Gas Turbine Inlet Air Cooling System Increases Performance Of A Natural Gas Injection Station

By Maurizio De Lucia and Ennio Carnevale, University of Florence, Florence, Italy and Massimo Falchetti and Alberto Tesei, Nuovo Pignone S.p.A., Florence, Italy

This article demonstrates how inlet air cooling systems improve gas turbine power output and efficiency. Three systems are discussed in detail and then applied to the specific plant requirements.

Gas turbine performance is known to seriously deteriorate at increased ambient temperature. This article focuses on improving gas turbine power output and efficiency with an inlet air cooling (IAC) system. Three systems were considered: 1) traditional compression cooling system; 2) absorption single-acting cooling system using a solution of lithium bromide; and 3) absorption double -acting cooling system using a solution of lithium bromide. The authors were not only interested in the increased power output that any of these systems would promote but also the economic factors involved, i.e., cost, installation and maintenance.

Inlet Air Cooling Effects

A gas turbine inlet air cooling system is advantageous because it may be used to increase machine power, as well as efficiency, under the same ambient conditions. Performance improvements realized with such a system include an increase in net available power due to a decrease in inlet air temperature, an increase in density and therefore an increase in machine mass flow rate; and an increase in machine efficiency due to operating closer to design conditions.

Figure 1 shows the main operating trends of a General Electric (GE) gas turbine model MS5002-C vs. ambient temperature. A 20 degrees C. inlet air temperature increase causes a 15 to 18 percent power loss.

Air Cooling Systems

The air cooling process is greatly affected by two factors: the initial cooling temperature and relative humidity. The latter parameter, even though not particularly affecting gas turbine behavior, does affect cooling capacity considerably. To better understand the importance of this parameter it should be noted that the power required to cool air from 30 degrees C. to 15 degrees C. practically doubles (increasing by 110 percent) if the relative air humidity is 90 percent instead of 50 percent (passing from 24 to 51 kJ/kg. All this must be carefully considered when selecting the most appropriate inlet air cooling system. Let's examine the various inlet cooling systems available.

Evaporative Cooling Systems. These systems exploit the latent heat of water vaporization in a process of adiabatic air saturation permitting temperature reduction from a dry to a wet bulb value. Therefore, their success in realizing higher ΔT (delta temperature) depends on the relative air humidity contents (the nearer one gets to

Presented at the American Society of Mechanical Engineers' International Gas Turbine & Aeroengine Congress & Exhibition, Orlando, Florida, June 2-5, 1997.

[redacted]

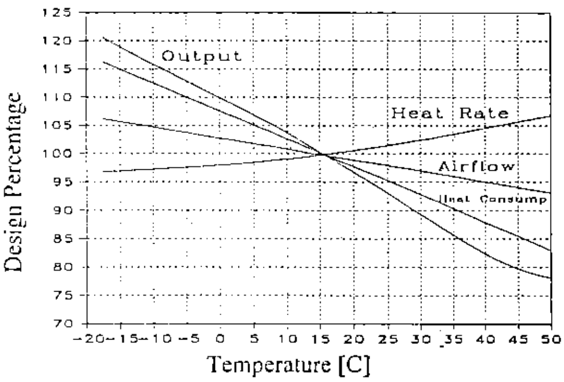

Figure 1: Effect of compressor inlet temperature (MS5002 C)

100 percent in terms of relative humidity, the lower is the obtainable ΔT. Although these systems are economical, they are suitable for hot, dry climates, rather than hot, humid ones, where they are unable to reach satisfactory ΔT.

Cooling Systems

Cooling systems use thermodynamic cycles. The heat is transferred from a low to a higher temperature source, exploiting the fluid property of vaporization or condensation at a different temperature as a function of pressure. These systems are the most suitable for application in a hot, humid climate. The Coefficient of Performance (COP), which indicates the efficiency of cooling cycles, is defined as the ratio between the heat removed at the cooling stage Q_{refr} and the energy used to perform this operation L_u. The two types of thermodynamic cycles usually used for industrial cooling systems are: compression systems and absorption systems.

Compression cooling systems. This is the most conventional system. The circulation of a suitable fluid between different pressure areas is carried out mainly by using the mechanical power supplied by a compressor. It transfers the fluid from a lower pressure area (evaporator) to a higher pressure one (condenser).

Absorption cooling system. The absorption cooling system uses heat instead of the mechanical power of the compression system as its energy source. This allows the recovery and use of waste heat coming from the gas turbine exhaust gases, by simply installing a heat recovery boiler. A very small quantity of mechanical

About The Authors

Maurizio De Lucia is an assistant professor in the Department of Energy Engineering "Sergio Stecco" at the University of Florence. He has a Ph.D. in Mechanical Engineering and holds a professional engineering license in Italy. In addition to his teaching responsibilities, De Lucia carries out research in energy engineering sector plants and their components. He has authored several papers and has collaborated on a mechanical handbook "Manuale del Perito Industriale" Edizioni Cremonese. He is currently collaborating with DGXVII to prepare a technical annex for the most recent THERMIE call for proposals.

Ennio A. Carnevale is a full professor in the Department of Energy Engineering "Sergio Stecco" at the University of Florence. Carnevale is ending a three year term as Dean of Engineering at the University this year. His research over the years has focused on optimization of energy use in industrial processes; cogeneration and combined plants; energy storage; advanced turbo-machinery design and testing; and environmental impact of power plants. He currently supervises the activities of a research group in the Department of Energy Engineering. He has authored some 50 articles and has attended several international conferences as a session chairman and author.

Massimo Falchetti is chief of the Engineering Department of the Industrial Plants Division of Nuovo Pignone in Florence, Italy. Prior to joining the company three years ago, he worked for Energy Saving Co. in Florence as their general manager. He has also worked for Ansaldo Tecnitalia in Florence.

Alberto Tesei is involved with the design engineering of turbomachinery for Nuovo Pignone in Florence, Italy. He is a graduate of the University of Rome with a degree in Engineering.

energy is required to drive the cooling fluid and cooling water circulation pumps.

The COP of these systems is lower with respect to traditional compression cycles, but this parameter is not a valid comparison element, since in its evaluation the difference between mechanical power and thermal power is not taken into account. Moreover, in this case, considering that the required heat is available and, if not used, would be somehow scattered in the atmosphere, it is a zero cost source.

Absorption cycles are to be considered technologically very mature with an increasing market. In 1992, 40 percent of large type chillers were absorption systems, and they have reached excellent reliability levels in relation to compression systems. Usually, they employ a solution of water and lithium bromide that is used to absorb steam acting as a cooling fluid. Because of the type of fluid used, temperatures lower than 4 degrees C. cannot be reached, in order to avoid problems of lithium bromide crystallization in the solution. They are characterized by very favorable behavior in part load operating conditions and this makes them particularly suitable for applications where the required power is extremely variable. COP can be expressed as follows:

$$COP = \frac{Qu}{Q_h + W_p} \cong \frac{Qu}{Q_h} = \left[\frac{1}{T_a} - \frac{1}{T_h}\right] / \left[\frac{1}{T_u} - \frac{1}{T_a}\right]$$

For symbol details see Figure 3.

Both single-stage and double-stage inlet air cooling systems are available on the market. Single-stage systems are older, very simple and use low pressure (about 1.5 bar) and relatively low temperature saturated steam or even overheated water. They reach COP values of about 0.7. Double-stage systems are more sophisticated and may reach a COP value of 1.1 to 1.2, according to the highest value of the evaporator temperature (Th) of the heat source that requires a higher supply steam pressure (about 8 bar) from the heat recovery boiler.

Compressor Station Description

The high pressure compression station considered is designed to recover the natural gas coming from the oil treatment system and re-inject it into the oil reservoir, to maintain pressure and enhance oil recovery.

The required duty is to compress 373 Nm^3/s (1200 MMSCFD) starting from a suction pressure of 75 bar (110 psi) up to a discharge pressure of 620 bar (9000 psi) to keep the reservoir pressure of 540 bar. The natural gas flow at station inlet has a temperature of 49 degrees C. (120 degrees F.). The overall service is achieved by gas turbine driven centrifugal compressor trains operating in parallel, each one consisting of three compression phases, with intermediate gas cooling. The total power required by the gas compressors is 134MW.

Compressors operate between 56 to 68 Nm^3/s (180 to 218 MMSCFD) by passing from the normal operating condition to that with maximum load achieved at 105 percent of nominal speed.

Ambient Conditions

Ambient condition data is very important for a correct selection and evaluation of the cooling system. This compression station is located in an area particularly unfavorable climatewise; it is a typically equatorial climate (humid and hot). Although limit values of 37.8 degrees C. (100 degrees F.) and 97 percent relative humidity were recorded, for the plant design the following values were assumed as design ambient parameters:

Air temperature	32.2 degrees C. (90 degrees F.)
Relative humidity	82 percent

The average power available from each gas turbine as a function of monthly average temperature, compared with cooling air at 10 degrees C. shows power losses, up to 3 to 4 MW, not only in the worst periods (i.e., summer), but throughout the year.

Injection Station Configuration

The project prior to the installation of the inlet air cooling system consisted of six operating turbo-compressor units, plus a standby unit, all driven by a gas turbine model MS5002-C. Each of the units provides 17 percent of total station capacity and each has a power margin of 10 percent (on design conditions 32.2 degrees C.

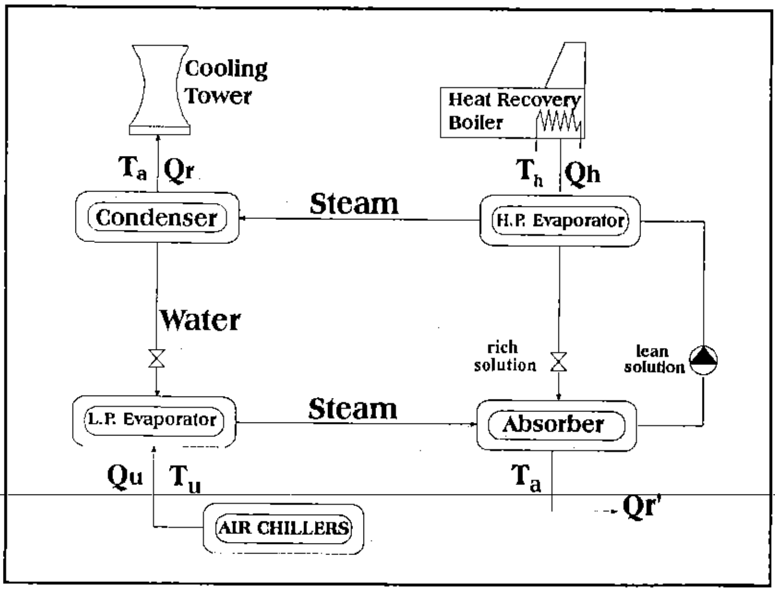

Figure 2: Absorption machine scheme.

Table 1					
Temp [C].	Relative Humidity (%)	GT Power [kW]	No. of Operating GT	Power Station [MW]	Total Power Margin (%)
15	60	28350	6	170.1	26.6%
25	100	26100	6	156.6	16.5%
37.8	82	23000	6	138	2.7%
32.2	82	24660	6	147.96	10%
10	100	29300	6	175.8	31%
10	100	29300	5	146.5	11%(*)
15	100	28350	5	141.7	7.6%(*)
5	100	30330	6	181.98	35.4%
5	100	30330	5	151.65	15.1%(*)

(*) Due to the compressor increased efficiency the compressor power margin will be higher.

and 82 percent relative humidity). Under the worst conditions, characterized by an ambient temperature of 37.8 degrees C., they are hardly sufficient to provide service (22970 kW_{TG} against 22400 $kW_{COMPRESSOR}$). Should only five operating units be available, the total capacity of the station would decrease to 83 percent of the total design value. It can be increased to 91 percent by exploiting the available power margin completely if temperature does not exceed 32.2 degrees C.

Compression station data summarized in *Table 1* shows the behavior of single gas turbine units, the compression station and the power margin in relation to the ambient conditions and the number of operating gas turbines.

For those solutions adopting five compressor trains, the value of the total power margin, evaluated on the injection compressors is higher due to the increased efficiency achievable by larger machines (by 1 to 2 percent).

It is possible to achieve the required compression duty only with five machines by keeping a power margin of 10 to 11 percent cooling air at 10 degrees C. Air cooling down to 15 degrees C. would also allow the required service to be provided, but with a slight power margin, to take into account the unavoidable performance losses caused by machine wear, compressor fouling, etc.

Proposed Station With Inlet Air Cooling

The proposed station would include five operating turbo-compressor units, plus a standby unit, driven by the same gas turbines and equipped with an inlet air cooling system. In this case, the injection compressors are designed for a unitary mass flow rate of 74.6 Nm^3/s, which will be kept constant with the inlet air cooling systems.

Types Of Cooling Systems Analyzed

For comparison between the different systems an identical heat power was considered for all solutions taken into account. This value is required to cool the air at the turbine inlet from reference ambient conditions (32.2 degrees C. and 82 percent relative humidity) to a temperature of 10 degrees C. The heat power required for inlet air cooling is about 8MW for each unit. The heat exchange batteries to be installed in the gas turbine air suction system are identical for the various cases taken into account.

Evaporative cooling systems are particularly simple and economical, but suitable for hot, dry climates. Its success in realizing higher ΔT depends on the relative air humidity contents at the system inlet. Considering the unfavorable ambient condition described earlier, this kind of cooling system is not suitable and therefore not considered here.

Propane cooling systems operating at pressures ranging from 4 to 20 bar, corresponding to -5 degrees C. and 81 degrees C. respectively, were chosen. A solution of water and glycol with temperature that is to be kept above 0 degrees C., in order to avoid icing on the heat exchange battery surfaces on the air side, circulates at the evaporator. The cooling plant is characterized by a COP=2.283 and requires a mechanical power of 17.5 MW. The project also provides for the splitting of the propane compression service into two compression units. For this purpose, it is necessary to provide for two units with centrifugal compressors driven by Nuovo Pignone gas turbines model PGT10 that, under design ambient conditions, have a slight power margin of 5 to 6 percent (without providing for inlet air cooling).

Advantages And Disadvantages Of A Compression Cooling System

Compression cooling systems offer the following advantages:

- High temperature at the condenser that permits reduction of its dimensions and increases in its efficiency, even in the case of high ambient temperature and humidity.
- Suitable for installation in various climates.

Disadvantages, however, include:

- High installation cost.
- High operating cost mainly due to fuel consumption
- High maintenance cost of the propane turbo-compressor.
- Poor performance at part load conditions.

Item	Size
Turbo-compressors	2x10.6 MW
Propane condenser	65 MW
Propane accumulator	$100 m^3$
Propane evaporator	40 MW
Air chiller	6x8 MW
Piping e auxiliaries	--
Total cost *USD10^6	11.5-12

Table 2
Costs Of Compression Cooling System

Cost Analysis

Table 2 shows an estimate of the costs of the different main components of the compression cooling system. This type of plant has the disadvantage of high running costs caused by fuel consumption. Supposing a "fuel gas" with Lower Heat Value (LHV) of 35000 kJ/kg, at the price of 0.02 US$/kg were used, an average daily consumption of 140000 kg/day can be estimated. This corresponds to an average yearly expenditure of about $1,000,000 i.,e., about 9 to 10 percent of the total investment cost of the cooling plant. The maintenance costs of the other two gas turbines required to drive the cooling unit and of the propane compressors are to be added to the above costs for an exhaustive cost evaluation.

Absorption Cooling System—Considering the size of the absorption machines available on the market, we deemed it suitable to use two lithium bromide units, 4,000 kW each, to cover all the cooling power required for each turbine. The air cooling plant consists, therefore, of the following main equipment:

- 12 absorbers;
- 6 small low pressure heat recovery boilers (8 bar), using about 15 percent of heat power recoverable at the gas turbine exhaust;
- water cooling towers and circulation pumps.

In this solution mechanical energy is only required to drive the water circulating pumps.

There is a clear difference between single-stage and double-stage systems. The double-stage absorber has a higher efficiency (almost double the single stage) and requires less energy supply, thus lowering the costs of all the auxiliary equipment. The single-stage absorber at present is much more economical (by about 30 percent) than the double stage-one.

Plant efficiency may be further increased by using cold water (about 10 degrees C.) returning from the heat exchangers (whose capacity may reach 10 m^3/h) for the replenishment of the cooling towers. Thus, there is a reduction in the thermal jump of the water in the cooling towers, that can reach 7 percent under the worst conditions. The condensate water coming from the gas turbine inlet heat exchangers (about 10 m^3/h at 10 degrees C.) can also be used for different purposes within the plant due to its favorable characteristics (low dissolved mineral content, etc.).

The performance of the absorption cooling cycle has a remarkable capacity for improvement, thanks to the great interest of industry in this type of technology. Considering that there is still much room for improvement (maximum declared COP on double-stage 1.2 against a theoretical one of 2.9 with T_h = 180 degrees C.), in the future one can expect great things from these systems.

In the future, the use of ammonia absorption systems, at present not available in the size required by these plants, may allow IAC systems down to tempeatures of c.4 to 5 degrees C., as is normally done with ice-storage systems, to further reduce the number of compression trains.

Cost Analysis

Table 3 shows an estimate of the costs of the main elements of the absorption cooling plant, for single and double stage systems.

Advantages And Disadvantages Of An Absorption Cooling System

Absorption cooling systems offer the following advantages:

- Installation costs 30 to 40 percent lower than compression cooling systems.
- Complete absence of fuel consumption.
- A negligible electric power consumption.
- High flexibility and good performance at part load conditions.
- Low maintenance costs

Disadvantages include:

- Large cooling towers due to low

Table 3
Absorption Cooling System Costs

	Single Stage		Double Stage	
Item	**Size**	**Cost (US$)**	**Size**	**Cost (US$)**
Heat recovery boilers	6x11.5 MW	1,170,000	6x7.5 MW	680,000
Absorbers	12x4 MW	4,000,000	12x4 MW	5,800,000
Air chillers	6x8 MW	1,000,000	6x8 MW	1,000,000
Cooling towers	10x9 MW	900,000	8x9MW	720,000
Pumps	$3x5000 m^3/h$	470,000	$3x4000 m^3/h$	400,000
Piping & Auxiliaries	--	750,000	--	650,000
Total costs	--	**8,290,000**	--	**9,250,000**

Table 4
Cost Comparison Referred To The Conventional System

Item	Compressor Cooling System	Absorption Cooling System
Capital costs	-10 %	-11%
Fuel costs	+2%	-13%
Operating & Maintenance	+10%	-6%

ΔT available.

- Inlet air temperature obtainable cannot be lower than 10 degrees C., due to lithium bromide crystallization.

Comparative Considerations

Table 4 shows an estimate of all costs involved in relation to the conventional compression station without an inlet air cooling system. Due to the saving of a complete natural gas injection unit, the capital cost will be reduced by 10 to 11 percent of the total station cost. Both the fuel and maintenance cost for the compression cooling system are higher, due to propane compression trains. In the case of the absorption cooling system, the fuel costs are expected to be 13 percent lower than the conventional compression station fuel cost.

Conclusions

The use of gas turbine inlet air cooling turned out to be very advantageous in terms of performance in particularly hot climates. The different inlet air cooling systems available at present were investigated:

Evaporative cooling system—simple and economical, but suitable only for hot, dry climates.

Compression cooling system—suitable for many different climatic conditions. However, it requires higher O&M costs.

Absorption cooling system—its installation cost is slightly lower than the compression cooling system. The O&M cost is markedly reduced but requires a large area to be installed.

All things considered, choosing the best inlet air cooling technique allows one:

- to save a complete natural gas compression unit for about $40 to $50 million.
- to reduce O&M costs of the compression station by at least 10 to 15 percent.
- to operate all the machines under design conditions independent of climatic conditions.

We can conclude that for this application the absorption cooling system is much more advantageous than other systems. Even though double-stage absorbers are much more efficient and offer several advantages with respect to single stage absorbers, at present their higher costs cancel any advantage related to the reduction in size and cost of heat recovery boiler, cooling towers, pumps, piping and auxiliary equipment. ■

Acknowlegements

The authors are grateful to C. Lanfranchi and T. Falorsi for their contribution to this research, while they were both members of the Energetics Department of the University of Florence, and M. Spaghetti and M. Canacci from Nuovo Pignone, for the coordination and realization of the detailed project and for their very useful suggestions during the preparation of this article.