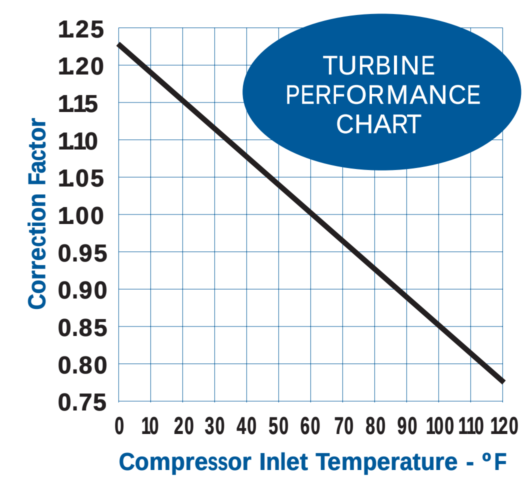
A Comparative Guide to Inlet Air Cooling Technologies

Under High Temperature/Humidity Conditions

An Overview

MEE INDUSTRIES, INC.

During hot weather, combustion turbine (CT) operators are posed a significant problem by the degradation of turbine generation capacity. The typical CT on a hot summer day, for instance, produces up to 20% less power than on a cold winter day. As a result, a number of cooling techniques have evolved over the years to maximize turbine output.



The basic theory of inlet air cooling for gas turbines is simple enough. Combustion turbines are constant volume machines – at a given shaft speed they always move the same volume of air – but the power output of a turbine depends on the flow of mass through it. That's why on hot days, when air is less dense, power output falls off. By feeding cooler air into the CT, mass flow is increased, resulting in higher output. Another factor is the power consumed by the CT's compressor. The work required to compress air is directly proportional to the temperature of the air, so reducing the inlet air temperature reduces the work of compression and there is more work available at the turbine output shaft.

There is, however, a limitation on the amount of inlet air cooling that can safely be accomplished. If the temperature is allowed to go too low, ice can form on the bell-mouth or inlet guide vanes, with the risk of this ice flaking off and doing mechanical damage to the compressor blades. This phenomenon can occur even when the inlet air temperature is above freezing, because suction at the turbine inlet creates a low pressure 'cool zone' at the bell-mouth. To avoid this problem, most turbine manufacturers recommend that inlet air be kept at or above 45ºF.

Traditionally, either mechanical chillers or media-type evaporative coolers have been used to cool combustion turbine inlet air.

Gas turbines typically operate at as little as 80% of their rated capacity on hot days due to the lower air density and higher temperatures. Inlet air cooling helps to make up the difference by increasing the air mass flow through the turbine and by cooling the air, which reduces the work of compression.

INLET AIR CHILLERS

Various refrigerant-type air chilling systems have been successfully employed for combustion turbine inlet air cooling. These range from compressor-type chillers to absorption chillers, which utilize "waste" heat as an energy source for the chilling process.

Thermal storage systems have also been successfully applied to CTs. These use relatively small chiller plants, running off-peak, to make ice or cold-brine solutions which are stored in an insulated tank and used to cool the inlet air during peak-power demand. Such systems have proven to be a cost-effective way to overcome power loss during peak-demand periods, while reducing the high costs normally associated with chiller plants.

Inlet Air Chillers

The most powerful method of inlet air cooling, chillers are capable of keeping inlet air at 45°F throughout the year, though costs can be higher than with other approaches.

Overall, chillers are capable of achieving a greater drop in inlet air temperature than other methods of inlet air cooling. The most powerful chillers, for example, are capable of keeping the inlet air at 45°F throughout the year, if desired. This compares well to its competing technologies which can manage temperature drops of anywhere from 15 to 25°F in temperate climates and as much as 40°F of cooling in arid, desert climates.

There are drawbacks to chillers, however, including high first costs, and high operating and maintenance costs. These factors may explain why few turbine operators have taken advantage of inlet air chillers.

Evaporative Coolers

The most widely used CT inlet air cooling system, media-type evaporative cooling is less effective in hot, humid conditions. In low humidity environments, though, it can boost power output by 10% or more, depending on ambient conditions.

EVAPORATIVE COOLERS

Evaporation is a natural process that results in the conversion of water from a liquid to a vapor. This conversion is called a phase change. When water changes phase, it either absorbs or releases heat. For instance, when a pound of water changes from the liquid phase to vapor phase it consumes 1160 BTUs of heat. A good example of evaporation is the cooling effect of a breeze on a summer day. Even if the air is hotter than body temperature, the breeze feels cooler because it evaporates perspiration off the skin.

Media-type evaporative coolers make use of this principle and are the most common cooling system employed in combustion turbine inlet air cooling. They generally consist of a wetted honeycomb-like pad of cellulose fiber material (the medium). When air is pulled through, it evaporates water off the convoluted surfaces of the wetted media, thereby cooling the inlet air.

Evaporative coolers are limited by the amount of moisture present in the air. Once saturation (i.e., 100% relative humidity) is reached, evaporative cooling systems are unable to evaporate more water into the air stream. For this reason, in hot, humid regions, it often isn't possible to accomplish more than about 10 to 15ºF of cooling. Chillers don't have this problem. They are not restricted by high ambient humidity and are therefore capable of giving a larger power boost than evaporative coolers.

Another factor to be considered with evaporative coolers is the cost of retrofitting and installing them. Although the units themselves are generally fairly inexpensive, installation usually calls for duct enlargement, as evaporative coolers require relatively low air velocities. If the air velocity across the wetted media is too high, it can strip water from the media, cause excessive wetting of the ducts and even fouling of the compressor blades. For these reasons, evaporative coolers are sometimes ruled out as a retrofit option. Overall though, if retrofitting or installation costs are not prohibitive, evaporative coolers work well. In low-humidity environments they are capable of increasing power output by as much as 15%, while in high-humidity areas, the power boost tends to be 10% or less.

HIGH PRESSURE FOGGING

High pressure fogging is a more recent addition to the roster of technologies employed for inlet air cooling. Fogging systems are similar to media-type evaporative cooling systems in that they cool by evaporating water, but instead of using an evaporative medium, the water is atomized into billions of super-small fog droplets.

Fog systems use high pressure water pumps to pressurize demineralized water to between 1000 and 3000 psi. The water then flows through a network of stainless steel tubes to fog nozzle manifolds that are installed in the air stream. These nozzles atomize the water into micro-fine fog droplets which evaporate quickly.

Other factors being equal, the speed of evaporation of water depends on the surface area of water exposed to the air. This is why media-type evaporative coolers use convoluted honeycomb type media – to maximize the surface area of water exposed to the air. In high pressure fogging, however, the evaporative surfaces are the fog droplets themselves. For this reason, the size of droplet generated by the fog system is a critical factor. For instance, because of the geometry of spheres, a given amount of water atomized into 10-micron droplets yields ten times more surface area than the same amount of water atomized into 100-micron droplets.

Fog systems have been installed on both base-loaded and peaking gas turbines and are used in both simple-cycle and combined-cycle plants. In most cases, turbine operators opt to install the fog nozzle manifolds downstream of the air filters and just upstream of the silencers. This form of installation usually requires one to two outage days and calls for minor modifications to the turbine inlet structures. Fog systems can also be positioned upstream of air filters, resulting in no outage time. This type of installation, however, requires the use of fog droplet eliminators to prevent wetting of the air filters. When fog nozzles are installed inside the air ducts, special attention must be given to the nozzle manifolds. They must be correctly designed to avoid the possibility of small parts breaking off and being ingested by the turbine.

One advantage of high pressure fogging is its efficiency level in hot, humid areas. As a comparison, take Houston, TX at 96°F in high humidity. In this climate, a fog system can achieve as much as 19 to 20°F of cooling, while a media-type evaporative cooler can get only about 15 to 17°F of cooling. A chiller takes the temperature far lower, but energy demands and installation costs are much higher.

High Pressure Fogging

In high humidity conditions, high pressure fogging usually can provide more cooling than media-type evaporative coolers. Chillers take the temperature lower yet, but with much higher installation and operating costs.

Fog Intercooling

While the limits of this technology have not been fully studied, fog intercooling shows tremendous promise in providing large power boosts – even in very humid environments

FOG INTERCOOLING

An innovative application of high pressure fogging, known as fog intercooling, is showing great promise as a means of increasing the power boost gained from traditional inlet air cooling fog systems. The basic concept is to inject more fog into an air stream than will evaporate with the given climate conditions. Unevaporated fog droplets are carried by the air stream into the compressor where they evaporate when the air is heated by compression. Since the compressor is consuming as much as half of the output of the turbine, and the work required to compress the air is directly proportional to the temperature of the air, the evaporation of fog inside the compressor results in a substantial increase in the net output of the turbine.

It's interesting to note that the higher output associated with intercooling is not due to the mass of the injected fog. In fact, water vapor is less dense than air at the same temperature. So increasing the water vapor content of the air, without also cooling the air, would decrease the density of the mix. However, with a fogging system, the water is added to the air in the liquid phase, so it cools the air when it evaporates and the cooling effect outweighs the addition of the inherently less dense water vapor.

The limits of fog intercooling have not been fully investigated. Several turbine manufacturers are looking into the idea as the benefits are substantial. Theoretically, it's possible to inject enough fog to cause a power boost that is as high as that obtained by inlet air chilling, and at a tiny fraction of the cost.

If the water droplets are too large, one possible drawback of intercooling is the potential for erosion of the compressor section. 'Liquid impaction erosion' is a term applied to this phenomenon. The bombardment of a metal surface with water droplets can lead to the development of micro-fractures in the crystalline surface of the metal and can eventually cause surface pitting. But experience has shown, and most experts agree, that compressor blades would not be subjected to damage unless the average droplet size exceeds about 20 to 30 microns. (The mean diameter of fog droplets is less than 5 microns.) To date, over 60 fog systems with fog intercooling capacity have been installed on turbines in the USA.

Case Study: Chiller Installation

Ripon Cogeneration, near Modesto, CA, is a good example of how compressor-type chilling is used for inlet air cooling. The company runs a GE LM 5000 gas turbine for power generation and supplies steam to the nearby Fox River paper mill. Producing 22,000 tons of paper annually, the 200-acre mill demands over 45,000 lbs of steam/hr when operating at full capacity. Power is also distributed to the public utility grid in California's Central Valley.

Ripon chose a Kohlenberger-patented 2000-ton, multi-temperature chilling system. It features Frick ammonia screw compressors, 3 Imeco evaporative condensers and Frigid Coil cooling coils. Two coils are set at different temperatures to provide stages, enabling the system providing higher thermodynamic efficiency.

"Because California's temperatures rarely dip below 60 degrees F, the chillers are capable of making the system believe it's a cool 44 degrees outside," says Plant Manager Steve Bates. "On a really hot day, though, the chillers don't get the temperature below 50 degrees."

The system works using ammonia compression, similar to a home air conditioner. A compressor draws ammonia vapor from a recirculation tank, compresses it and discharges it to the evaporative condensers. These remove the heat of compression and liquefy the ammonia vapors. Liquid ammonia then returns to the recirculation tank, and from there it is pumped to the coils (situated in the air inlet duct, after the filters). Hot inlet air is fed past the coils, resulting in thermal energy absorption and vaporized ammonia. These vapors and a small percentage of liquid return to the recirculation tank.

"Power consumption is higher with this type of system," says Bates. "It varies from 1 to 14 MW per hour depending on the load." To keep consumption to a minimum, the screw compressors have slide valves, which regulate the amount of compression performed according to system needs.

Ripon bought the chiller unit to increase peaking capacity, improve fuel efficiency and generate additional steam power. The result: power output rose from 42 to 48 MW on hot days.

Case Study: Evaporative Cooling

Nevada Power's Clark Generating Station in Las Vegas operates 4 Westinghouse 501B6 gas turbines, each producing 80 to 82 MW per hour. It is a combined cycle plant, with the heat from the gas turbines being utilized to drive an additional steam turbine. This provides another 90 MW of power.

Three of the utilities' gas turbines have been retrofitted with Premier

Industries' evaporative coolers. "The fourth cooling system is due to be installed in the last turbine later this year," says control room operator Ron Moore. "The capital has been allocated and work should begin after the summer."

These units consist of a stainless steel, grade 304 housing, a sump section and the cooling media. The sump section includes a recirculating water distribution system with pump, flow adjustment controls and flow meters to pump water from the sump to header pipes over each level of the cooling media. The cooling media is a rigid media manufactured by Glacier-Cor. It is made of a cellulose fiber construction with 45/15 degree transverse flutes. Media thickness is 16 inches, provided in two eight-inch sections to reduce replacement costs without loss of cooling efficiency. Moisture drift eliminators are also included to trap raw moisture entrained in the air flow and return it to the sump. Demineralized water is used. After Premier Industries installed the units, Nevada Power measured MW output for the entirety of 1998 and compared it to 1997 figures when no evaporative cooling system existed. July provided the highest monthly increase of 12.32 percent. The average power boost per month is 7 percent.

Case Study:
High Pressure Fogging Installation

In 1997, Portland General Electric Co. (PGE) built a new combined cycle plant at Boardman, Oregon, using a GE Frame 7-FA gas turbine (159 MW). After investigating several cooling options, the utility found that most were expensive to implement and required structural modifications to buildings and air inlet housing. "Media-type evaporative cooling, for instance, worked out to be 250 percent more costly to install than inlet fogging," says Cheryl Bryant, the mechanical engineer in charge of specifying and implementing the cooling system. After factoring in maintenance and running costs, PG&E decided to install a Mee Industries high pressure fogging system.

At this facility, 1120 fog nozzles are installed downstream of air filters/ upstream of silencers and trash screens, by far the most common location. Operating pressure is 2,000 psi and pressure drop is virtually nil. Demineralized water is used.

Two pump skids are required, each containing four FM-630-B1057 pumps. These pumps manage eight stages of cooling, which can be controlled by ambient temperature and humidity sensors, as well as manually.

The only reported problem at Coyote Springs was water collecting in the inlet duct. A drain line, installed downstream of the fog nozzles, eliminated this situation.

The result: 30°F of inlet air cooling, a 16 MW output and a significant improvement in heat rate.

Case Study:
Chiller & High Pressure Fogging #1

Calpine Gilroy Cogen, LP of Gilroy, CA, operates a GE Frame 7-EA cogeneration plant which supplies 120 MW to PG & E and provides steam to a nearby garlic plant. The plant uses chillers to cool turbine air regardless of ambient temperature. But running costs make it desirable at certain times to add a cheaper supplemental system.

At first, Calpine Gilroy tried media-type evaporative cooling. But water entered the air stream and fouled the compressor. As a result, turbines had to be washed regularly. Also, water pumps required additional maintenance and media needed frequent replacement. In 1994, the company decided to drop evaporative coolers, retain chillers and supplement them with high pressure fogging.

Gilroy was one of the first to install inlet fogging and the system was not without its problems. Water would sometimes stagnate in the supply lines to the fog pump units, causing bacteria to grow, which plugged the fog nozzles and water filters. The lesson learned here is that a fog system which is left shutdown for extended periods of time must be drained, even when demineralized water is used. Other initial problems involved the design and installation of the system, such as the use of PVC pipes to supply the water to the fogging pumps, and vibrations in the discharge pipes causing mechanical fatigue. Calpine Gilroy now uses stainless steel supply pipes and has installed pulsation dampeners to cure pump vibration – both standard features on today's fog systems.

The company currently operates its thermal energy chillers during periods of peak power demand and otherwise relies on the fogging system. Result: a significant reduction in cooling costs since switching to high pressure fog and an additional 3 to 6 MW power increase.

Case Study:
Chiller & High Pressure Fogging #2

Las Vegas Cogen operates a peaking plant, which starts up 560 times per year using a GE LM 6000 turbine. The electricity is sold to Nevada Power and thermal energy is used to heat a 12-acre hydroponic greenhouse owned by the company.

Because it takes time for the chillers to get online, the cogeneration facility uses high pressure inlet fogging to provide maximum power right away. The Mee Industries fog system is used exclusively when it's below 70°F outside. If temperatures rise above 70°, a steam absorption chiller is added.

Although the fog system was installed upstream of air filters, the final barrier filters remain dry and the filters stay cleaner due to the scrubbing effects of the mist. The facility achieves around 15°F of cooling, which represents a 500 kW power increase.

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Case Study:

Evaporative Coolers & High Pressure Fogging

The UtiliCorp United plant in Greenwood, MO has standard media-type evaporative coolers installed on four of its Frame 7001B units. However, the company's GE MS-7001E gas turbine (85.4 MW at ISO conditions) uses a Mee Industries fog system to provide evaporative cooling and intercooling. Eight fog-cooling stages – a total of 1,196 nozzles – deliver a temperature drop of 20 to 32°F, depending on ambient conditions.

After two summers, company officials have found that the fog system is easier to clean and maintain than the evaporative coolers. The evaporative coolers carry-over untreated water, resulting in compressor fouling, while the fog, which is demineralized water, helps to clean the compressor. In addition, the fog system takes about three minutes from startup to full power boost, compared to 30 minutes with the media-type systems. The company plant manager said that even on a 100°F day with humidity in the range of 45-50%, the fog system provides a power boost of approximately 4 MW or nearly 7%.

CHOOSING THE RIGHT SYSTEM

When considering which cooling system to implement, it's important to study the existing situation at the plant, climatic conditions, budget limitations, power output expectations and project economics. There are no simple answers, correct in all cases, and sometimes a combination of systems may be best.

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