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Upgrade of the Intake Air Cooling System for a Heavy-Duty Industrial Gas Turbine

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ABSTRACT

This paper describes continued efforts, spanning over number of years at the Watson Cogeneration plant located in Carson California, to improve the intake air cooling system in enhancing power output and performance of the four existing heavy-duty GE 7EA gas turbines. In early 2010, a decision was made to remove the media-type evaporative cooling system from one of the GT units (Unit #4) and rely completely on the high pressure fogging system to cool the compressor inlet air for power augmentation. The reasons and the efforts made for modifying the intake air system are elaborated in this paper including discussion on the results obtained due to implemented changes.

Steam turbine condensate at 49 °C is utilized as the fogging water in contrast to the commonly used demineralized water at the ambient conditions. A discussion on the implication of using high temperature fog water is included here.

NOMENCLATURE

D	droplet diameter [μm]
DBT	dry-bulb temperature [°C]
HR	heat rate [KJ/KW-hr]
RH	relative humidity [%]
V	droplet relative velocity [m/s]
We	Weber number [-]
WBT	wet-bulb temperature [°C]

Greek Symbols

ρ	Air density [kg/m^3]
σ	Water surface tension [N/m]

Acronyms

EC	Evaporative Cooler
FOD	Foreign Object Damage
GPM	Gallons Per Minute
GT	Gas Turbine
IA	Intake Air
IAS	Intake Air Silencers
OEM	Original Equipment Manufacturer
WCC	Watson Cogeneration Company

INTRODUCTION

The Watson Cogeneration Company (WCC) plant, fully commissioned during the first part of 1988, consists of four GE 7EA gas turbines, two Dresser-Rand Steam Turbines and four dual-pressure heat recovery steam generators.

The original installation of the Intake Air (IA) ducting incorporated media-type Evaporative Cooler (EC) system for power boosting which was designed to provide 85% evaporative cooling efficiency for the site rated ambient conditions. The EC media was wetted and the GT inlet air was cooled using the “once-through-water” system.

At the time when WCC plant was designed and commissioned, the EC method for power augmentation was well established. Whereas, the high pressure fogging for power augmentation was in its infancy and very few GT units were furnished and/or retrofitted with the fogging system around the world.

From the very beginning of operation of the GT Units at the WCC plant, it became evident that there was a carry-over of the wet-media cooling water into the compressor. The results of this carry over were significant fouling of the compressor blades and erosion of the first stage compressor's rotor blades resulting in the loss of GT power output and increase in its heat rate (HR). To mitigate operational and performance issues associated with the EC system, the EC system had to be operated at the part-load until 1998 when a fogging system was installed downstream of the EC system to make-up with the losses of the EC system.

A decision to remove the EC system took several years and was accelerated due to the fact that the water supplying authorities projected curtailment and possibly total cut-off of the water required with the once-through-water EC cooling system. Therefore, in 2010 a decision was made to remove the EC system from the GT Unit #4 and rely completely on the fogging system for power augmentation needs.

This paper describes the efforts made for modifying the IA system including discussion on the results obtained due to implemented changes. The fogging system suppliers recommend the use demineralized water for the fogging system. However, the steam turbine condensate available at 49 °C has been used since 1998 at the WCC plant. A discussion on the implication of using high temperature fog water is discussed in this paper.

REASONS FOR REMOVAL OF THE EVAPORATIVE COOLER SYSTEM

A decision to remove the EC system took several years and was accelerated due to the fact that the water supplying authorities projected curtailment and possibly total cut-off of the EC cooling water in the coming period.

The existing EC media is installed in six modules, each module 2.42 meters by 3.33 meters, and it is positioned in two levels (see Fig.1) inside the IA filter house. These modules created a barrier between the filtered IA and the existing fog manifold located downstream of the EC system. Figure 1 shows the IA house structure without the EC media. The frame holding the EC media modules was not removed because of the lack of time during the recent implementation of the fogging system in the GT Unit #4.

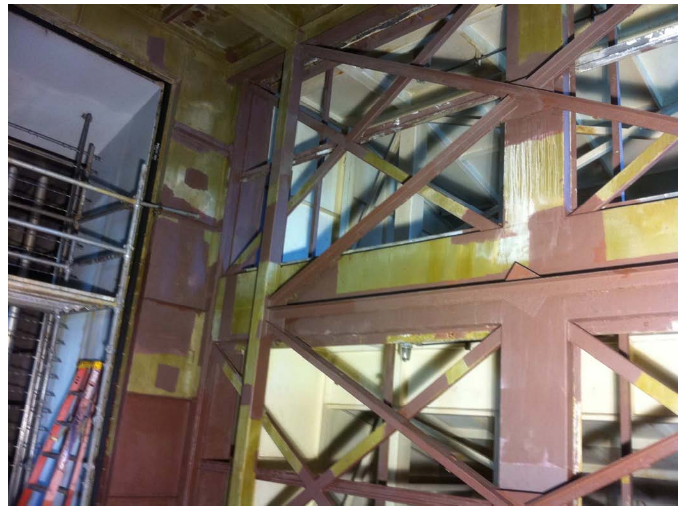

Figure 1 A view of the empty frame for the evaporative cooler media

In order to get 85 % evaporative efficiency for the EC system, the wet-media required a surface area and thickness of 120 m^2 and 0.30 m, respectively. The media is normally replaced with new media during each major inspection scheduled after 48,000 operational hours for each GT unit at the WCC plant.

The EC media is continuously wetted with the once-through-cooling water at the rate of 15.13 l/s of at the site rated ambient conditions of 43.3 °C dry-bulb temperature (DBT) and the corresponding 15% relative humidity (RH).

This barrier EC media was fouled with calcium carbonate in the once-through EC cooling water supply. The EC media manufacturer predicted a maximum pressure drop of 2.50 cm of water column due to the fouling of their media. This inlet pressure drop associated with the EC system results in GT power output loss of approximately 0.30 MW (0.34%) for the GE 7EA gas turbine.

Removal of the EC system also eliminates completely once-through water carry-over into the compressor suction. Simultaneously, it also eliminates potential bombardment of large water droplets in case they are ingested into the compressor and causing erosion of its first stage rotor blades.

During the IA cooling using the EC system only, about 12% of the cooling water is evaporated; the balance is drained and some small amount of cooling water is carried-over with IA stream into the compressor suction. Special, rather comprehensive drainage system of un-evaporated cooling water is necessary. Separate drain lines are connected to the main drain manifold and from there to a suction tank for the EC water transfer pump. Since removal of the EC system eliminated water puddles accumulation at the floor of IA house, the drain line points were permanently plugged.

Removal of the EC media, refer to Figure 1, revealed significantly altered picture of the IA inside ducting. The IA house is now treated as a dry chamber, hermetically sealed to the outside unfiltered air. The only moisture in IA filter house will come from the ambient air. Even this moisture amount may be reduced by implementing atmospheric moisture coalescing blankets over each IA filter element.

There are two additional positive aspects of replacing the EC system with the "all fog" IA cooling system:

1. There is no need for operator to enter IA house in order to adjust cooling water flow to each EC module and
2. Corrosion rate of the IA house interior steel walls is greatly diminished.

A decision was made to run the all-fog system for the first six months with the EC system readily available, on the stand-by, in case of eventual fog system's malfunctions and possible side effects which were not anticipated nor predicted with the implemented changes to the GT Unit.

In case the EC system would be necessary, re-installation of the available EC media would be relatively short and easy and could be made during the weekend.

REQUIREMENTS FOR THE FOGGING SYSTEM

The fogging system demands high pressure (138 barg) water and also the water must be pure. Demineralized water is most pure and is recommended by the fogging system supplier. However, the demineralized water can cause corrosion to the carbon steel commonly used in the construction of the IA ducting. While implementing fogging system during 1998 in combination with the existing EC system at the WCC plant and to avoid changing the existing IA ducting, it was decided to use the steam turbine condensate in place of the demineralized water. An additional discussion on the use of condensate will be presented later in this paper.

The intent of the fogging system is to generate water fog particles as small as possible (less than 20 microns diameters) to encourage the most efficient evaporation when mixing with IA [1, 2]. The intent is also to evaporate as much as possible of fog particles prior to their entry into the compressor. In other words the fogging system's designers strive to reach 100% saturation of the IA prior to its entrance into the compressor suction under different ambient conditions at the given site.

The fog manifold serves to carry fog-generating nozzles and is situated in the rectangular portion of the IA duct, perpendicular to the IA flow. In order to obtain the most efficient cooling effect, it is important to understand the air flow velocity distribution within the IA ducting.

Figure 2(a) presents results of a CFD (computational fluid dynamic) analysis showing air flow velocity distribution inside a similar IA duct. Whereas, Fig. 2 (b) shows the average air flow velocity distribution as a function of the duct length and the duct configuration assumed in Fig. 2 (a). The plot clearly shows a strong increase in the average flow velocity going from the filter region to the duct outlet, where velocity values are close to 90 m/s. Velocities of IA are shown also in horizontal plane. There is a sharp increase of IA flow velocities entering the space between the silencer panels.

Field experience has demonstrated, when the silencer is old and dirty, that the fog system, installed upstream of the silencer panels, acts as an excellent scrubber of accumulated dirt on the silencer panels resulting in compressor blades fouling.

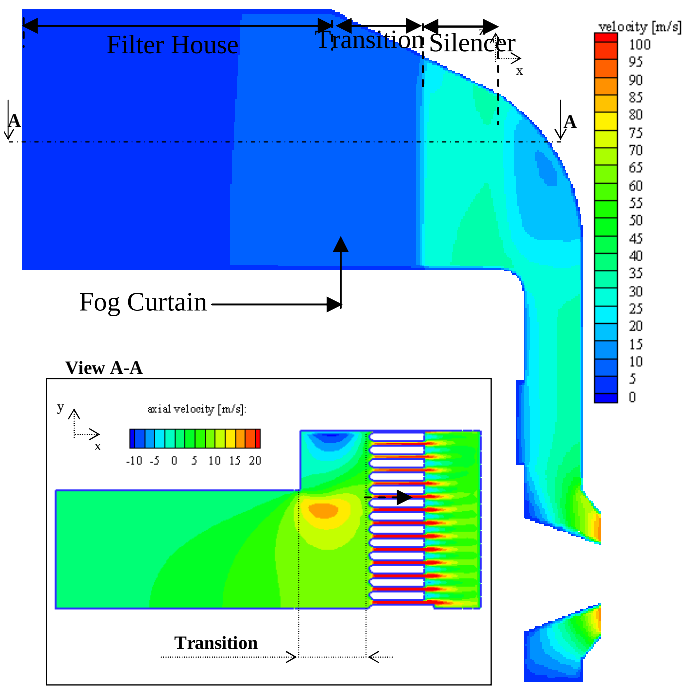

Figure 2 (a) Intake air velocities distribution [3]

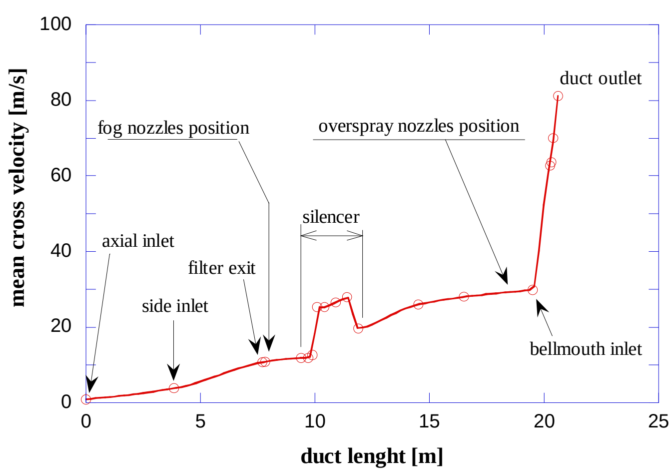

Figure 2-b Distribution of IA *average* velocities inside IA duct. Arrows show preferable location of fog-generating, impact-type nozzles [3]

The overspray fog nozzle grid is not presently used in Watson Cogeneration Plant.

Fog Manifold Location

Location of the fog manifold is very important in order to provide sufficient residence time for the fog particles (droplet diameters of 20 microns and larger) to evaporate prior to entering the compressor suction or bell mouth. Unfortunately, what is best for evaporation of the fog water is not necessarily possible because of configuration of the existing IA ducting and the inlet air filter house.

Frequently designers of the IA system (air filter house and the associated ducting) are not motivated by its aerodynamics but rather by simplicity of fabrication and the cost of material which is normally low for the use of carbon steel and sometimes stainless steel in vicinity of the compressor suction. In addition when the fog system installation is implemented in mature GT units, maintaining the cleanness of the Intake Air Silencer (IAS) panels may prohibit installation of the fog manifold upstream of the IAS panels. The user is then forced either to replace the IAS panels or to install the fog manifold just downstream the IAS panels. There are known cases, based on experiences at the WCC plant, where fog scrubbed the dirt from the silencer panels and in turn air stream carried this dirt into the compressor. Instant fouling of the axial compressor was recorded and resulted in up to 10% drop of the GT power output. The remedy for this type of malfunction is relocation of the fog manifold just downstream of the IAS panels. Since the IAS panels' dimensions are significant, fog particles residence time in the intake duct was significantly reduced and any fog particles large than 20 microns were sucked into the compressor. This can be also explained by the air stream acceleration as it comes closer to the compressor bell mouth.

In light of the above discussion on the air flow velocities in a typical IA duct, the concentration of fog-generating nozzles should be the highest where the IA velocities are the highest. This is difficult to implement because of the fog manifold supporting columnar structure and because the fog grid may be installed upstream of the IAS panels. In case, the distance between the fog manifold and the IAS panels is less than 1 m (distance and airflow velocity that allows enough response time for un-evaporated droplets to follow the airflow between the silencer panels), fog particles will strike the vertical panels of the silencer and agglomerate into larger droplets size particles. These large water particles will fall due to gravity onto the floor of the duct and from there continuously drain outside the IA duct. This portion of the fog water is counted as a loss and the theoretical psychometric chart for air must be corrected for actual conditions in the IA duct. Field measurements, taken at the WCC plant, have demonstrated that regardless of the ambient conditions the amount of fog water accumulated at the floor of IA duct is virtually the same; about 12% of the original fog water amount

In order to prevent agglomeration of tiny fog particles (equal or smaller than 20 microns) the fog manifold is normally located in such a way that the fog plumes bypass obstruction such as the IAS panels and also that the plumes are far enough from the other obstructions such as the trash screens.

The IA duct dimensions for the GT unit under discussion are shown in Fig 3. Figure 3 shows also location of the fog manifold which is 1.1 m upstream of the IAS panels' leading edge. The leading edge of each IAS panel is rounded to reduce the air turbulence losses.

Figure 3 also shows the location of trash screen mandatory per any OEM in order to prevent foreign object entering compressor suction. Typical trash screen is made form wire mesh, where wire is normally 1/16 inch diameter and the space between the wires is not greater than 1/4 inch. The wire mesh is properly framed and its area facing on-coming air stream and fog is not insignificant. Fog particles strike the wires and the frame, agglomerate and then drop due to their increased weight. Some of these large water particles may entrain axial compressor causing steady erosion of the first stage blade leading edges especially if they are not protected by erosion-resistant coatings.

The original fog manifold of 480 nozzles was modified as shown in Fig. 4 in which the number of nozzles is increased to 600 nozzles. The intent was for nozzles to face the space between adjacent silencer panels.

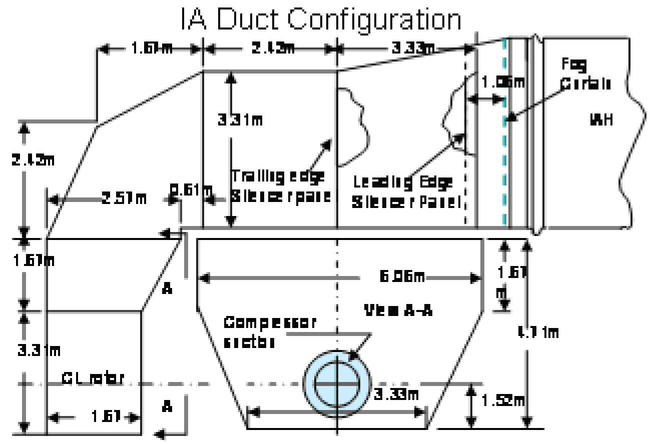

Figure 3 IA duct configuration and dimensions for the upgraded GT Unit

Figure 4 New fog manifold installed in the same location as the original fog manifold

Fog water drainage

Numerous tests were conducted during the summer of 2010 on the GT Unit #4. The test data summarized in Table 1 shows that the test were conducted on two different days with multiple combinations of the inlet air cooling systems (namely, only media EC system, only fogging system, both EC and fogging systems operational, and no cooling systems operational). The purpose of these tests was to estimate the amount of fog particles which were not evaporated in the IA stream. According to the psychometric charts, the cooling of IA depends on the ambient conditions (coincidental values of DBT and RH at a given time of the GT units' operation).

The tests however contradicted the expectation that is for a wide range of ambient temperatures and relative humidity the amount of drained water (around 10 percent) was surprisingly steady.

Table I illustrates relative insensitivity of un-evaporated amount of fog water drained just upstream of IA silencer. Table I also shows that compressor discharge pressure is also insensitive. However, compressor discharge temperature drops as much as 8°C.

At 40°C ambient temperature and relative humidity 17%, the un-evaporated fog water drain was 0.076 liters per second and for the ambient temperature 17 °C and relative humidity 85% the water drainage was measured 0.11 liters per second.

Table 1 Performance data on GT Unit #4 before implementation of the modified fog manifold

Parameter \ Time/Date		9/22/2010 7:30:00	9/22/2010 8:10:00	9/22/2010 8:15:00	9/27/2010 7:05:00	9/27/2010 7:55:00	9/27/2010 10:30:00	9/27/2010 13:30:00
Dry Bulb Temperature	ºC	19.2	18.9	18.9	23.9	26.3	35.0	40.0
Relative Humidity	%	87	73	73	53	45	24	20
Atomized Water Fog Flow Rate	l/sec	0	1.237	1.230	0.662	0.732	0.707	0.757
Wet Media Water Flow Rate	l/sec	0	0	0	6.309	6.309	6.309	6.309
Gas Turbine Power	MW	82.3	84.6	88	80.5	82.7	83.9	81.5
Compressor Discharge Pressure	Bar	11.38	11.51	11.65	11.17	11.24	11.31	11.10
Compressor Discharge Temperature	ºC	356.7	346.7	348.3	357.8	361.1	355.6	356.1
Turbine Discharge Temperature	ºC	537.8	535.6	536.7	540.0	552.8	552.2	555.0
Fuel Flow	kg/sec	5.03	5.18	5.41	5.05	5.14	5.27	4.86
DENOX Steam Flow	kg/sec	6.36	6.36	6.91	6.28	6.45	7.41	5.91
Firing Temperature	ºC	1104.4	1104.4	1123.9	1104.4	1123.9	1123.9	1123.9
Drained Fog Water	l/sec	0	0.114	0.114	0.089	0.083	0.079	0.076

Figure 5 illustrates the relative insensitivity of the un-evaporated fog water drain as the function of ambient temperatures.

The measured amount of un-evaporated fog water is result, as indicated before, of fog particles agglomeration in the moment air stream with un-evaporated fog particle strikes the panels of the IA silencer. The agglomerated fog particles now form large droplets of water which fall due to the gravity just upstream the silencer panels. The measurements of water flows that did not evaporate and was routed to the drain were taken with EC shut down.

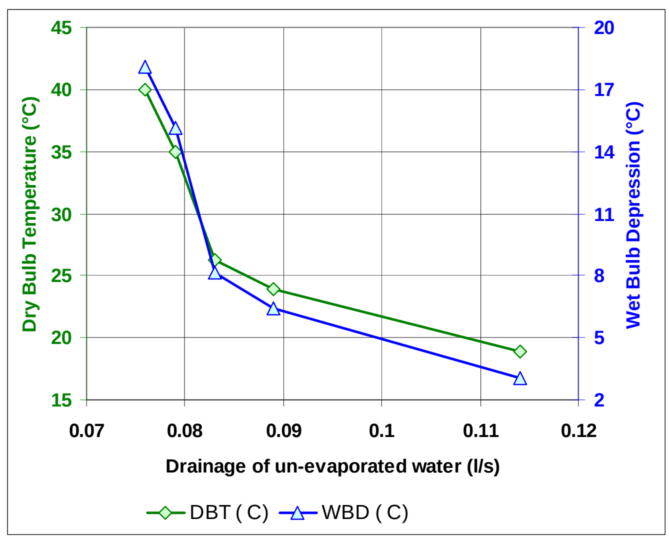

Figure 5 Fog water drain just *downstream* of IA silencer panels

THERMODYNAMICS OF FOG DROPLETS EVAPORATION

Significant research works, Bianchi et. al. [4] were completed and presented dealing with evaporation of the fog particles in the air and resultant cooling of the air when the fog water droplets temperatures being above the IA temperatures.

They concluded that the GT performance improved with smaller fog water particles and with the fog water of higher temperatures. This is somewhere in contrast with the field testing in WCC during the summer of 2010.

Khan and Wang [7] research on droplet heat transfer model describes the heat transfer from surrounding air to the droplets of fog. They state that the droplet heat transfer depends on slip velocity (between the droplet and main fluid) temperature difference, diffusion coefficient, size diameter of droplet and other. They also conclude that that the droplet temperature is predominantly affected by convection mechanism of heat transfer.

Figure 6 presents results based on the theoretical model (see appendix A for more details) verified by numerous laboratory tests [6]. Figure 6a shows the transient behavior of a 20 micron droplet (corresponds to the DV90 of the atomized water) with starting conditions of droplet temperature at 50 °C and air temperature and relative humidity of 26.7 °C and 42%, respectively.

To explain the evaporation-condensation process, let's assume a droplet surrounded by a volume of air. At the instant that the droplet touches the dry air, assumed to contain no water vapor at all, the evaporation-condensation process begins and the exchange starts only by evaporation from the droplet surface to the surrounding air. This is due to a high vapor pressure close to the surfaces of the droplet when compared to far away regions within a given volume of surrounding air. As the evaporation from the droplet surface to the surrounding air increase, the density of water molecules and consequently humidity in the surrounding air increase, and the temperature of the droplet converge to the wet bulb temperature.

With the increase in the density of the water molecules around the droplet, the probability that these molecules collide with droplet surface increases leading to a continuous decrease in evaporation and an increase in condensation. The air reaches the saturation level when a state of equilibrium between the molecules of water evaporating from the droplet surface is equal to the ones condensing on the droplet surface occurs. Consequently, it is possible to approach saturation within the time frame available for gas turbine inlet fogging. A full saturation requires infinite of time before being reached.

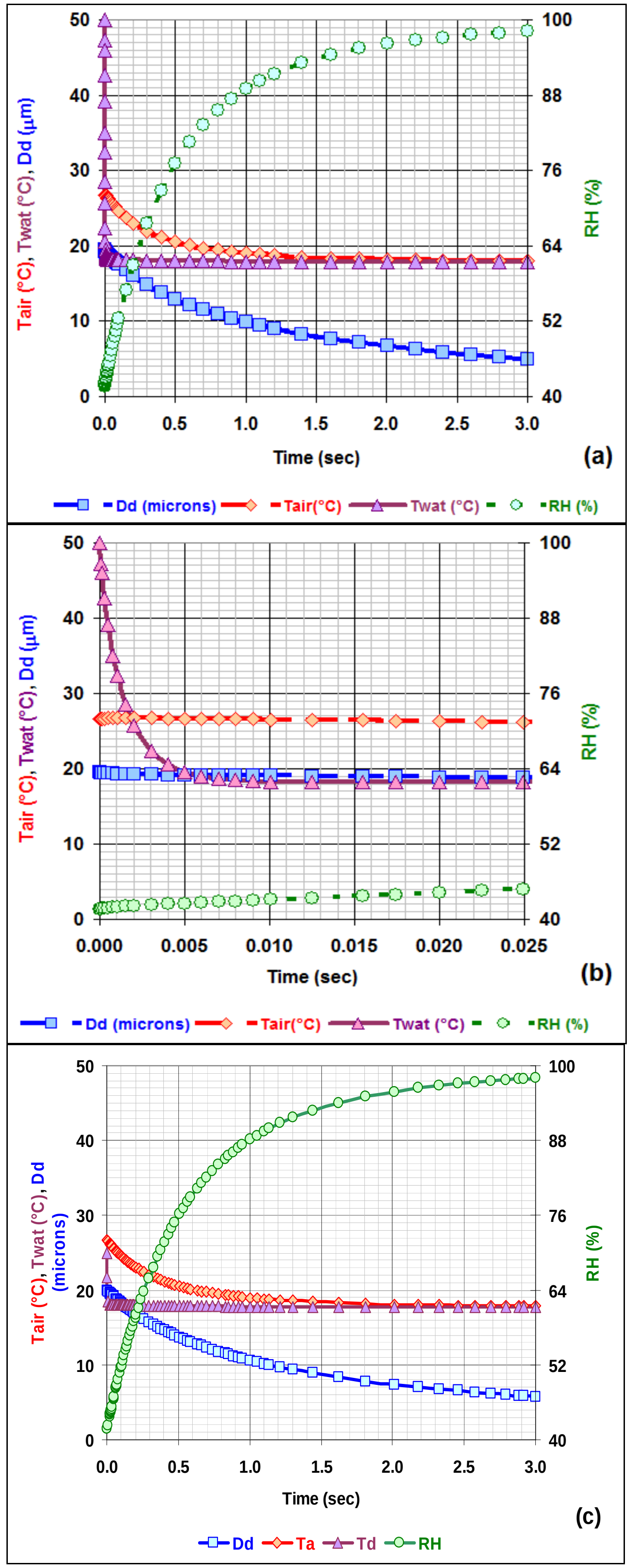

Figure 6 Influence droplet diameters on time to evaporate.

In Fig. 6 (a) we can see the instant decrease in droplet temperature to the WBT of 17.8 °C, the fast increase in relative humidity from 42 to 90 % within 1 second. We can see also that we approach saturation (100% of RH) without ever reaching it. To go from 90% to 98% RH in this case we need around 2 more seconds.

A smaller scale picture of the evaporation process during the first 0.025 seconds is given in Fig. 6 (b). In this figure, the result of the model shows that within 0.005 seconds (5 cm from the nozzle with airflow velocity of 10 m/sec, a typical airflow velocity for the specified nozzle manifolds location), the temperature of the droplet decreases from 50°C to close to the Wet-Bulb Temperature of 19°C.

While the two figures above show the evaporation process for a droplet of 20 microns, it should be noted that more than 90 % volume of the atomized water actually consists of droplets of a diameter less than 20 microns and consequently the evaporation process of the entire distribution in the plume will be faster for the smaller droplets [6].

The instant transformation of tiny spherical fog droplets, range 20 microns or less, takes the place when heat exchange forces overcome viscous forces holding molecules of water in tight formation.

Another point of interest is that the fog water temperature has little impact on the rate of its evaporation as it can be seen in figure 6-C with water temperature of 25°C [4, 6]. The size of the fog droplet however has significant impact on its evaporation. Smaller the fog water spherical droplet, higher ratio of aerodynamic inertia versus surface tension forces holding water molecules together. This ratio can be expressed as Weber Number $We = \rho D V^2 / \sigma$ which is a function of fog droplet's density, diameter, velocity, and surface tension, σ.

Bianchi et. al. [4] showed the influence of water droplet diameter and surface temperature effect on GT performance. The results of their studies are as expected; smaller droplet diameter more efficient cooling of the surrounding air and un-expected; GT power increases as the fog water temperature increases.

The importance of generating fog droplets as small as possible can be illustrated by comparing behavior of 30 micron sphere and 20 micron sphere. For example, 30 micron sphere will have (compared to 20 micron sphere):

- Three-to-four times greater mass and force of impact
- 33% less surface area per unit volume, and
- Two times faster fall (gravity) rate.

In case the fog droplet is greater than 30 microns, it may be carried over un-evaporated to the compressor suction. Once un-evaporated 30 micron particle of fog enters axial compressor (overspray) its residence time inside is less than 0.015 seconds.

Latest research works [8] demonstrated that in some cases 30 micron droplets may pass entire compressor. Some field observations are supportive of the theory that some of 30 microns particles find their way to combustors and evaporate there.

Making the wire mesh with larger opening would allow foreign object to pass and damage compressor blades. Removal of the trash screen strategically positioned by OEM is not recommended and typical User of GT Units is not willing to take the risk associated with potential intrusion of the foreign objects (FOD) into the compressor suction. Eventual entrainment of un-evaporated fog water can be prevented by introducing de-watering fixtures such as dams, double bottom plates, shrouds and troughs.

The most interesting is amount of water drained in the trays on the floor just before and after IAS. As expected the water drain just downstream IAS is approximately 20% of water drain just upstream the silencer. This phenomenon may be explained as follows:

- IA accelerates in the moment it enters the space between adjacent silencer panels, and
- IA de-accelerates in the moment it leaves the silencer and enters the duct plenum.

In addition to IA acceleration prior to entering the space between IAS panels, some of fog collides with leading edges of the panel, agglomerates and drops to specially designed water tray.

OVERSPRAY OF FOG

All fog was selected for the most likely case of ambient conditions; anything exceeding ambient design dry bulb and relative humidity would indicate the shortage of the cooling and conversely any ambient conditions where the parameters are lower than the design parameters would indicate start of overspray that is introduction of water droplets into the compressor suction.

For Frame 7, Model EA GT all entrained fog particles are expected to evaporate by the time they pass stage No 7 as discussed by Haskel [9].

Figure 10 New fog curtain installed in the same location as original fog curtain.

Further research and experiments Khan and Wang [8] confirmed that if the fog particles are equal or greater than 30 microns, they tend to reach compressor discharge un-evaporated.

Overspray of remnant un-evaporated fog particles, either due to particular ambient conditions (low DBT and high RH) , larger than 20 microns droplets or agglomerated droplets striking obstructions in IA duct such as panels in IA silencer and the trash screen downstream IA silencer may have the following effects:

- Erode leading edges of row No 1 blades, and
- Clean the compressor blades.

Erosion of blade leading edges can be slowed down by applying erosion-resistant coating on the leading edges of the aerofoil blades or selecting upgraded material more resistant to particles water bombardment.

Self-cleaning of compressor blades by agglomerated fog particles may be compared to "on-line" compressor wash, though fog agglomerated particles are still significantly smaller than particles of water being issued from "on-line wash" nozzles. These carry-over agglomerated particles will eventually erode chrome carbide protective coating in case GT unit is in continuous, base load service. It is advisable to recoat the leading edges of the first stage compressor blades after each MI.

The field testing results of existing fog system show that efficiencies of saturated "atmospheric" fog compared to efficiency of overspray fog are approximately the same. Research done by Khan and Wang [5] concludes that pound-per-pound of fog water atmospheric fog is more efficient in cooling the atmospheric air.

CONTROLS

Normally each fog generating skid is furnished with local weather station and control system which enables user to decide whether to saturate IA 100% or to continue to generate maximum amount of fog which in turn enters compressor suction in the form of tiny droplets. These droplets evaporate typically 100% by the time they reach the 8th stage of compression.

In WCC a decision was made to provide each fog-generating pump with a dedicated riser header which in turn branches off into horizontal lines with impact-type fog nozzles. Based of ambient conditions operator has freedom to start fog pumps as required.

For example, refer to Figure 11, in case ambient DBT is 15 °C and RH around 50% only one fog pump is needed to avoid overspray. Another extreme is when ambient DBT reaches 32 °C, RH is around 20%, when all 5 fog pumps are needed to obtained desired cooling of IA.

The above matrix enables the operators to start up or shut down individual fog pumps.

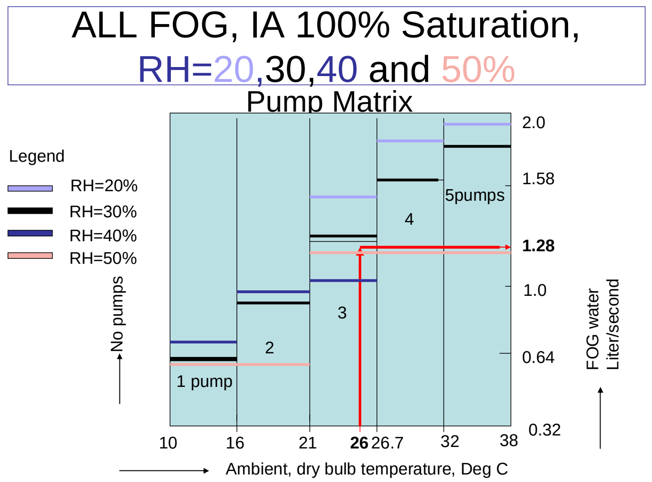

Figure 11 Fog pump matrix for various ambient conditions.

Figure 12 shows fog generating pump delivering to multiple horizontal headers with the fog-generating nozzles. Each pump delivery header is furnished with high pressure water filter which serves mainly to arrest the debris particles in case of the fog pump catastrophic failure.

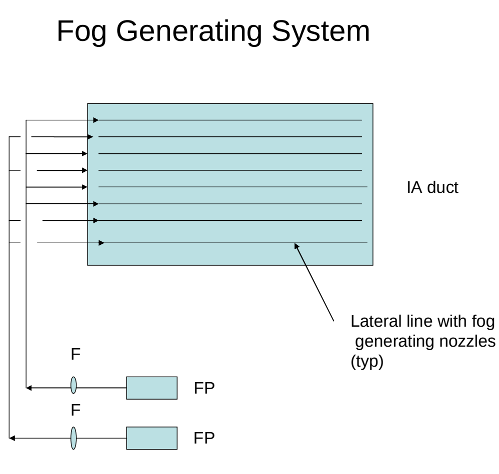

Figure 12 Start of individual fog pump to meet ambient conditions.

SUMMARY AND RECOMMENDATIONS

1. The replacement of existing EC cooler with fog was motivated mainly by uncertainty of cooling water supply form outside responsible agencies.
2. The accumulated operating experience with existing fog cooling system, in tandem with evaporative cooler system, demonstrated that fog is reliable and efficient way to cool IA prior to its entering the compressor suction.
3. Replacement of EC system was also motivated by the fact that the cooling water carry-over into the compressor suction caused some erosion of the compressor R1 blades and also fouled the compressor blades.
4. Summer of 2010 tests demonstrated that certain amount of fog particles do not evaporate when expected because of their agglomeration when striking obstruction such as IA silencer panels and the trash screen.
5. Summer of 2010 tests also demonstrated that the temperatures of fog water have little influence on efficiency of evaporation.
6. Summer of 2010 tests demonstrated that ambient temperature and humidify have also little impact on amount of fog water drained outside the IA duct.
7. Summer of 2010 tests were conducted with fog water flows equal to 1.23 L/s and the drain of un-evaporated fog water was close to 0.13 L/s.
8. Summer of 2010 tests were conducted with EC water flow at its 50% capacity, this to prevent the carry-over into the axial compressor.
9. Removal of 0.30 meters thick EC media introduced extra difficulty when opening IA filter house doors and also introduced possibility of the birds entering IA duct. Trash screen downstream the IA silencer protects GT in such events.
10. The operator of the seasoned power plant should carefully weigh pros and cons in replacing EC with fog system.
11. The operator of seasoned power plant should not place the fog manifold upstream the IAS which is typically dirty and covered with layer of smudge.
12. Place for manifold upstream the silencer, minimum one meter distance, when the silencer is new.
13. Distribute fog-generating nozzles in such a way that they face the space between the silencer panels.
14. Place the trash screen upstream as far as practical and safe from the compressor suction.

15. Avoid usage of de-mineralized water in case the IA duct is made from carbon steel.

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APPENDIX- A

Heat and mass transfer occur at the interface of the droplet and the surrounding air, mainly by convection and diffusion. This transfer depends on the thermal characteristics of the air (hygrometry, total pressure and temperature) and the droplet (size, characteristics and temperature).

The heat quantity stored in a droplet between instant t and instant t+Δt is given by

$$\Phi = m_d Cp_d \frac{\left(T_{d(t+\Delta t)} - T_{d_t}\right)}{\Delta t} \qquad (1)$$

Where:

m_d	Mass of the droplet (kg)
Cp_d	Specific heat of water ($J.kg^{-1}.K^{-1}$)
T_d	Droplet Temperature (K)
Δt	Time Step (s)

The thermal equilibrium between the droplet and the surrounding air occurs when the quantity of heat received by the droplet Φ, in a given time, is equal to the flux exchanged by convection and latent heat

$$\Phi = \Phi_{conv} + \Phi_{lat} \qquad (2)$$

Convective exchange: The rate exchanged by thermal convection between the droplet and the air is given by

$$\Phi_{conv} = h_{cv} \times S_d \times \left(T_a - T_d\right) \qquad (3)$$

S_d Droplet surface (m^2)
T_a Temperature of air (K)

h_{cv} is the coefficient of thermal convective exchange ($w.m^{-2}.K^{-1}$), and is derived from the Nusselt number

$$h_{cv} = \frac{\lambda_a}{D_d} \cdot \left[2 + 0.6 \times \left(\frac{\rho_a^2 .g.(T_a - T_d).(D_d)^3}{\mu_a^2 .T_a} \right)^{0.25} \left(\frac{\mu_a}{\rho_a Df_a} \right)^{0.33} \right] \tag{4}$$

Where:

λa Thermal conductivity, air ($W.m^{-1}.K^{-1}$)
μa Dynamic viscosity, air ($kg.m^{-1}.s^{-1}$)
ρ_a Density, air ($kg.m^{-3}$)
Df_a Mass coefficient of diffusion for air ($m^2.s^{-1}$)
D_d Droplet diameter (m)
g Gravitational acceleration ($m.s^{-2}$)
T_a Temperature of air (K)
T_d Droplet Temperature (K)

Latent heat exchange: The latent heat exchange is equal to

$$\Phi_{lat} = \frac{\Delta m_d \, L_v}{\Delta t} \tag{5}$$

Δm_d Mass variation of the droplet (kg)
Δt Time Step (s)

L_v is the latent heat of water vapor ($J.kg^{-1}$) given by

$$L_v = 1000\,(2498 - 2.413 \times T_d) \tag{6}$$

As stated before, both the temperature of the air and that of the droplet converge rather fast to the WBT, and in these conditions the convective flux becomes equal to zero, the heat absorbed from the air to balance the lost in the mass from the droplet being done by latent heat exchange.