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Analyzing the Impact of Operating Conditions and Ambient Temperature on Gas Turbine Power Plant Performance

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تحليل تأثير ظروف التشغيل ودرجة الحرارة المحيطة على أداء محطات توليد الطاقة بالتوربينات الغازية

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Abstract:
This study investigates how operating parameters specifically compression ratio and air-to-fuel ratio along with ambient temperature impact the overall performance of a gas turbine power plant. An analytical model was developed using Microsoft Excel to assess the plant's operational characteristics across varying environmental temperatures. Such an assessment is particularly vital for regions like Libya, which experience significant temperature fluctuations annually. Findings indicate that greater compression ratios enhance both specific work output and thermal efficiency, whereas elevated ambient temperatures and higher air-to-fuel ratios diminish them. Furthermore, specific fuel consumption rises as the ambient temperature and air-to-fuel ratio increase, particularly at lower compression ratios.

Keywords: Compression Ratio, Air-To-Fuel Ratio, Ambient Temperature Impact, Gas Turbine Power Plant, Libya

الملخص
يعرض هذا البحث دراسة تحليلية لتأثير درجة حرارة المحيط والظروف التشغيلية (كنسبة الانضغاط ونسبة الهواء للوقود) على كفاءة محطات الطاقة الغازية. تم الاعتماد على برنامج إكسل لمحاكاة أداء المحطة تحت درجات حرارة متباينة، وهو ما يكتسي أهمية بالغة في بيئة كليبيا نظراً للتفاوت الكبير في درجات الحرارة على مدار السنة. بينت النتائج أن الكفاءة الحرارية والشغل النوعي يرتفعان بزيادة نسبة الانضغاط، في حين يتراجعان مع ارتفاع حرارة المحيط ونسبة الهواء للوقود. كما لوحظ ازدياد معدل الاستهلاك النوعي للوقود مع ارتفاع درجة الحرارة ونسبة الهواء للوقود وانخفاض نسبة الانضغاط.

الكلمات المفتاحية: نسبة الانضغاط، نسبة الهواء للوقود، درجة الحرارة متباينة ، محطات الطاقة الغازية، ليبيا.

1. Introduction

In its fundamental design, a gas turbine operates as a continuous-flow heat engine. The working cycle involves drawing in atmospheric air, compressing it, elevating its temperature via fuel combustion, and ultimately expanding the resulting hot gases to the environment. This process shares thermodynamic similarities with internal combustion engines regarding the working fluid, yet aligns more closely with steam turbines due to its steady-flow nature [1].

The overall efficiency and output of a gas turbine plant are highly sensitive to ambient weather conditions. An increase in outside air temperature reduces the air density, meaning the compressor draws in less air mass for a given volume. Consequently, the power output drops for a specified turbine inlet temperature. Furthermore, the work required by the compressor increases proportionately with the intake temperature [2]. Because gas turbines draw their combustion air directly from the surrounding atmosphere, fluctuations in weather strongly dictate their performance capabilities [3]. Despite this sensitivity, gas turbine plants remain highly favored due to their relatively low capital investment requirements, operational flexibility, reliability, and simple architecture [4].

A standard gas turbine converts fuel energy into useful mechanical output or thrust. It comprises a gas generation section (compressor and combustor) and a power extraction section (turbine). The turbine generates sufficient power to drive the compressor while delivering net useful work. These engines see extensive use in aviation, marine propulsion, industrial power generation, and petrochemical sectors

Numerous studies have thoroughly examined how ambient air temperature impacts gas turbine performance. For instance, Shanazar et al. [5] demonstrated that a gas turbine with an installed capacity of 127.1 MW operating at 15 °C consumes 7.7 kg/s of natural gas, achieving an energy efficiency of 36% (100% of its nominal value). As the ambient temperature rises to 25 °C, fuel consumption drops to 7.3 kg/s, and efficiency decreases to 34.7% (84% of its nominal value). Further increasing the temperature to 40 °C reduces natural gas consumption to 6.5 kg/s, while energy efficiency falls significantly to 30% (60% of its nominal value).

Mohd Saif and Mohammad Tariq [4] analyzed the performance of a simple open-cycle gas turbine power plant located in Uran, Raigad district, Maharashtra, India. The study evaluated the plant's operation under varying ambient temperatures and pressure ratios, comparing the results against standard ISO conditions. The findings indicate that as the ambient temperature rises from 283 K to 323 K, thermal efficiency decreases by 3.28% at a pressure ratio of 9, with this loss expanding to 3.97% at a pressure ratio of 21. Furthermore, the same temperature increase causes a net power reduction of 4.19 MW (3.87%) at a pressure ratio of 9, which grows to a loss of 5.92 MW (4.46%) at a ratio of 21. Ultimately, the analysis demonstrates that ambient temperature and pressure ratios significantly impact the overall performance of the gas turbine power plant.

In their study, M. M. Rahman et al. [6] investigated the impact of ambient temperature and operating conditions on the performance of gas turbine power plants. They found that both turbine work output and thermal efficiency decrease as the ambient temperature rises. Furthermore, their results indicated that thermal efficiency increases linearly with a higher compression ratio and a lower ambient temperature. Lastly, specific fuel consumption increases with higher ambient temperatures and lower turbine inlet temperatures.

According to Abdul Ghafoor Memon et al. [7], system performance improves when the turbine inlet temperature is raised and the compressor inlet temperature is reduced.

This paper evaluates the thermodynamic performance of a gas turbine system to determine how key operating variables—ambient temperature, pressure ratio, and air-to-fuel ratio—affect turbine inlet temperature, specific fuel consumption, and net work output.

Modeling of gas turbine

A standard gas turbine power plant comprises four primary components: a compressor, a combustion chamber, a turbine, and a generator. As illustrated in the schematic diagram (Figure 1), the cycle begins with the compressor drawing in ambient air and pressurizing it into the combustion chamber. There, liquid or gaseous fuel is ignited to substantially elevate the temperature of the compressed air. The resulting high-temperature gases then expand through the turbine, generating mechanical work before being exhausted into the atmosphere (depicted as states 1, 2, and 3 in Fig. 1).The overall success of a gas turbine plant relies heavily on the efficient compression of massive volumes of air, a task typically accomplished using either axial-flow or centrifugal (radial-flow) compressors. The primary objective in modern compressor design is to maximize airflow for a given diameter using the fewest possible stages, all while ensuring high efficiency and aerodynamic stability across the entire operating range.The performance analysis of the system incorporates the isentropic efficiencies of the compressor (η_C) and the turbine (η_T). On the Temperature-Entropy (T-S) diagram shown in Figure 2, the ideal processes are denoted by solid lines, whereas the actual processes are represented by dashed lines. Mathematically, these efficiency parameters are defined in terms of temperature as follows [6]:

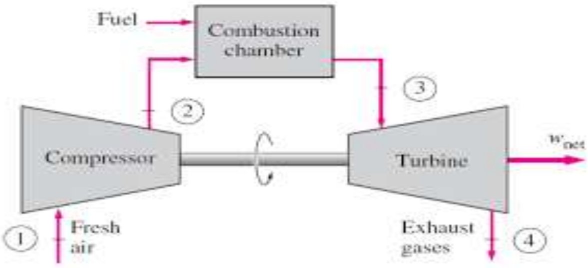

Fig. 1. Schematic diagram for simple gas turbine

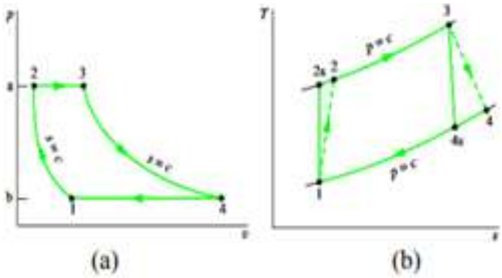

Figure. 2. (a) P-V diagram and (b) T-S diagram for gas turbine

The compression ratio for the compressor can be defined as :

$$r_p = \frac{P_2}{P_1} = \frac{P_3}{P_4} \qquad (1)$$

$$\frac{T_{2S}}{T_1} = (r_P)^{\left(\frac{K-1}{K}\right)} \qquad (2)$$

$$\frac{T_3}{T_{4S}} = (r_P)^{\left(\frac{K-1}{K}\right)} \qquad (3)$$

$$\eta_C = \frac{T_{2S} - T_1}{T_2 - T_1} \qquad (4)$$

$$\eta_T = \frac{T_3 - T_4}{T_3 - T_{4S}} \qquad (5)$$

From equation (4)

$$T_2 = T_1 + \frac{T_{2S} - T_1}{\eta_C} \qquad (6)$$

So, the work of the compressor (Wc) when blade cooling is not taken into account can be calculated from

$$W_C = C_{Pa}(T_2 - T_1) \qquad (7)$$

From energy balance in the combustion chamber

$$\dot{m}_a C_{Pa} T_2 + \dot{m}_f LHV = (\dot{m}_a + \dot{m}_f) C_{Pg} T_3 \qquad (8)$$

$$T_3 = \frac{\dot{m}_a C_{Pa} T_2 + \dot{m}_f LHV}{(\dot{m}_a + \dot{m}_f) C_{Pg}} \qquad (9)$$

$$T_3 = \frac{\frac{\dot{m}_a}{\dot{m}_f} C_{Pa} T_2 + LHV}{\left(\frac{\dot{m}_a}{\dot{m}_f} + 1\right) C_{Pg}} \qquad (10)$$

$$W_T = C_{Pg}(T_3 - T_4) \qquad (11)$$

The specific work output of the gas turbine (Wnet) is calculated from the equation:

$$W_{net} = W_T - W_C \qquad (12)$$

The specific fuel consumption (SFC) can be determined by

$$SFC = \frac{3600\left(\frac{\dot{m}_f}{\dot{m}_a}\right)}{W_{net}} \qquad (13)$$

The heat supplied (Q_{add}) is formulated as in

$$Q_{add} = C_{Pg}(T_3 - T_2) \qquad (14)$$

The gas turbine efficiency (η_{th}) is expressed as in

$$\eta_{th} = \frac{W_{net}}{Q_{add}} \qquad (15)$$

I. ASSUMPTION

This study was conducted based on the following assumptions:

- Steady state operation of system components.
- Ideal gas behavior by air and combustion gas constituents.
- Complete combustion of natural gas.
- Change in kinetic energy and potential energy of fluid stream neglected.
- The isotropic efficiency of both the compressor and turbine was chosen to be 0.85.
- The specific heat ratio and specific heat of air at constant pressure are constant and equal 1.4 and 1.11 (K=1.4) and specific heat of the air (Cpa=1.005 KJ/Kg 0C)
- The specific heat ratio and specific heat of the fuel gas at constant pressure are 1.3 and 1.005 (Cpa=1.005 KJ/Kg 0C).
- The low heating value of fuel is 43000.

2. Results and Discussion

This paper presents simulation results detailing the effects of ambient temperature and operating conditions on gas turbine cycle performance, specifically in terms of specific work output, thermal efficiency, and specific fuel consumption. To conduct the analysis, Microsoft Excel was utilized to evaluate key operating parameters such as ambient temperature, air-fuel ratio, and compression ratio.

a. Effect ambaint temprature on turbine inlet temprature

Figure 3 illustrates the relationship between turbine inlet temperature and ambient temperature across various air-fuel ratios. As shown, the turbine inlet temperature rises when the ambient temperature increases or when the air-fuel ratio decreases. Specifically, assuming a constant air-fuel ratio, a 10 °C rise in ambient temperature results in an approximate 23 °C increase in the turbine inlet temperature. Conversely, increasing the air-fuel ratio significantly lowers the inlet temperature; for instance, at a fixed ambient temperature of 7 °C, raising the air-fuel ratio from 35 to 50 caused the inlet temperature to drop from 1271 °C to 924 °C.

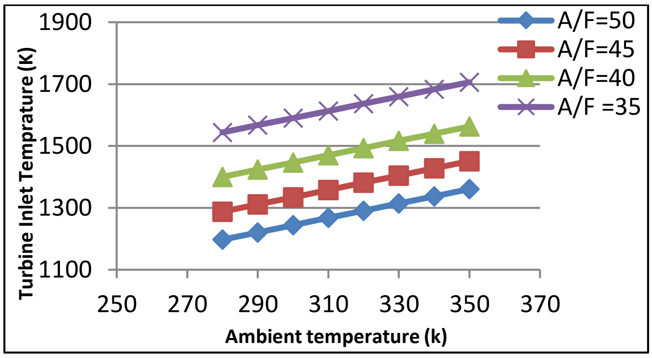

Figure. 3. Effect ambient temperature and air fuel ratio on turbine inlet temperature

Figure (4) shows the effect of an ambient temperature on the turbine inlet temperature for several different values of pressure ratio.. It can be seen from the figure that as the ambient temperature and pressure ratio increases, the turbine inlet temperature also increases. The temperature of the air entering the turbine is crucial for a higher pressure ratio. The inlet temperature increase from 1552.503 k to 1825.721k for the increase in pressure ratio from 05 to 20, at ambient temperature 280k.

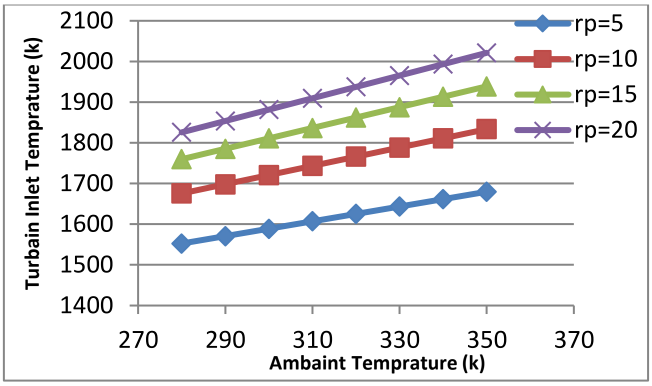

Figure. 4.Effect ambient temperature and pressure ratio on turbine inlet temperature

A. Effect ambaint temprature on gas turbine specific work output

Figure 5 illustrates the variation in the gas turbine's specific work output across different ambient temperatures for various air-fuel ratios. As depicted, a decrease in ambient temperature increases air density, which subsequently reduces the required compressor work and ultimately yields a higher specific work output for the gas turbine.

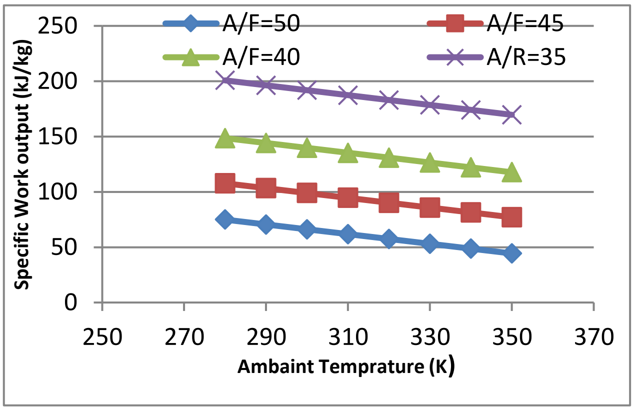

Figure. 5. Effect ambient temperature and air fuel ratio on specific work output

"Figure 6 illustrates how ambient temperature affects specific work output across various pressure ratios. The data indicates that specific work output declines as ambient temperature rises. Additionally, elevating the pressure ratio from 5 to 20 yields an approximate 37% increase in specific work output.

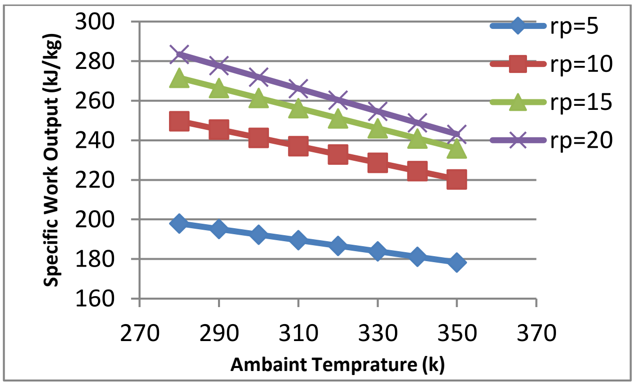

Figure. 6. Effect ambient temperature and pressure ratio on specific work output

b. Effect ambaien temprature on thermal effecincy of gas turbine power plant

Figure (7) illustrates the impact of ambient temperature and air-fuel ratio on thermal efficiency. The data indicates that thermal efficiency improves as both ambient temperature and the air-fuel ratio decrease. This temperature dependence occurs because cooler ambient air is denser, which reduces the work required by the compressor and consequently boosts the net output work of the gas turbine. Conversely, higher ambient temperatures and increased air-fuel ratios negatively affect performance. For instance, at a constant ambient temperature of 280 K, raising the air-fuel ratio from 35 to 50 causes the thermal efficiency to drop significantly from 19.24% to 11.37%.

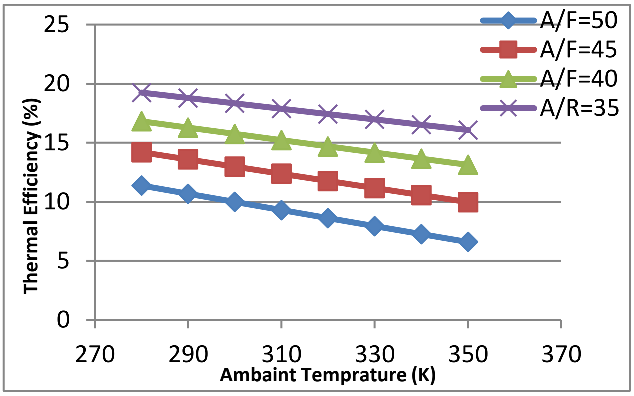

Figure. 7. Effect ambient temperature and air fuel ratio on Thermal Efficiency

Figure 8 illustrates the impact of ambient temperature and pressure ratio on thermal efficiency. The data shows that for any given ambient temperature, thermal efficiency improves as the pressure ratio increases from 5 to 20. Furthermore, thermal efficiency exhibits a slight decline as the ambient temperature rises, indicating it is highest at lower temperatures.

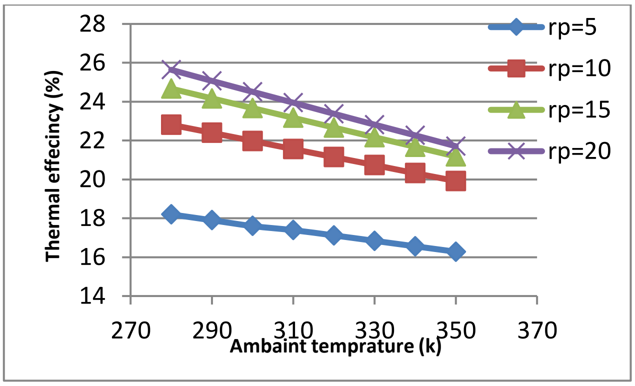

Figure. 8. Effect ambient temperature and pressure ratio on Thermal Efficiency

c. Effect ambiant temprature on specific fuel consumption

Figure 9 illustrates the impact of ambient temperature and the air-to-fuel ratio on specific fuel consumption. The data indicates that specific fuel consumption rises in tandem with increases in both ambient temperature and the air-to-fuel ratio. This upward trend occurs because higher ambient temperatures reduce the mass flow rate of air entering the compressor. Consequently, the fuel mass flow rate increases to maintain a constant air-to-fuel ratio. Furthermore, as noted earlier, a rise in ambient temperature leads to a decline in net power output, which ultimately drives up the specific fuel consumption rate.

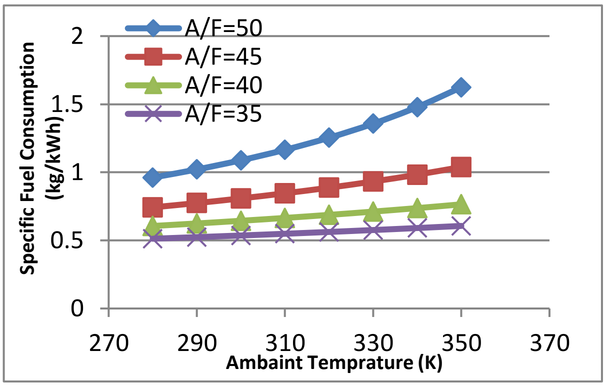

Figure. 9. Effect ambient temperature and air fuel ratio on Specific fuel consumption

Figure (10) also shows the effect of the ambient temperature on the specific fuel consumption at several different values of the compression ratio. We notice that by increasing the compression ratio, the specific fuel consumption decreases, and as we also notice from Figure (10), the compression ratio has no effective effect on the specific fuel consumption.

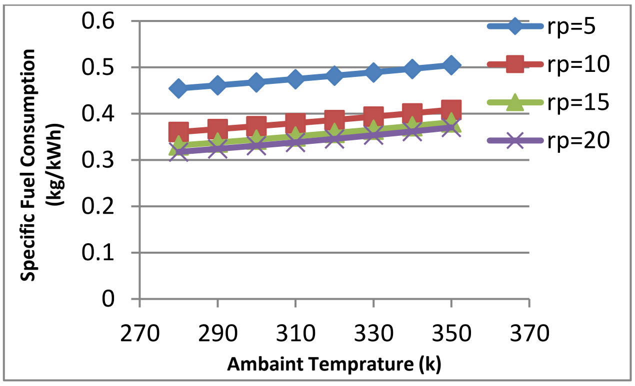

Figure. 10. Effect ambient temperature and pressure ratio on Specific fuel consumption

Conclusions

This study presents simulation results detailing the impact of ambient temperature and operating conditions—specifically the air-fuel ratio and compression ratio—on gas turbine cycle performance. Key performance indicators, including specific work output, thermal efficiency, and specific fuel consumption, were analyzed using an Excel-based model. The graphical data demonstrates clear correlations between these variables. The main findings are summarized as follows:

- An increase in ambient temperature leads to a decrease in both thermal efficiency and specific work output, while specific fuel consumption increases.
- Increasing the air-fuel ratio negatively impacts performance by decreasing useful work output and thermal efficiency, while increasing fuel consumption.
- Conversely, elevating the pressure ratio enhances system performance by increasing both work output and thermal efficiency, while reducing fuel consumption.

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