

Subsequently, the causes of compressor blade coating wear were analysed in detail. Considering that the pressure side of the blades were not inspected before start of fogging, and keeping in mind the ambient air quality at GPEC, it was felt that three main factors contributed to the coating wear. One was fogging, second was reuse of inlet filters after pressure cleaning and third was on-line filter changing sometimes under emergency conditions. It is important to note that with a hostile ambient quality, the demineralised water can become acidic so accelerating the coating wear process. Some of the facts pointed to fogging being the major cause for coating wear. One was that when a GT was previously disassembled in July 1999 after running for 18,000 Equivalent Operating Hours (EOH) before fogging was installed, no coating wear was observed on any of the compressor blades. In another GT, subsequent to installation of Fogging, it was observed that the new blades replaced in July 2000 had about 15 mm coating wear after just 4500 EOH with fogging running only for 69 hours. The coating wear on all GTs also showed progressive increase during inspection as fogging continued.

Looking into the coating wear on the compressor blades, and the fact that fogging was needed as it gave considerable benefits to the station, GPEC started looking for a solution to the problem in consultation with the fogging system supplier and also blade coating companies. As a first step, it was decided to discontinue the use of hand cleaned air filters and also stop the procedure of on-line filter changing. The worn out blades were sent for examination and it was found that the blade parent metal was also eroded. As a means to overcome the problem, it was decided to try out a different type of coating which is more erosion resistant. Sermatech, whose coating is originally used on the compressor blades, suggested an alternative coating. Station decided to try this coating and the refurbished set of first three stage blades have been coated with new type of coating. These blades are now in use and coating wear will be monitored.

CLOSURE

This paper has described the successful design, installation, commissioning and operation of a large scale inlet fogging system at a 655 MW combined cycle power plant. Selection, ordering, installation and commissioning was done on a fast track to reap the benefits during peak demand periods The benefits of the Fogging have been good with an availability increase of as much as 2%,. The effect on the compressor blades needs further understanding and a solution will evolve as further experience is gained. In a long run, the best solution may be to replace the blades with new type of material.

Inlet fogging provides a low cost technique to boost plant power and to avoid dramatic drops in power due to exceedingly high ambient temperatures during the summer months. Additionally, it provides a benefit in controlling the temperature to a region where the IGVs can be kept open resulting in even more power than might be possible.

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Table – 1 : Gas Turbine Inlet Fogging Performance Data

14/04/2000

GT-11

	Reading Set-1		Reading Set -2		Reading Set-3	
	Fog-OFF	Fog-ON	Fog-OFF	Fog-ON	Fog-OFF	Fog-ON
IGV Position	Full Open	Full Open	Full Open	Full Open	Full Open	Full Open
Compressor Inlet temp degC	36.8	25	36.6	25.1	36.5	25.3
Compressor outlet temp degC	354	346	354	347	354	344
Compressor outlet pressure bar	9.19	9.41	9.21	9.41	9.21	9.23
Frequency	48.93	48.92	49.08	49.11	48.92	48.97
MW	127	131	128	131	127	131

GT-13

	Fog-OFF	Fog-ON	Fog-OFF	Fog-ON	Fog-OFF	Fog-ON
IGV Position	Full Open	Full Open	Full Open	Full Open	Full Open	Full Open
Compressor Inlet temp degC	36.1	25.5	36.3	24.09	36.3	25.6
Compressor outlet temp degC	351	343	352	344	352	342
Compressor outlet pressure bar	9.3	9.56	9.32	9.667	9.3	9.56
Frequency	49.1	49.06	49.24	49.24	49.01	49.04
MW	132	137	133	137.6	132	138

Data on availability gain compared for the same month of consecutive years before and after installation of Inlet Fogging :

1) Generation higher by 3 %. Out of which 1.7 % attributable to increased capacity and 1.3 % attributable to prevention of deloading.

2) Availability increase by 4.24 %