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Full Length Research Paper

Thermodynamic performance analysis of gas-turbine power-plant

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This paper was presented the parametric study of thermodynamic performance on gas turbine power plant. The variation of operating conditions (compression ratio, turbine inlet and exhaust temperature, air to fuel ratio, isentropic compressor and turbine efficiency, and ambient temperature) on the performance of gas turbine (thermal efficiency, compressor work, power, specific fuel consumption, heat rate) were investigated. The analytical formula for the specific work and efficiency were derived and analyzed. The programming of performance model for gas turbine was developed utilizing the MATLAB software. The results show 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. However, the specific fuel consumption and heat rate increases linearly with increase of both ambient temperature and air to fuel ratio. Thus the thermodynamic parameters on cycle performance are economically feasible and beneficial for the gas turbine operations.

Key words: Gas turbine, compression ratio, air to fuel ratio, thermal efficiency, power, turbine inlet temperature.

INTRODUCTION

The gas turbine (GT) performance is affected by component efficiencies and turbine working temperature. The effect of temperature is very predominant for every 56°C increase in temperature; the work output increases approximately 10% and gives about 1.5% increase in efficiency (Johnke and Mast, 2002). Overall efficiency of the gas turbine cycle depends primarily upon the pressure ratio of the compressor. It is important to realize that in the gas turbine the processes of compression, combustion and expansion do not occur in a single component as they occurred in a reciprocating engine.

It is well known that the performance can be qualified with respect to its efficiency, power output, specific fuel consumption as well as work ratio. There are several parameters that affect its performance including the compressor compression ratio, combustion inlet temperature and turbine inlet temperature (TIT) (Mahmood and Mahdi, 2009, Rahman et al., 2010). Taniquchi and Miyamae (2000) were carried out the study on the effects of ambient temperature, ambient pressure as well as the temperature of exhaust gases on performance of gas turbine as shown in Figure 1. There is an obvious drop in the power output as the ambient air temperature increases, if an increase of intake air ambient temperature from ISO condition 15 to 30°C which is 10% decrease in the net power output. This is particularly relevant in tropical climates where the temperature varies 25 to 35°C throughout the year (Boonnasa et al., 2006).

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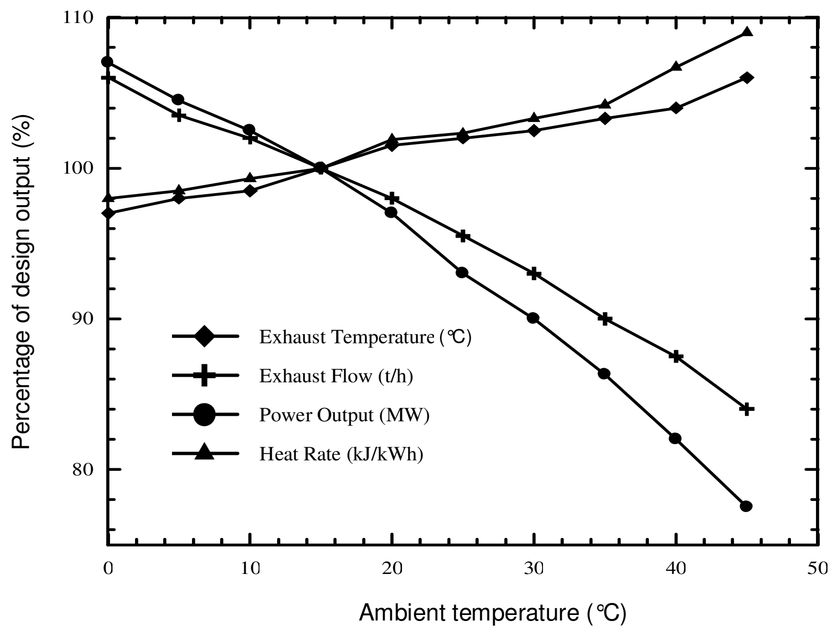


Figure 1. Effect of ambient temperature on gas turbine performance.
Source: Taniquchi and Miyamae, 2000.

The mainly fashionable way to improve the capacity of the combined cycle power plant is to lower the intake air temperature to around 15℃ (ISO) and relative humidity (RH) of 100% before entering the air compressor of the gas turbine (Mohanty and Paloso, 1995; Ibrahim et al., 2010). Usually, the operation conditions for the gas turbine module are measured to calculate the output power and the efficiency (Horlock et al., 2003). However in many cases, the estimated parameters are not always optimal inside the gas turbine. It is required to control the input parameters with the aim of enhancing the performance of gas turbine. Obviously, these parameters have been actually improved by various gas turbine manufactures as mentioned above. Meanwhile, the operating parameters including the compression ratio, ambient temperature, air to fuel ratio, turbine inlet temperature, and both compressor and turbine efficiencies on the performance of gas turbine power plant were carried out. Consequently, a parametric study on the effect of operation conditions requires managing the operation conditions of the system. Thus, the aim of the present work is to develop a strategy to determine the performance of gas turbine power plant utilizing the effect of operating conditions.

THERMODYNAMIC MODELING OF GAS TURBINE

The first practical success was obtained by the Societe Anonyme des Turbomoteurs French Company, which built a gas turbine in 1905. This engine, the first constant pressure gas turbine to run under its own power, had an efficiency of 3% which is used into the engine with multistage centrifugal compressor (20 stages or more) having a pressure ratio of 4 and compressor efficiency not more than 60% as well as the maximum gas temperature was about 393ºC. However there was an elapse of many years, until in 1939, a Brown Boveri (BBC) unit for emergency electrical-power supply was put into operation in Neuchatel, Switzerland (Figure 2). The power output was 4000 kW and efficiency of 18%. The turbine with inlet temperature 550℃ was provided 15,400 kW at 3000 rpm (Zurcher et al., 1988).

Basically, the gas turbine power plants consist of four components including the compressor, combustion chamber (CC), turbine and generator. A schematic diagram for a simple gas turbine is shown in Figure 3. The fresh atmospheric air is drawn into the circuit continuously and energy is added by the combustion of the fuel in the working fluid itself. The products of combustion are expanded through the turbine which produces the work and finally discharges to the atmosphere.

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 4) (Al-Sayed, 2008).

The compressor compression ratio (r_p) can be defined as (Al-Sayed, 2008):

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

where p_1 and p_2 are compressor inlet and outlet air pressure,

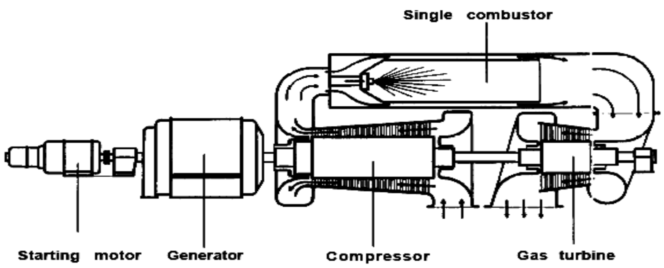


Figure 2. World's first industrial gas turbine set with single combustor (Zurcher et al., 1988).

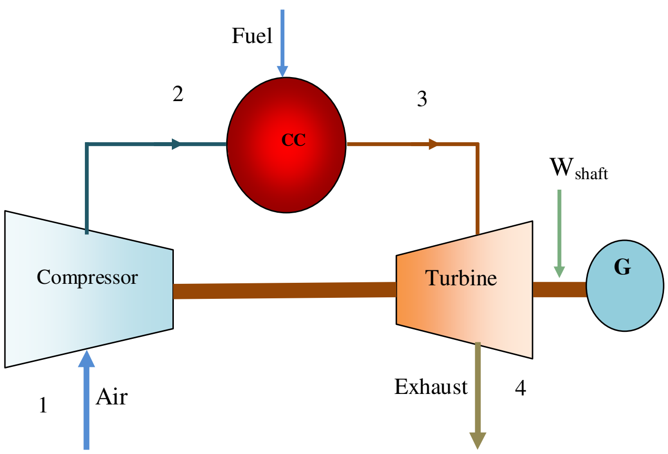


Figure 3. The schematic diagram for a simple gas turbine.

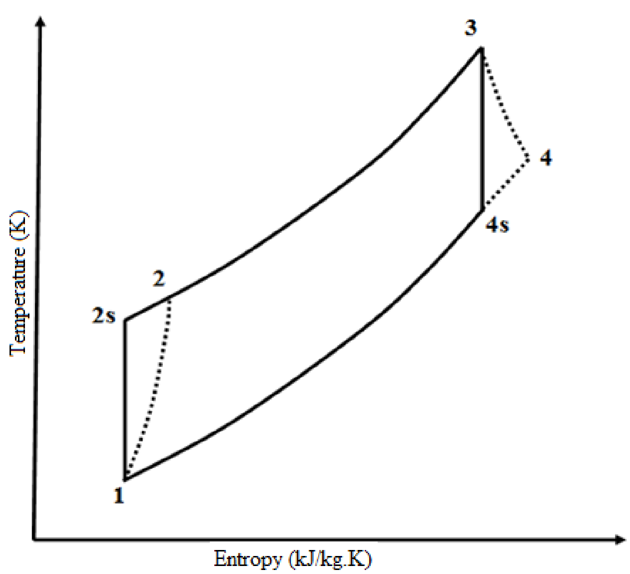


Figure 4. Temperature-Entropy diagram for gas turbine.

respectively.

The isentropic efficiency for compressor and turbine in the range of 85 to 90% is expressed as (Rahman et al., 2011):

$$\eta_C = \frac{T_{2s} - T_1}{T_2 - T_1} \quad (2)$$

where T_1 and T_2 are compressor inlet and outlet air temperature respectively, and T_{2s} compressor isentropic out let temperature.

The final temperature of the compressor is calculated from Equation (3) (Rahman et al., 2010):

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

Therefore it can be simplified these relations by Equation (4):

$$Rpa = \frac{r_p^{\frac{\gamma_a - 1}{\gamma_a}} - 1}{\eta_c} \quad and \quad Rpg = \left(1 - \frac{1}{(r_p)^{\frac{\gamma_g - 1}{\gamma_g}}}\right) \quad (4)$$

where $\gamma_a = 1.4$ and $\gamma_g = 1.33$.

The work of the compressor (W_c) when blade cooling is not taken into account can be calculated as:

$$W_c = \frac{c_{pa} \times T_1\left(r_p^{\frac{\gamma_a - 1}{\gamma_a}} - 1\right)}{\eta_m \times \eta_c} = \frac{C_{pa} \times T_1 \times Rpa}{\eta_m} \quad (5)$$

where C_{pa} is the specific heat of air which can be fitted by Equation (6) for the range of 200K<T<800K (R) and η_m is the mechanical efficiency of the compressor and turbine (Rahman et al., 2011):

$$C_{pa} = 1.0189\times10^3 - 0.13784T_a + 1.9843\times10^{-4}T_a^2 + 4.2399\times10^{-7}T_a^3 - 3.7632\times10^{-10}T_a^4 \quad (6)$$

where $T_a = \frac{T_2 - T_1}{2}$ in Kelvin.

The specific heat of flue gas (C_{pg}) is given by Naradasu et al. (2007):

$$C_{pg} = 1.8083 - 2.3127\times10^{-3}T + 4.045\times10^{-6}T^2 - 1.7363\times10^{-9}T^3 \quad (7)$$

From the energy balance in the combustion chamber is expressed as:

$$\dot{m}_a C_{pa} T_2 + \dot{m}_f \times LHV + \dot{m}_f C_{pf} T_f = (\dot{m}_a + \dot{m}_f) C_{pg} \times TIT \quad (8)$$

where, $\dot{m}_f$ is fuel mass flow rate (kg/s), $\dot{m}_a$ is air mass flow rate (kg/s), LHV is low heating value, T_3 = TIT = turbine inlet temperature C_{pf} is specific heat of fuel anf T_f is temperature of fuel.

After manipulating Equation (8), the fuel air ratio (f) is expressed as:

$$f = \frac{\dot{m}_f}{\dot{m}_a} = \frac{C_{pg} \times TIT - C_{pa} T_2}{LHV - C_{pg} \times TIT} \quad (9)$$

The exhaust gases temperature from gas turbine is given by Eq. (10):

$$\mathrm{T}_4 = T_3 \left(1 - \eta_t \times \left(1 - \frac{1}{r_p^{\frac{\gamma_g - 1}{\gamma_g}}} \right) \right) = T_3 \left(1 - \eta_t \times Rpg \right) \quad (10)$$

The shaft work (W_t) of the turbine is given by Equation (11):

$$W_t = C_{pg} \times TIT \times \eta_t \times Rpg \; / \, \eta_m \quad (11)$$

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

$$W_{\mathrm{net}} = W_t - W_C \quad (12)$$

The output power from the turbine (*P*) is expressed as:

$$P = \dot{m}_a \times W_{net} \quad (13)$$

The specific fuel consumption (*SFC*) is determined by Equation (13):

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

The heat supplied is also expressed as:

$$Q_{\mathrm{add}} = C_{pg_m} (TIT - T_1 (1 + Rpa)) \quad (15)$$

The gas turbine efficiency (η_{th}) can be determined by Equation (15) (Ibrahim et al., 2010):

$$\eta_{th} = \frac{W_{\mathrm{net}}}{Q_{\mathrm{add}}} \quad (16)$$

The heat rate (HR) is the consumed heat to generate unit energy of electricity can be expressed as (Saravanamuttoo et al., 2009):

$$HR = \frac{3600}{\eta_{th}} \quad (17)$$

RESULTS AND DISCUSSION

The parameter influence in terms of compression ratio, turbine inlet temperature, air to fuel ratio, and ambient temperature on the performance of gas turbine cycle power plant are presented in this section. The effects of operation conditions on the power output and efficiency are obtained by the energy-balance utilizing MATLAB10 software. The flowchart of simulation of performance process for simple gas turbine power plant is shown in Figure 5.

Effect of compression ratio

Figure 6a presents a relation between the gas turbine cycle thermal efficiency versus compression ratios for different turbine inlet temperature. It can be seen that the thermal efficiency increases with compression ratio at higher turbine inlet temperature. The deviation of thermal efficiency at lower compression ratio is not significant while the variation at higher compression ratio is vital for thermal efficiency. The certain limit depends on the turbine inlet temperature which reveals an ejective relationship as the efficiency increases as turbine inlet temperature increases. Also the thermal efficiency increase with increase the compression ratio and decrease the ambient temperature as shown in Figure 6b, but the increase in the air to fuel ratio cause low decrease in the thermal efficiency comparing with effect the compression ratio that caused high increased in the thermal efficiency as shown in Figure 7. Figure 8 present the effect of compression ratio on compressor work, this work increase with increase the compression ratio and the ambient temperature.

Figure 9a shows the effect of compression ratio on the thermal efficiency with variation isentropic compressor efficiency. Note that the thermal efficiency is increased with compression ratio and isentropic compressor efficiency. Also the increased in compression ratio and isentropic turbine efficiency caused increased in the thermal efficiency as shown in Figure 9b. Figure 10 represented the relation between the thermal efficiency and turbine inlet temperatures for five values of air to fuel ratio (40 to 56 kg air/fuel) and six values compression ratios (3 to 23). Thermal efficiency has an ejective relationship with turbine inlet temperature, the efficiency increases when turbine inlet temperature increases, also the decreased in air to fuel ratio caused incased thermal

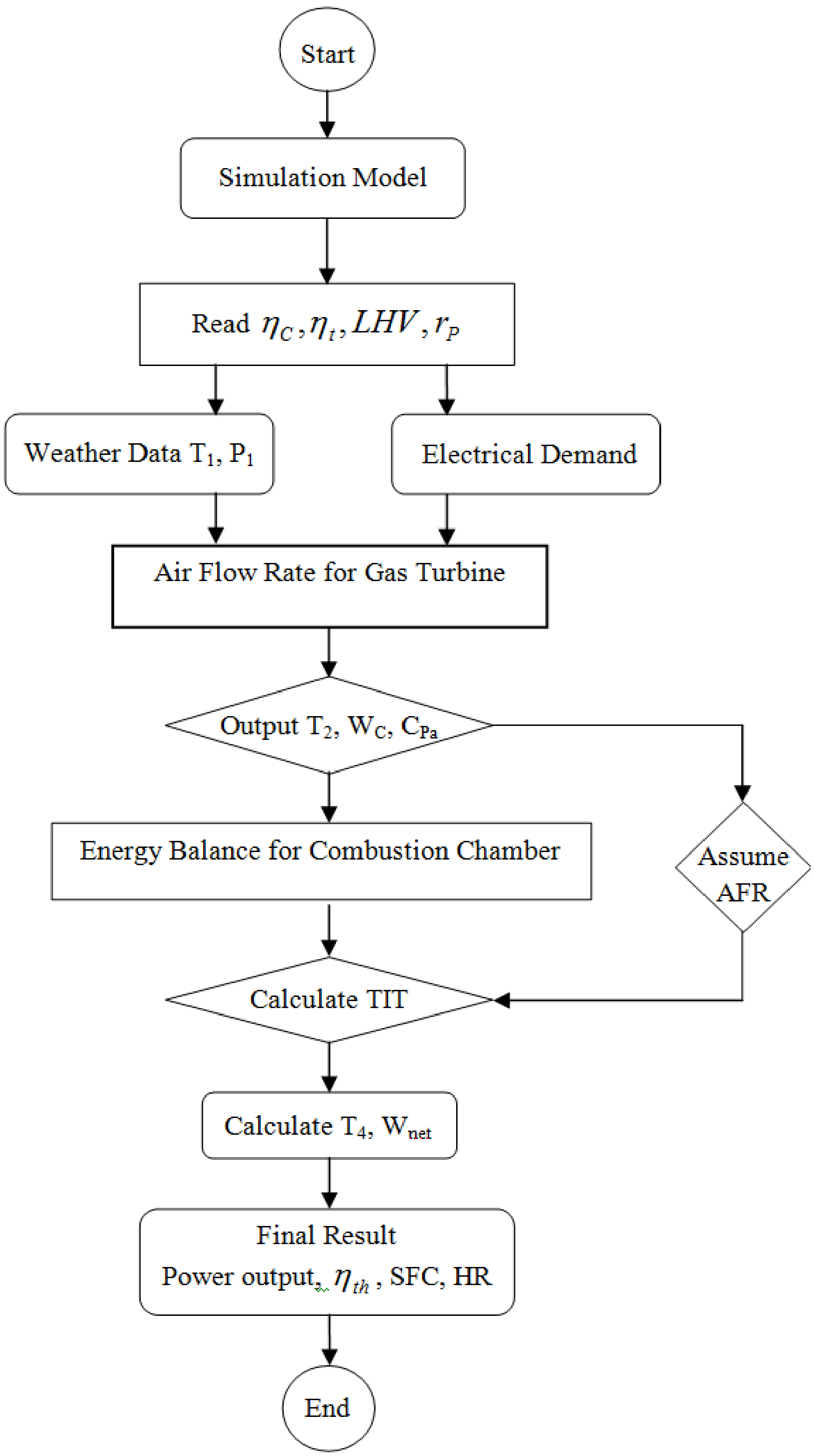
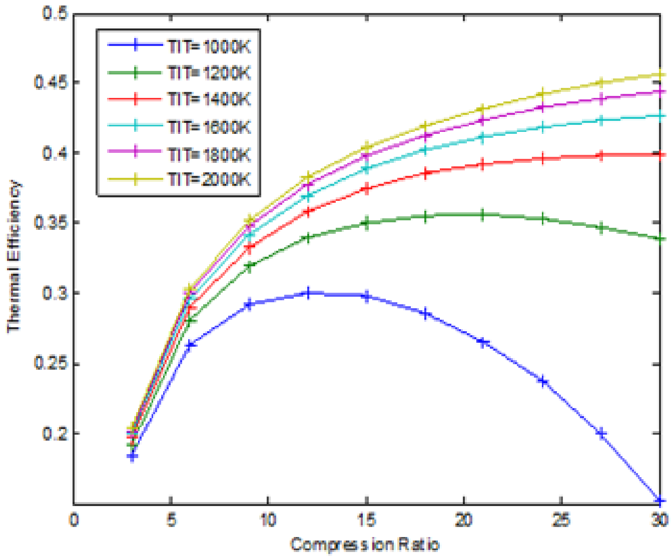
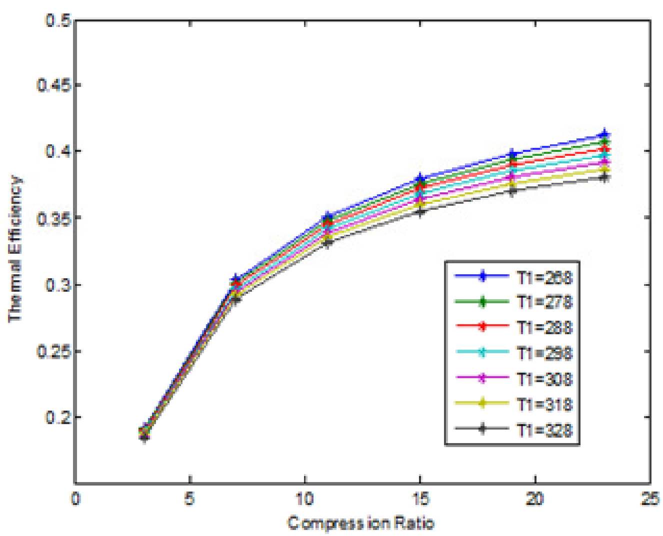


Figure 5. Flowchart of simulation of performance process for simple gas turbine power plant.



(a) Turbine inlet temperature



(b) Ambient temperature

Figure 6. Variation of compression ratio, turbine inlet temperature and ambient temperature on thermal efficiency.

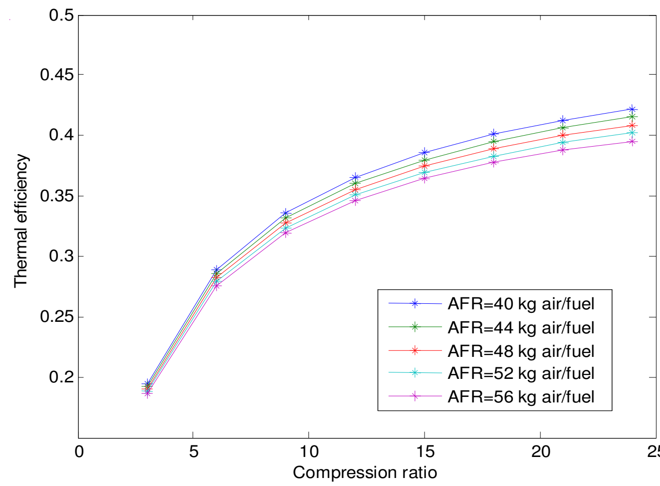


Figure 7. Variation of compression ratio and air to fuel ratio on thermal efficiency.

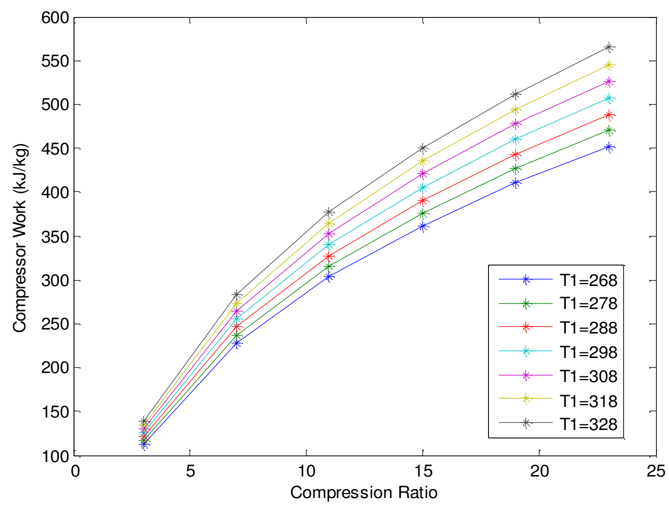


Figure 8. Effect of compression ratio and ambient temperature on compressor work.

efficiency and turbine inlet temperature.

Effect of ambient temperature

Figure 11 show that the gas turbine thermal efficiency is affected by ambient temperature due to the change of air density and compressor work since; a lower ambient temperature leads to a higher air density and a lower compressor work that in turn gives a higher gas turbine output power as shown in Figure 12. Figure 11 shows that when the ambient temperature increases the thermal efficiency decreases. This is because, the air mass flow rate inlet to compressor increases with decrease of the ambient temperature. So, the fuel mass flow rate will increase, since air to fuel ratio is kept constant. The power increase is less than that of the inlet compressor air mass flow rate; therefore, the specific fuel consumption increases with the increase of ambient temperature. This occurs because of increased losses due to the increased amount of flue gases. The output power from

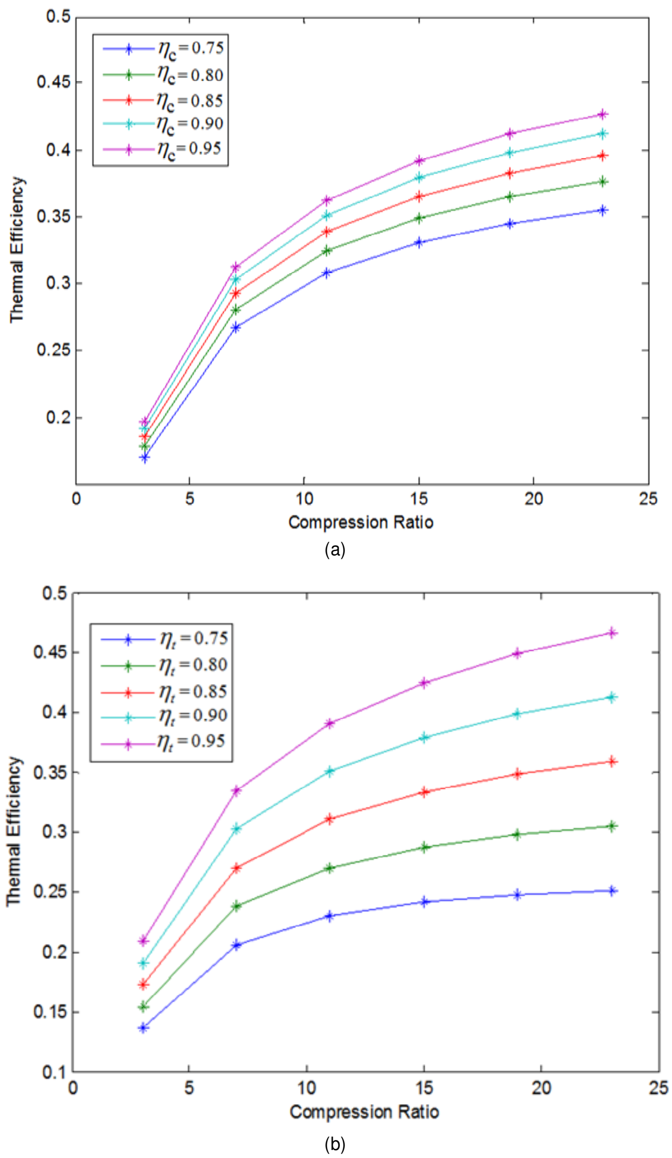


Figure 9. Variation of compression ratio, isentropic compressor efficiency and isentropic turbine efficiency on thermal efficiency. (a) Isentropic compressor efficiency (b) Isentropic turbine efficiency.

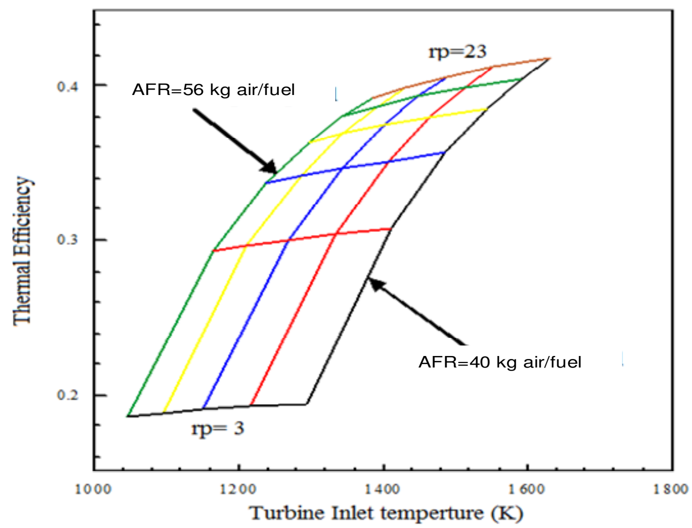


Figure 10. Variation of turbine inlet temperatures with thermal efficiency for several compression ratio and air to fuel ratio.

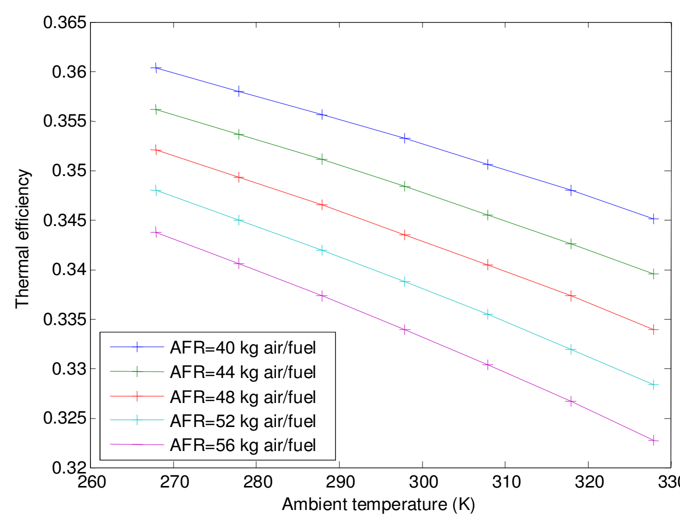


Figure 11. Effect of ambient temperature and air to fuel ratio on thermal efficiency.

simulation model is higher than the practical data from Baiji gas turbine power plant as shown in Figure 13. However, increased the ambient temperature and increased the air to fuel ratio caused increased of specific fuel consumption and heat rate as shown in Figures 14 and 15.

Figure 16 shown effect of air to fuel ratio on thermal efficiency with variation ambient temperatures. The thermal efficiency decreases with increase the air to fuel ratio because increases the flue gases losses, but the specific fuel consumption increased with increase air to fuel ratio as shown in Figure 17. Figure 18 represent the variation of exhaust temperatures with thermal efficiency for several ambient temperature and air to fuel ratio. Noted the thermal efficiency is increased with decrease the ambient temperature and air to fuel ratio, but the thermal efficiency decreases with increase the exhaust temperature.

The thermal efficiency decreases with increases the

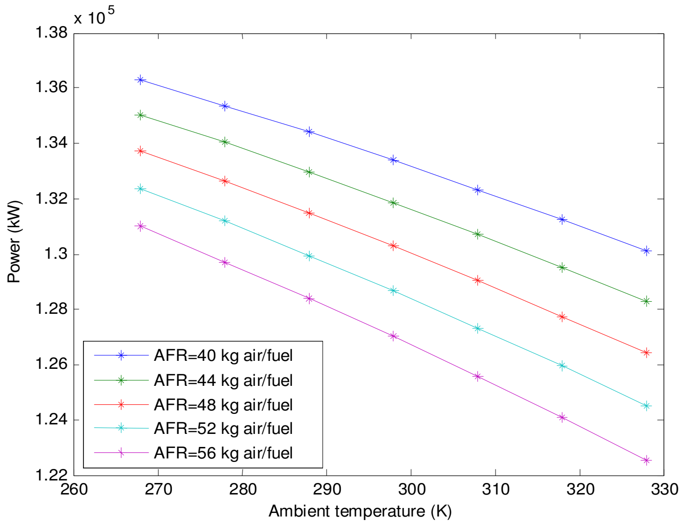


Figure 12. Effect of ambient temperature and air to fuel ratio on power.

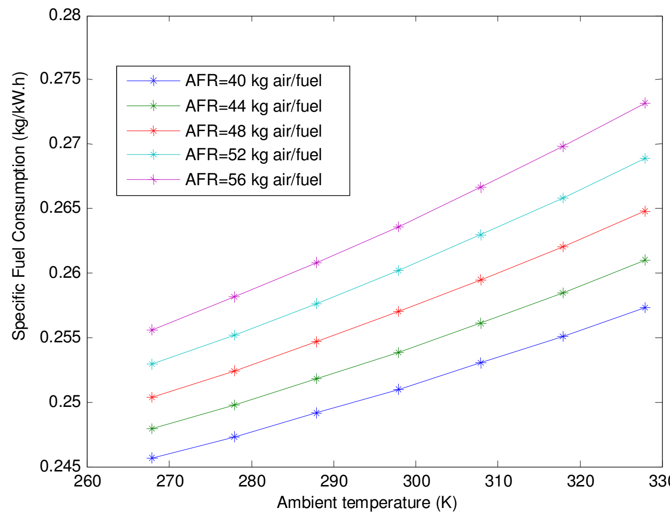


Figure 14. Effect of ambient temperature and air to fuel ratio on specific fuel consumption.

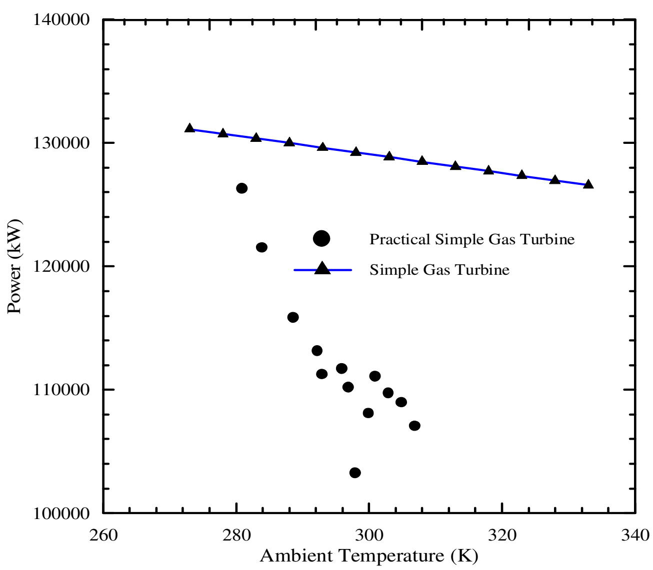


Figure 13. Effect of ambient temperature on power output.

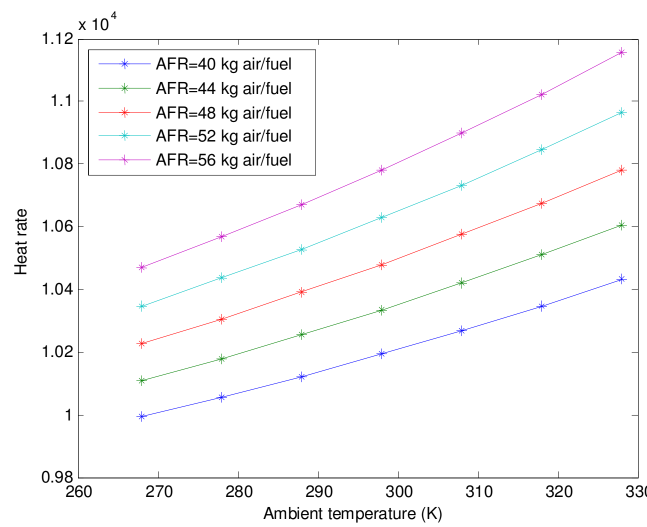


Figure 15. Effect of ambient temperature and air to fuel ratio on heat rate.

exhaust temperature.

Effect of compressor and turbine efficiencies

Figures 19 and 20 highlight the effect of the compressor and turbine isentropic efficiencies on the thermal efficiency for different air fuel ratio. The thermal efficiency increase with increase the compressor and turbine isentropic efficiencies, this is mean the thermal losses have been reduced in both compressor and turbine respectively, this lead to increased power output.

DISCUSSION

The efficiency and power output of gas turbine depends on the operation conditions were presented in earlier section. The variation of thermal efficiency at higher

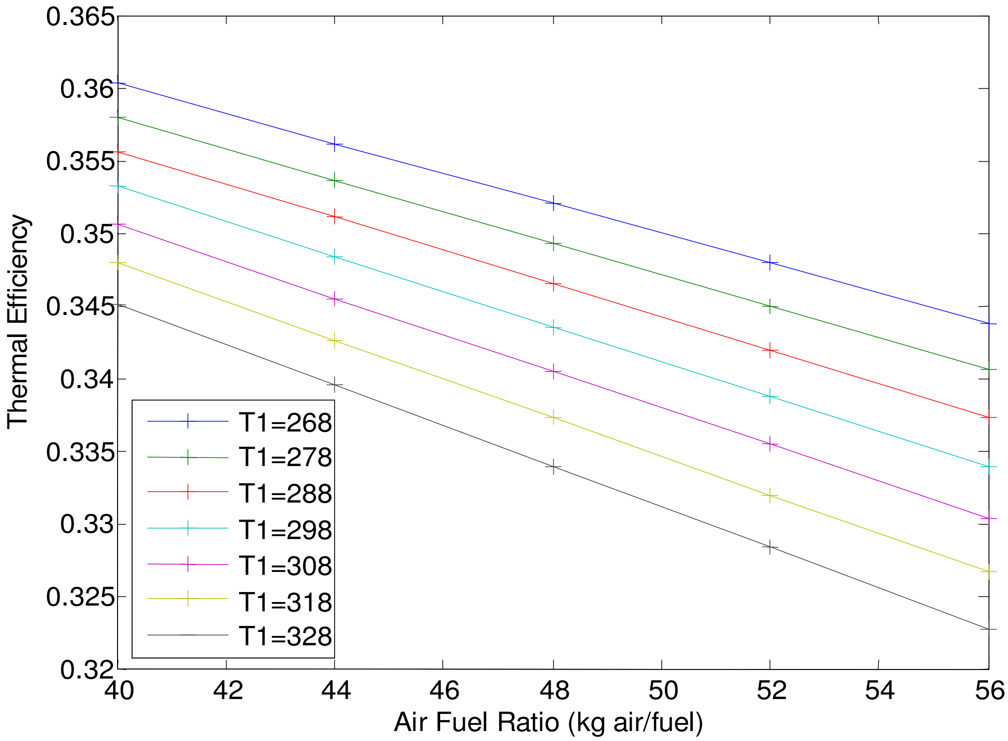


Figure 16. Effect of air to fuel ratio and ambient temperature on thermal efficiency.

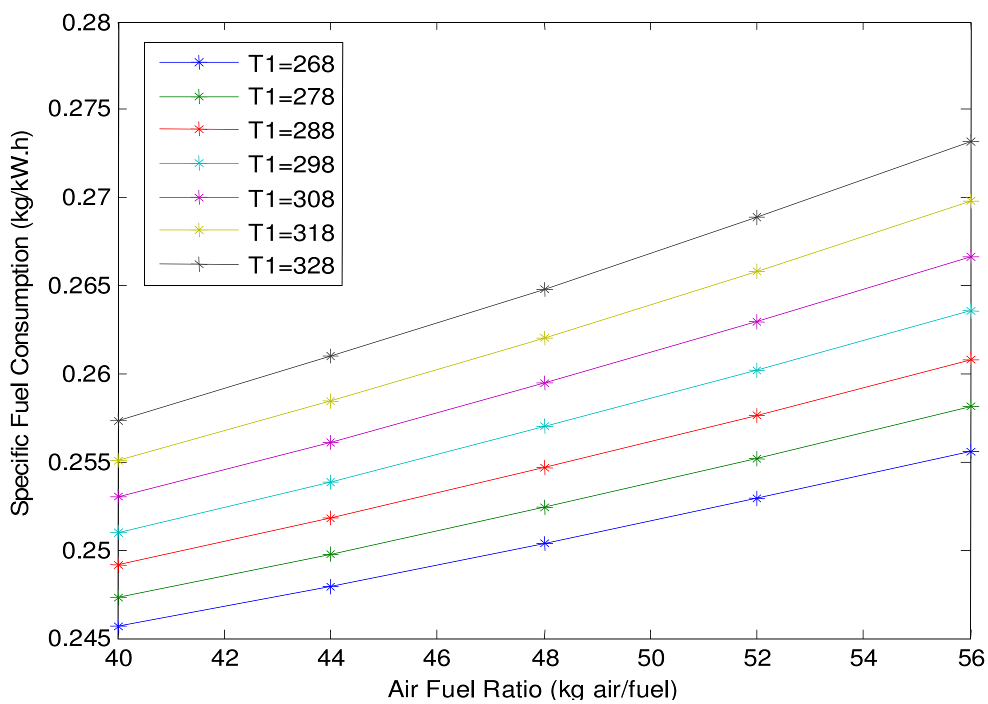


Figure 17. Effect of air to fuel ratio ambient temperature on specific fuel consumption.

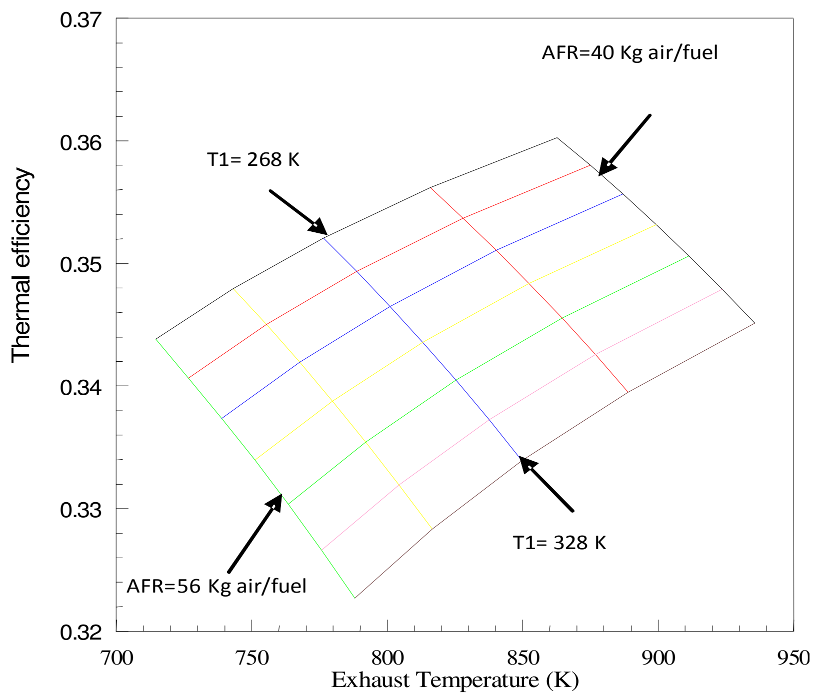


Figure 18. Variation of exhaust temperatures with thermal efficiency for several ambient temperature and air to fuel ratio.

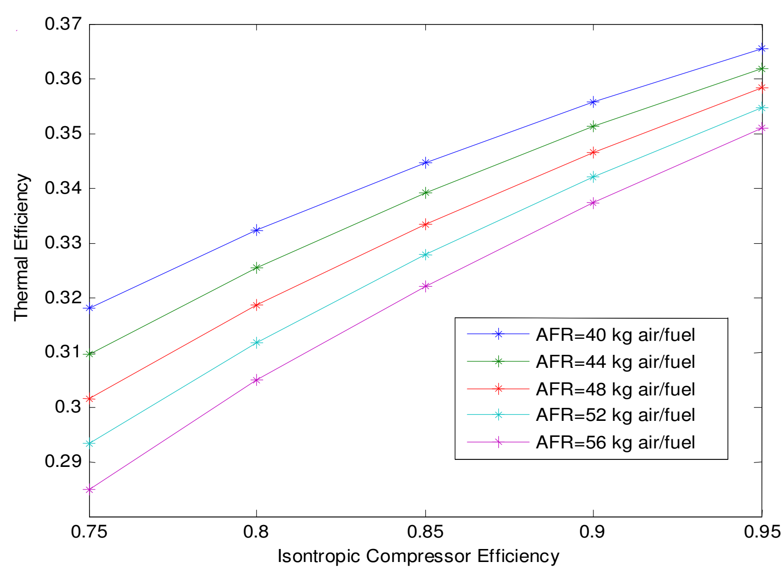


Figure 19. Effect of isentropic compressor efficiency air to fuel ratio on thermal efficiency.

compression ratio and ambient temperature are very crucial. The thermal efficiency is affected by ambient temperature due to the change of air density and compressor work since a lower ambient temperature leads to a higher air density and a lower compressor work that in turn gives a higher gas turbine output power

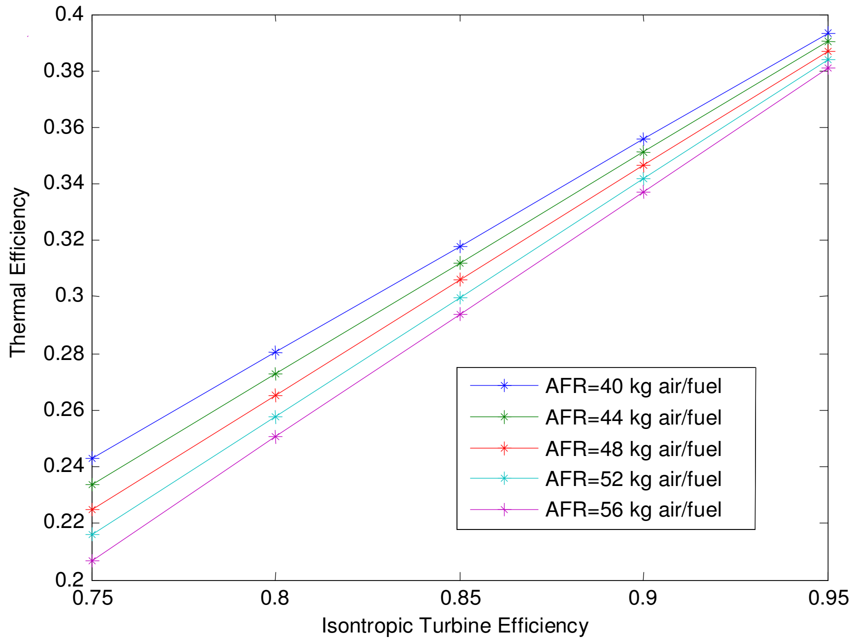


Figure 20. Effect of isentropic turbine efficiency air to fuel ratio on thermal efficiency.

as shown in Figure 11. The increases of ambient temperature lead to decrease the thermal efficiency. It can also be seen that the specific fuel consumption increases with increase of air to fuel ratio and ambient temperature because of the air mass flow rate inlet to compressor increases with decrease of the ambient temperature. Thus, the fuel mass flow rate increases since the air to fuel ratio is kept constant. The variation of power out is less than that of the inlet compressor air mass flow rate. Therefore, the specific fuel consumption increases with the increase of ambient temperature due to the flue gases losses. The increase in compression ratio for gas turbine power plant lead to a continuous increase of thermal efficiency and this result move the gas turbine power plant to reaches the highest efficiency and then begins to decrease. Therefore, the overall enhancement of the effect of operation conditions on efficiency of gas turbine can be highly positive, especially when considering the possibility to take advantage from increase turbine inlet temperature and then increase the output power and the thermal efficiency.

Conclusion

The simulation result from the modeling of the influence of parameter showed that compression ratio, ambient temperature, air to fuel ratio and turbine inlet temperature effect on performance of gas turbine power plant. The results were summarized as follows:

1. The compression ratios, ambient temperature, air to fuel ratio as well as the isentropic efficiencies are strongly influence on the thermal efficiency of the gas turbine power plant.
2. The variation of thermal efficiency at higher compression ratio, turbine inlet temperature and ambient temperature are very important.
3. The thermal efficiency and power output decreases linearly with increase of ambient temperature as well as the air to fuel ratio.
4. The specific fuel consumption and heat rate increase linearly with increase of both ambient temperature and air to fuel ratio.
5. The peak efficiency, power and specific fuel consumption occur at higher compression ratio with low ambient temperature.

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