Influence of Operating Conditions on the Performance Parameters of Gas Turbine Cycle Power Plant

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الخلاصة

محور هذه الدراسة يتمركز على إمكانية تشغيل و عمل محطة قدرة التربين الغازي تحت ظروف تشغيل مختلفة، للحصول على ناتج قدرة عالية حسب الظروف المناخية و القيم التصميمية. حيث الموقع الجغرافي و الظروف المناخية تلعب دور كبير في تحسين أداء المحطات الغازية، الكفاءة الحرارية، استهلاك الوقود النوعي، القدرة الإنتاجية. بالإضافة إلى التصميم الهندسي، البنية الداخلية للمادة والتي تدخل تحت دراسة علم المواد. في هذه الورقة تم تقديم دراسة تحليلية على مدى تأثير ظروف التشغيل و درجة حرارة الجو المحيطة على أداء محطة قدرة التربين الغازي. الدراسة تتضمن نموذجا للديناميكا الحرارية للدورة، باعتبار تأثير درجة حرارة الجو المحيط المؤسس على القانون الأول للديناميكا الحرارية. حيث تم الحصول على نتائج باستخدام نموذج رياضي طُور باستعمال برمجة لغة فورتران90 على أساس عرض مقدم في صورة أنماط و مخططات **(graphs and patterns)** توضح تغير مؤثرات الأداء مثل الكفاءة الحرارية و الاستهلاك النوعي للوقود و شغل الضاغط و القدرة الإنتاجية تحت ظروف تشغيل مختلفة كنسبة الانضغاط و درجة حرارة مدخل التربين و درجة الحرارة المحيطة و الكفاءة الأيزنتروبية للضاغط و التربين. حيث يُلاحَظ من النتائج أنه قد تم الحصول على أفضل كفاءة حرارية عند أعلى ظروف تشغيل لنسبة الانضغاط ودرجة حرارة مدخل التربين مع درجة حرارة أقل لمدخل الضاغط ، كذلك يقال بالنسبة لأقل معدل استهلاك النوعي للوقود يمكن الحصول عليه عند تلك الظروف. أما ناتج الشغل النوعي يكون في أفضل الظروف عند نسبة انضغاط 15 عند ظروف تشغيل معينة مع مراعاة الكفاءة الأيزنتروبية للضاغط و التربين، و كما يلاحظ أيضا من النتائج أن درجات الحرارة الأقل عند مدخل التربين، و درجات الحرارة الأعلى عند مدخل الضاغط، لها تأثير على معدل استهلاك الوقود النوعي، هذا وبشكل ملحوظ ذو أهمية كبيرة من حيث اقتصاديات محطات القدرة الغازية.

Abstract

The focus of this study focuses on the possibility of operating and working the gas turbine power plant under different operating conditions, to obtain a high power output according to climatic conditions and design values. Where, the geographical location and climatic conditions play a major role in improving the performance of gas stations, thermal efficiency, specific fuel consumption, and production capacity. As well as the geometrical design, the internal structure of the material which is involved under the study of materials science which came up with special alloys that can withstand high temperatures. In this paper, an analytical study is presented on the effect of operating conditions and ambient air temperature on the cycle performance of a gas turbine plant. The study includes a thermodynamic model for the cycle, considering the effect of ambient temperature based on the first law of thermodynamics. Where results were obtained using a mathematical model developed utilizing the programming language Fortran 90 on the basis of a presentation presented in the form of graphs and patterns showing the variation of performance parameters such as thermal efficiency, specific fuel consumption, compressor work and specific work output under different operating conditions like the compression ratio , turbine inlet temperature(TIT), ambient temperature and isotropic efficiency of the compressor and the turbine. It can be observed from the results that the best thermal efficiency was obtained at the highest operating conditions for the compression ratio and turbine inlet temperature with a lower temperature for the compressor inlet, as well as for the lowest specific fuel consumption rate that can be obtained under the same these conditions. As for the specific work output, it is in the best conditions at a compression ratio of 15 under certain operating conditions, taking into account the isotropic efficiency of the compressor and the turbine. Also, lower temperatures at turbine inlet and higher temperatures at compressor inlet have the influence on the specific consumption rate of fuel. This is significantly of great importance in terms of the economies of power plants.

Index Terms- Gas Turbine; Thermal Efficiency; Ambient Temperature, Compression Ratio, Compressor Inlet Temperature (CIT)
Turbine Inlet Temperature (TIT)

Table (1): List of Symbols, Greek Letters, Subscripts and Abbreviations.

Symbols & Nomenclature			
r_p	Compression ratio (-)	W_{Net}	Net work (Specific work output) ,(kJ/kg)
Cp	Specific heat at constant pressure (kJ/kg.K)	Q_{add}	heat supplied (kJ/kg)
T	Temperature (K), (°C)	P	Pressure (pa)
F	Fuel air mass ratio kg of fuel/kg of air	$\dot{m}$	Mass flow rate (kg/s)
η_c, η_t	The isentropic efficiency for compressor and turbine in the range of (85-90%)		
Greek Letters			
η	Efficiency	γ	Specific heat ratio
Subscripts			
1,2,3,4	Points denoted Fig.1and 2	*th*	Thermal efficiency
A	Air	*f*	Fuel
T	Turbine	*g*	Flue gas
C	Compressor		
Abbreviations			
W	Work	*HR*	Heat rate (kJ/kWh)
GT	Gas turbine	*LHV*	Lower heating value (kJ/kg)
TIT	Turbine inlet temperature (k)	*SFC*	Specific fuel consumption (kg/kW.h)
CIT	Compressor inlet temperature (k)		

1. INTRODUCTION

Gas turbines play a vital role in industry and electrical power generation. They are important part in the field of mechanical drive, gas transmission and power generation. Where, become very popular as a result of the high power to weight ratio, compactness, and ease of installation. Performance of the gas turbines cycle power plant mainly depend on the cycle compression ratio, turbine inlet temperature and ambient air conditions. As well as the material science which came up with special alloys that can withstand high temperatures, enabled the gas turbine to enter a new competition as a main power plant for generating electricity.

The low efficiencies of the gas turbine plants are tired to many factors which include: operation mode, poor maintenance procedures, age of plant, discrepancies in operating data, high ambient temperature and relative humidity. Power output and efficiency of a gas turbine plant depends largely on the condition of the compressor inlet air temperature (Cortes and William, 2003) [1].

M. M. Rahman et al [2] evaluated in their study of the thermodynamic performance analysis of gas-turbine power-plant, They concluded that the compression ratio, ambient temperature, air to fuel ratio as well as the isentropic efficiencies are strongly influence on the thermal efficiency. In addition, the thermal efficiency and power output decreases linearly with increase of the ambient temperature and air to fuel ratio. Also, the specific fuel consumption and heat rate increases linearly with increase of both ambient temperature and air to fuel ratio. Moreover, thermodynamic parameters on cycle performance are economically feasible and beneficial for the gas turbine operations.

Anoop and Onkar [3] investigated the effect of compressor inlet temperature & relative humidity on gas turbine cycle performance. Investigation reported that there was 0.77 percent increase in the specific power output and 0.65 percent increase in thermal efficiency for every 15 percent increase of relative humidity of GT cycle power plants. Also there was 10.12 percent gain in the specific work output, 3.45 percent in thermal efficiency and 3.43 percent saving of fuel by decreasing the compressor inlet temperature from 318K to 282K.

Thamir K. Ibrahim1 et al [4] studied the influence of operation conditions and ambient temperature on performance of gas turbine power plant. They concluded that the peak efficiency, power and specific fuel consumption occur when compression ratio increased. Maximum power for the turbine inlet temperatures are selected a compression ratio 6.4 for a turbine inlet temperature of 1000K result in a higher thermal efficiency.

2. MODELING OF GAS TURBINE CYCLE (The Brayton Cycle)

A simple gas turbine consists of four main sections a compressor, a combustor, a power turbine and generator. As shown in figure (1). The compressor supplies a fresh air at high pressure to combustion chamber, which provides a power turbine and flue gas at high temperature and pressure.

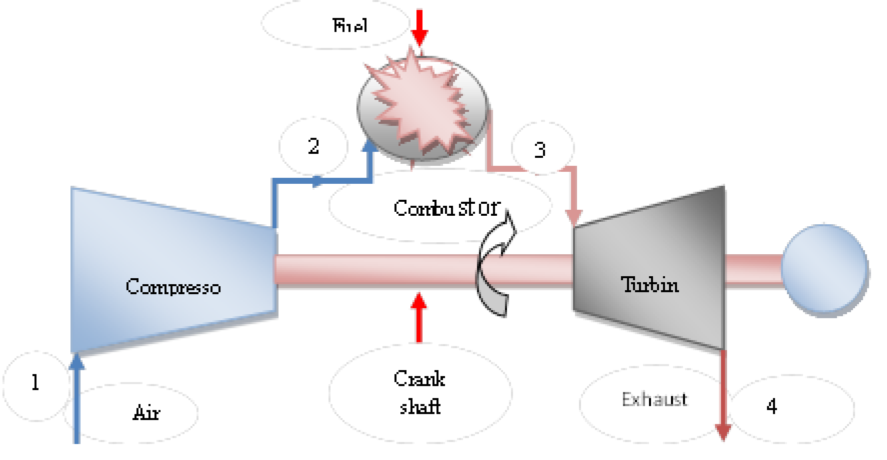
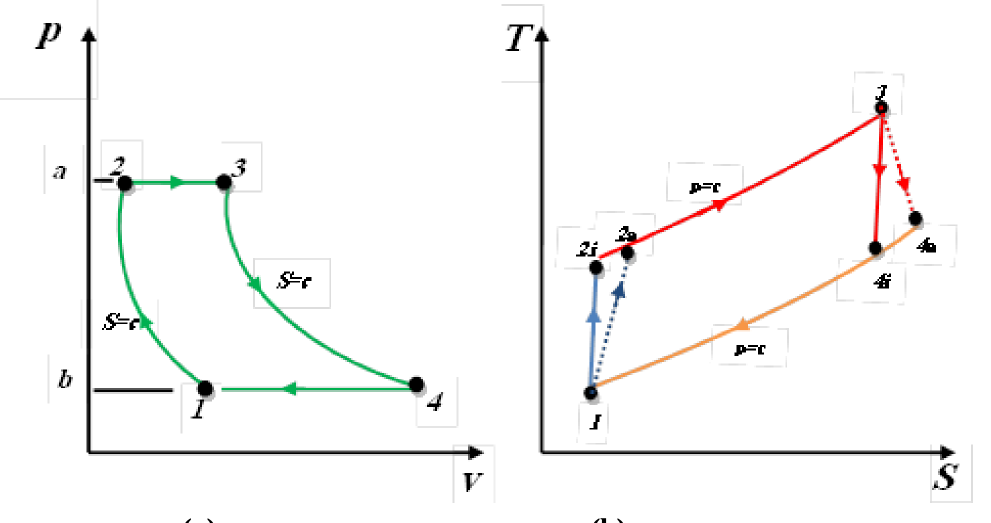


Figure (1): schematic diagram for a simple gas turbine

A combustor converts the thermal energy from a combustible fuel to the mechanical energy, where the air is mixed with fuel, and burned under constant pressure conditions in the combustor. The turbine module is important part of gas turbine cycle that it extracts power from hot burnt gases flow, resulting by the combustion of fuel with air. The electrical generator is connected directly with turbine module to convert the kinetic (mechanical) energy into electrical energy produces nearly all of the electricity that consumers use. The compressor module, combustor module, turbine module, connected by one or more shafts are collectively called gas generator.

The Gas Turbine Cycle:

The Brayton cycle is the cycle which the engineers and researchers make it the reference for them to compare and try to reach. In reality, the gas turbine does not work as the ideal Brayton cycle. It works under many effects, such that both the compression process (1-2) with fluid friction and the expansion process (3-4) with fluid friction results in an increase in entropy. The ideal processes and actual processes are represented in full line and dashed line, respectively, on the T-S diagram as shown in Figure (2).These parameters in terms of temperature are defined as [15]:



(a) **(b)**

Figure (2): (a) P-V diagram and (b) T-S diagram of ideal and non-ideal Brayton cycle (a indicates actual process)

The compression ratio for the compressor (rp) can be defined as eq. (1):

$$r_p = \frac{P_2}{P_1} \qquad (1)$$

The isentropic efficiency for compressor and turbine in the range of as eq. (2):

$$\eta_c = \frac{T_{2s}-T_1}{T_2-T_1} \quad \text{And} \quad \eta_t = \frac{T_3-T_4}{T_3-T_{4s}} \qquad (2)$$

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

$$T_2 = T_1 + \frac{T_{2s}-T_1}{\eta_c} = T_1\left(1 + \frac{r_p^{\frac{\gamma_a - 1}{\gamma_a}} - 1}{\eta_c}\right) \quad (3)$$

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

$$W_c = \left(\frac{c_{pa'avg}\, T_1\left(r_p^{\frac{\gamma_a - 1}{\gamma_a}} - 1\right)}{\eta_m}\right) \quad (4)$$

Where $C_{pa'avg}$ is the specific heat of the dry air at constant pressure, determined as a function of the average temperature across the compressor (Alhazmy, M.M and Najjar,Y.S.H.,2004) [10]. It can be fitted by eq. (5) for the range of 200 K < T < 800 K [11]:

$$C_{Pa}(T) = 1.04841 - \left(\frac{3.8371T}{10^4}\right) + \left(\frac{9.4537T^2}{10^7}\right) - \left(\frac{5.49031T^3}{10^{10}}\right) + \left(\frac{7.9298T^4}{10^{14}}\right)$$
(5)

Where, CIT= T_a in Kelvin.

The specific heat of flue gas is given by eq. (6) [12]:

$$C_{Pg}(T) = 0.991615 + \left(\frac{6.99703T}{10^5}\right) + \left(\frac{2.7129T^2}{10^7}\right) - \left(\frac{1.22442T^3}{10^{10}}\right) \quad (6)$$

From energy balance in the combustion chamber

$$\dot{m}_a c_{pa} T_2 + \dot{m}_f \times LHV + \dot{m}_f c_{pf} T_f = (\dot{m}_a + \dot{m}_f) c_{pf} \times TIT \quad (7)$$

Where, T_3 = TIT, is turbine inlet temperature.

After manipulating from (7), the ratio of mass flow rate (f) is expressed as eq. (8):

$$f = \frac{\dot{m}_f}{\dot{m}_a} = \frac{c_{pg} \times TIT - c_{pa} T_2}{LHV - c_{pg} \times TIT} \quad (8)$$

Where LHV is the lower heating value of the fuel (natural gas; 48235.63 KJ/kg) [13], ($\dot{m}_f$) is the mass flow rate of fuel, and ($\dot{m}_a$) is the mass flow rate of air.

The shaft work (W_t) of the turbine is given by eq. (9):

$$W_t = c_{pg\prime avg} \times TIT \times \eta_t \left(1 - \frac{1}{r_p^{\frac{\gamma g-1}{\gamma g}}} \right) \quad (9)$$

Where $C_{pg'avg}$ is the flue gas specific heat at constant pressure, calculated as a function of the average temperature across the turbine (Alhazmy, M.M and Najjar,Y.S.H.,2004) [10].

The network of the gas turbine (W_{net}) is calculated from the equation (10):

$$W_{net} = c_{pg\prime avg} \times TIT \times \eta_t \left(1 - \frac{1}{r_p^{\frac{\gamma g-1}{\gamma g}}} \right) - c_{pa} T_1 \left(\frac{r_p^{\frac{\gamma a-1}{\gamma a}}}{\eta_c} \right) \quad (10)$$

Also, the output power from the turbine (P) can be expressed as eq. (11):

$$P = \dot{m}_a \times W_{net} \quad (11)$$

The heat supplied (Q_{add}) is formulated as eq. (12):

$$Q_{add} = c_{pg\prime_{avg}} \times \left[TIT - T_1 \times \left(1 + \frac{r_p^{\frac{\gamma a-1}{\gamma a}} - 1}{\eta_c} \right) \right] \quad (12)$$

Where $C_{pg'avg}$ is the flue gas specific heat at constant pressure, calculated as a function of the average temperature across the combustion chamber (Alhazmy, M.M and Najjar,Y.S.H.,2004) [10].

The performance parameters of the gas turbine cycle power plant are specific work output (network), specific fuel consumption, cycle efficiency and heat rate and are calculated from the following governing equations.

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

$$SFC = \frac{3600 f}{W_{net}} \quad (14)$$

$$\eta_{th} = \left(\frac{W_{net}}{Q_{add}} \right) \quad (15)$$

The heat rate (HR) which is the consumed heat to generate unit energy of electricity can be expressed as eq. (16).

$$HR = \frac{3600}{\eta_{th}} \quad (16)$$

3. RESULTS AND DISCUSSION

This paper presents the simulation results of effect of ambient temperature and operating conditions on the performance of the gas turbine cycle as the power output and thermal efficiency. The operating parameters like ambient temperature, turbine inlet temperature Compression ratio are calculated using Fortran90 for carrying out the analysis.

Figure (3) depicts the relation between the ambient temperature and the thermal efficiency for several different values of turbine inlet temperature. It can be observed that the increase in ambient temperature leads to an increase in the specific work of compressor that is decreased of specific work output of gas turbine cycle. Thus reduce cycle efficiency for gas turbine, so when the turbine inlet temperature is risen, this leads to an increase in the thermal efficiency. It can be said that the thermal efficiency linearly increases with rises of turbine inlet temperature, while decreases with increases of ambient temperature.

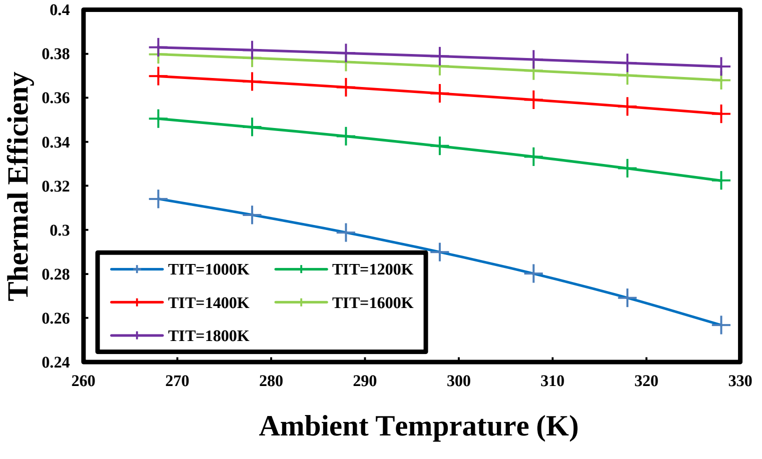


Figure (3): Effect of ambient temperature and turbine inlet temperature on thermal efficiency.

The effect of ambient temperature and turbine inlet temperature on specific fuel consumption is shown in Figure (4), where can be watched that specific fuel consumption increases linearly with increases of ambient temperature and lower turbine inlet temperature. Also, on the other hand the specific fuel consumption decreases with increases of turbine inlet temperature; we notice a sudden increase in the rate of fuel consumption at lower turbine inlet temperature with increases ambient temperature, which means that the combustion of fuel is incomplete, therefore should be increased turbine inlet temperature with take into consideration the burning of fuel.

In figure (5) represents the variation of thermal efficiency with different gas turbine cycle compression ratio on various compressor inlet temperatures (CIT). Here the thermal efficiency decreases with increase in compressor inlet temperature for varying compression ratios. However, the increase in compression ratio gives increment in power output as a result of thermal efficiency increase. Also we can note that the effect of ambient temperature on the thermal efficiency of cycle is relatively low, when compared with the effect of different compression ratios.

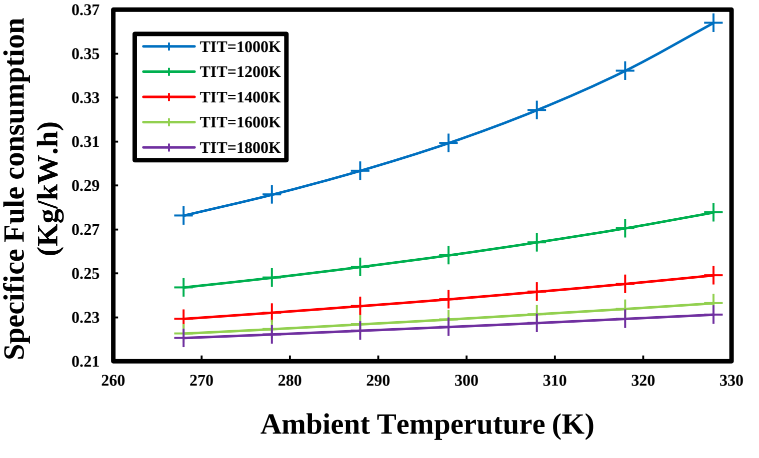


Figure (4): Variation of specific fuel consumption of GT power cycle with different ambient temperature and turbine inlet temperature.

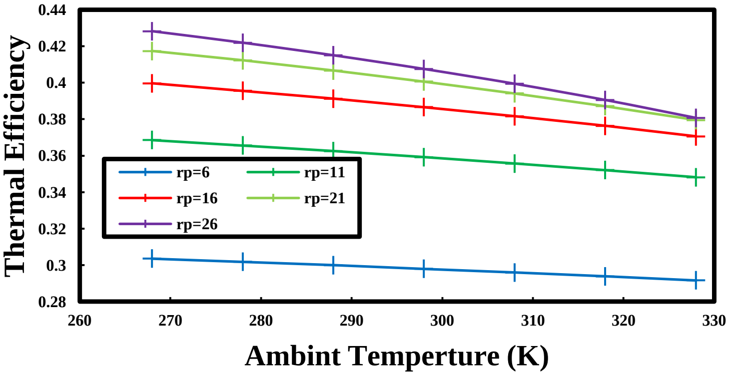


Figure (5): Variation of thermal efficiency against the ambient temperature and compression ratio.

Figure (6) shows the variation between thermal efficiency and compression ratio for several different values of turbine inlet temperature, where the thermal efficiency almost linearly increases at lower compression ratio, especially, when the turbine inlet temperature is increased. The thermal efficiency turns at certain value of compression ratios, this means that the thermal efficiency depends on the turbine inlet temperature. There is a sharp drop in the thermal efficiency at lower turbine inlet temperature, which indicates the need to increase the fuel quantity and the turbine inlet temperature to improve the efficiency of the cycle.

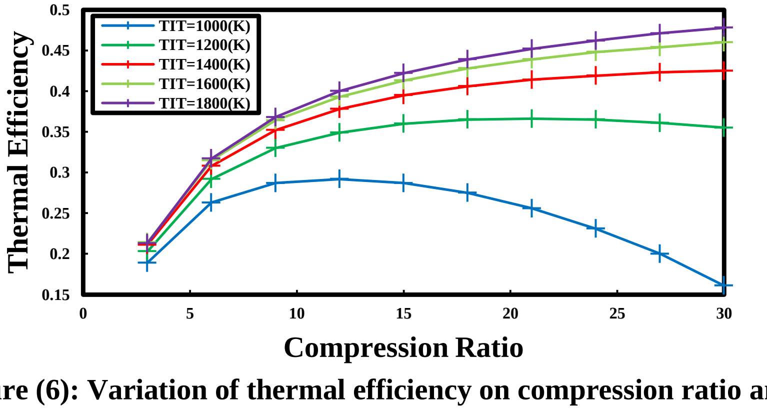


Figure (6): Variation of thermal efficiency on compression ratio and turbine inlet temperature.

Figure (7) presents the relation between specific fuel consumption (SFC) against the compression ratio and turbine inlet temperature. Here it is observed that the (SFC) decreases with increases of compression ratio and turbine inlet temperature at certain value, after that gradually increases dramatically for lower turbine inlet temperature (TIT). It is also noted that the turbine inlet temperature should be increased at a certain value only then it is stopped, because the rate of specific fuel consumption becomes almost constant at higher turbine inlet temperatures. In figure (8) shows the variation of compressor work with different compression ratio on various ambient temperatures. Here the compressor work increases with the increase of compression ratio and the ambient temperature. Also we can say that the isentropic compressor efficiency plays a major role in increasing the thermal efficiency of gas turbine cycle.

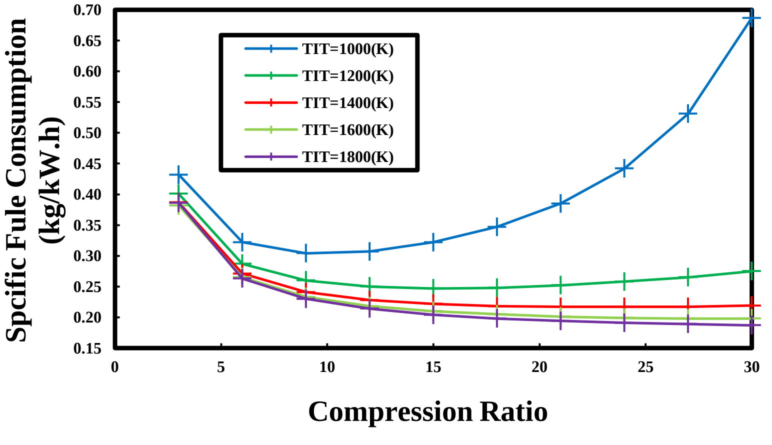


Figure (7): Variation of specific fuel consumption of GT power cycle with different compression ratio and turbine inlet temperature.

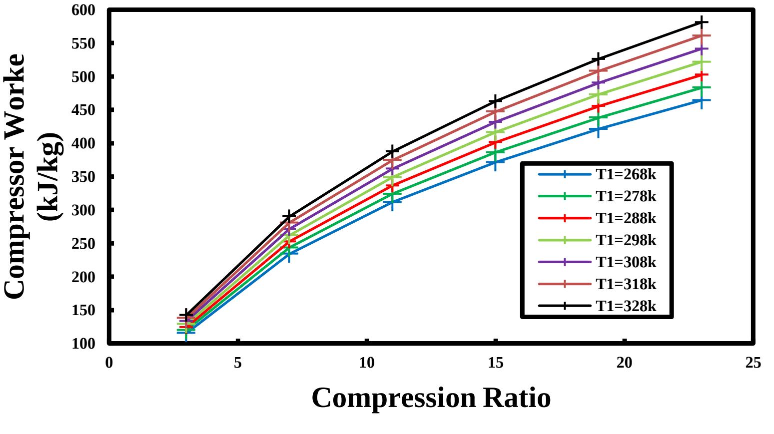


Figure (8): Variation of compressor work of GT power cycle with different compression ratio and ambient temperature.

Figure (9) illustrates the effect of compression ratio and ambient temperature on the specific work output. It can be evident that specific work output initially increases at higher value for compression ratio by 7 to 15, after that the increase in specific work becomes slower, because of increasing component of compression work.

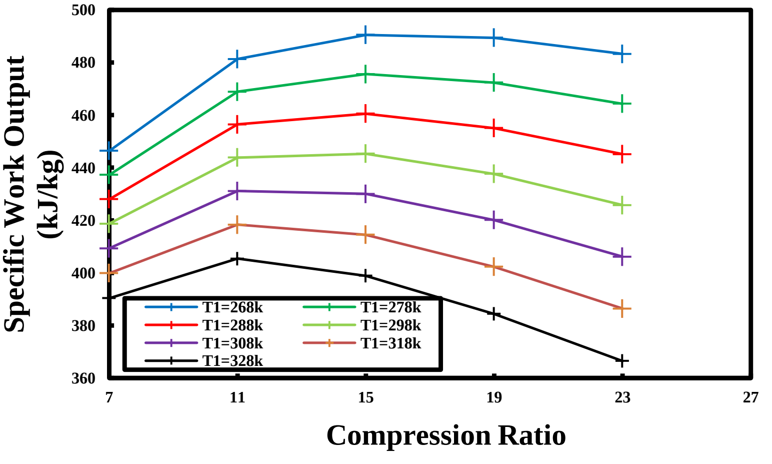


Figure (9): Variation of specific work output of GT power cycle with different compression ratio and ambient temperature.

Figure (10) describes the effect of compression ratio and compressor inlet temperature (CIT) on specific fuel consumption. It can be noticed a reduction in the specific fuel consumption rate with increase of compression ratio. Also, the specific fuel consumption increases with increasing compressor inlet temperature (CIT). However, an increase and decrease of compression ratio and ambient temperature of gas turbine cycle determine the extent of fuel economy and consumption.

The effect of compression ratio on the thermal efficiency of the gas turbine cycle on various compressor inlet temperatures (CIT) is shown in Figure (11). It can be seen that the thermal efficiency values are very close at lowest compression ratio 3 on different ambient temperature. This indicate that the effect of ambient temperatures are relatively little, increasing the compression ratio of the gas turbine cycle produces more specific work output at lower compressor inlet temperature which give more thermal efficiency

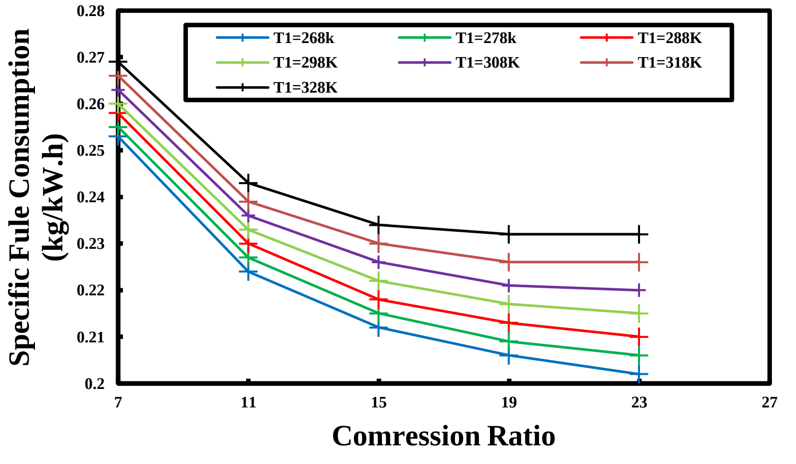


Figure (10): Variation of specific fuel consumption of GT power cycle with different cycle pressure ratio and ambient temperature.

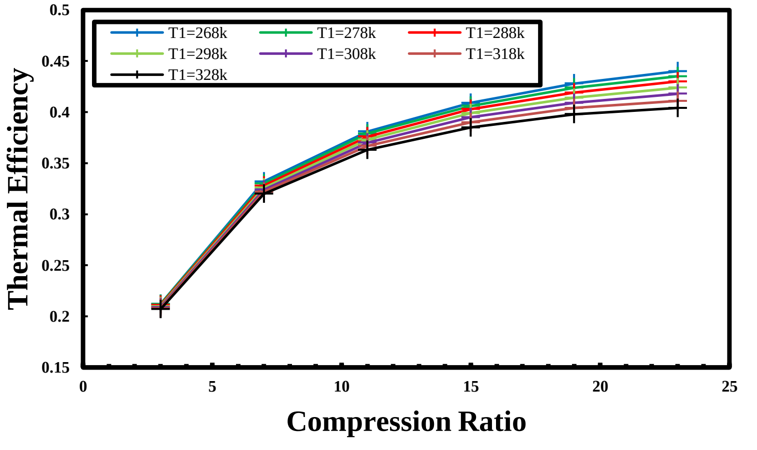


Figure (11): Variation of thermal efficiency with compression ratio and ambient temperature.

5. CONCLUSIONS

In this the present study the simulation results has been obtained by a developed computational model using Fortran90, which gives the influence of operating conditions on the gas turbine power plant. The results of this study were summarized below:

1- In general, the operating parameters like ambient temperature, compression ratio, turbine inlet temperature have significantly the influence on the performance parameters of gas turbine cycle.
2- Increasing the compressor inlet temperature increases the specific fuel consumption rate and decreases the thermal efficiency of cycle.
3- Increasing in the compression ratio increases the specific work output which increases the thermal efficiency. Also, decreases the specific fuel consumption rate.
4- The compressor work increases with increasing the compression ratio and compressor inlet temperature that decreases the specific work output as result for decrease the thermal efficiency.
5- Maximum efficiency and minimum specific fuel consumption rate are at higher compression ratio and turbine inlet temperature with lower ambient temperature.

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