

## Assessment and performance improvement of gas turbine inlet air cooling in a combined cycle power plant

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**Abstract:** The temperature of the turbine inlet-air has a significant effect on the power output and efficiency of gas turbine plants. In high ambient temperatures, there is a significant loss in air mass flow rate and consequently a considerable decrease in turbine output. In this paper, the effect of lowering the compressor intake-air temperature by means of a fogging system on the performance of a 79 MW gas turbine in Mashhad power plant is studied. Since Mashhad is located in a dry and relatively hot region, fogging method has been selected as the compressor inlet air cooling system. The result show that by employing this method during hot months of the year, there is 8.8% increase in the turbine output. In addition, the output power at best condition increases by 13 MW. Economic analysis shows that the payback period is 1.66 years and rate of return is 60%. According to these calculations, evaporative cooling has economic advantage over other cooling methods in hot and dry climates. Results also reveal that ambient relative humidity plays an important role in the efficiency of fogging systems.

**Key words:** *Gas turbine; Performance; Power plant*

### 1. Introduction

There are several environmental factors such as ambient temperature, pressure and relative humidity that affect a gas turbine performance. The compressor intake air temperature has received a great attention in literature and numerous studies have been carried out concerning this factor (Alhazmy and Najjar, 2004; Bassily, 2001; Mohanty and Paloso, 1995; Ameri and Hejazi, 2004; Ameri et al., 2005; Kakaras et al., 2004). High ambient air temperature can result in decreasing the turbine power output by two means: as the air temperature increases, the air mass flow rate decreases and as the result the power output which is a direct function of air mass flow rate reduces. On the other hand, Eq (1) shows that the compressor work is function of the temperature of inlet air:

$$W_{\text{comp}} = T_{\text{in}} c_{p,\text{air}} \left( r_c^{\frac{\gamma_c-1}{\gamma_c}} - 1 \right) \quad (1)$$

Where  $c_{p,\text{air}}$  is the specific heat of air at constant pressure,  $T_{\text{in}}$  is the inlet air temperature,  $r$  is the pressure ratio, and  $\gamma_c$  is the specific heat across the compressor. According to Eq (1), higher air temperature results in more compressor work which also causes decrease in total power output.

Gas turbines are designed to operate at ISO conditions (intake air at 15°C and 60% relative humidity), but most of the times they work at off-design conditions. As the result, much of their potential to produce power is lost at off-design

working. Compressor inlet air cooling is a cost-effective way to add machine capacity when peaking power periods are usually encountered on electric utility systems.

Most of the studies on inlet air cooling have focused on chiller systems (Mohanty and Paloso, 1995; Ameri and Hejazi, 2004; Ameri et al., 2005; Kakaras et al., 2004). Unfortunately, fogging systems have not been investigated extensively and few papers are available in literature. Chaker et al. (2008) studied the theory of droplet thermodynamics and heat transfer and provided practical points of application of inlet fogging to gas turbines. Yap and Wang (Yap and Wang, 2006) investigated the power enhancement by employing gas turbine inlet fog cooling and compared the results with power increase caused by steam injection. They showed that by using the same amount of water mass flow rate, steam injection proved to be less effective than inlet fog cooling in augmenting power output.

Although there has been some efforts to calculate the effectiveness of fog systems, but still there is lack of systematic studies that show the absolute benefits of employing fogging systems especially in hot and dry climates. This paper investigates the effect of using fogging system for compressor inlet air cooling at a 79 MW gas turbine located in a hot and dry region. In addition, By means of economic analysis the cost-effectiveness of this method is examined.

### 2. Gas turbine system

A gas turbine, also called a combustion turbine, is a rotary engine that extracts energy from a flow of

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combustion gas. It has an upstream compressor coupled to a downstream turbine, and a combustion chamber in-between. Energy is released when air is mixed with fuel and ignited in the combustor. The resulting gasses are directed over the turbine's blades, spinning the turbine and powering the compressor, and finally are passed through a nozzle, generating additional thrust by accelerating the hot exhaust gases by expansion back to atmospheric pressure.

Ambient temperature has a significant effect on gas turbine performance. Output power, heat input, exhaust flow rate and exhaust temperature are functions of air inlet temperature. To determine the performance of turbine under different ambient temperatures and assess the effect of installing air cooling equipment at the inlet of compressor, it is necessary to have the air mass flow rate and output power as functions of ambient temperature. In this paper, a 79 MW gas turbine located in Mashhad power plant is studied and performance curves of this machine are depicted in Fig. 1. It can be seen that there is a dramatic change in the amount of power output and air mass flow rate as the inlet air temperature increases. Required correlations have been derived from performance curves:

$$P(\%) = -0.5898T_{amb} + 108.89$$

$$\dot{m}_{air}(\%) = -0.3617T_{amb} + 105.43$$

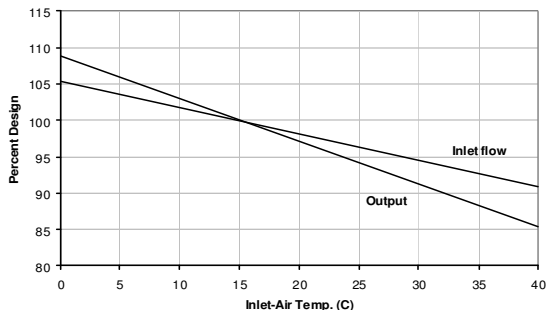


Fig. 1: Gas turbine performance curves

It is evident from Eq. (2) and Eq. (3) that for each 1°C increase in ambient temperature, the power output and air mass flow rate decrease by 0.59% and 0.36%, respectively.

Mashhad is located in northeast of Iran in a dry region, and experiences high temperatures during hot months of year. As it can be seen through Fig. 2 and Fig. 3, ambient condition in Mashhad in most of the times is deviated from ISO condition during the hot months. According to Fig. 2 and Fig. 3, the highest temperature is 32°C and the lowest relative humidity is 6%.

### 3. Inlet-air cooling techniques

#### 3.1. Evaporative Cooling

Evaporative cooling systems make use of vaporization latent heat of water in order to reduce the air dry bulb temperature down to its wet bulb temperature. A further effect is the reduction of emissions of oxides of nitrogen. These systems have the lowest capital cost, lowest O&M cost and can operate on raw water. At the same time they are highly influenced by the site wet bulb and can be employed in areas where relative humidity is rather low. Similarly it can be employed in areas where relative humidity is rather low (Omidvar, 2001).

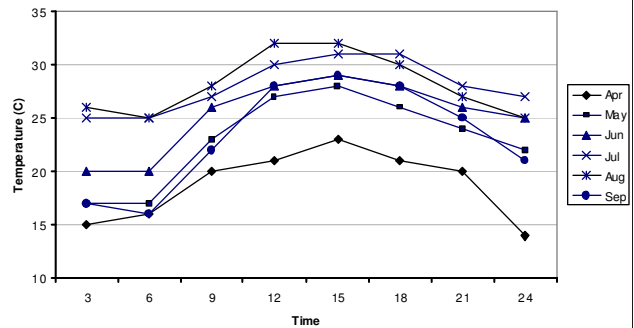


Fig. 2: Variation of local temperature during hot months

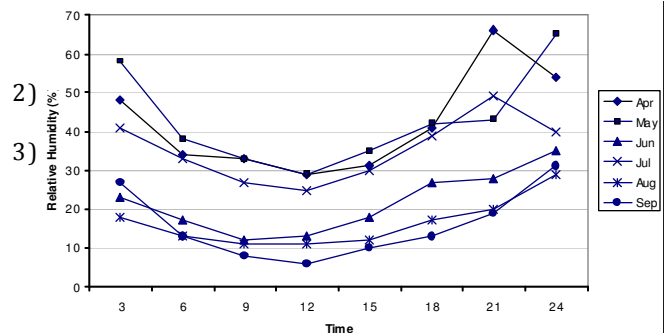


Fig. 3: Variation of local relative humidity during hot months

#### 3.2. Fogging systems

Inlet fogging is a type of evaporative cooling method, where de-mineralized water is converted into a fog by means of high-pressure nozzles operating at 70 to 200 bar. This fog then provides cooling when it evaporates in the air inlet duct of the gas turbine. The air can attain 100% relative humidity at the compressor inlet, and thereby gives the lowest temperature possible without refrigeration (the wet bulb temperature) (Boyce, 2002). Fog inlet cooling also has low capital and O&M costs but can increase gas turbine performance better than evaporative cooling.

#### 3.3. Mechanical refrigeration systems

In these systems, refrigerant vapor is compressed using a screw, reciprocating, or centrifugal compressor. After compression, the vapor passes through a condenser. The condensed vapor is then expanded to provide the cooling effect. The evaporator chills the cooling water, which is

circulated to the gas turbine inlet cooling coils. Mechanical chillers can increase gas turbine performance better than evaporative cooling and fog system and are not very sensitive to ambient air wet bulb temperature. The disadvantages of these systems are high initial capital cost, high O&M cost and long delivery and installation time (Omidvar, 2001).

### 3.4. Mechanical Refrigeration Systems with thermal storage

In these systems, the chilled water produced by mechanical chiller or the ice produced by ice maker in off-peak hours is stored in a thermal storage for using in peak hours. Thermal storage systems are used in areas where relative humidity is rather high and there is a wide variation in electricity tariff between peak and non-peak hours. The disadvantages of these systems are very high initial capital and O&M cost, longer delivery and installation time and higher expertise is needed to operate and maintain the plant.

### 3.5. Absorption chiller

Absorption Cooling systems are similar to the mechanical refrigeration systems except that instead of using mechanical chillers, these systems use absorption chillers that require thermal energy (steam or hot water) as the primary source of energy and require much less electric energy than the mechanical chillers. The advantage of this system is that it has much less parasitic load and its major disadvantage is that its capital cost is much higher than even mechanical refrigeration systems.

## 4. Proposed cooling scheme

As noted above, there are several methods for cooling the compressor inlet air. Since relative humidity in Mashhad is low and consequently the difference between dry bulb temperature and wet bulb temperature is high, evaporative cooling or fogging systems can operate effectively under this condition. Evaporative cooling and fogging systems have similar mechanisms but it has been approved that fog inlet cooling is more efficient (Omidvar, 2001). So a fogging system as shown in Fig. 4 is proposed.

Unlike evaporative cooling, raw water cannot be used for fogging systems. So the raw water is taken into the water treatment plant and then the demineralized water being stored in a tank. Next the demineralized water is pumped to high pressure spray nozzles which are designed to generate very small fog droplets (Fig. 4). Droplets of approximately 10 microns ( $\mu\text{m}$ ) diameter are desired, as they have a faster evaporation rate than larger sizes. The fogging system is provided with modulated control system so that the water spray is introduced in stages. The modulation is achieved completely

automatically with the ambient temperature and relative humidity continuously assessed and the pump and valve actuators controlled by this continuous measurement process. The fogging system is designed to have 100% efficiency and therefore can decrease the air temperature down to ambient wet bulb temperature. The control process is adopted in such a way that air temperature doesn't become lower than  $5^\circ\text{C}$ . It is because of avoiding the freezing phenomena in early stages of compressor. According to Mashhad weather data, the design point is selected at  $35^\circ\text{C}$  and 11% humidity. The required water flow rate is obtained as follows:

$$\omega_{\text{Dry,DP}} = 0.0035 \text{ kgw/kg a} \quad (4)$$

$$\omega_{\text{Wet,DP}} = 0.0135 \text{ kgw/kg a} \quad (5)$$

$$\dot{m}_{\text{w,DP}} = (\omega_{\text{Wet,DP}} - \omega_{\text{Dry,DP}}) \dot{m}_{\text{air,DP}} = 11.034 \text{ m}^3/\text{h} \quad (6)$$

In which  $\dot{m}_{\text{air,DP}}$  can be evaluated through Eq. (3). Since  $1.5 \text{ m}^3$  of raw water is needed for producing  $1 \text{ m}^3$  de-mineralized water, there should be  $16.551 \text{ m}^3/\text{h}$  supply of raw water for each unit.

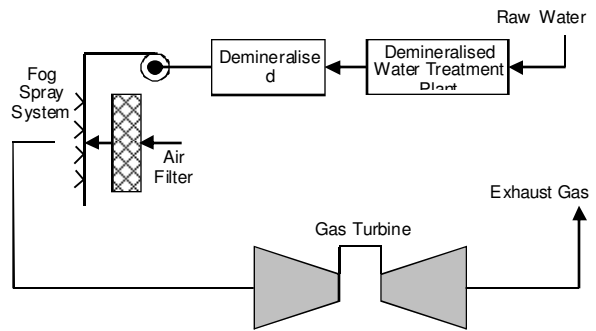


Fig. 4: Fogging system

## 5. Results

The gas turbine power improvement by using fogging system has been studied on a 79 MW gas turbine in Mashhad, located in north east of Iran. Fig. 5 illustrates the power improvement during typical days of hot months of the year (Apr-Sep). It can be seen that power improvement during the day increases to a maximum and then decreases. The maxima occur in afternoon when the temperature is higher and relative humidity is lower. Among hot months of the year, the highest power improvement occurs in August (13 MW), which according to Fig. 2 and Fig. 3 has the highest temperature and low relative humidity. Power enhancement in peak hours (19-22) varies between 7 and 11 MW which is a considerable amount.

Fig. 6 shows the total power improvement during hot months. It shows that even in April, in which the lowest temperature occurs among hot months, there is almost 7 percent increase in total power output. Like Fig. 5, the highest power enhancement takes place in August. The net power in 6 months increases by around 8.8% (12,200 MW).

Table 1 shows the economic analysis results. The economic feasibility analysis of this project considers the additional system efficiency in producing electricity and the capital costs of the project. It is a cost benefit analysis. The benefit of electricity production during six hot months of a year is calculated to be 305000 US\$ based on the current electricity prices in Iran which is 2.5 Cents/kWh for off-peak hours. The analysis is based on 17% for the domestic interest rate, 7% for the foreign interest rate and 12 years for the equipment life.

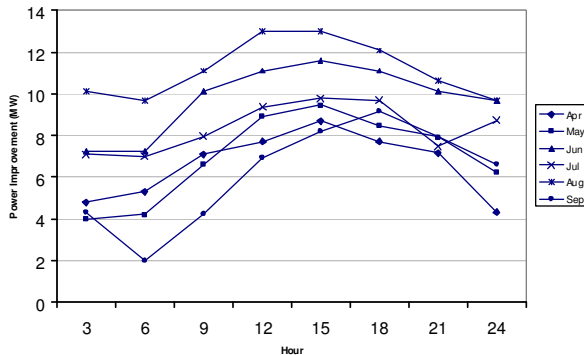


Fig 5: Power improvement

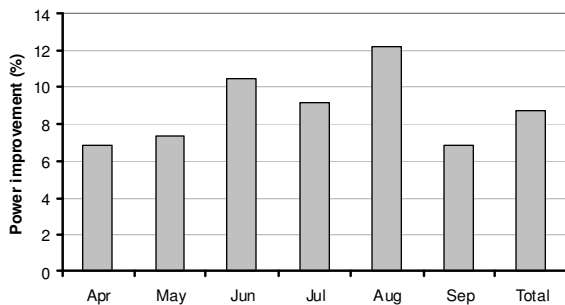


Fig. 6: Total power improvement

Table 1: Economic analysis

Net power increase	12,200,000 (kW)
Fogging system cost	300,000 US\$
Water refinery plant cost	180,000 US\$
Total capital cost	480,000 US\$
Annual O&M costs	15,000 US\$
Annual benefit	305,000 US\$
Cost of electricity	0.8 Cents/kWh
Payback period	1.66 years
Rate of return	60%

## 6. Conclusion

In this study, fogging cooling process has been selected as the compressor intake-air cooling system for a 79 MW gas turbine in Mashhad power plant which is located in a dry and relatively hot region. The power enhancement of this system has been studied for hot months and it was found that at best condition the output power increases by 13 MWh. The net power augmentation through 6 months is 12,200 MWh. It was concluded from economic analysis that rate of return is 60% and payback period is 1.66 years which is much less than what

Ameri et al (2004) obtained for refrigeration cooling system. The cost of electricity was also calculated to be 0.8 Cents/kW which is less than current electricity prices in Iran (2.5 Cents/kWh).

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## References

- Alhazmy, M.M., and Najjar, Y.S.H., 2004, Augmentation of gas turbine performance using air coolers, *Applied Thermal Engineering*, 24, pp. 415-429.
- Bassily, A. M., 2001, Effects of evaporative inlet and after cooling on the recuperated gas turbine cycle, *Applied Thermal Engineering*, 21, pp. 1875-1890.
- Mohanty, B., and Paloso JR, G., 1995, Enhancing gas turbine performance by intake air cooling using an absorption chiller, *Heat Recovery Systems & CHP*, 15 (1), pp. 41-50.
- Ameri, M., and Hejazi, S. H., 2004, The of capacity enhancement of the Chabahar gas turbine installation using an absorption chiller, *Applied Thermal Engineering*, 24, pp. 59-68.
- Ameri, M., Hejazi, S. H., and Montaser, K., 2005, Performance and economic of the thermal energy storage systems to enhance the peaking capacity of the gas turbines, *Applied Thermal Engineering*, 25, pp. 241-251.
- Kakaras, E., Doukelis, A., and Karellas, S., 2004, Compressor intake-air cooling in gas turbine plants, *Energy*, 29, pp. 2347-2358.
- Chaker, M., Meher-Homji, C. B., and Mee III, T., Inlet Fogging of Gas Turbine Engines—Part I: Fog Droplet Thermodynamics, Heat Transfer, and Practical Considerations, *Journal of Engineering for Gas Turbines and Power*, 126 (3), pp. 545-558.
- Yap, M. R., and Wang, T., 2006, Simulation of Producer Gas Fired Power Plants with Inlet Fog Cooling and Steam Injection, *Proceedings of GT2006*, Spain.
- Omidvar, B., 2001, Gas turbine inlet air cooling system, *The 3rd Annual Australian Gas Turbine Conference*, Melbourne, Australia.
- Boyce, P. M., 2002, *Gas Turbine Engineering Handbook*, second ed., Butterworth-Heinemann, Gulf Professional Publishing, pp. 96-98.