PARAMETRIC STUDY OF GAS TURBINE CYCLE WITH FOGGING SYSTEM

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Abstract

Fogging system is used as a method for cooling the inlet air to the compressor by the direct injection of water, in order to reduce the ambient air temperature until it reaches the wet bulb temperature and thus increasing the net power. The effects of ambient temperature, relative humidity, firing temperature, and pressure ratio on the open cycle gas turbine performance are studied. The ambient temperature range, which is considered in this study, ranged from (10 to 60°C); the relative humidity range was (10% to 90%), the pressure ratio range was (3 to 23) and the firing temperatures were 1100K, 1200K, 1400K, and 1600K. The results of this study showed that output power and efficiency increase continuously with increasing the firing temperature, and reduces with increasing the ambient temperature, and the efficiency increases with pressure ratio reaching a maximum value then it begins reducing. When the relative humidity increases it is gives a reverse effect on the power and efficiency of this cycle. The present work reveals that using fogging system in the front of the compressor in the open cycle gas turbine can improve the efficiency and enhance the output power of the cycle due to reducing the inlet air temperature interring to the compressor.

Key words: open cycle gas turbine, pressure ratio , work in gas turbine , fogging system

Symbols	
B	Pressure ratio
C_p	Specific heat at constant pressure (kJ/kg.K)
f	Fuel air mass ratio kg of fuel/kg of air
h	Enthalpy (kJ/kW.hr)
HR	Relative humidity
m	Mass (kg)
p	Pressure (bar)
Q_w	Water flow rate (m3/s)
R	Gas constant (kJ/kg. K)
T	Temperature (K), (°C)
Subscripts	
a	Air
c	Compressor
f	Fuel
g	Gas
m	Mechanical
v	Vapor
s	Saturation
wet	Wet bulb temperature
Greek Letters	
μ	Humidity Ratio
γ	Specific Heat Ratio
ρ	Density
η	Efficiency
Abbreviations	
GT	Gas turbine
LCV	Lower heating value (kJ/kg)
OCGT	Open cycle gas turbine

1. INTRODUCTION

Turbines have been used in stationary electric power generation since 1930s. Gas turbines have long been used by utilities for peaking capacity. However, with changes in the power industry and advancements in the technology, the gas turbine is now being increasingly used for base load power [1]. Gas turbines are used by themselves in very wide ranges of services [2], because of the fuel flexibility, reliability and life. The thermal efficiency of the gas turbine is a function of the pressure ratio, inlet air temperature, turbine inlet temperature, the efficiency of the compressor and the turbine elements [3].

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 [4]. Several techniques are used to increase the output power and the efficiency of gas turbines. One of these techniques is the inlet air cooling, which is an economical solution for optimizing power generation assets [5].

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[6]. 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. In order to restore the output power and the efficiency of gas turbine in hot weather conditions several methods of inlet air cooling systems are used, these methods are [7]:

1) Refrigeration system

This is utilized when cooling below the wet bulb temperature is desired [8]. This method is cost effective way to increase capacity through inlet cooling [9] .

2) Evaporative cooling

In this system the water is brought in contact with the incoming air. The water evaporates as it absorbs heat from the incoming air, thereby reducing the dry bulb temperature of entering air to the compressor [8]. It is widely used due to its low capital cost; uses a spray of water directly into the inlet air stream [1].

3) Fogging system

Fog achieves adiabatic cooling by injecting water through special atomizing nozzles producing a fog of very fine droplets which evaporate almost instantaneously. The basic idea of the fogging system is to reduce the work for adiabatic compression by the injection and subseqent operation of water in the compressor [10].

1.1.Fogging arrangement

Typical fogging system consists of:

1)High pressure pumps that are mounted on skid

2)Programmable logic controller (PLC) based control system with temperature, and humidity sensor.

3) Array of nozzles installed in the inlet air duct. The arrangement of fogging system is shown in Fig.(1)[7].

2.1 Generation of fog

Fog is generated by the application of high pressure demineralized water between (70 to 200) bar to array of specially designed fog nozzles [4]. The nozzles consist of a small orifice, the water emanating from this orifice impact a specially designed impaction pin that breaks up the jet into billions of micro fine fog droplets. The rate of evaporation of the droplet essentially depends on the surface area of the water exposed to the air [11].

1.3 Demineralization process

This process means removing of the ionic materials (dissolved in the water in ion form) by ion exchange (resins) by two types (cation and anion), cation resins has a positively charged hydrogen ion attached to a negatively charged polymer, while anion has a negatively charged attached to a positively charged polymer [2].

1.4 Position of fog nozzles system

The location of the systems in the air intake can vary [12], there are two main options for installing the inlet fogging system as shown in Figures.(1) and (2) respectively [4]:

1)Up stream of the air filters

One advantage to positioning the fog nozzle in this type is that the installation can be accomplished without outage time[10]. In this case a fog droplet filter must be added down stream of the fog manifold to remove any unevaporated fog. This type requires more fog nozzles, more water, and is generally more expensive to operate and install, but this increase air filter life [13].

2) Down stream of the air filters

The common location for high pressure fog nozzle is down stream of air filters and up stream of silencers and trash screen. In this case installation requires an outage of one to two days and calls only miner modifications to the turbine inlet structure. There is more residence time for the droplets to evaporate [12].

1.5 Fog nozzles and pumps

The key of effective fogging is the design of the fogging nozzles. These nozzles are fabricated of (316 stainless steel) and have an especially designed impaction pin. Typically the pumps used to drive the (130-200)bar pressurizes used for GT inlet air fogging systems are positive displacement ceramic–plunger stainless steel pumps with stainless steel heads [13]. Each high pressure pump is connected to a fixed number of fog nozzles representing one discrete stage of fog cooling. The rise in air temperature during summer months is reduced by the evaporation of enough droplets water to establish thermodynamic equilibrium between the water vapor, the liquid droplets remaining, and the air [14].

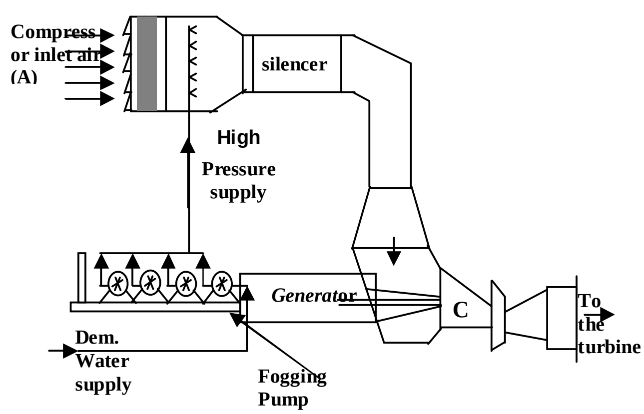

Fig.(1) Typical fogging system diagram

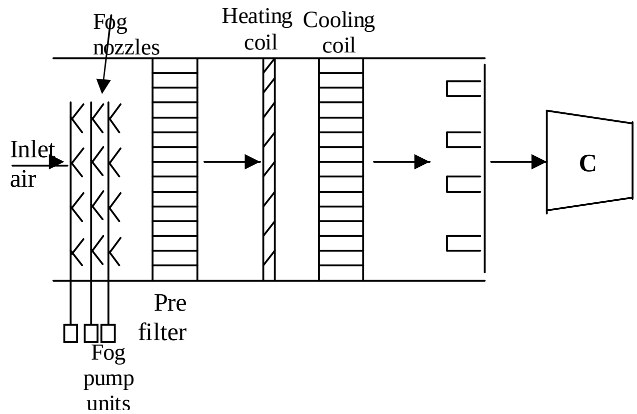

Fig.(2) Fogging nozzles up stream

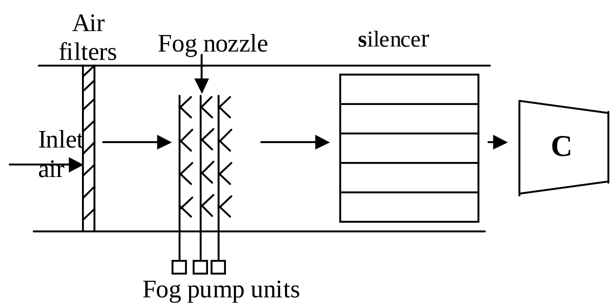

Fig.(3)Fogging nozzles down stream air filters[12].

2. Historical review

The principle of water injection into gas turbine compressor inlets is an old concept. Water injection is used in the older jet engines to boost takeoff thrust when aircrafts were operating on hot days. The power gain came mainly from the cooling of the air and from the intercooling effect in the compressor, as opposed to the increase in mass flow rate caused by the injected water itself. Recently, with the advancement in high-pressure, the concept of water fog technology has gained popularity in the industrial market and is being applied in the power generation plants [12].

More than 700 gas turbines in the world have been fitted with fogging systems. A significant difference in these systems is injected water mass flow rate [4]. Famous recent OCGT that use fogging system may be briefly reviewed here with their main technical data. The coyote springs cogeneration power plant [15] in Boardman, Ore. Which runs a 159MW GE Frame 7-EA turbine: This plant installed the fogging system in 1997, to regain the power losses due to the high ambient temperature. This system consists of two pumps skids; it Contains a number of high-pressure pumps, typically 0.02 bar, which provide eight stages of cooling. For example on its operation on a 15°C day with approximately 34% relative humidity; this plant produces 8 to 9 MW increase at the gas turbine. The fog inlet air cooling system for the gas turbine in Rey power plant, in Iran: Site climate conditions in the summer have been studied by Amiri, et al [13]. Fog is generated by the application of high-pressure demineralized water between 70bar to 200bar to an array of specially design fog nozzles. The design rated output of each unit is 26.21MW.The wet bulb, dry bulb temperature and volume flow rate of inlet air are designed at 21°C, 37.8°C and 130m^3/s respectively for this power plant. The maximum augmented power percentage of power increase are 3.19MW and 12.17% respectively, the

relative increase in efficiency at design conditions is about 3.14%. For instant when the ambient temperature is 38°C and relative humidity is 20% application of fog cooling system results in a 16 degrees temperature fall in the incoming air of the compressor, the amount of output power in the aforementioned conditions would be 3.2MW.
Wet compression applied to nine W501 series gas turbines in meefog company (1998) [12] with the lead unit having accumulated 25000 hours of system operation: System performance has been demonstrated in field operation and power increases in the range of about 10 to 25% are been attained.

An application of direct fogging on a frame 7001E-model gas turbine has been made by the mee fog group company (1997) [8]. The gas turbine is operated at base load power at peaking service and its base load rated at 60.9 MW. The compressor inlet temperature was dropped from (28.8°C) to the wet bulb temperature of around (21°C). Power increased from the direct fogging evaporative cooling was approximately 3.5 % for every 10°C of inlet cooling. There was a 5% power gain attained for each 1% (of air flow rate). A total of 1120 nozzles were arranged in eight stages with each stage providing 3.75°C of cooling. Operation of all eight stages would result in cooling of up to 30°F. The nozzle atomization pressure is (20bar) and the total fogging water flow is 5.35*105m3/s. In this application, the pump skid has four 15kW high-pressure pumps. The facility has reported an output increase of approximately 2MW per cooling stage (256K per stage).

3.Theoretical Analysis without Fogging system

The basic gas turbine cycle is Brayton cycle. Air enters the compressor, compressed and heated after that goes to the combustion chamber. Fuel is burned at constant pressure, raise the temperature of air to the firing temperature T_3. The resulting high temperature gases then enter the turbine where they expand to generate the useful work, the exhaust gases leaving the turbine in the open cycle are not re-circulated [16].
The processes in OCGT in a normal case can be divided into:
1-Irreversible adiabatic compression in the compressor
2-Constant pressure heat supply in the combustion chamber
3-Irreversible adiabatic expansion

3.1 Compression process

Efficient compression of large volume of air is essential for a successful gas turbine engine. The pressure ratio for the compressor (B_c) can be defined as [6]:

$$B_c = \frac{p_2}{p_1} \tag{1}$$

The final temperature of the compressor is calculated from [17]:

$$T_2 = T_1 + \frac{T_1}{\eta_c}\left(B_c^{\frac{\gamma-1}{\gamma}} - 1 \right) \tag{2}$$

T1: the ambient air temperature
The work of the compressor (W_c) can be calculated from [17] :

$$W_c = C_{pa}\frac{(T_2 - T_1)}{\eta_{mc}} \tag{3}$$

Where

C_{pa} the specific heat of air that can be fitted by the following equation for the range of 200K< T < 800K [17] :

$$C_{pa}=1.0189134\times10^{3}-1.3784\times10^{-1}\ T+1.98434\times10^{-4}\ T^{2}+4.2399\times10^{-7}\ T^{3} \quad (4)$$

η_{mc} is the mechanical efficiency of the compressor.

3.2 Combustion Chamber

The function of the combustion chamber is to receive the air from the compressor and deliver it at the desired temperature [18]. The mass of fuel needed to reach a certain desired turbine inlet temperatures is obtained by applying the first law of thermodynamic to the combustion chamber. Calculation of the fuel/air ratio f required to transform unit mass of air at T_2 and kg of fuel at the fuel temperature T_f to $(1+f)$ kg of products at T_3 the process is adiabatic with no work transfer, the energy equation simply as [17] :

$\sum \dot{m}_i h_{i\ inlet}=\sum \dot{m}_o h_{o\ outlet}$

The inlet streams are the air coming from the compressor and the fuel needed for the combustion process, the exit stream is the fuel gas (combustion products) [17], by substituting ($f=\frac{m_a}{m_f}$) and by rearranging the variables and, making use of the enthalpy of reaction at a refrence temperature of 25 °C, Δh_f=LCV [19].

Since: f<0.05, $f\times C_{pf}\times(298-T_f)$ can be neglected, thus the fuel air mass ratio at the combustion chamber(f) can be calculated as [17]:

$$f=\frac{C_{pg}(T_3-298)-C_{pa}(T_2-298)}{LCV-C_{pg}(T_3-298)} \quad (5)$$

3.3 Gas Turbine

Gas turbines use more relatively large quantities of air through the cycle at very high velocities. The gas turbine in its most common form is a heat engine operating through a series of processes, and the process in the turbine, expansion of the hot gases and discharging of the gases to the atmosphere [20].

The pressure losses coefficient K_p is calculated by [6]:

$$K_p=\frac{\left(1-\frac{\Delta p_2}{p_2}\right)}{\left(1+\frac{\Delta p_4}{p_4}\right)} \quad (6)$$

Δp_2: is pressure losses through the compressor.

Δp_4: is the pressure losses through the turbine.

The combustion chamber delivers the working fluid to the turbine at the desired temperature T_3. The working fluid flowing through the turbine consists of the flue gases and dry air with a total mass equals to [17]:

$$m_{total}=m_a+m_f=m_a(1+f) \quad (7)$$

Where mass of air (m_a) is calculated by knowing the air density and the volumetric rate of the air entering to the compressor. The a temperature of the expansion is [17] :

$$T_4 = T_3 + \eta_{PT} T_3 \left(\left(\frac{1}{B_C} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right) \tag{8}$$

Where:

B_t: the expansion ratio at the turbine.

The shaft work of the turbine is given by [19]:

$$w_t = (1 + f) \times (h_3 - h_2) \times \eta_{mt} \tag{9}$$

And the work of turbine in another form by using the specific value of inlet hot gases to turbine becomes [16]:

$$w_t = (1 + f)C_{pg}(T_3 - T_4)\eta_{mt} \tag{10}$$

Where η_{mt} is the mechanical efficiency of the turbine machine.

The specific heat of gas entering to the gas turbine (C_{pg}) can be calculated as follows [19] :

$$C_{pg} = 950 + 0.21 \times T \quad \text{(kJ/kg.K)} \tag{11}$$

The net work of the cycle (W_0) is calculated from the equation [6] :

$$w_o = w_t - w_c \tag{12}$$

Also, the output power from the turbine becomes [6] :

$$P = m_a \times (W_t - W_c) \tag{13}$$

And the OCGT efficiency (ηo) is [17] :

$$\eta_0 = \frac{W_o}{f\ LCV} \tag{14}$$

3.4 Theoretical analysis of the fogging system

The same analysis could be modified by including a fogging system at the inlet to the compressor of OCGT. The saturated pressure over water surface and for the temperature range from 0°C to 100°C can be found from the equation [21]:

$$\ln(p_s) = \frac{C_1}{T} + C_2 + C_3 T + C_4 T^3 + C_5 T^3 + C_6 \ln(T) \tag{15}$$

Where

$C_1, C_2, C_3, C_4, C_5, C_6$: are constants.

P_s: the saturation pressure in P_a units.

T: the temperature in compressor, in (K).

The partial pressure of the vapor can be calculated from knowing the saturation pressure and the relative humidity for the ambient air entering to the compressor by the equation [19].

$$RH = \frac{p_v}{p_s} \tag{16}$$

By assuming air and water vapor as perfect gases, since the water vapor and dry air have the same volume and temperature then the moisture content calculated from [17] :

$$w = 0.622 \times \left(P_v / P_a \right) \qquad (17)$$

The temperature of the inlet air entering to the compressor can be found from the equation below [21] :

$$T_1 = T_a - \left(\frac{p_a - p_s}{p_a} \right) / A \qquad (18)$$

Where: A: constant = 6.66×10^{-4} in C^{-1} units.

The process in the fogging system involves evaporation of water droplets and transformation of heat energy from the air to the water, thermodynamic changes that can take place between the air and the water that are in a direct contact with the moving air stream [22].

3.5 Compression process in case of fogging system

The OCGT with the fogging system begins with a fogging part in the front of the compressor, the remaining parts are the same like that without fogging. The air entering to the compressor is humid instead of dry air, so the sensible and latent change occurs into the compressor.

The enthalpy of the humid air entering to the compressor is calculated from the equation [23]

$$h = (1.007\times t - 0.026) + \omega\,(2501 + 1.84\times t) \qquad (19)$$

Where t the temperature in ° C units.

So the work absorbed by the compressor (W_c) when blade cooling is not taken into account [17]:

$$W_c = C_p \times (T_2 - T_1)/\eta_{mc} + w(h_2 - h_1) \qquad (20)$$

3.6 Combustion Chamber

The inlet streams to the combustion chamber are the moist air coming from the compressor, so the term $\dot{m}_w h_{w2}$ added to eq.(5) and by simplifying this equation in a similar way to that without fogging system results [17]

$$f = \frac{C_{pg}(T_3 - 298) + w(h_3 - h_2) - C_{pa}(T_2 - 298)}{LCV - C_{pg}(T_3 - 298)} \qquad (21)$$

5.3 Gas Turbine

The processes in GT in case of fogging system is similar to that without fogging system exept the working fluid flowing through the turbine consists of flue gases and water vapor with a total mass equals to [17] :

$$m_{total} = m_a + m_w + m_f = m_a(1 + \omega + f) \qquad (22)$$

Turbine work becomes [17] :

$$W_t=(1+w+f)\times C_{pg}\times\eta_{mt}\times(T_3-T_4) \qquad (23)$$

3.8 Fogging system analysis

The main parameters that affect the fogging system are:
1- Inlet water flow rate
2-Injection pressure
3-Nozzle geometry (droplet size, velocity, spray angle and spray distance) [24].

3.9 Inlet water flow rate

The amount of water that evaporates depends on the water flow rate through the fogging system. The water flow rate must be adjusted to meet the actual water requirements to reach saturation [25]. In order to find the relation between water flow rate and the OCGT parameters, the followig assumptions are listed:
1-Constant inlet air conditions (T_a, RH_1)
2-Constant firing temperature (T_3), and pressure ratio
3-Constant air flow rate into the compressor.

In these cases w_1 is still constant, till it is calculated from the inlet air conditions; the mass of air flow is also constant because air flow rate is constant. Then the humidity ratio at exit of the fogging system is found by using [8]:

$$\omega=\omega_2-\omega_1 \qquad (24)$$

By substituting: $\dot{m}_w=Q_w\rho_w$ in eq.(24) we obtained:

$$w_2=\frac{Q_w\rho_w}{m_a}+w_1 \qquad (25)$$

Sub. w_2 in eq.(20) to find the compressor work which is related to Q_w:

$$w_c=C_{pa}(T_2-T_1)+\left(\frac{Q_w\rho_w}{m_a}\right)(h_2-h_1) \qquad (26)$$

And by substitute w_2 in eq.(22) to find the relation of $\dot{m}_{total}$ with the water flow rate results:

$$m_{total}=m_a\left(1+\frac{Q_w\rho_w}{m_a}\right)+f \qquad (27)$$

To calculate the turbine work related to Q_w sub. w_2 in eq.(23):

$$W_t=\left(1+\frac{Q_W\rho_W}{M_A}+f\right)C_{pg}\eta_{mt}(T_3-T_4) \qquad (28)$$

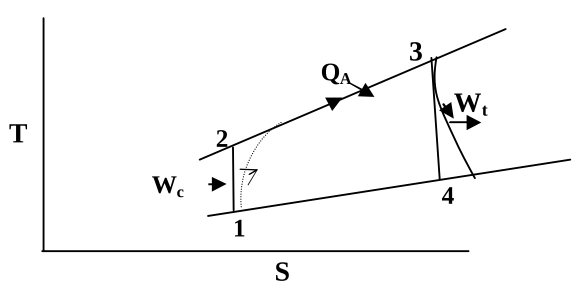

Fig.(4) The OCGT process on T-S diagram

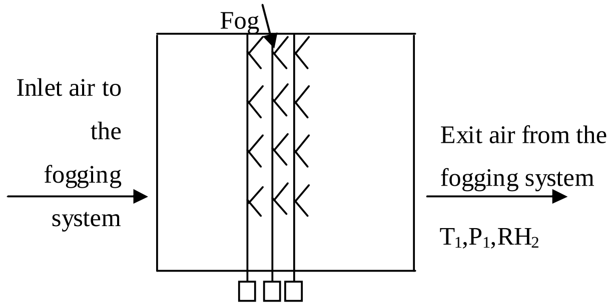

Fig.(5) The fogging system

4. Results and discussion

This section explaine the theoretical analyses of (OCGT) without and with fogging system. The present study comprise the effect of gas turbine parameters; like ambient temperature (T_a), pressure ratio (B), firing temperature (T_3) and ambient relative humidity (RH) on the performance of OCGT with and without fogging system. A graphical presentation between the input data and output results can be seen readily in this section. The major assumptions underlying the present analysis are:

- LCV of natural gas	42500 (kJ/ kg. K)	
- η_{pc}	89	(%)
- η_{pt}	88	(%)
- η_b	90	(%)
- $\eta_{mc, gt}$	90	(%)

4.1.Effect of ambient temperature (Ta)

Fig.(6) is plotted for overall efficiency versus ambient air temperature T_a for OCGT at various firing temperatures. It can be seen that the efficiency of OCGT decreases with the increase of inlet air temperature due to the increment of compressor work, since a lower T_a gives a lower compressor work that in turn gives a higher gas turbine network. A reduced efficiency of 7.5% in OCGT registered when ambient temperature change from 10°C to 60°C. Thus, a lower T_a gives a better overall efficiency. This figure shows also the improvement in OCGT efficiency due to using a fogging system. Fig .(7) Shows the relation between the output power and the ambient air temperature. This figure is plotted for constant pressure ratio=10 and for different firing temperatures. It can be seen that the OCGT power is affected by T_a due to the change of air density and compressor work, a lower T_a which leads to a higher air density and, when T_a increases the air density reduces; so the net power reduces. This figure shows also the improvement in output power due to using fogging system. As T_a increases, air mass flow rates (the density of air with constant volumetric flow of a gas turbine), decreases and T_2 increases.

Figures (8)&(9) are plotted between cycle efficiency, output power versus the ambient air temperature for different values of pressure ratio and for constant firing temperature T_3=1100K. It is clear from these figures that the (efficiency and output power) reduces with increasing the ambient air temperature, these values rises with an increase of B until a limited value after which they suffer reduction in their values due to the increase of compressor work.

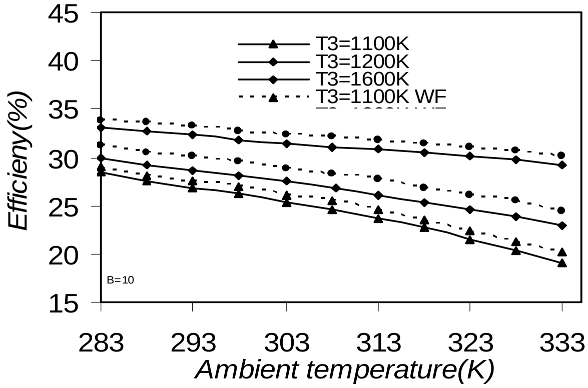

Fig.(6) Effect of ambient temperature on the efficiency at different firing temp.

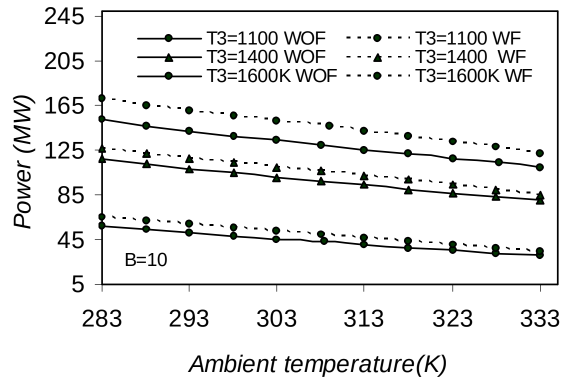

Fig.(7) Effect of ambient temperature on output power at different firing temp

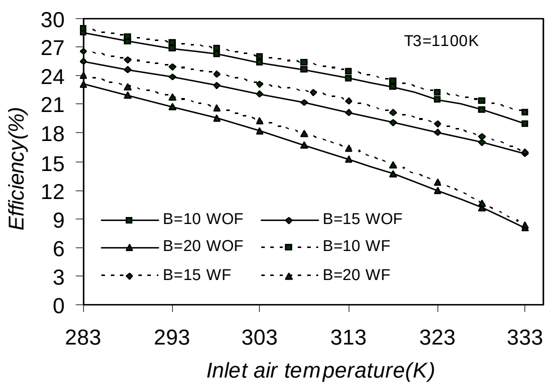

Fig.(8)The relation between efficiency and inlet air temperature

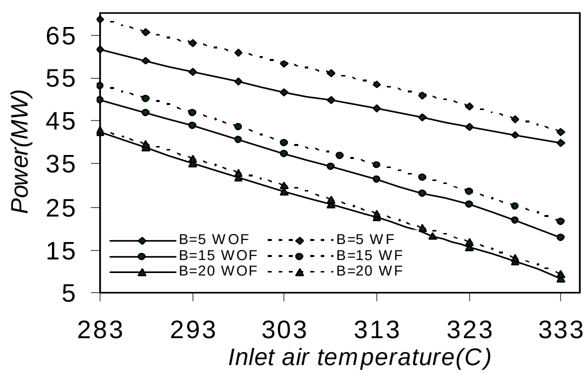

Fig.(9) The relation between power and inlet air temperature

4.2. Effect of pressure ratio (B)

Fig.(10) shows the variation of efficiency with pressure ratio this figure is plotted for constant T_a=10°C and for different firing temperature. It is clear from the figure that as pressure ratio increases efficiency increases since the net work increases until it reaches a value of B (ranging between 8-12 depends on the firing temperature) then it begins decreasing because the compressor work increases. Fig.(11) is plotted between output power versus pressure ratio, this figure is plotted for constant T_a=10°C and for different firing temperature. It is clear from the figure that as pressure ratio increases the output power increases since the net work increases until it reaches a value of B (ranging between 8-12 depends on the firing temperature) then it begins decreasing because the compressor work increases.

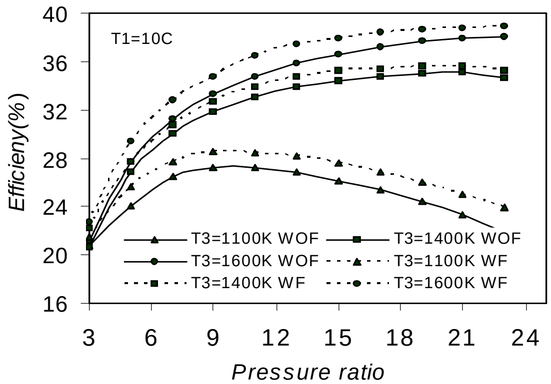

Fig.(10) The relation between efficiency and pressure ratio

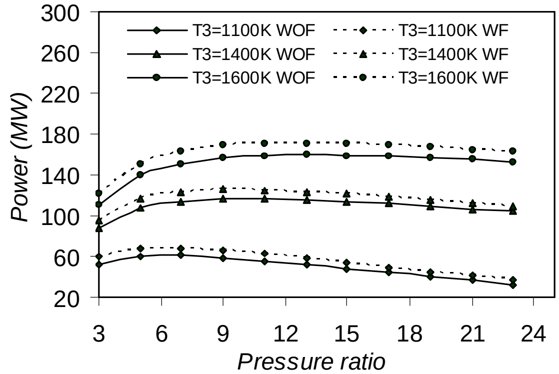

Fig. (11) The relation between power and pressure ratio at different firing temperature

4.3. Effect of relative humidity (RH)

Dry air has a low wet-bulb temperature while humid air has a high wet bulb temperature [26]. Fig.(12) is plotted between the overall efficiency and the ambient relative humidity; plotted for constant B=10, T_3=1600K and different ambient temperature. It is clear from this figure as relative humidity increases the efficiency decreases due to reducing the difference between dry and wet bulb temperature of air entering to the compressor. A 6.28% reduction in efficiency was observed when operating at an ambient condition of T_a= 60°C and 60% RH over that of 60°C and 10% RH.

Fig. (13) shows the relation between masses of the injected water needed to reach saturation temperature. This figure is plotted for different values of relative humidity and for constant B=10, T_a=60°C and T_3=1600K, It can be noticed as RH of the inlet air increases mass of water required for saturation is reduced since the difference between T_{dry} and T_{wet} is reduced, so the gain in efficiency and output power reduces due to the drop in ambient temperature when using a fogging system is reduced.

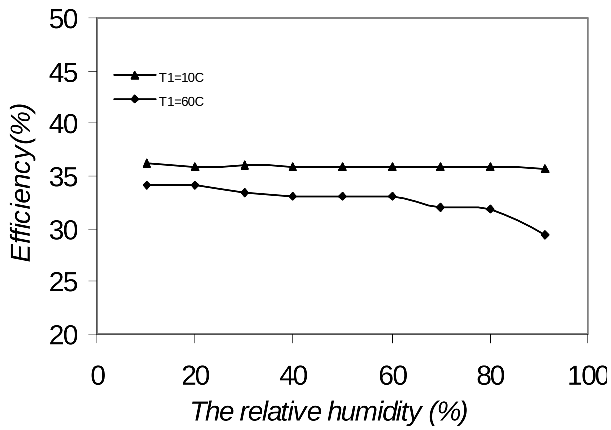

Fig. (12) The relation between efficiency and relative humidity of ambient air

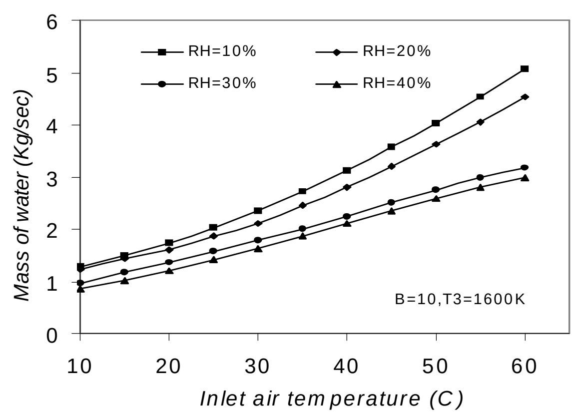

Fig. (13) The relation between inlet air temperature and mass of water

5.Conclusions

A parametric study of the effect of ambient temperature (T_a) , pressure ratio (B) , firing temperature (T_3), and relative humidity (RH) on. The OCGT performance when using fogging system leads to the following conclusions:

1)Water injction at the front of the compressor increases the power and efficiency of the OCGT.

2) It is clear from this study that the effectiveness of the fogging system when the ambient condition is dry and hot larger than when it is hot and humid.

3) It is clear from studies that are conducted in the world about the fogging system that using a fogging system to increase the output power in the hot and dry months is less expensive than building a new gas turbine plant.

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الخلاصة

منظومة التضبيب تستخدم كاحدى طرق تبريد الهواءالداخل الى الضاغطة وذلك بحقن الماء بصورة مباشرة في مدخل الضاغطة لغرض تقليل درجة حرارةالهواء الداخل الى الضاغطة حتى تصل الى درجة حرارة البصلة الرطبة للهواء فيقل شغل الضاغطة وتزداد كثافة الهواء ولذلك تزداد القدرة الخارجة من التوربين . في هذه الدراسة أخذ تاثير كل من درجة حرارة الجو و الرطوبة النسبية و درجة حرارة الاحتراق داخل التوربين و نسبة الانضغاط على ادائية التوربين الغازي. ان حدود درجة حرارة الجو اختيرت لتتراوح بين (10−60) درجة مئوية،الرطوبة النسبية (10−90)%, نسبة الانضغاط بين (3−23) ودرجة حرارة الاحتراق داخل التوربين (1100 ، 1200 ، 1400 و 1600)كلفن . النتائج المستحصلة من هذه الدراسة اثبتت ان القدرة الخارجة والكفاءة تزداد مع زيادة درجة حرارة الاحتراق وتقل مع زيادة درجة حرارة الجو وكذلك الكفاءة تزداد مع زيادة نسبة الانضغاط لحد معين ثم تبدا بالهبوط بينما كانت زيادة الرطوبة النسبية للجو تعطي نتائج معكوسة على قدرة وكفاءة الدورة.عموما ان هذه الدراسة وضحت ان استخدام منظومة التضبيب في مقدمة الضاغط يؤدي الى تحسين القدرة والكفاءة لدورة التوربين الغازي.