TURBINE INLET AIR COOLING METHODS

3.1 Introduction

Power generation from gas turbines is penalized by a substantial power output loss with increased ambient temperature. By cooling down the gas turbine intake air, the power output penalty can be mitigated. A substantial number of new power plants in the world would not need to be built if TIC is used to utilize the hidden capacity of existing combustion turbine plants. TIC provides economic and environmental benefits. These benefits are good for the combustion turbine plant owners, the rate payers and the general public. These benefits include:

**Economic:**

I. Capture the “hidden” MW when most-needed and most-valuable

II. Enhance the combustion turbine asset value via:

a. Low capital cost per MW capacity gain

b. Improved heat rate (Lower fuel cost per kwh)

c. Fast capital cost payback (High Return on Investment)

d. High Net Present Value

III. Lower end user rates (Lower rates to electricity users)
Environmental:

IV. Allow minimum use of inefficient and polluting power plants by allowing maximum use of efficient and cleaner combustion turbine plants

a. Conserves nations' natural fuel resources

b. Reduces emissions of pollutants (SOx, NOx etc)

c. Reduces emissions of global warming/climate change gas (CO2)

V. Minimize/eliminate commissioning of new power plants

The purpose of this chapter is to review the state-of-the-art in applications for reducing the gas turbine intake air temperature and examine the merits from integration of the different air-cooling methods in gas-turbine-based power plants. Following TIAC methods are discussed in this section: (see also figure 3.1)

1. Evaporative cooling- media based
2. Evaporative cooling- Fogging system
3. Over spray fogging
4. Evaporative cooling of Pre-compressed air
5. Refrigeration Cooling- Mechanical Chiller
6. Refrigeration Cooling- Absorption Chiller
7. Thermal Energy Storage(TES) Systems
8. Swirl Flash System (Patented)
9. LNG Evaporation system
10. Indirect Evaporative Cooling (Patented)
3.2 Evaporative Cooling- Media Based

Evaporative cooling is based on the evaporation of water in the intake air of the gas turbine. As water evaporates, the latent heat of evaporation is absorbed from the surrounding air. As a result, the air is cooled during the process. In the limiting case, the air leaves the cooler at a saturated state. The evaporative cooling process is, essentially, identical to the adiabatic saturation process, since the heat transfer between the air stream and the surroundings is usually negligible. Therefore, the evaporative cooling process follows a line of constant
enthelpy on the psychrometric chart as shown in Figure 3.3. M.Chaker et al and R K Bhargava et al [8,18] provide a thorough analysis of this method with climatic and weather modeling. Traditional evaporative coolers that use media for evaporation of the water have been widely used in the gas turbine industry over the years, especially in hot arid areas. In this type of cooler, water is distributed over media blocks which are made of fibrous corrugated material positioned at the gas turbine intake. The air flow through the blocks evaporates the water. The effectiveness of these coolers is defined as the ratio of the temperature difference between inlet and exit of the cooler and the temperature difference if the air left the cooler at a saturated state, as given in equation (3.1). Its values typically range from 80–85%.

\[
\text{Cooler effectiveness} = \frac{T_{1_{DB}} - T_{2_{DB}}}{T_{1_{DB}} - T_{2_{WB}}} \quad (3.1)
\]

Where: \( T_{1_{DB}} = \) Entering Air Dry Bulb Temperature
Figure 3.3 Psychrometric chart showing the path taken by an evaporative cooling process and an inlet air chilling process.

This means that the wet bulb temperature can never be attained. In addition, the increased pressure loss caused by the media blocks reduces the power output gain. Water quality requirements, however, can be less stringent than those required for direct fog-cooling systems.

3.3 Evaporative Cooling - Fogging System

It is a method of cooling where demineralized water is converted into a fog by means of high-pressure nozzles operating at 70–200 bar. This fog then provides cooling when it evaporates in the air inlet duct of the gas turbine. This technique, in contrast to the traditional evaporative coolers, allows effectiveness close to 100% to be attained. An
elaborate discussion on the aspects of direct inlet fogging can be found in ref. [8-12] A schematic layout of direct inlet fogging for a gas-turbine-based power plant is shown in figure 3.4

![Schematic Layout of a direct Inlet Fogging System](image)

Figure 3.4 Schematic Layout of a direct Inlet Fogging System [42]

### 3.4 Overspray Fogging

Overspray fogging; also referred to as high fogging, wet compression, and fog inter cooling is derived by the deliberate introduction of fog droplets into an axial flow compressor of a gas turbine. The compressor of a gas turbine consumes a considerable amount of the gross work produced by the gas turbine. One of the main advantages of overspray fogging is that it enhances power output as a result of decrease in compression work associated with the continuous evaporation of water within the compressor. Other factors which contribute to power augmentation are increased flow rate through the turbine and increase in specific heat capacity of the fluid mixture flowing through the turbine. For most applications, the amount of overspray is in the range of 0.5–1% of the air mass flow rate of the gas turbine.
Evaporative cooling is the most commonly employed system for inlet air-cooling because of the simplicity of components, installation and the low equipment cost. Unfortunately, the gain from the use of an evaporative cooler is limited by the difference between the dry and wet bulb temperatures and it is high for dry ambient conditions, whereas the gain for wet ambient conditions is low. In order to further increase power augmentation, high fogging or wet-compression systems as described above can be used. About 6% power gain can be achieved for 1% water mass flow relative to compressor air mass flow [42].

3.5 Evaporative Cooling of Pre-Compressed Air

In this innovative gas turbine inlet air-cooling method, an electrically driven fan is used for pre-compression of the inlet air supplied to the compressor of the gas turbine,

resulting in a temperature rise of the intake air. The pre-compressed air is then cooled by an evaporative cooler. Evaporative cooling of pre compressed air is quite effective because of the higher potential of evaporative cooling for the hotter pre-compressed air stream. This method can be applied to compensate for the reduction in the air mass flow as a consequence of high ambient temperatures. This can be achieved by controlling the pressure rise of the fan, so that the air mass flow at the inlet of the compressor is
maintained largely constant, regardless of ambient conditions. Using this method, the gas
turbine can be operated over a long period of time at its optimum operating point with
regard to power output and efficiency. Also, more heat can be recovered from the exhaust
gases compared to the non cooled case. This means that, for a cogeneration system, steam
production can be held constant to meet the required process steam demand. The
maximum possible airflow rate is limited by the exhaust condition for the turbine and
flow conditions through the compressor surge limit. A description of the modeling of this
system has been presented by E.Kakaras et al [42]. A schematic layout of evaporative
cooling of pre-compressed air is shown in figure. 3.5

3.6 Merits and Demerits of Evaporative Cooling Systems

The power gains realized by evaporative cooling technologies depend on the ambient
temperature and humidity conditions. Evaporative technologies produce their largest
power gains when ambient conditions are dry and hot, and less gains when the conditions
are very humid. In addition, the wet-bulb temperature and the amount of water that can
be injected for the compressor inter-stage cooling limit the maximum power gain
achievable by these technologies. These technologies also consume lot of water that may
require extensive water treatment/conditioning depending upon manufacturers’
specifications and the quality of available water. The primary advantages of these
technologies are the very low capital and operating costs.

3.7 Refrigeration Cooling

Refrigeration cooling is used when cooling below the wet bulb temperature is desired. Both
mechanical and absorption refrigeration systems are available for gas turbine intake air-
cooling. A TIC system that uses a chiller draws the turbine inlet air across a cooling coil
in which either chilled water or a refrigerant is circulated. Air side pressure drop across
the cooling coil could be 2.5 to 5.0 cms of water column [26]. The chilled water could be
supplied directly from a chiller or from thermal energy storage (TES) tank that stores ice
or chilled water. Chiller capacities are rated in terms of ton refrigeration (TR). One TR
capacity chiller is capable of removing heat at the rate of 3.517 kW. The two most com-
mon type of chiller technologies used for TIC are the mechanical chillers and absorption chillers.

3.7.1 Mechanical Chiller
Mechanical Chillers, also known as vapor compression chillers, are the most common chillers used for TIC. These chillers are similar to those commonly used in heating, ventilation, and air conditioning (HVAC) systems for cooling air in large commercial buildings. A mechanical chiller can cool the turbine inlet air to any temperature down to 5°C. Even though the chiller could cool the inlet to temperatures even lower than 5°C, the lower temperatures are generally not desirable to avoid the potential of forming ice crystals in the bell mouth of the compressor. The temperature drop across the bell mouth is estimated to be about -12°C and therefore, the turbine inlet air is not recommended to be cooled below 5°C. A mechanical chiller could be driven by an electric motor, natural gas engine, or steam turbine. A schematic layout of this type of inlet air-cooling system for a gas-turbine-based power plant is shown in figure 3.6

![Diagram of Mechanical Chiller and Chilling Coils](image)

Figure 3.6 Layout of Air Cooling with Mechanical Chiller and Chilling Coils [42].

When a mechanical chiller is operated by an electric motor, it requires electric power in the range of 0.7 to 0.8 kW/TR [29], depending on the chiller design. Most of this power
requirement is for operating the compressor (0.6 to 0.65 kW/TR). Mechanical chillers do produce net power enhancement for the power plant by TIC. Electric motor-driven chillers represent the least capital cost option for TIC systems using chillers.

### 3.7.2 Absorption Chiller

Absorption Chillers are different from the mechanical chillers in that these chillers do not need a mechanical compressor for compressing the refrigerant and that the refrigerant they use is either water or ammonia, instead of a hydrocarbon fluid used in mechanical chillers. The primary source of energy for absorption chillers can be thermal, instead of electrical. The source of thermal energy for absorption chillers could be hot water, steam, or a fuel, such as natural gas. These chillers require very little electrical energy to operate only a few pumps. A schematic layout of a typical absorption chiller with direct contact air cooler is shown in figure 3.7. Absorption chillers could be single-effect or double-effect chillers. The double-effect chillers are more energy efficient but require higher temperature heat and more capital cost. Absorption chillers could incorporate a mixture of lithium bromide and water, or ammonia and water. Absorption chillers that use lithium bromide-water mixture are significantly more commonly used than the ammonia water.

![Figure 3.7 Layout of Air Cooling with Absorption Chiller](image-url)
mixture chillers. A single-effect absorption chiller (lithium bromide and water mixture) system will have a COP of 0.7 - 0.8 and a double effect unit a COP of 1.2-1.3, also depending on the quality of heat source. These absorption chillers are generally used to cool the turbine inlet air to about 10°C. Absorption chillers using ammonia-water mixture can cool the inlet air to 5°C, just as the mechanical chillers.

3.7.3 Merits and Demerits of Refrigeration Cooling Systems
The primary advantage of using chiller technologies is that they allow cooling of the turbine inlet air to much lower temperatures and thus, achieve much higher power capacity enhancements than those possible with evaporative cooling technologies. Unlike evaporative cooling technologies, chillers allow cooling of inlet air to any desired temperature, within the limitations of the selected chiller, almost independent of ambient temperature and humidity conditions. The chiller technologies also do not require any water treatment and consume very little or no water.

Part load performance of absorption systems is relatively good and efficiency does not drop off at part load as it does with mechanical refrigeration systems. Absorption systems also have lower operating and maintenance costs than mechanical refrigeration systems and very low auxiliary power consumption.

The primary disadvantage of the chiller technologies is their capital cost. The capital costs of chiller technologies are much higher than those for evaporative cooling technologies. Since the chiller systems also require the inlet air to be drawn through cooling coils, these systems incur more pressure drop (generally a few centimeters of water column) on the air-side compared to evaporative cooling technologies. However, in spite of the high capital cost and additional pressure drop, these technologies cost much less than the combustion turbines without any cooling for providing additional power capacity in hot weather.

3.8 Thermal Energy Storage Systems (TES)
Mechanical chilling has applications for both continuous duty power plants and peaking units where it is economically justifiable to deliver a constant lowered compressor inlet air temperature. Peaking units have greater applications of using Thermal Energy Storage
TES) during off-peak power demand periods. TES systems employ similar chiller equipment and auxiliaries as mentioned above, but also have an additional chilled fluid storage tank and pump requirements. TES systems operate the primary chilling circuit during off-peak power demand periods, typically at night, and charge the thermal storage tank with a chilled fluid reserve during this time. As peak power demand time cycles on line, the mechanical chiller equipment is off-line and only the chilled fluid pumping load is realized as chilled fluid is circulated.

3.9 The Swirl Flash System

The compression of air requires less energy at low temperatures than at high temperatures, because of the smaller volume. In most designs, intercoolers are used to reduce the temperature, but heat exchangers are expensive and should be avoided wherever possible. By spraying water into the compressor and allowing the droplets to evaporate, a similar effect can be achieved. However, round-the-clock water injection could cause problems with erosion, water separation etc. The droplets must therefore be small. The challenge is to generate a spray of tiny droplets (typically 1 to 5 µm in diameter) in a quantity sufficient to cool the air during compression. Experiments show that this can best be done by the newly emerged swirl flash technology. The swirl flash technology is based on a simple but robust principle. Water is pressurized (typically 100-150 bar), heated-up to about 200 °C and fed to a swirl nozzle. Due to the swirl movement, the water sprouts out of the nozzle in a typical spray pattern, which has the shape of a cone. The droplets size is about 25 µm. However, when the water is significantly above the boiling point at the ambient pressure, it starts boiling violently (flashing). As a result, each droplet of 25 µm explodes in a thousand fragments, each having the size of about 2.5 µm. See figure 3.8 (a) and 3.8 (b). The typical spray cone of a swirl nozzle changes because of partial flashing to a parabolic shape [64]. The ultra fine spray ensures almost instant evaporation and cooling. The droplet size distribution is indicated below (up to $10^{12}$ droplets per second!) see figure 3.9 [64]

The idea of cooling air by adding hot water sounds strange. But the amount of heat extracted from the compressed air by means of evaporation is far greater than the amount of heat added by utilizing the hot water spray. The result is a drop in compressed air
temperature and a corresponding drop in compressor discharge temperature. In order to keep the turbine inlet temperature constant, the system has to supply more fuel. In combination with the lower parasitic work for the compressor, this results in a higher output.

Figure 3.8(a) Spray pattern under cold conditions [64]  
Figure 3.8 (b) Spray pattern in the swirl flash mode [64]

Single shaft gas turbines show a power augmentation of 10%, double shaft turbines can do even more because the shaft of the compressor is not necessarily limited to a fixed number of revolutions.

Figure 3.9 The droplet size distribution in swirl flash nozzle and a swirl nozzle [64]
As a result the compressor can supply (within limits) extra air and the turbine can supply even more power. The compressed humidified air reduces also the stoichiometric adiabatic flame temperature during combustion. This reduces the thermal NOx. For diffusion burners the NOx reduction can be up to 40% and for dry low-NOx burners it is typically 20-25%.[62]

The Swirl Flash technology has a very favorable behavior when it comes to applicability under various ambient conditions. The classical inlet air chillers can not work properly at high temperatures and low relative humidity. The cold-water over-spray injection systems are limited to ambient temperatures above 10 °C in order to avoid ice formation at high air velocities. The Swirl Flash system, however, can be used in a much wider range. At high temperatures and high humidity, the evaporation takes almost completely inside the compressor. At high temperatures and low humidity the system realizes inlet air chilling while the remainder of the water evaporates inside the compressor. At high temperatures (0 °C) and high humidity the hot spray acts as an inlet air de-icing system and can still be used. Only when the humidity of the inlet air is close to zero, the inlet air temperature must be 5 °C in order to avoid ice formation. These features result in a far wider range of temperatures and humidity, where the swirl flash over-spray can be applied. Because of this, the amount of extra-generated power is far greater than any other system.

3.10 LNG Evaporation System

LNG vaporization systems are useful for power plants located near to a liquefied natural gas (LNG) facility. In supplying natural gas for power plant or other applications, LNG must be vaporized by a heat source. For applications in turbine air inlet cooling, the inlet air is used as a heat source. Here an intermediate fluid such as glycol is used. The gas turbine inlet air heats the glycol and is cooled in this process. The glycol heats the fuel. Significant reduction (5-10 °C) in inlet air temperature is typical for this system.
3.11 Indirect Evaporative Cooling

This method developed by Everest Sciences [24] is the latest development of the kind in the field of turbine inlet air cooling. Currently the systems are available only up to 60 MW capacities. Unlike conventional solutions, the Everest Cycle cools by evaporating water into a secondary air stream. The secondary air then cools the gas turbine's inlet air stream, through an air-to-air heat exchanger as illustrated in figure 3.10. No moisture is added to the inlet air, so a given temperature reduction results in higher inlet air density and greater mass flow through the turbine. Everest Sciences' $h^3$ technology incorporates supplementary refrigeration into the Everest Cycle. The temperature reduction by the indirect evaporative cooling process becomes the starting point for the refrigeration cycle. The process is illustrated in figure 3.11 on a psychrometric chart. This results in substantially less required refrigeration to reach a target inlet temperature. When comparing this new indirect evaporative technology to direct evaporation or fogging, a gas turbine using the Everest Cycle can achieve significantly greater power output and
efficiency. When comparing to refrigeration, it provides greater net power and efficiency through significantly lower parasitic loads. The increased net power output and improved efficiency resulting from the Everest Cycle means added revenue at lower cost for the plant operator. More researches are under way in this direction.

3.12 Summary of the TIC Methods

This chapter discussed the various approaches to cooling turbine inlet air for enhancing the performance of combustion turbines. The selection of the appropriate technology for a particular plant depends on various factors like the site climatic conditions, availability of water, legal restrictions, installation and maintenance costs etc. The present study concentrates on five common techniques of TIC and the selection of the right method is based on the detailed analysis that follows.