National Conference in Mechanical Engineering Research and Postgraduate Studies (2nd NCMER 2010)
3-4 December 2010, Faculty of Mechanical Engineering, UMP Pekan, Kuantan, Pahang, Malaysia; pp. 135-144
ISBN: 978-967-0120-04-1; Editors: M.M. Rahman, M.Y. Taib, A.R. Ismail, A.R. Yusoff, and M.A.M. Romlay

EFFECTS OF OPERATION CONDITIONS ON PERFORMANCE OF A GAS TURBINE POWER PLANT

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ABSTRACT

This paper presents the effect of operation conditions (compression ratio, turbine inlet temperature, air to fuel ratio and efficiency of compressor and turbine) on the performance of gas turbine power plant. The computational model was developed utilizing the MATLAB codes. Turbine work found to be decreases as ambient temperature increases as well as the thermal efficiency decreases. It can be seen that the thermal efficiency increases linearly with increases of compression ratio while decreases of ambient temperature. The specific fuel consumption increases with increases of ambient temperature and lower turbine inlet temperature. The effect of variation of SFC is more significance at higher ambient temperature than lower temperature. It is observed that the thermal efficiency linearly increases at lower compressor ratio as well as higher turbine inlet temperature until certain value of compression ratio. The variation of thermal efficiency is more significance at higher compression ratio and lower turbine inlet temperature. Even though at lower turbine inlet temperature is decrement the thermal efficiency dramatically and the SFC decreases linearly with increases of compression ratio and turbine inlet temperature at lower range until certain value then increases dramatically for lower turbine inlet temperature.

***Keywords**:* Gas turbine, power plant, performance, ambient temperature, operation condition

INTRODUCTION

Gas turbines installed until the mid seventies suffered from low efficiency and poor reliability. This limited the use of gas turbines to peak power demand and as a stand-by power unit (Taniquchi and Miyamae, 2000). However, the recent developments in aerodynamics which led to a significant increase in isentropic compressor and isentropic turbine efficiencies (up to 90%), as well as the adventure in 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. Modern gas turbine technology has extensively used compressor intercooling and high turbine temperatures in order to achieve high net power and thermal efficiency requirements. Both of these solutions lead to additional investment cost, but higher turbine inlet temperatures are still limited by turbine blade cooling requirement and metallurgical improvements (Horlock et al., 2003). A more recent gas turbine manufactured by General Electric used a turbine inlet temperature of 1425 ºC and produced up to 282 MW while achieving a thermal efficiency of 39.5% in the simple cycle mode (Cengel and Boles, 2008). Accordingly, gas turbines are rapidly becoming the choice for current and future power generation systems because they offer efficient fuel conversion, reduced cost of electricity, low installation and maintenance cost, can be put in service with minimum of delay time, occupy less room than other plants for the same capacity, and the ability to consume wide range of hydrocarbon fuels (Nag, 2008). Their exhaust gases are relatively less pollutant to the environment, and can be used for preheating air before entering the combustion chamber, or for district heating as in combined heat and power plants (Wang and Chiou, 2002).

Gas turbine performance can be qualified with respect to its efficiency, power output, specific fuel consumption and work ratio. There are several parameters that affect its performance, such as the compressor pressure ratio, the combustion inlet temperature and the turbine inlet temperature (TIT). Obviously, these parameters have been actually improved by various gas turbine manufactures, as it has been mentioned above. Meanwhile, operating parameters such as ambient temperature, altitude, humidity, inlet and exhaust losses also affect the performance of gas turbine units. Basically, gas turbines draw air directly from the atmosphere. Its performance is undoubtedly changed by anything that would affect the air density or mass flow rate of the air intake into the compressor. Ambient air conditions are the number one uncontrolled varying parameters from the reference design conditions of 15 ˚C and 1.013 bar. These reference conditions used by the gas turbine industry are established by the International Standards Organization (ISO), and frequently referred to as ISO conditions. Figure 1 shows the effect of ambient temperature on the performance of the gas turbine. Each gas turbine model has its own temperature effect curve because it depends on the cycle parameters and component efficiencies as well as air mass flow rate (Saravanamuttoo et al., 2009). Most gas turbines typically produce 30% higher electric power output when the ambient air temperature is 15 ˚C compared to 45˚C. Thus the cost of installing a gas turbine or combined cycle plant rated at temperature of 45 ˚C is 20-30% higher than that rated at 15 ˚C (Mahmood and Mahdi, 2009). This inherent disadvantage of reduced gas turbine electric power output at high ambient temperatures can be mitigated by the reduction of gas turbine compressor inlet air temperature.

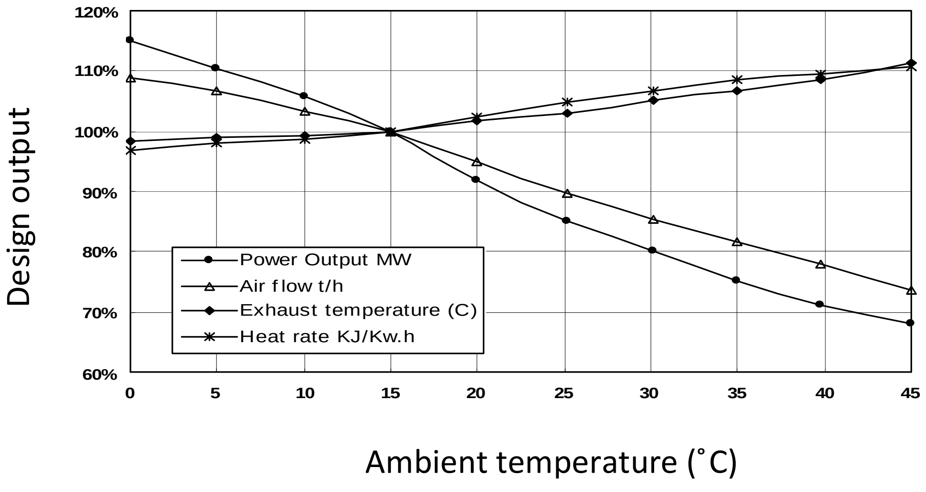

Figure 1: Effect of ambient temperature on the gas turbine performance (Saravanamuttoo et al., 2009).

MODELING OF GAS TURBINE

Gas turbine power plants consist of four components, compressor, combustion chamber, turbine and generator. A schematic diagram for a simple gas turbine is shown in Figure 2. Air is drawn in by the compressor and delivered to the combustion chamber. Liquid or gaseous fuel is commonly used to increase the temperature of compressed air through a combustion process. Hot gases leaving the combustion chamber expands in the turbine which produces work and finally discharges to the atmosphere [1, 2, 3].

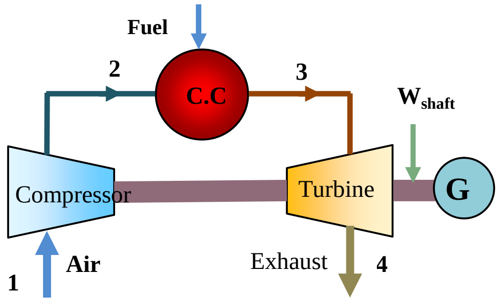

Figure 2: schematic diagram for a simple gas turbine

Efficient compression of large volume of air is essential for a successful gas turbine power plant. This has been achieved in two types of compressors, the axial flow compressor and the centrifugal or radial flow compressors. Most power plant compressor design is to obtain the most air through a given diameter compressor with a minimum number of stages while retaining relatively high efficiency and aerodynamic stability over the operating range. It is assumed that the compressor efficiency in η_c, and the turbine efficiency is η_t. The ideal processes and actual processes are represented in full line and dashed line, respectively, on the T-S diagram Figure 3. These parameters in terms of temperature are defined as (Al-Sayed, 2008):

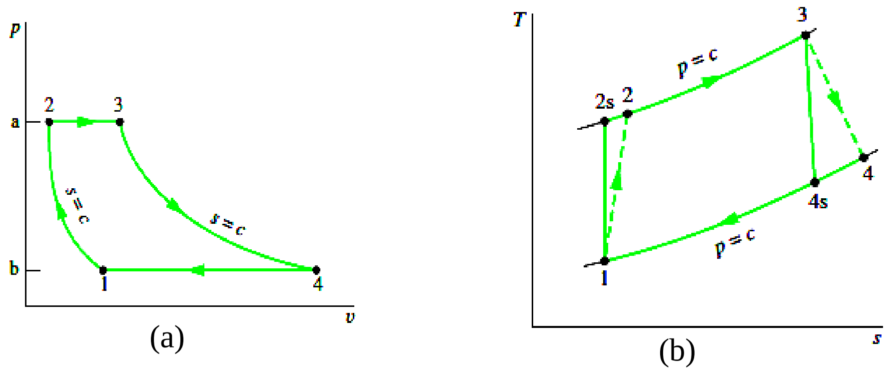

Figure 3: (a) P-V diagram and (b) T-S diagram for gas turbine

The compression ratio for the compressor (r_p) can be defined as Eq. (1):

$$r_p = \frac{P_2}{P_1} \tag{1}$$

The isentropic efficiency for compressor and turbine in the range of (85-90%) as Eq. (2)

$$\eta_c = \frac{T_{2s} - T_1}{T_2 - T_1} \text{ and } \eta_t = \frac{T_3 - T_4}{T_3 - T_{4s}} \tag{2}$$

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

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

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

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

where c_{pa} : The specific heat of air which can be fitted by the following equation for the range of 200K<T<800K (R) and η_m is the mechanical efficiency of the compressor. The specific heat of air can be expressed as Eq. (5).

$$c_{pa} = 1.0189\times10^3 - 0.1378T_a + 1.9843\times10^{-4}T_a^2 + 4.2399\times10^{-7}T_a^3 - 3.7632\times10^{-10}T_a^4 \tag{5}$$

where, T_a in Kelvin.

The specific heat of flue gas is given by Eq. (6) (Naradasu et al., 2007)

$$c_{pg} = 1.8083 - 2.3127\times10^{-3}T + 4.045\times10^{-6}T^2 - 1.7363\times10^{-9}T^3 \tag{6}$$

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From energy balance in the combustion chamber

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

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

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

where, $T_3 = TIT$ = turbine inlet temperature.

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

$$W_t = c_{pg} TIT.\eta_t\left(1 - \frac{1}{r_p^{\frac{\gamma_g - 1}{\gamma_g}}}\right) \tag{9}$$

The net work of the gas turbine (W_{net}) is calculated by Eq. (10)

$$W_{\text{net}} = c_{pg} \times TIT \times \eta_t \left(1 - \frac{1}{r_p^{\frac{\gamma_g - 1}{\gamma_g}}} \right) - c_{pa} T_1 \left(\frac{r_p^{\frac{\gamma_a - 1}{\gamma_a}}}{\eta_c} \right) \tag{10}$$

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

$$\text{Power, } P = \dot{m}_a \times W_{net} \tag{11}$$

The specific fuel consumption (SFC) can be determined by Eq.(12):

$$SFC = \frac{3600 f}{W_{net}} \tag{12}$$

The heat supplied (Q_{add}) is formulated as Eq. (13)

$$Q_{\text{add}} = c_{pg_m} \times \left[TIT - T_1 \times \left(1 + \frac{r_p^{\frac{\gamma_a - 1}{\gamma_a}} - 1}{\eta_c} \right) \right] \tag{13}$$

The gas turbine efficiency (η_{th}) is expressed as Eq. (14):

$$\eta_{th} = \frac{W_{\text{net}}}{Q_{\text{add}}} \tag{14}$$

The heat rate (HR) which is the consumed heat to generate unit energy of electricity can be expressed as Eq. (15).

$$HR = \frac{3600}{\eta_{\text{th}}} \tag{15}$$

RESULTS AND DISCUSSION

The simulation results of effect of ambient temperature and operation condition on gas turbine power plant are presented in this study. The variation of thermal efficiency with ambient temperature and compression ratio is shown in Figure 9. It can be seen that the thermal efficiency increases linearly with increases of compression ratio while decreases of ambient temperature. The increase in compression ratio means that increase in power output as a result of the thermal efficiency increase. However, the effect of ambient temperature has low effect on thermal efficiency for gas turbine power plant.

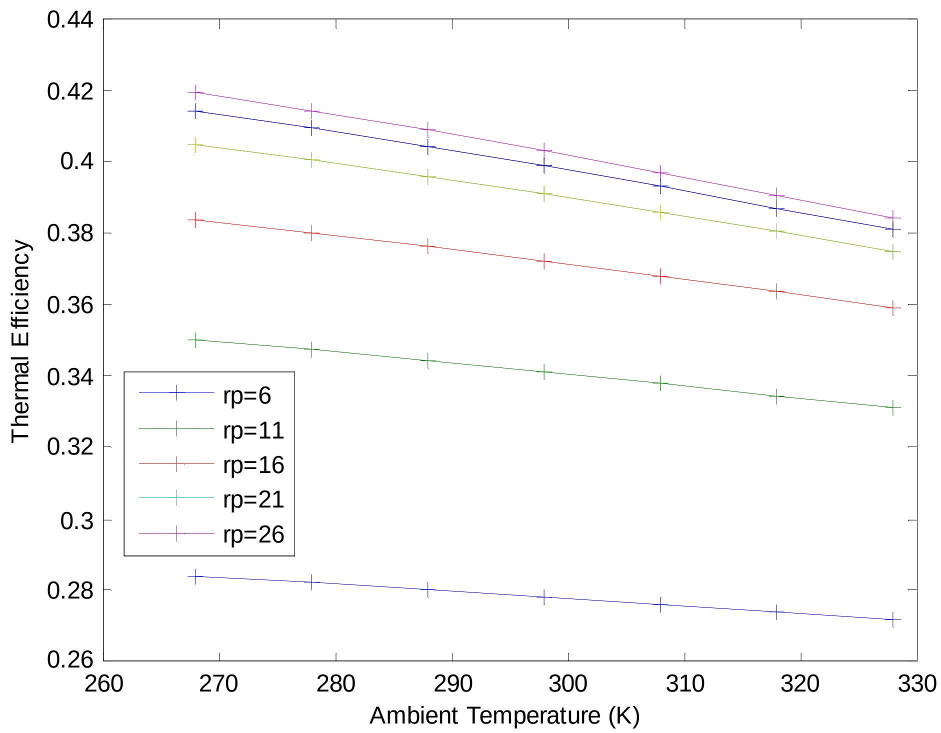

Figure 9: Variation of thermal efficiency against the ambient temperature and compression ratio.

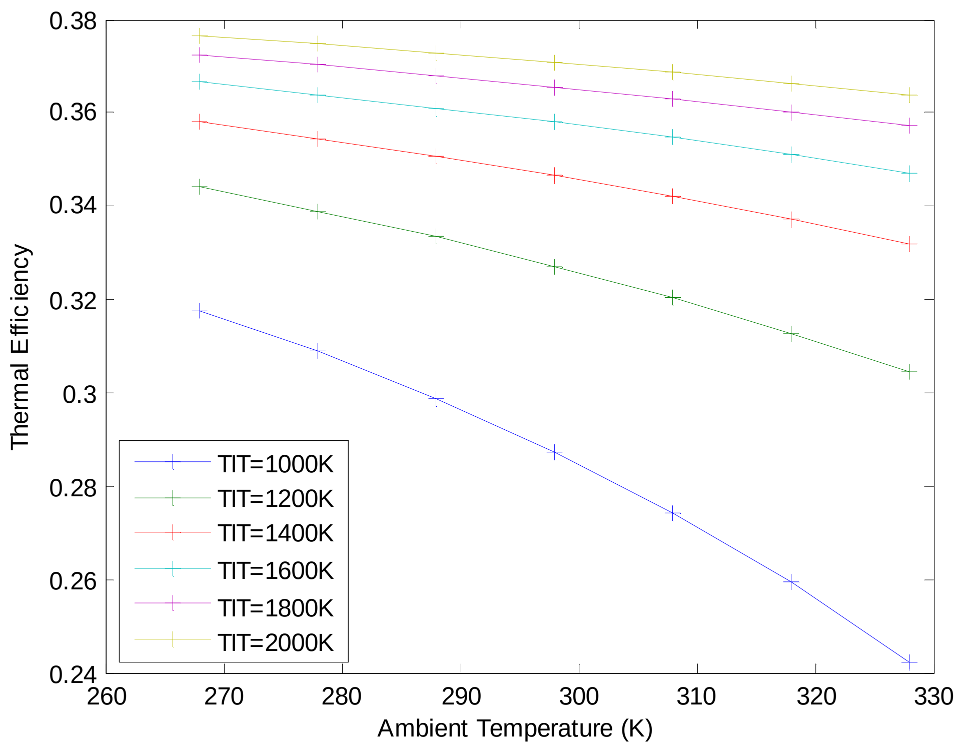

Figure 10: Effect of ambient temperature and turbine inlet temperature on thermal efficiency.

Figure 10 shows the relation between the ambient temperature and thermal efficiency for different values of turbine inlet temperature. As the ambient temperature increases, the specific work of the compressors increases (Nag, 2008), thus reduce cycle efficiency for the gas turbine. Also when the turbine inlet temperature is increase leads to an increase in the thermal efficiency, then the increased in the thermal efficiency about (6-14%) with increased the turbine inlet temperature from 1000K to 2050K. Variation of thermal efficiency at higher ambient temperature more significant that lower ambient temperature. The inverse phenomenon can be seen for specific fuel consumption as shown in Figure 11. The specific fuel consumption increases with increases of ambient temperature and lower turbine inlet temperature. The effect of variation of SFC is more significance at higher ambient temperature than lower temperature. The turbine inlet temperature increased means that more fuel should be burned which leads to decrease the specific fuel consumption.

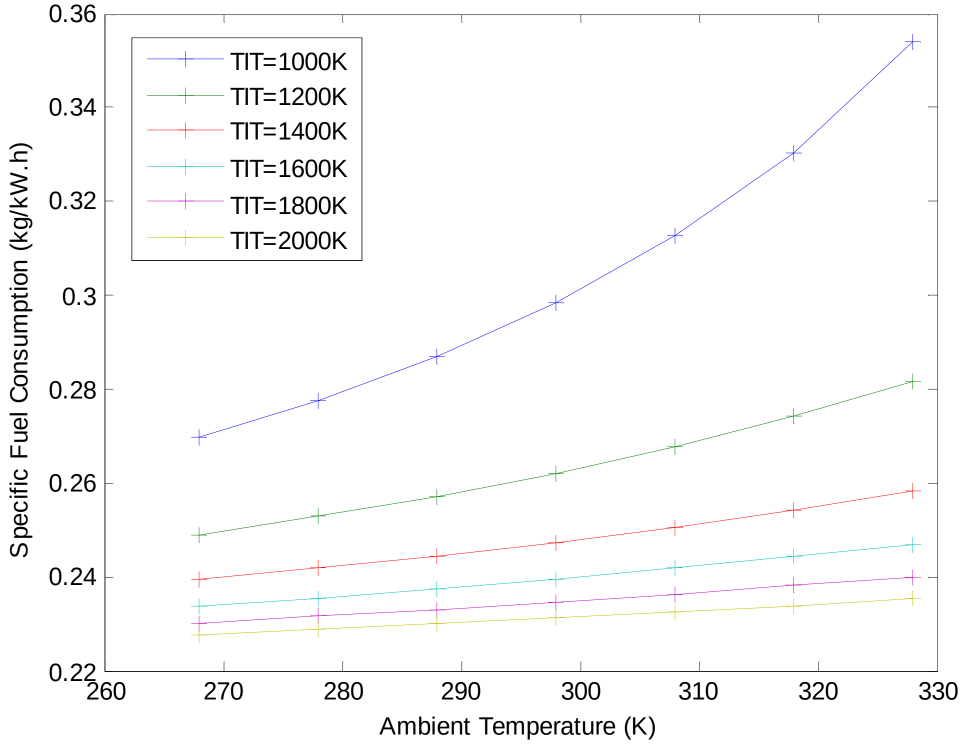

Figure 11: Effect of ambient temperature and turbine inlet temperature on specific fuel consumption.

Figure 12 illustrates the relation between gas turbine cycle thermal efficiency versus compression ratios for different turbine inlet temperature. It can be seen that the thermal efficiency linearly increases at lower compressor ratio as well as higher turbine inlet temperature until certain value of compression ratio. Then turn the thermal efficiency decrease with increase compression ratio, this limit dependent on the turbine inlet temperature, which reveals an ejective relationship as the efficiency increases as turbine inlet temperature increases. The variation of thermal efficiency is more significance at higher compression ratio and lower turbine inlet temperature. Even though at lower turbine Inlet temperature is decrement the thermal efficiency dramatically. Fig. 13 shows that the effect of compression ratio and turbine inlet temperature on specific fuel consumption. It is also observed that the SFC decreases linearly with increases of compression ratio and turbine inlet temperature at lower range until certain value then increases dramatically for lower turbine inlet temperature.

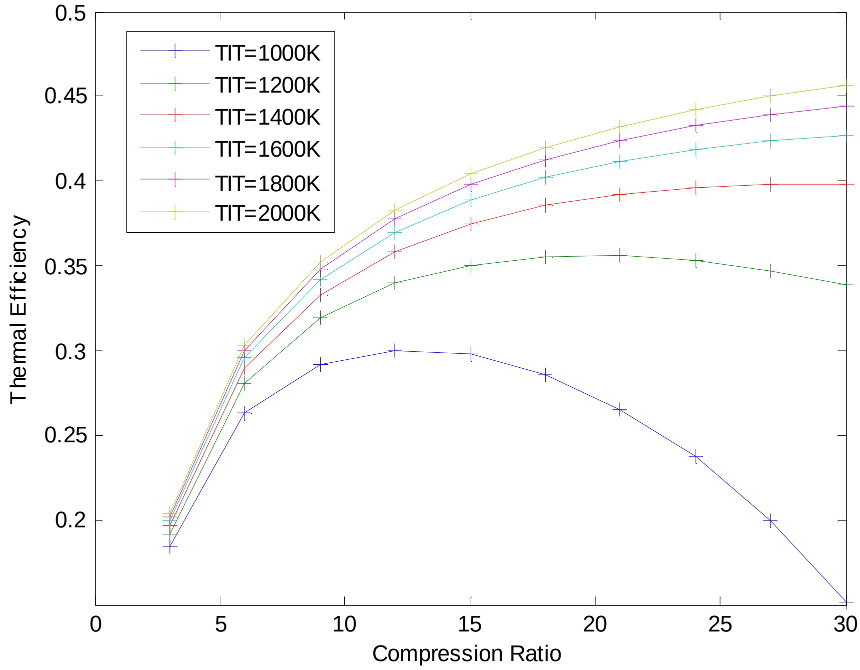

Figure 12: Effect of compression ratio and turbine inlet temperature on thermal efficiency.

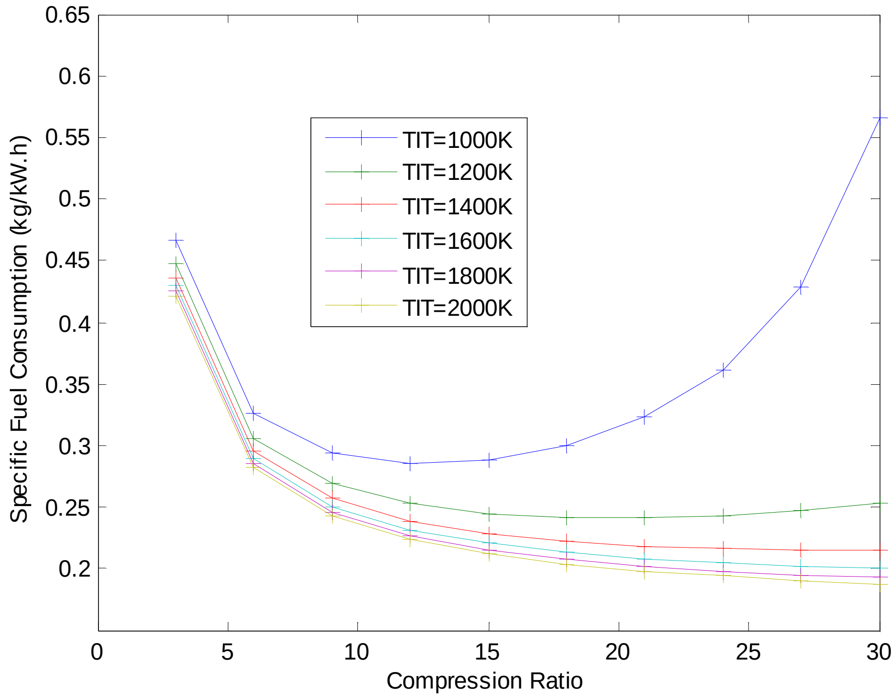

Figure 13: Effect of compression ratio and turbine inlet temperature on specific fuel consumption.

Figure 14 represents the relation between the thermal efficiency and power output for eight turbine inlet temperatures (1000-2050K) and compression ratios (3-21). The compression ratio for maximum power are selecting a compression ratio 6.4 for a turbine inlet temperature of 1000K result in a higher thermal efficiency, however, the maximum power output was at compression ratio 21 for the turbine inlet temperature 2050K and that yield the highest thermal efficiency.

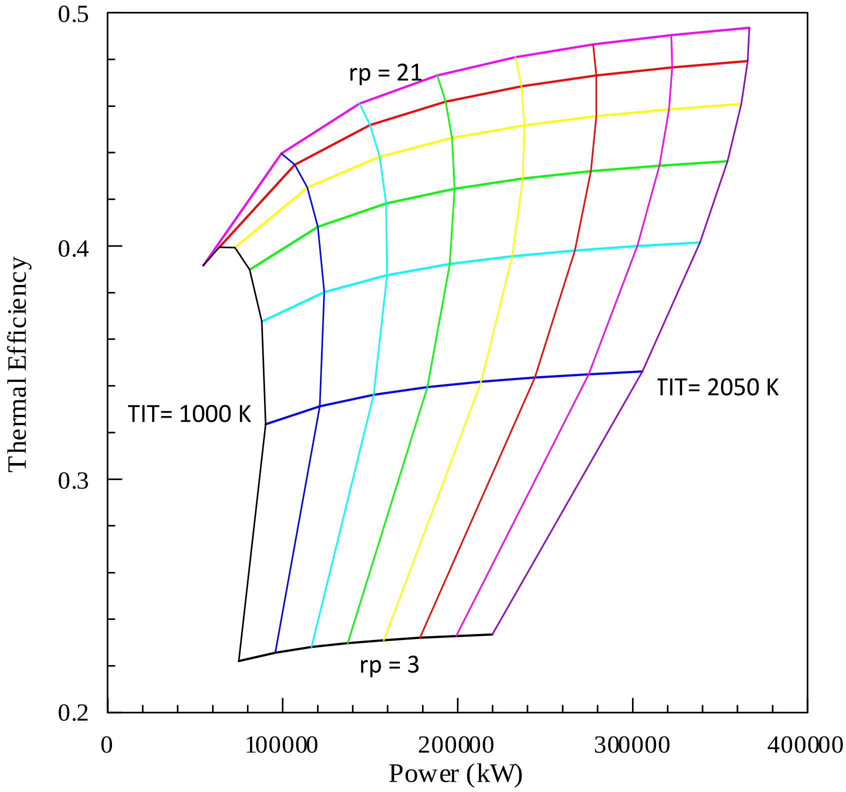

Figure 14: Variation of power with thermal efficiency for several compression ratio and turbine inlet temperatures.

CONCLUSION

The results were summarized as follows.

i) Increasing the turbine inlet temperature increases the output power and thermal efficiency as a result of increasing the turbine work.
ii) The peak efficiency, power and specific fuel consumption occur at when compression ratio increased in the gas turbine power plant.
iii) Maximum power for the turbine inlet temperatures are selecting a compression ratio 6.4 for a turbine inlet temperature of 1000K will result in a higher thermal efficiency.

ACKNOWLEDGEMENTS

The authors would like to thank Universiti Malaysia Pahang for provides laboratory facilities and financial support under Doctoral Scholarship scheme.

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