Boosting gas turbine power . . .

WHAT THE NUMBERS SAY ABOUT INLET COOLING AND SUPERCHARGING METHODS

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The power output of gas turbines vary with the density of air. During hot weather the demand for power peaks as air conditioning load increases. However, hot weather decreases air density which means that less mass of air flows into a gas turbine and less power is produced.

Due to this characteristic, many gas turbine owners have installed inlet cooling technologies to "fool" their turbines into performing as if the weather was cooler.

Since 1990, Fern Engineering, under a program sponsored by the Electric Power Research Institute (EPRI), Palo Alto, California, has been investigating low-cost techniques for increasing the power output of existing gas turbines. Developing a software package called Strategic Capacity Augmentation Analysis & Database (SCAAD), the company has calculated site-specific and turbine-specific impacts of a group of the most economically feasible techniques.[1]

The important inlet cooling technologies are:

- Evaporative cooling with media
- Evaporative cooling with foggers
- Water fog overspray or wet compression
- Inlet chilling
- Supercharging with after-cooling

Raw water saves costs

Evaporative cooling lowers the compressor inlet temperature of a gas turbine by using sensible heat in the ambient air to evaporate water. However, evaporative cooling processes are limited by the amount of water that can be absorbed by the ambient air. If the air is at 100 percent relative humidity, no evaporative cooling can take place. On the other hand, in dry climates, this method can achieve significant amounts of cooling (up to 20°C).

There are two types of evaporative cooling technologies for gas turbines:

- Wet media-based evaporative coolers
- Inlet fogging systems

In media-based coolers, water flows down through a porous material, typically made of plastic or coated cellulose. Air flows horizontally through the porous media and some of the water is evaporated into the air. The rest of the water is recycled to the top of the media or purged from the system. A demisting pad is typically located just downstream of the wet media to prevent any entrained water droplets from flowing downstream.

In order to minimize pressure drop across the porous media and to curtail droplet entrainment, a media-based evaporative cooler must be placed in a large cross-section area where the air velocity is less than 3 m/s (10 ft/s) and preferably less than 2 m/s (6.7 ft/s).

While some operators use demineralized water in their media-based evaporative coolers, most use untreated, raw water (well water) to minimize operating costs. The downside of using raw water is the greater potential for fouling of the gas turbine compressor when droplets slip past the demister. Also raw water will eventually leave mineral deposits on the porous media, which then must be replaced every 3 or 4 years. To minimize fouling it is necessary to periodically test the water and adjust the bleed-off rate to control hardness and alkalinity. Also biocide chemicals can be added to prevent microbial growth.

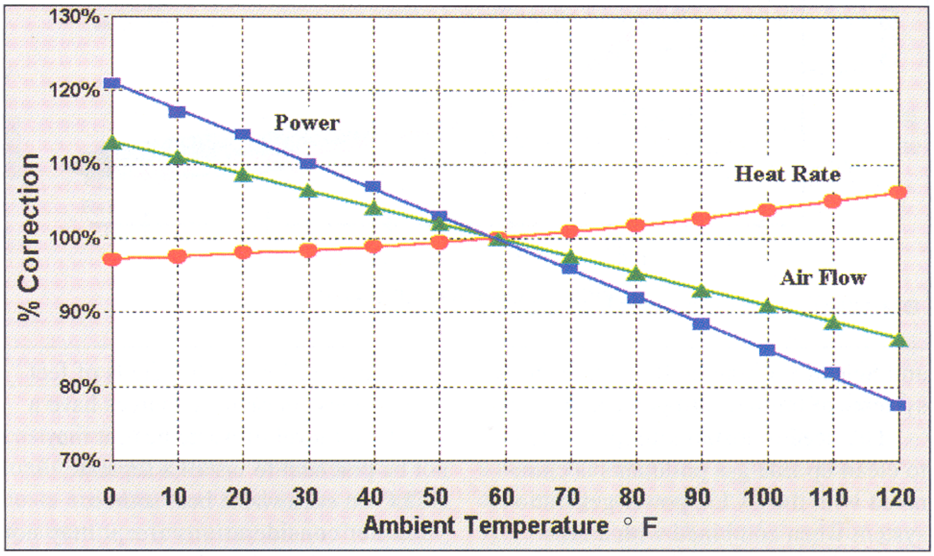

Figure 1: A 16.7°C (30°F) increase in compressor inlet temperature results in a 10 percent decrease in power or approximately 0.6 percent per 1°C

Humidity limits fogging

Inlet fogging systems consist of an array of fog nozzles that are placed in the inlet air duct of a gas turbine and a pumping skid that delivers high pressure (up to 200 bar or 3000 psi) demineralized water to the nozzle arrays. The nozzles are typically placed just downstream of the air filter elements to maximize the amount of time the fog droplets have to evaporate before entering the compressor section of the gas turbine.

The controls of an inlet fogger ensure that no more water than necessary to saturate the air is delivered to the fog nozzles. This minimizes demineralized water consumption while also ensuring that little or no water is ingested by the compressor.

Advantages of inlet fogging include its low capital cost, low maintenance requirements, and the fact that it can be

Overspray boosts aeroderivative power

A Small Business Innovative Research (SBIR) project conducted by Fern Engineering for the US Navy showed that aeroderivative gas turbines such as the GE LM2500 get more than a five percent boost in power for every one weight percent of entrained overspray. The reason is the free spinning spool of the gas generator in an aero-derivative turbine. The spool will speed up when overspray is used and this increases mass flow through the turbine by more than just the amount of ingested water. Figure 2 shows results from simulations on an LM2500 conducted during the SBIR study. The results indicate power will increase by approximately 6.5 percent for every one percent of overspray. Note also that the design rpm limit of the gas generator spool eventually limits the amounts of overspray that can be entrained to no more than 1.5 percent.

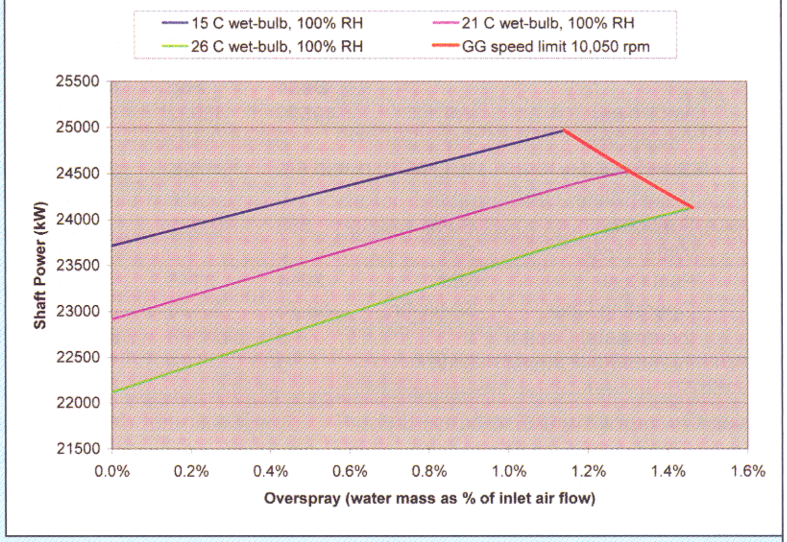

Figure 2: Power increases by 6.5 percent for every 1 percent of overspray

quickly installed (typically requires only a 1- to 2-day shutdown). An advantage over traditional media-based evaporative cooling techniques is that the pressure drop across the nozzle array is negligible. As the chart in Figure 1 indicates, cooling the inlet air temperature will also result in a slight decrease in heat rate over most of the operating range of an inlet fogger.

Disadvantages of inlet fogging include the need for demineralized water, and the fact that the power boost available from fogging will be limited by the ambient wet bulb temperature – on rainy days very little cooling will be obtained. Also, to prevent frost formation at the compressor inlet, most operators turn off a fogger whenever the ambient dry bulb temperature is less than 10°C.

OEM concerns

While gas turbine owners have embraced fogging technology with more than 1,000 units installed by all vendors combined, gas turbine suppliers have not uniformly embraced the concept. General Electric, in particular, issued a directive to all of its F class turbine owners in February of last year to "cease all inlet fogger operation" and conduct inspections for compressor blade erosion.[2]

However, GE recently removed its restriction on fogging for its F class machines, provided modifications are carried out on the blades of the first stage of the rotor. According to the operations manager of one 7F machine, GE is modifying the blades by undercutting the base to relieve stress. In some cases the blades may also be coated to prevent erosion.

It should be noted that throughout the ban on fogging of F class turbines, GE continued to allow fogging on all of its other combustion turbines.

Benefits of overspray

Water fog overspray, also called wet compression, is simply fogging with more water than that needed to saturate the air. The excess water droplets are entrained into the gas turbine's compressor where the heat of compression causes the droplets to evaporate – thus providing "in situ" intercooling of the compressor. Intercooling reduces the amount of power consumed by the compressor, so more power is delivered to the output shaft. The mass of the overspray water also provides additional mass flow through the turbine section of the engine just as combustor water injection does.

The amount of cooling, and therefore the amount of power boost, that can be accomplished with overspray is much greater than what can be accomplished with fogging only to the ambient wet bulb temperature. Figure 3 shows that the difference between the dry bulb and the wet bulb temperatures of the air inside a gas turbine compressor can be on the order of hundreds of degrees.

Overspray will typically provide at least a 5 percent increase in power for every 1 percent (kg-water/kg-air) of overspray entrained into the compressor. Older machines with less efficient compressors will yield bigger increases in

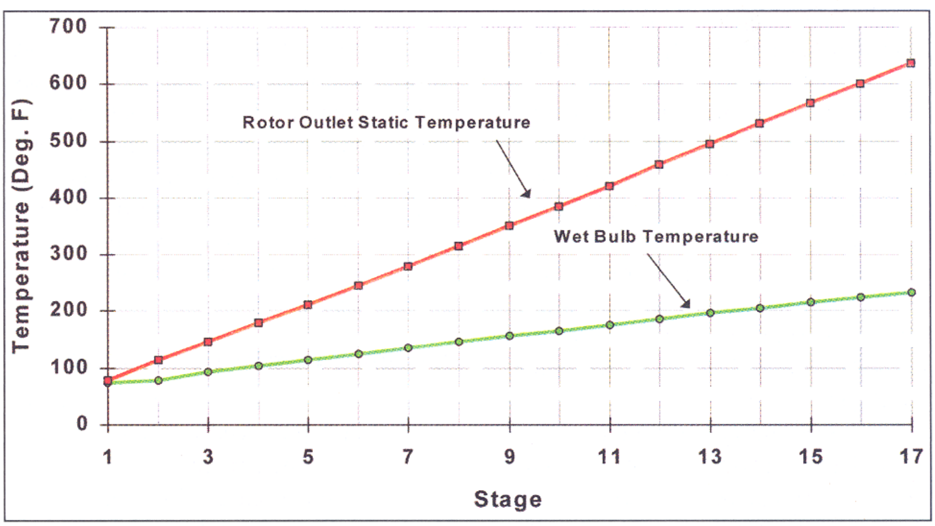

Figure 3: Dry and wet bulb temperature differences inside the compressor can be more than 100°F

Table 1: Economic and Performance Impact of Evaporative Cooling with Wet Media, Inlet Fogging and Wet Compression

		Base	Case 1 Fog	Case 2 Evap. Media	Case 3 Wet Comp.
Net Power	kW	49599	55032	54942	58473
Power Gain	kW	0	5433	5343	8874
Thermal Effcy.	% LHV	30.6%	31.5%	31.5%	31.1%
Demin Water Use	gpm	0	16	0	57
Fuel Use	GJ/hr	583	629	628	677
Water Cost	$/hr	0	4.8	0	17.1
Fuel Cost	$/hr	2914	3145	3140	3383
Operating Cost	$/MW-hr	58.75	57.23	57.14	58.15
Incremental Capital	$	0	243,098	258,875	483,369
Incremental Capital	$/kW	0	45	48	54

power. Overspray will also cause the heat rate to decrease slightly. Because overspray results in lower compressor discharge air temperatures, NOx formation in the combustor is reduced. NOx emissions can decrease by as much as 30 percent when using overspray.

Other advantages of overspray include the fact that the power boost is not limited by wet bulb temperature – overspray can be used even on rainy days, and capital cost is relatively low.

Disadvantages include the fact that, like fogging, overspray cannot be used when the ambient dry bulb temperature is less than 10°C. Also, overspray uses more demineralized water than fogging (and produces less power per gpm of water consumed). Finally, there is risk of erosion of compressor blades due to long-term use of overspray. However, general experience with overspray has been quite positive.

Two items are critical to successful implementation of overspray: high purity water and generation of very small water droplets. The former is needed to prevent fouling of the compressor with residual deposits.

There are two reasons for needing small droplets. First, due to high flow velocities, the residence time of a packet of air as it passes through a gas turbine compressor is about 20 milliseconds. Consequently, the droplets must evaporate quickly in order to have a cooling effect within the compressor (preferably in the first several stages to maximize the effect).

Since the amount of time it takes for a droplet to evaporate is proportional to the diameter squared, only very small droplets can meet the requirement of evaporating within a few milliseconds. The second reason favoring small droplets is that droplets smaller than 20 microns are more likely to follow the streamline of the air flow and not collide with the compressor blades, thereby reducing the risk of erosion.

Consider three different cases of a Pratt & Whitney's FT-4C Twin Pac operating at ambient conditions of 32°C (90°F) and 40 percent relative humidity. Case 1 uses fogging to cool the inlet air to within 1°C of wet bulb (equivalent to 90 percent saturation efficiency). A total of 16 gpm of fog spray is required for the design ambient conditions. The installed cost of Case 1 including a demin water system is $243,098. Case 2 uses a media-type evaporative cooler to achieve 90 percent saturation of the air. The installed cost for Case 2 including an insert into the inlet house structure to accommodate the cooler is $258,875. Case 3 uses wet compression at a rate of 1 percent of the inlet air flow or 41 gpm of fog spray in addition to the 16 gpm needed for saturation. The installed cost for Case 3 including a demin water system is $483,369.

A summary of the economic and performance estimates for these three cases is presented in Table 1. It should be noted that the reason the net power for the media-based evaporative cooler is slightly less than the net power from fogging is the additional inlet pressure drop caused by the presence of the porous media.

Chilling outcools fogging

Inlet chilling involves the use of chilled water that is produced with a refrigeration system. The chilled water is circulated through cooling coils mounted in the gas turbine air intake – typically just behind the filter elements. Inlet chilling systems can typically cool the air down to 7 to 10°C.

As is the case with inlet fogging, the colder inlet air allows the gas turbine to produce more power. Typically the extra power produced by the gas turbine is 3 to 4 times the power consumed by an electric-motor-driven refrigeration system. Absorption-based refrigeration systems use much less electrical power and instead require low pressure steam to produce the chilled water.

A packaged chiller system consists of only three major components: chiller skid, inlet cooling coil, and cooling tower. An air-cooled condenser can be substituted for a wet cooling tower in locations where raw water is not available.

The use of packaged systems with an intermediate water cooling loop allows the refrigeration components to be fully integrated on a single skid. The chiller skid package contains the evaporator, condenser, compressor, all of the refrigerant, and includes the chilled water and condenser cooling (cooling tower) pumps and the power and control connections. The packaged systems benefit from high efficiency, lower costs of assembly, improved factory testing and lower installed costs.

Safety, maintenance, and reliability issues are also important. New halocarbon refrigerant options have evolved that are safe, efficient, and friendly to the environment. Packaged systems are designed so that all of the refrigerant can be pumped into the evaporator or a separate tank when maintenance work is required. Certified operator and maintenance training are available, as the commercial and industrial refrigeration technology is so well developed. Multi-skid and duplex compressor arrangements result in redundancy and the ability to repair one compressor while still operating the system with the remaining compressors.

A basic limit to an application may be the space needed for the skids and cooling towers. However, packagers have recognized that layout space may be limited and have incorporated design features such as vertical pumps to help reduce the footprint. In fact, the total space required for the skids and the cooling tower may be as low as four tons of refrigeration per square foot (151 kW per square meter). A ton of refrigeration equals 12,000 Btu/hr or 3.516 kW.

Two key components of a chiller skid

are the compressor and evaporator. These are typically close-coupled devices.

An advantage of inlet chilling is that is does not require demineralized water and can actually be a net producer of water if the air is cooled to below its dewpoint. Condensed water will drain off of the cooling coils and can be used as make-up to the cooling tower or for other uses. Another advantage of inlet chilling compared to overspray is that there are no risks of compressor blade erosion due to entrained water droplets

The wet bulb temperature does not limit the amount of power boost that can be provided by an inlet chilling system. However, chilling should only be used when the ambient dry bulb is greater than 10°C in order to avoid icing.

Disadvantages of inlet chilling include its high capital cost and, in the case of electrically driven refrigeration, its large auxiliary power load (nominally 0.7 kW/ton of refrigeration). However, inlet chilling can be cost-effective at a site with a long season of hot weather.

Supercharging option

Supercharging is a technique in which a fan is added in front of the gas turbine compressor to increase the pressure at the gas turbine inlet. As is the case with inlet cooling techniques, turbine power output is boosted because of the higher density of the inlet air. Supercharging is particularly applicable to high altitude sites where the engine suffers from a derating due to the lower barometric pressure.

Supercharging can be implemented with evaporative cooling in the form of fogging either upstream or downstream of the fan. There is only one supercharged gas turbine installation known to the authors, and that is a 1960s vintage Westinghouse 301G combined cycle located in San Angelo, Texas. However, patents have recently been obtained by a new company which is now offering supercharging retrofits.[4]

Similar to inlet chilling, the amount of additional power produced by the gas turbine due to supercharging is typically 3-4 times the power consumed by the auxiliary load, the supercharging fan motor.

Advantages of supercharging include the fact that the power boost is not limited by ambient conditions. Because the fan actually raises the inlet air temperature, supercharging and fogging can be used even during cold weather. In fact, supercharging is an efficient alternative to using compressor bleed air for inlet heating on cold days.

Disadvantages include the fact that this technique is relatively unproven, although, its individual components are all well-proven in other applications. Other disadvantages are its large auxiliary power load and its relatively high capital cost.

Consider two different cases for an FT-4 Twin Pak. The first case uses inlet chilling to cool the ambient air down to 7°C. Its installed cost is $3,437,918 including an evaporative cooling tower. The second case uses supercharging to boost the inlet air pressure by 100 mbar (40 inches H_2O). Its installed cost is estimated to be $1,340,982 including a 29 gpm fogging system. The results of the SCAAD economics and performance estimates are summarized in Table 2.

Inlet cooling techniques based on evaporation of water have a strong capital cost advantage over inlet chilling and supercharging. However, the latter two methods have the advantage of providing a boost in power that is not dependent on ambient conditions.

A decision on which method is "best" depends on the yearly climate conditions at a site and the number of hours per year that the combustion turbine operates. For example, fogging or wet compression might be best for a peaking plant in a dry climate while supercharging might be the logical choice for a pipeline compressor station located in a humid climate and operating 8,000 hours per year. TI

Table 2: Inlet Chilling and Supercharging Performance and Economic Summary

		Base	Inlet Chill	Supercharging + Aftercooler
Net Power	kW	49599	60501	57441
Power Gain	kW	0	10902	7842
Thermal Effcy.	% LHV	30.6%	31.3%	31.9%
Water Use	gpm	0	0	29
Fuel Use	GJ/hr	583	695	649
Water Cost	$/hr	0	0	8.7
Fuel Cost	$/hr	2914	3476	3244
Operating Cost	$/MW-hr	58.75	57.45	56.63
Incremental Capital	$	0	3,437,918	1,340,982
Incremental Capital	$/kW	0	315	171

References:

[1] SCAAD (Strategic Capacity Analysis and Database) User's Manual , EPRI, Palo Alto, CA,: 2001. Software Product Manual ID 1004583.

[2] GE Technical Information Letter TIL-1389-1R1, "Compressor Rotor Blade Erosion for Water Ingestion Used in Power Augmentation", 20 Feb. 2003.

[3] P. Levine, "Augmented Gas Turbine Engine", Final Report to the US Navy, SBIR Contract N00167-99-C-0053, Nov. 1999.

[4] Enhanced Turbine Output, LLC, Washington, DC, www.etollc.com

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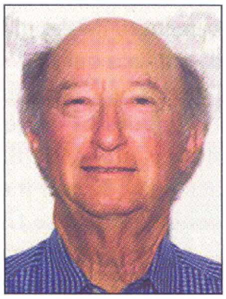

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