Enhancement of Gas Turbine Power Plant Performance Using InletWater Atomization

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Abstract: *In hot and dry air climates such as Iraq, Saudi Arab and other countries, which they have over shooting of ambient temperature; gas turbine engine power output is declined dramatically because of the reduction in air mass flow rate. This paper investigates effect of cooling technique on inlet ambient temperature to perform the power generation of gas turbine station. A gas turbine power plant performance has affected by anything that changes the density and mass flow of the air, which enters to the compressor because air density is a function of ambient temperature and pressure. This search deals with the enhancement the gas turbine power plant performance using air cooling technology which enters the inlet of gas turbine engine by using water atomization that it installed in front of the compressor intake at different ambient conditions in summer season to increase the air mass flow rate and obtain a reasonable rated power generation.AL-DORA gas turbine power plant 35 MW was chosen to predict these effects on its performance. Software programmer MATLAB is used to expect the thermodynamic parameters as power generation, compressor ratio, compressor work, air mass flow rate. Cooling the air to the wet bulb temperature is increased the density of the air, so that, air mass flow is increased linearly and boost compressor pressure ratio and the rated power output consequently while compressor work is decreased. Therefore, the amount of extracted gas leaving the turbine will increase the work done and rated power output will increase consequently. It is observed that air density is inversely related to the dry bulb temperature and gas turbine output is found to be a strong function of air mass flow and its effects on the power generation and the efficiency of the gas turbine power plants and hence, the cycle performance shifts towards favorable conditions.*

Keywords: air mass flow rate, ambient temperature, cooling system, density, power plant

1. Introduction

Air density or the mass flow rate of the gasses pass through the engine play major rule for controlling the gas turbine power plant operation and its performance, So that the power output is declined at the increasing of the ambient temperature, in the same way power output will be supported and can be improved using air-cooling system.

In Iraq for summer season, it is required to install air-cooling unit such as methanol-water injection on a gas power plant to avoid the degradation of Compressor efficiency and to improve output power.Purifiedwater is compressedand used under high pressure then injected into the inlet of compressor through an array of stainless steel fog nozzles. Purified water has an advantage that prevents corrosion of the compressor blades that would occur if water with mineral content or contamination were evaporated in the airflow.

There are two major methods for injection the water or the coolant into the airflow: -
1) Spray directly into the compressor inlet.
2) Inject the water into the combustion chamber.

The water injection system is one of these melt used to booster or restored the power output or the thrust and increase the efficiency of gas turbine engine and performance. First method concerns with the water sprayed into the compressor inlet, the temperature of the air is increasing the density of the compressor air inlet and consequently the power is increased.

Nguyen Huy Hoang et al [1], studied the principles of cooling system using water Injection of Centrifugal Compressor for micro gas turbine. They provided a method of utilizing Ultrasonic humidifier to produce fine water droplets and gives thermodynamics investigation on wet compression process in the centrifugal compressor. The results from this analysis show that the water evaporative cooling can decrease the air temperature rise as much as (50k) at maximum and it will reduce the amount of the compression work by approximately (7%) when the pressure ratio of the compressor is (3).

Kakaras [2] declared that the efficiency and performance of gas power stations depends on the amount of change in ambient temperature, where the station's capacity is reduced to 5 to 10 percent of the value designed for $15C^0$ for every 10K increase in air temperature

Roumelioties et al [3], examine the most techniques that carry out the water injection to observe its effects of water on the gas turbine and compressor off- design operation. They concluded that Water injection shifts the characteristics to higher mass flow ratio. A thermal efficiency increase along with a substantial power boost has been predicted.The results are analyzed according tothe engine operation and the improvement of performance to give further insight on gas turbine operation with water injection.

R.Kadi et al [4] studied the improvement of the performances of gas turbine, using pre-heating and injection of the steam water at the gasinlet ofcombustion chamber to increase efficiency. The aimof this study is to predict the effect of the climatic conditions on the thermodynamic cycle processes of gas power plant, using analytical relations. Technical specification of gas turbine power plant are used to show the effect of water injectionon power generation and efficiency.Results obtained when using injections were more consistent with the design data of the plant if compared with the results obtained in the case of non-injection

Pratt et al 1996 [5], studied the effect of water injection on turbine engine. They concluded that the power is increased 10 to 30percent of additional powerby injecting water into the engine either at the compressor air inlet or at some other point such as the diffuser case.

Pollav[6],Discover how to increase the performance of the axial compressor using a mixture of water and ethanol through theoretical analysisto determine the impact of this mixture on the system's operation.The results of this investigation is to improve gas turbine compressor by preventing local disruption of the airflow in the compressor, therefore stall margin and pressure rise coefficient will increase

2. Plant Configuration

The plant consists of main four gas turbines parts with type of GT20 and rated capacity of 37.5 MW. Coolant system used to recover ambient temperature heat from the atmospheric. The following table represents the design specifications of the gas station and Fig.1 shows the main parts of AL-DORA gas turbine power plant

Technical Specifications (1)

Types of fuel	Gas oil and Natural gas
Frequency	50 HZ
Electrical output	37.5 MW
Thermal efficiency	0.28
Ambient Temperature	$15C^0$
Turbine speed	4918 r.p.m
Compressor pressure ratio	11/1
Inlet air flow rate	169 kg/sec.
Exhaust gas flow temperature	$490\ C^0$
Atmospheric pressure	0.966 bar

3. Theory of Calculations

Summer season in Iraq is dry and has a high temperature range of 40∘C to 55∘C.The following simulations were conducted in these climatic conditions for simple cycle gas turbine. For the purpose of calculating, the gained power increase in case of cooling by fogging system. In analysis of flow, the governing equations will usually be used in particular coordinate system suitable to the problem. The fluid flow problem is defined by the low of conservation of mass, momentum and energy, Solving Euler equations, on one dimension.

4. Continuity Equation

"The law of conservation of mass gives the continuity equation

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho V_x)}{\partial X}+\frac{\partial(\rho V_y)}{\partial Y}+\frac{\partial(\rho V_z)}{\partial Z}=0 \text{---------(1)}$$

Where V_x, Vy,Vz are the components of the velocity vector in the X, Y and Z directions respectively.
Where
ρ= density (kg/m³)
$$T = time \quad (sec)$$
For one dimensional, conservation of mass becomes

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho V_X)}{\partial x}=0-------(2)$$

For steady flow

$$\frac{\partial(\rho V_X)}{\partial x}=0-------(3)"$$

Because of the Mach number is less than (0.4), therefore the flow passes through the compressor is incompressible, that's to say, density is constant, therefore the conservation of mass for the incompressible flow is represented by following equation.

5. Mass Flow Rate

Mass flow rate of inlet air enters the engine is denoted by

$$"\rho \frac{\partial v}{\partial x}=0 \text{ ----------------- } \quad (4)$$
$$\dot{m}=\rho VA \text{ ---------------- } (5)"$$

It is suggested that mass flow rate of air inter the plates is equal the mass flow exit the plates, therefore

$$"\dot{m}=\dot{m}out$$

$$\rho_1 v_1 A_1 = \rho_2 v_2\ A_2 \text{ ------ } (6)"$$

According to the principle of incompressible is constant.

The evaluation of derivative of the density with respect to pressure comes from the equation of state

$$"P=\rho RT \quad \text{------- } (7)$$
$$\rho=\frac{P}{RT}"$$

"V= Air velocity enters the intake (m/sec).
A_n = Cross sectional Area of layers (m²).
R= Gas constant (air) (kJ/kg.k).
T = ambient temperature (K)."

6. Thermodynamic Analysis

Gas turbine power plants depend on the principle ofBrayton cycle, which is used to specify thermodynamic analysis. Typical thermodynamics parameters of the Brayton cycle using pressure, temperature, compressor work, compressor and turbine efficiency, In addition to the adiabatic compression and expansion index .
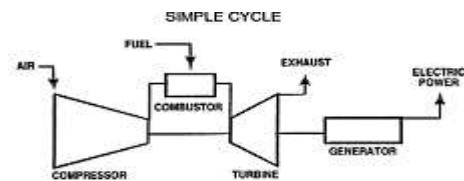

Figure 1: Gas power plant main parts

In general, gas turbine power plants include four main parts, compressor, combustion chamber, turbine and generator.

The gas station's function is to receive the air after it is withdrawn from the external environment and then press through the central compressor and insert it into the combustion chamber after adding a quantity of fuel to form another process, which is adding the fuel and burning it with the air to form additional heat energy. The combustion product is a gas that can be extended through the phase of the

turbine to generate a job on the turbine fins and rotate the rotor axis, which is connected to the generator.

It is assumed that the compressor efficiency and the turbine efficiency are represented η_c and η_t respectively. The ideal and actual processes on the temperature-entropy diagram are represented in full and dashed line respectively as shown in (Figure 2) [Al-Sayed, 2008].
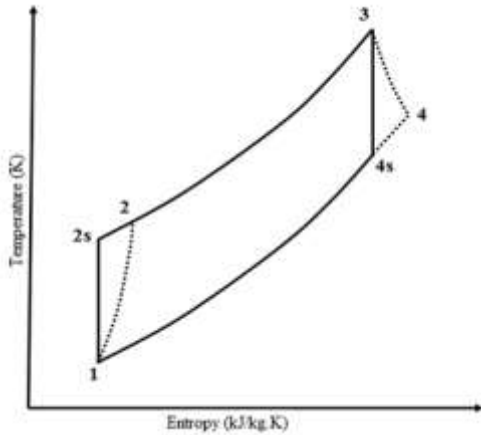

Figure 2: T-S diagram for gas turbine cycle

The compressor compression ratio (r_P) can be defined as (2008 AL Sayed, [7]):

$$\text{"r}=\frac{p_2}{p_1}\text{---------------- (8)}$$

Where
P_1 and P_2 are compressor inlet and outlet air pressure, respectively".Therefore, equation (7) represents the isentropic efficiency of compressor efficiency and its range (85%).

$$\text{"}\eta_c = \frac{T_{2s}-T_1}{T_2-T_1}\text{-------------------- (9)"}$$

The final temperature of the compressor is calculated in Eq.(3)

$$\text{"}T_2 = T_1\left[1 + \frac{r_P^{\gamma-1/\gamma}-1}{\eta_c}\right]\text{---------------- (10)"}$$

So, the work of the compressor (*Wc*) when blade cooling is not taken into account can be calculated in Eq. (4)

$$\text{"}W_c=\frac{C_{pa}T_1\left[r_P^{\frac{\gamma_a-1}{\gamma}}-1\right]}{\eta_m}\text{--------------------(11)}$$

$$W_t = C_{pg}T_3.\eta_t\left[1 - \frac{1}{r_p^{\frac{\gamma_g-1}{\gamma_g}}}\right]\text{----------(12)}$$

$$W_{net}= W_t\text{-}W_c\text{----------------------------(13)}$$

$$P = m_a\times W_{net}\text{--------------------------(14)}$$

$$Q_{add} =C_{pg}[T_3\text{-}T_1\{1+r_P\text{-}1$$

$$\eta_{th}=W_{net}/Q_{add}\text{"}$$

7. Results and Discussion

Gas turbine performance are affected by an environmental operating parameters such as ambient temperature and air mass flow rate that play a major for varying both power and efficiency. The power decreases due to degradation of air mass flow rate the density of air temperature increases) as well as efficiency decreases because the compressor requires more power to compress the air for higher temperatures.The minimizing of ambient temperature, that it enters the inlet duct, can be achieved by the application of air-cooling using fogging system in front of inlet ducting to satisfy suitable gas power plant performance. Water injection method is created to provide suitable ambient temperature that enters the intake then directly to compressor using atomization system for water-methanol mixture as a liquid phase in front of the intake.

Figure (3) represents the change of rated power (P) against ambient temperature variation, during the year. The change of rated power (P) on winter approximately is constant versus ambient temperature, while in hot and severe climates conditions, the power is declined gradually as an increasing of ambient temperature and varied proportional linearly. It shows that the effect of ambient temperature on the power output of gas turbine cycle is varied due to the change of air density in winter and summer season. It is clear from the figures that increasing of the ambient temperature decreases the gain of power output. As the ambient temperature increases, the total work of the compressors increases, thus work net is reduced.
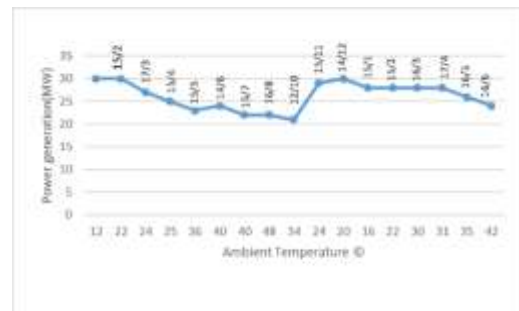

Figure 3: power generation against ambient temperature during the year

Figure (4) shows the rated power during the day in summer season against ambient temperature and the effect of cooling system using water atomization in front of power plant intake to enhance the performance of gas turbine power plant The effect of cooling system is started from the morning when the environmental temperature is gradually increased .Therefore ,cooling system plays a major role for reducing the ambient temperature from 40C to 22C,so that the curve of rated power will increase continuously and approximately is constant value until 21Pm.During the night at 10Pm ,the cooling system is turned off, and the environmental temperature is still so high ,the rated power curve is declined gradually and reached to(18MW),therefore the power is returned to decreased gradually as an increasing of ambient temperature.

Figure 4: Power generation against ambient temperature during summer season

Figure (5) represents the variation of air mass flow rate against the ambient air temperature during the day in summer seasons to show the effect of cooling system on air temperature and air density with and without fogging operation. Air temperature will drop up to 22 degrees and the amount air flowing to 165 kg/sec. where it continues in this way, or the situation until four in the afternoon with the continuation of the cooling process and then increase the flow to 167 kg/sec. when the temperature continues to drop to 20 degrees at nine pm. This fact is coupled with increasing air density because of proportionality relation between air flowing amount of the slot entrance, which increases down the temperature of the air and this clear and evident to decline of flow when extinguishing the cooling system and the rise of temperature directly back to 37 degrees of up to 157 kg / sec. at ten pm.

Figure 5: Air mass flow rate against ambient temperature during summer season

The amount of compression ratio has increased at the low temperature of the air inside of the station when the cooling system works because of the heat exchange between the inside air and the water atoms that have been injected and this helps the compressor to increase the compressed air due to increased amount of air flowing and thus increase the compression ratio, as shown in figure (6)

Figure 6: Compressor ratio against ambient temperature during summer season

The amount of work carried out on the air inside the compressor starts to decrease when the air temperature is reduced due to the continuous operation of the cooling unit due to the positive relationship between the temperature of the air and the work performed by the compressor on air, as shown in Figure (7).
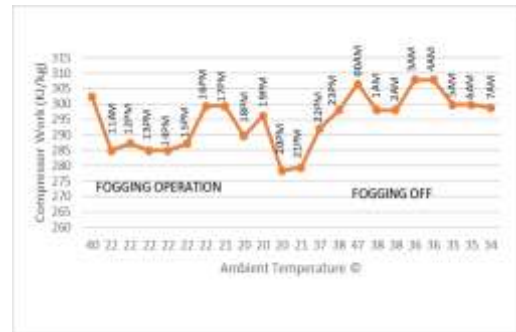

Figure 7: Compressor work against ambient temperature during summer season

Many operation conditions effect on the rate of gas turbine performance. All the increasing of air temperature, both the power and efficiency decrease, the power decreases due to degradation of air mass flow rate (m), it means the density of air temperature increases so that the efficiency decreases because the compressor requires more power to compress the air of higher temperature.

The efficiency of the station is closely related to the climatic conditions, especially the ambient temperature, so the efficiency of the plant is affected by the decline of high ambient temperature. In the winter and low temperatures, the air density is increasing and in contrast, the amount of work for the compressor on the air will decrease and thus increase the amount of power produced, while in summer season, the power and the efficiency have decreased due to ambient air temperature increase sing, so that the increasing of ambient temperature causes a decreasing in air density

This decay of the air density leads to decline the amount of air inside the compressor. Therefore, work carried out by the compressor on the air is increased as well as the specific net work output will decrease. As a result, thermal efficiency degrades as shown in figure (8).

Figure 8: Thermal efficiency against ambient temperature during summer season

Because of these changes, the enhancement is achieved by using the application of fogging system to prepare suitable

ambient temperature that it enters the intake as a higher density with maximum mass flow rate.

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