A STUDY AND EXAMPLES OF POWER GAINS ACHIEVED BY FOG INLET AIR COOLING OF GAS TURBINES IN S.E. ASIA.

1. Introduction

From its introduction to the gas turbine world in 1989, inlet air fog cooling of gas turbines has demonstrated significant advantages in price, ease of installation and operation around the world. There are now over 700 fog-cooling installations in operation on a wide variety of land based gas turbines from 2MW to 250MW in size. Power gains of up to 30% are possible with fog cooling, depending on turbine type and site location.

2. What is Fog Inlet Cooling?

One basic method of increasing gas turbine output in a fixed speed application such as electric power generation, is to cool the inlet air. Cooler air is denser and so more power can be generated. The more conventional methods of cooling inlet air are:

1. Media Type Evaporative Systems
2. Refrigeration Type Chillers
3. Absorption Type Chillers

All of these methods have been in use for the past 30 years or so. Fog cooling most closely resembles media type evaporative cooling, except instead of using a passive, water saturated media through which the inlet air is passed, fog cooling is an active system and uses very fine fog droplets of high purity water injected at discrete points across the inlet duct through special atomizing nozzles, at high pressure to create the cooling effect. The amount of fog to be added is continuously controlled by a weather station that monitors dry and wet bulb ambient conditions and adjusts the amount of fog cooling as needed.

A typical fog cooling system consists of a high-pressure pump skid connected by feedlines to an array of manifolds located at a suitable plane across the compressor inlet duct. The manifolds have a number of fog nozzles positioned along their length, which inject very fine droplets of water into the inlet air. Each nozzle flows at 3 ml per second and produces about 3 billion droplets per second. The very fine fog evaporates very quickly, thus dropping inlet temperature. **Figure A** shows a typical fog-cooling array in a gas turbine inlet duct.

3. Advantages of Fog Cooling

There are a number of unique advantages of fog cooling over these other conventional cooling technologies:

a. Ease of Retrofit on Existing gas turbines, no major changes/additions or extensions to inlet ducts needed.

b. Lowest cost per MW gain of all inlet cooling technologies, about 1/6th that of chillers and 1/3th that of media evaporators.

c. Lowest downtime for installation, typically 1 to 3 days.

d. Fastest payback, sometimes less than 1 year.

e. Pressure drop in the duct is negligible, less than 0.1—water. (Compare with media evaporative systems where pressure drop is typically 1 to 2 inches, resulting in a significant performance penalty year round).

f. Close to 100% evaporation possible with fog, so higher evaporation effectiveness than media type evaporative system is possible.

g. Overspray possible, where extra fog is deliberately injected into the compressor inlet, thus generating further power.

Figure A " Typical Large Turbine Inlet Fog Cooling Array

4. Weather Conditions in Asia

There appears to be a misconception amongst power producers in some Asian regions that inlet evaporative cooling of gas turbines cannot yield useful economic gains. Local weather conditions are considered to be too humid to make any attempt at inlet evaporative cooling economically worthwhile. This idea may be based on the earlier evaporative cooling technologies, which required higher up-front costs, longer down-times and major changes/additions to inlet duct design and were less effective at achieving wet bulb conditions.

The introduction of inlet air fog cooling with its lower initial and operating costs, short down-time and higher cooling efficiency has changed the economics enough to make it a viable option for power augmentation even in the more humid regions of Asia.

4.1 Weather Data ”Reporting

Another important factor to consider is that reported weather data can often be misleading. Rarely are the dry bulb temperature and the coincident wet bulb data available. Weather services will often quote the highest dry bulb temperature of the day and the highest humidity, BUT these do not occur at the same period of time. There is a lot more evaporative cooling available than is at first realized.

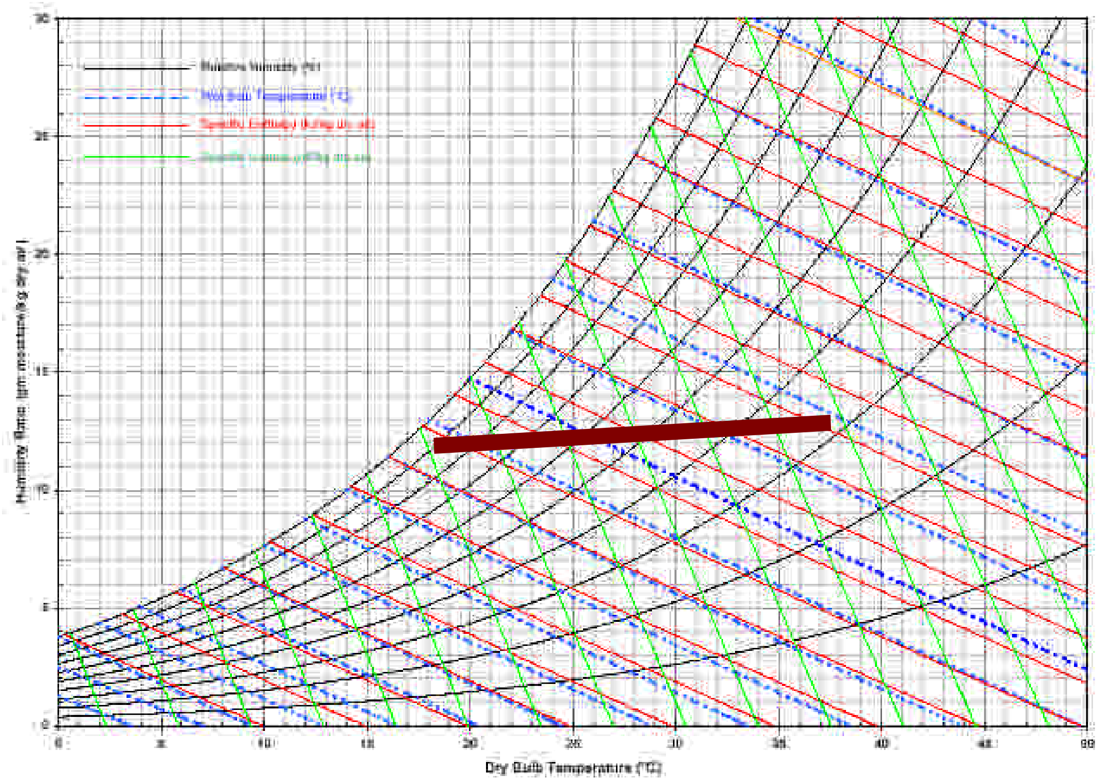
A review of **Figure B** demonstrates this relationship. Figure B is a standard psychrometric chart with a solid line showing the variation of temperature and relative humidity over a 24-hour period of a typical Asian coastal region. The actual amount of water in the air is surprisingly constant and is determined by local conditions such as ocean temperature and wind direction.

As we can see from the chart, a night-time temperature of 19°C will have a relative humidity (r.h.) of 90% but during the day, but as dry bulb temperature rises, and humidity drops, and since the water content of the air does not change much in the course of a day, we can reach a dry bulb temperature of 37C and the coincident r.h. has now dropped to 33%.

Thus at the hotter condition we could achieve 13°C of evaporative cooling, which can generate a 13% power gain on a typical gas turbine, by fog evaporative cooling.

Figure B ” Psychrometric Chart

Showing a Typical Daily Range of Temperature and Relative Humidity.



5. Definition of Fog Cooling Terms

To start off this discussion we will address the following definitions of some terms. The key terms used in defining evaporative cooling potential are:

- *Wet Bulb Depression (or Possible Cooling Degrees)*

This is the difference between dry bulb and wet bulb temperature at a given moment in time. During a typical day, the maximum wet bulb depression occurs at the hottest times of the day. This is a measure of how much cooling is possible from evaporative cooling.

- *Site Evaporative Cooling Degree Hours (ECDH)*

This is the number of Evaporative Cooling Degrees times the number of hours that they occur in a given time period for a particular site.

A good source of Asian weather data is available from NCDC (National Climatic Data Center) in the USA. We used 2 databases for our study:

1. International Station Meteorological Climate Summary Weather Data 1996 of over 6,300 sites around the world.

2. Engineering Weather Data of 800 worldwide sites.

From the recorded weather data we can calculate the number of ECDH that occur over a day, week, month or year at a given site. This data is easily extracted from the weather data for the specific site as discussed above.

- *Site Design Point Cooling Potential*

This is the maximum expected wet bulb depression (WBD) as extracted from the site yearly weather data and is used to size the fog cooling system. WBD is the difference between dry bulb and wet bulb temperature at any given moment.

In a typical gas turbine site the maximum WBD from the weather data may only occur for 0.5 hours per year, so the design point figure is usually selected for a WBD that occurs or is exceeded at least 20 hours a year or more, depending on the site conditions and the need for more power under these extreme conditions. This number defines the maximum cooling capacity and therefore the overall size and cost of the fog cooling system.

- Expected Gas Turbine Power Gain "MW

This is calculated from the gas turbine manufacturer's rating for the particular turbine, and reflects the cooling effect of the fog system on the inlet air. Typically a frame gas turbine will generate slightly less than 1% extra power for each 1 °C of inlet cooling. Thus a fog system designed to give 15°C of cooling will generate an extra 10-15% more power at the design point. This gain can be even higher in the case of an aeroderivative gas turbine such as a GE LM 6000, a RR Avon or a P&W FT-4.

- Expected Site Power Gain MW-hrs

Of more general interest to users is the total amount of extra power that can be generated by the fog cooling system at a particular site on a particular turbine. This can be calculated from the weather data ECDH for the particular site.

The formula for this is simply:

Site Power Gain = Base MW x ECDH x %Power Gain/Cooling Degree

Thus for a typical Asian turbine site with an ECDH of 20,000, a gas turbine average output of 80 MW in the summer months and with 1%/Degree C power gain we can predict a site power gain of:

80 x 20,000 x 0.01 = 16,000 MW-hrs from fog cooling

With a value of $30/MW-hr this fog power generates an extra $480,000 in revenue. A fog system for this turbine would be priced in the range of $190,000, so you can see that the payback is very good. Inlet air fog cooling also improves heat rate, which further enhances payback as is discussed later.

6. Weather Data for Specific Asian Sites

The following tables present weather studies of a wide diversity of regions in Asia. This weather data has been taken from the NCDC databases discussed earlier.

Table 1 - Site Evaporative Cooling Degree Hours

As the data shows, there is a surprising amount of site Evaporative Cooling Degree Hours (ECDH) available in most Asian regions. The data is based on a minimum wet bulb temperature of 12.8°C. Below this condition the fog system is automatically turned off.

REGION	CITY	ECDH
JAPAN	Tokyo	17,300
JAPAN	Osaka	18,300
KOREA	Seoul	13,500
MALAYASIA	Kuala Lumpur	21,900
PHILIPPINES	Manila	28,800
SINGAPORE	Singapore	17,300
TAIWAN	Taipei	21,000
THAILAND	Bangkok	35,900
VIETNAM	Ho Chi Minh	29,800
AUSTRALIA	Adelaide	23,100
BURMA	Rangoon	28,700
CHINA	Hong Kong	26,200
CHINA	Beijing	17,100
INDIA	Mumbai	37,800
	Delhi	51,200

Table 2 - Site Power Gain (MW-hrs) by Region

This data shows the power gain expected at the various sites for different types of gas turbine. Aeroderivative gas turbines are most sensitive to temperature changes and so they show the largest gains.

Site Country-City	Turbine Make /Model	Base Power MW	Fog Gain MW-hrs
JAPAN	ABB 13E2	148.6	10,035
- Tokyo	Mitsubishi 701F	228.8	26,900
	GE LM6000PC	32.30	8,750
MALAYSIA	ABB 13E2	148.6	12,700
-Kula Lumpur	Mitsubishi 701F	228.8	33,900
	GE LM6000PC	32.30	11,000
THAILAND	ABB 13E2	148.6	20,800
-Bangkok	Mitsubishi 701F	228.8	55,800
	GE LM6000PC	32.30	18,200
CHINA	ABB 13E2	148.6	14,940
- Hong Kong	Mitsubishi 701F	228.8	40,300
	GE LM6000PC	32.30	13,100
INDIA	ABB 13E2	148.6	29,200
- Delhi	Mitsubishi 701F	228.8	79,700
	GE LM6000PC	32.30	25,900

7. Fog Overspray Power Gain- An Added Benefit

Fog cooling allows another method of power gain, which is different from inlet air-cooling. It is called overspray cooling. Since fog cooling is an active system, more fog can be added to the airflow than can be fully evaporated. This extra fog flow is injected directly into the compressor and inter-cools the air between compression stages thus improving overall turbine efficiency.

This inter-stage cooling method is not as efficient as inlet air cooling in terms of water usage but it has the advantage of being independent of weather conditions and so can be run continuously, thus generating extra power at all dry bulb temperatures above 12.8°C. A number of overspray systems are now in operation with as much as 0.6% to 1% overspray being achieved.

Table 3. Overspray Power Gain

This table shows the extra power in MW generated from a fog system with 0.6% overspray (O/S), running for 8,000 hours a year on various gas turbine models with an average ambient temperature of 22°C and 50% r.h..

Turbine Model	Base MW	Evap Fog MW	0.6% O/S Fog MW	0.6% O/S Fog MW-hr
GE Frame 5361	23.8	25.2	27.1	15,200
GE Frame 9171E	115.7	120.9	128.1	57,600
Westinghouse 501D5	101.9	106.9	114.0	56,800
Mitsubishi 701F	252.6	263.8	278.0	113,600
ABB 13E2	150.3	157.1	167.1	80,000
LM6000 PC	37.6	42.0	NA	NA

As can be seen from the data above, the overspray power gain numbers are impressive. The data was derived using GT-Pro software by Thermoflow Inc., USA. Compare with Table 2 data for Evaporative Fog Power Gain MW-hrs.

8. Heat Rate Improvement ” A Major Benefit of Fog Cooling

Another advantage of fog cooling is the beneficial effect it has on heat rate. By cooling the compressor inlet air, the overall turbine cycle efficiency is improved, resulting in reduced fuel consumption per MW. This heat rate improvement is not limited to the extra power but applies to all of the power output of the turbine. An example of various heat rate improvements for different gas turbines is shown in Table 4 for 5.5°C of fog cooling.

Table 4. Heat Rate Improvements for Various Turbines

The table below shows the heat rate improvement for 5.5°C of cooling on various turbine models at a design point of 32°C and 65% r.h. The figures show that the extra power produced is achieved with typically 25-35% less fuel consumption than the base power production.

POWER AND HEAT RATE CHANGES WITH FOG

TURBINE	Power MW	Power MW	Heat Rate	Heat Rate	%Heat Rate Reduction
MODEL	Fog Off	Fog On	Fog Off	Fog On	Per Extra MW
GE Frame 5361	21.9	23.0	13625	13403	-34%
GE Frame 9E	107.7	112.3	11179	11077	-22%
Westnghse501D5	94.8	99.0	11065	10948	-25%
Mitsubishi 701F	236.4	245.3	9840	9747	-26%
LM 2500	18.9	19.8	10076	9995	-18%
LM5000	27.0	28.9	10551	10359	-28%
LM 6000	34.4	37.3	9532	9174	-48%
ABB 13E2	140.3	145.6	10186	10088	-26%

This fuel savings more than offsets the added cost of demineralized water, for the fog system to generate the extra power. Demin water is necessary to protect the turbine internal components.

9. Operating and Maintenance Costs of Fog System

The largest operating cost of the fog system is demineralized water. A typical fog system consumes about 200 gallons (800 liters) of water per MW-hr of extra power. Again this number is much lower for aeroderivative turbines. Thus for the 80 MW example discussed above, where an extra 16,000 MW-hrs is produced by fog cooling, this translates to 3.2 million gallons of demin water consumed per year. This sounds high but the average water consumption would be in the order of 18 gpm (67 lpm) over the estimated 3,000 hours of fog cooling operation.

With an average cost of US$0.0015 per gallon, the cost of demin water will be around US$16 per hour, or $48,000 for the year. Maintenance costs of the fog system are about $3 per operating hour. Based on 3,000 hours usage this amounts to $9,000 per year. The fog system high-pressure pumps consume a very small amount of the power increase, in the order of $2,500 per year.

9.1 Fuel Savings

The fuel savings easily offsets all of these costs. As described above, the extra power is generated with 25% less fuel than the base power as shown in Table 5 above.

With fuel costs at say $4/MMBTU and an average heat rate of 10,000 BTU/kW-hr, the yearly fuel savings for the extra 16,000 MW-hr (or 16,000,000 kW-hr) of power generated by fog cooling is:

$$16{,}000{,}000 \times 0.25 \times 10{,}000 \times \$4 / 1{,}000{,}000 = \$160{,}000.$$

Thus fuel savings alone is almost <u>3 times more</u> than all of the operating, water and maintenance costs of the fog system.

10. Examples of Existing Fog Cooling Applications in Asia

Now we will cover some actual fog cooling installations and see what results were achieved. There are already a number of fog cooling installations in Asia and actual measured performance data from some of these is presented.

10.1 Example A - Kuala Lumpur. Malaysia

An inlet fog cooling system was installed on an ABB 13E simple cycle for Tenaga Nacional Bernad at their Connaught Bridge Power Station near Kuala Lumpur, Malaysia. The fog installation was completed on time and an in-depth test of the fog system was done to ensure that it met the guaranteed power gains at the design point. The test was successful and the power gain exceeded the guarantee by a significant margin.

10.2 Test Results:

The guarantee point was an increase of 8.5% (11.0 MW) at the design temperature of 32°C and 65% r.h. The fog system had a cooling capacity of 21.9°C of cooling with a flow rate of 266 lpm. All fog stages were on, thus there was about 6.3°C evaporative cooling (equivalent to 0.24% of air mass-flow) and the remaining fog flow was injected into the compressor (equivalent to 0.6% of air mass-flow) as overspray.

A summary of the test results taken on March 21st and 22nd 2001 are shown below.

CONNAUGHT BRIDGE ”TEST RESULTS

TEST ”1 (21-3-2001)

			FOG POWER GAIN RESULTS			
FOG	$T_{dry\ bulb}$	R.H.	Measured	Corrected*	MW Gain	% Gain
OFF	31.9 C	59.6%	129.9	129.2	-	-
ON	32.5 C	57.6%	143.2	143.2	14.0	11.1%

Another test was run the next day and the following power gains were measured.

TEST ”2 (22-3-2001)

			FOG POWER GAIN RESULTS			
FOG	$T_{dry\ bulb}$	R.H.	Measured	Corrected*	MW Gain	% Gain
OFF	30.2 C	59.0%	133.0	131.8	-	-
ON	31.3 C	55.5%	143.5	143.5	11.7	8.2%

*Corrected for change in ambient temperature effect on power between the 2 test points.

10.3 Power Gain Test Results

The tests showed an average power gain of 9.7%, thus comfortably exceeding the guaranteed value of 8.5%.

10.4 Fog System Operation

The fog flow, fuel flow and other data measured during the actual test program is presented in the Table below:

Table 4" Test Results

Measured Parameter	Fog OFF	Fog ON
Temp	31.9	32.5
r.h.%	59.6	57.6
Cooling Available	6.3	6.7
GT Output MW	129.9	143.2
GT Fuel Flow SCM/hr	38,982	41,182
Fog Water Flow (lpm)	-	270
Fuel Flow SCM/MW-hr	300	288
Overall Fuel Reduction	-	(-4%)
Power Gain	-	13.7MW
Fuel Flow Increase/Power Gain	-	161
Net Fuel Reduction on Power Gain		(-46%)

Note that the extra power gain was produced with an overall fuel savings of 4% on the entire turbine output power. Or put another way, the **extra** power gain was produced with 46% less fuel per MW than that used for the base load power.

10. 5 Example B. Medan, Indonesia

Another fog cooling installation was completed on a Siemens V94.2 for PLN and was done at their Belawan Plant near Medan, Indonesia. The fog system was installed in May 2002 and commissioning was completed the same month.

Table 5 " Test Results

Date	Time	Dry Bulb	Wet bulb	RH	Power Output MW	
		Degree C		%	Min	Max
Before Fog						
22/5	18:57	28.3	25.5	78.8	125.67	126.46
			Average Value		**126.1**	
After						
22/5	19:17	28.5	25.5	77.1	129.82	131.73
			Average Value		**130.8**	
Before						
23/5	10:46	30.3	25.5	67.1	122.97	126.01
			Average Value		**124.5**	
After						
23/5	11:29	31.9	26.1	63.8	128.37	131.46
			Average Value		**129.9**	
Before						
24/5	19:06	30.4	26.0	74.0	121.51	123.98
			Average Value		**122.7**	
After						
24/5	19:30	30.2	26.0	74.0	126.34	128.71
			Average Value		**127.5**	

The gas turbine was operating on diesel fuel. The fog system was designed for a maximum flow of 22.7 gpm (86 lpm) of demin water. This gave 6C of fog cooling. Power gains of 4.7 MW, 5.4 MW and 4.8MW were achieved. Power gain average was 1.2 MW per degree C of cooling. This is about 0.9% power gain per degree C. The fog system was run in evaporative cooling plus 0.1% over spray mode.

11. Conclusions

Over the past 12 years, gas turbine inlet fog cooling has demonstrated that it is an effective and economical method of cooling inlet air on gas turbines and thus generating extra power. The technology has now been installed in over 700 gas turbine installations worldwide, so has a well-established track record.

Due to its lower installed and operating costs, fog cooling has proven to be an economically viable method for increasing power output of gas turbines in S.E. Asian regions, which might otherwise be considered marginal for the previously available cooling technologies.

Fog cooling systems have been installed on a wide variety of gas turbine makes and models, both in simple cycle and combined cycle plants from 2MW to 250 MW capacities.

Typical fuel savings from fog cooling and the revenue from extra power generated can pay for the installation costs and operating costs including demineralized water consumed, in 2 years or less, depending on the site location, the turbine type and local power demands.

Fog cooling power gain can be further augmented by use of overspray and a number of overspray fog systems have been installed. Overspray has the added attraction of producing power independently of the weather conditions.