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A Review - Effect of Cooling System on the Efficiency and Output Power Gas Turbine

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ABSTRACT

Gas turbines are machines that work directly with ambient air, then anything that causes a change in the inlet air condition, effect on turbine efficiency. Relative humidity, Mean sea level and environment temperature have a direct effect on gas turbine efficiency. In this research, reviews the type and effect of cooling system on the efficiency and out power turbine. Cooling the turbine inlet air (even by a few degrees) can increase power output substantially. This is because cooled air is denser, giving the turbine a higher mass-flow rate and resulting in increased turbine output and efficiency - even as much as 0.4% per degree Fahrenheit or about 0.7% per degree Celsius. Typically a 1° F temperature increase will result in a 0.5% decrease in power.

Keywords: Gas Turbine, Cooling Inlet Air, Output Power Turbine

I. INTRODUCTION

Turbine power output and efficiency factors include ambient air temperature, relative humidity, Mean sea level, inlet air pressure and fuel type that can decrease outlet power of gas turbine rather than design condition (ISO condition) [1]. inlet air temperature and Mean sea level of installation place have most effect on application parameters of turbine that mean sea level cannot be ignored and all outlet power enhancement methods and efficiency improvement concentrated on inlet air cooling. comparing with new power plant construction costs, apply inlet air cooling methods are less expensive that cause outlet power of gas turbine become closer to nominal power and a significant portion of excess demand will be compensated.

Generally, peak demand for electricity occurs during the summer time, that the output power of the gas turbine reaches its minimum value for high temperature of inlet air. This makes a lot of pressure on the power industry and to compensate for excess demand, there will always be a need for further investment of new plants.

In more operating gas turbine, cooling inlet air is under consideration because it is an independence process. this method without any change or modification in main components of gas turbine and considering some technical point is applicable. However Installation location of its equipments is almost independent and separate from main components of gas turbine cycle , all of these cooling inlet air methods are applicable during design, manufacturing or installing.

Power enhancement and efficiency improvement of gas methods is mainly divided into three very general categories were

a. power enhancement method by inlet air cooling
b. efficiency improvement and power enhancement methods by using outlet hot gas
c. saving energy methods

First and second category except using outlet hot gas in absorption chillers for cooling inlet air, all methods need changes in combustion turbine cycle that need turbine design parameters and its thermodynamic conditions. Therefore applying these methods is only possible for companies that access to the turbine design conditions. Considering this restriction, preconditions of power enhancements using inlet air cooling method [2, 3], investigated and determined. it should be taken into by technical-economical criteria and final score to determine optimal method of each power plant, because it can't be expressed by considering only technical advantage of one method or lower cost of another one. The briefly explain each of them following:

a) Water is evaporated in the compressor inlet air duct in evaporation methods. Thus latent heat of water evaporation is token from air and air is cooled. Reducing the maximum inlet temperature to the dew point or vapor saturation point temperature is fundamental limits and lower primary and operating costs is its benefits of these methods.

b) In method of compression refrigeration, a radial or impact chiller is used to cooling compressor inlet air by a cooling coil or placing evaporator in air path. Primary cost and especially high operating cost and energy consumption is disadvantages of this method but independent from environmental condition is benefits of this method.

c) To cool compressor inlet air, an absorption chiller with Liquid refrigerant has been used in absorption refrigeration method. High Primary cost is the problem of this method and lower energy consumption, low operating cost and independence from environmental condition is benefits of this method. In high pressure fog spray in inlet air ducts method, water particles are sprayed into the air intake duct. These fine particles of water, by heat absorbing, evaporated and cause cooling the inlet air compressor. On the other hand, the addition of water to the air, which increases flow density, cause power output will increase It should be mentioned, overspray method for this turbine, by using the software is not recommended. To analyze efficiency improvement method using Thermo flow software, three different methods of evaporation, fog spray and compression and absorption refrigeration (which are divided into four methods) were selected.

De Lucia et al. [4] concluded that evaporative inlet-cooling could enhance power by 2 –4% a year depending on the weather.

Thermodynamic analyses from literature show that thermal efficiency and specific output decrease with the increase of humidity and ambient temperature, but the temperature ambient is the variable that has the greatest effect on gas turbine performance [5]. The ambient conditions under which a gas turbine operates have a noticeable effect on both the power output and efficiency. At high inlet air temperatures, both the power and efficiency are decreased[6].

Hall et al. [7] documented the performance of a 36 MWCT plant in which a chilled water-based storage refrigeration system was tasked with cooling inlet air. The cooling system was able to reduce the air temperature from an ambient 35°C to 7°C, thus enhancing plant performance by 10%.

Ana Paula P et al. [8] built a thermodynamic model of a gas turbine to calculate heat rate, power output and thermal efficiency at different inlet air temperature conditions. Computational results are compared with ISO conditions herein called "base-case". Therefore, the two cooling methods are implemented and solved for different inlet conditions (inlet temperature and relative humidity). Evaporative cooler and absorption chiller systems results show that when the ambient temperature is extremely high with low relative humidity (requiring a large temperature reduction) the chiller is the more suitable cooling solution. The net increment in the power output as a function of the temperature decrease for each cooling method is also obtained.

A. A. J. AL-Luhaibi and M. Tariq [9] analyze the film cooling technique that was developed to cool gases in the initial stages of the turbine blades, where temperature is very high (>1122 K). It is found that the thermal efficiency of a cooled gas turbine is less as compare to the uncooled gas turbine for the same input conditions. The reason is that the temperature at the inlet of the turbine is decreased due to cooling and the work produced by the turbine is slightly decreased. It is also found that the power consumption of the cool inlet air is of considerable concern since it decreases the net power output of gas turbine. In addition, net power decreases on increasing the overall pressure ratio. Furthermore, the reviewed works revealed that the efficiency of the cooled gas turbine largely depends on the inlet temperature of the turbine and previous research said that the temperature above 1123K, require cooling of the blade.

There are several methods available for power augmentation by Inlet air cooling [10]. In general, they can be classified into three broad classes:

- Refrigerated inlet cooling systems-Utilizing absorption or mechanical refrigeration
- Evaporative methods-Either conventional evaporative coolers or direct water fogging
- Thermal energy storage systems-These are intermittent use systems where the cold is produced off-peak and then used to chill the inlet air during the hot hours of the day.

II. GAS TURBINE CYCLE THERMODYNAMICS

A representation of a single shaft gas turbine utilized for power generation applications is presented in Figure 1, which will be used for the discussion here. The behaviour of split shaft aero-derivative machines is different and will be addressed ahead.

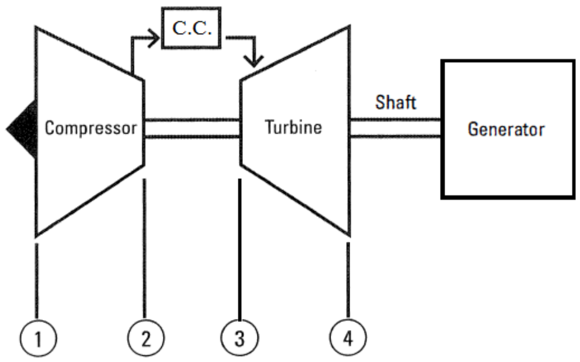

Figure 1. Representation of a single shaft Gas Turbine

In the pressure volume (P-V) diagram shown in Figure 2, process 1-2 represents compression, 2-3 represents heat addition in the combustor, and 3- 4 represents the expansion in the turbine. The shaded area represents the work of the cycle. Moving the compressor line to the left will reduce the work of compression (area under the curve).

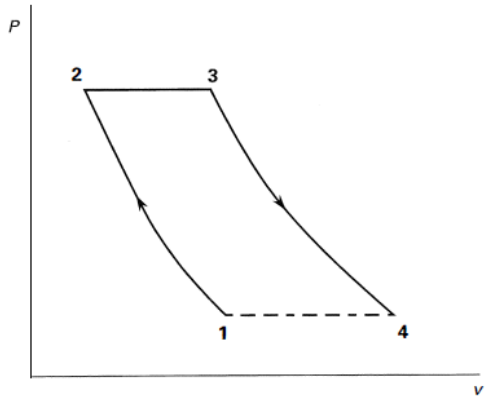

Figure 2. Pressure - Volume Curve (Brayton Cycle)

The corresponding temperature entropy (T-S) diagram, shown in Figure 3, shows ideal or isentropic compression from 1-2 with the actual compression process being 1-2'. Line 2'-3 represents heat addition in the combustor. The expansion in the turbine is represented by process 3-4 (isentropic) with the actual expansion being 3-4'.

$$W_{Compressor} = CP\ [T_2' - T_1] = [\ h_2' - h_1] \qquad (1)$$

$$W_{Expansion} = CP\ [T_3\ - T_4'] = [h_3\ - h_4'\ ] \qquad (2)$$

The very reason that a gas turbine can produce output power is that the work of expansion must be greater than the work of compression, i.e., the line described by 3-4 must be greater than 1-2. This occurs because the constant pressure lines in Figure 3 diverge as shown. This is an important feature of the T-S diagram.

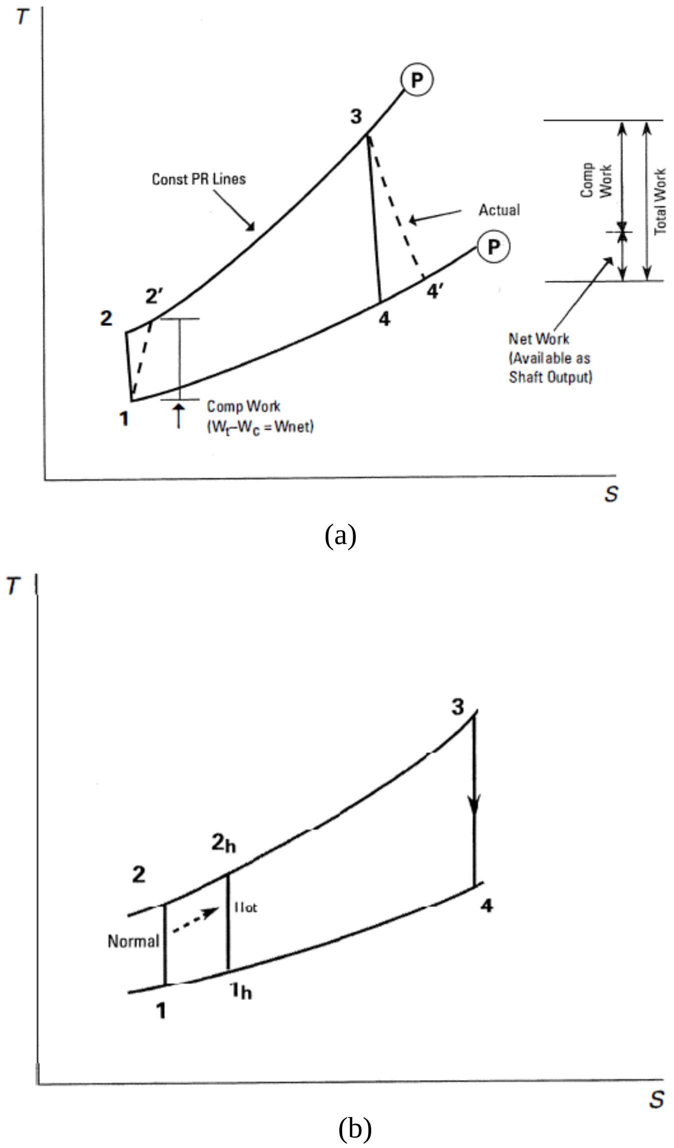

Figure 3. a) T-S Diagram; b) T-S Diagram of hot &cold day compression

The power output of a gas turbine depends on the mass flow rate through it. This is precisely the reason why on hot days, when air is less dense, power output falls off [9]. The mass flow rate is proportional to the absolute compressor, inlet pressure and inversely proportional to the absolute inlet temperature.

$$\dot{m} = K\ (P_1/T_1) \qquad (3)$$

Gas turbines take in filtered, fresh ambient air and compress it in the compressor stage. The compressed air is mixed with fuel in the combustion chamber and ignited. This produces a high-temperature and high-pressure flow of exhaust gases that enter in a turbine and produce the shaft work output that is generally used to turn an electric generator as well as powering the compressor stage.

As the gas turbine is a constant volume machine, the air volume introduced in the combustion chamber after the compression stage is fixed at certain shaft speed (rpm). The quantity of fuel introduced in the mixture depends on the oxygen that the air contains. The air mass in is directly related to the density of air, and the introduced volume.

$$m = \rho V \tag{4}$$

where m is the mass, ρ is the density and V is the volume of the gas. As the volume V is fixed, only density ρ of the air can be modified to vary air mass. The density of the air depends of the relative humidity, altitude, pressure drop and temperature.

$$\rho = \frac{p}{R_{specific} \cdot T} \tag{5}$$

where: p is the Pressure in (psia), R: Specific gas constant (for dry air = 53.3ft., 287.05°K. Kg/J) and T: Temperature ('R), ρ: Density (lb/ft^3).

High ambient temperature causes a drop in density of the air and this causes a drop in the mass flow rate through the gas turbine .

III. TURBINE INLET COOLING

Turbine inlet cooling (TIC) is cooling of the air before it enters the compressor that supplies high pressure air to the combustion chamber from which hot air at high pressure enters the combustion turbine.

Cooling inlet air to compressor enhances both power and engine efficiency by increasing the air density, so raising the specific mass flow rate through the engine. Power produced by the gas turbine is strongly influenced by several parameters, particularly by the temperature, and the density of the air sucked by the compressor [11].
The primary reason TIC is used is to improve the power output of combustion turbines (CTs) when ambient air temperature is above 59°F. The rated capacities of all CTs are based on the standard ambient conditions of 59°F (15°C), 14.7 psia at sea level selected by the International Standards Organization (ISO). One of the common and unattractive characteristics of all CTs is that their power output decreases as the inlet air temperature increases.

The benefit of TIC is that it allows the plant owners to prevent loss of CT output, compared to the rated capacity, when ambient temperature rises above 59°F or the plant is located in a warm/hot climate region[12].

Power output of a CT is directly proportional to and limited by the mass flow rate of compressed air available to it from the air compressor that provides high pressure air to the combustion chamber of the CT system. An air compressor has a fixed capacity for handling a volumetric flow rate of air. Even though the volumetric capacity of a compressor is fixed, the mass flow rate of air it delivers to the CT changes with changes in ambient air temperature. This mass flow rate of air decreases with increase in ambient temperature because the air density decreases when air temperature increases. Therefore, the power output of a combustion turbine decreases below its rated capacity at the ISO conditions (59°F, 14.7 psia at sea level) with increases in ambient temperature above 59°F. TIC allows increase in air density by lowering the temperature and thus, helps increase mass flow rate of air to the CT and results in increased output of the CT.

Gas turbine is usually designed at ISO conditions which meet ambient temperature and relative humidity of 15°C and 60% respectively. But the ambient temperature increases up to 40°C in summer.
There are two main inlet cooling types[13]:

(i) Evaporative or fogging cooling

(ii) Chillers cooling-electrical or absorption.

A. Evaporative Systems Inlet Cooling

Evaporative systems cool the inlet air by evaporating water into the air stream. The water evaporation causes the air temperature to drop. Low humidity climates are suitable for use of this cooling technology.

the advantage of this method is Economical operation, Uncomplicated system and the disadvantage is Cooling efficiency depends on relative humidity of ambient intake air....high humidity can inhibit cooling effect, Need source of make-up water.

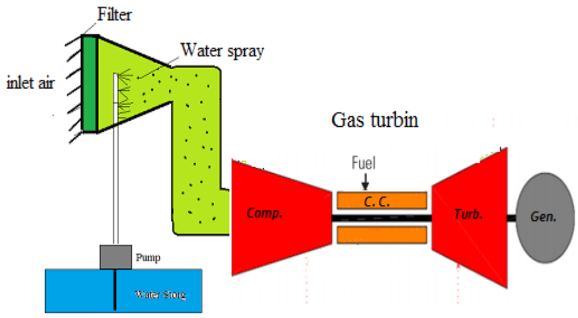

Figure 4. Schematic of fogging system

Direct inlet fogging is a method of cooling where dematerialized water is converted into a fog by means of high-pressure nozzles operating at 1000 psi to 3000 psi. This fog then provides cooling when it evaporates in the air inlet duct of the gas turbine as shown in figure 4. This technique allows a 100 percent effectiveness in terms of attaining 100 percent relative humidity at the gas turbine inlet, and thereby gives the lowest temperature possible without refrigeration (the wet bulb temperature). Direct high-pressure inlet fogging can also be used to create a compressor inter-cooling effect by allowing excess fog into the compressor, thus boosting the power output considerably.

B. Chillers System Inlet Cooling

Title In a chilled water system, water is first cooled in the water chiller then pumped to the water cooling coils in terminals in which air is cooled and dehumidified after flowing through the coils, the chilled water increases in temperature up to 15.6 to 18.3°C and then returns to the chiller. Chiller operation is based on the refrigeration cycle and understanding this cycle is necessary in the refrigeration cycle, in which air passing over the cooling coils raises the water temperature which is circulated through the evaporator as shown in figure 5. Two working fluids are used in the chiller system, the first one is the refrigerant in the refrigeration machine which consists of a compressor, evaporator, condenser and expansion device. The refrigerant is used in this cycle to cool secondary fluid, usually chilled water, which is pumped through an air-water heat exchanger located at the gas turbine inlet to cool air coming into the compressor.

The air passes through the chiller coils, raises the temperature of the liquid refrigerant to its boiling point and evaporates it into a gas.

The chillers system method has the advantage of being able to reduce the air temperature to 5°C, Can cool the inlet air regardless of ambient humidity, Can be sized for small or large systems • Broad range of cooling achievable, down to 45F/7C. The disadvantage is Need source of chilled water, Causes slightly higher ΔP than an evaporative cooler does and it involves very high capital cost.

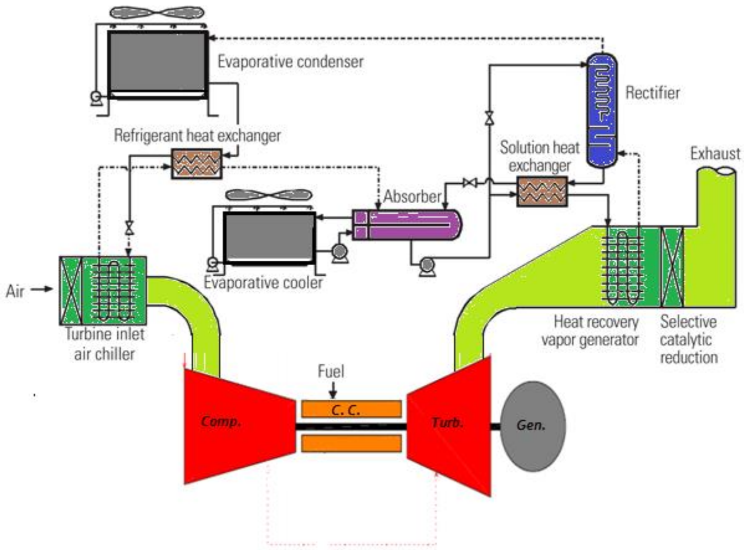

Figure 5. Schematic of chillers system

Gas turbine output is a strong function of the ambient air. temperature with power output dropping by 0.3 percent to 0.5 percent for every 1°F rise in ambient temperature. While this characteristic is inherent in any gas turbine, the effect can be more severe on certain aero derivative engines. This loss in output presents a significant problem to utilities, co-generators, and independent power producers (IPPs) when electric demands are high during the hot months. the reduction in output of mechanical drive gas turbines curtails plant output. One way to counter this drop in output is to cool the inlet air [14].

The compressor section of a gas turbine ingests a constant volume of air regardless of the ambient air temperature. The air temperature and its corresponding air density entering the compressor has a direct affect upon turbine power output. If the air density is increased, which is accomplished by lowering air temperature, the compressor has less work to perform allowing the gas turbine to increase its output. In hot climates, this reduced power output will be significant and therefore, costly. In addition to increased power output, air cooling allows the turbine to operate with a higher efficiency thereby lowering fuel costs.
As the temperature is lowered (i.e., air becomes more dense), the machine will operate at a higher mass flow rate and higher pressure ratio, and this results in increased power output and improved heat rate. The opposite occurs when the ambient temperature increases.

IV. REFRIGERATED INLET COOLING SYSTEMS

Two techniques for refrigerating the inlet of a gas turbine are vapor compression (mechanical refrigeration) and absorption refrigeration.

A. **Mechanical Refrigeration**

In a mechanical refrigeration system, the refrigerant vapour is compressed by means of a centrifugal, screw, or reciprocating compressor. Centrifugal compressors are typically used for large systems m excess of 1000 tons and would be driven by an electric motor. Mechanical refrigeration has a significantly high auxiliary power consumption for the compressor driver and pumps required for the cooling water circuit. After compression, the vapor passes through a condenser where it gets condensed. The condensed vapour is then expanded in an expansion valve and provides a cooling effect. The evaporator chills cooling water that is circulated to the gas turbine inlet chilling coils in the airstream. Chlorofluorocarbon (CFC) based chillers are now available and can provide a large tonnage for a relatively smaller plot space and can provide cooler temperature than the lithium-bromide (Li-Br) absorption based cooling systems. The drawbacks of mechanical chillers are high capital and operation and maintenance (O&M) cost, high power consumption, and poor part load performance.

Direct expansion is also possible wherein the refrigerant is used to chill the incoming air directly without the chilled water circuit. Ammonia, which is an excellent refrigerant, is used in this sort of application. Special alarm systems would have to be utilized to detect the loss of the refrigerant into the combustion air and to shut down and evacuate the refrigeration system. Mechanical refrigeration for gas turbines is covered by Sadek (1981) [15].

B. **Absorption Cooling Systems**

Absorption systems typically employ lithium-bromide (Li-Br) and water, with the Li-Br being the absorber and the water acting as the refrigerant. Such systems can cool the inlet air to 50 °F. The heat for the regenerator can be provided by gas, steam, or gas turbine exhaust. Absorption systems can be designed to be either single or double effect. A single effect system will have a coefficient of performance (COP) of 0.7 to 0.9, and a double effect unit, a COP of 1.15 [16]. Part load performance of absorption systems is relatively good, and efficiency does not drop off at part load like it does with mechanical refrigeration systems. Absorption systems have lower O&M costs than mechanical refrigeration systems [17].

C. **Thermal Energy Storage Systems**

This method is used when power augmentation is required only for a few hours in a day. In this approach, a cold reserve is built up during the nonpeak hours and this cold energy is utilized during the peak hours to chill the inlet air, thus increasing turbine output. As it operates in this intermittent mode, it is possible to reduce the size of the refrigeration system compared with a system that has to provide continuous cooling.

The energy storage media can be ice, water, or other heat transfer liquids.

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