Thermal Analysis of Open-Cycle Regenerator Gas-Turbine Power-Plant

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***Abstract*—**Regenerative gas turbine engine cycle is presented that yields higher cycle efficiencies than simple cycle operating under the same conditions. The power output, efficiency and specific fuel consumption are simulated with respect to operating conditions. The analytical formulae about the relation to determine the thermal efficiency are derived taking into account the effected operation conditions (ambient temperature, compression ratio, regenerator effectiveness, compressor efficiency, turbine efficiency and turbine inlet temperature). Model calculations for a wide range of parameters are presented, as are comparisons with simple gas turbine cycle. The power output and thermal efficiency are found to be increasing with the regenerative effectiveness, and the compressor and turbine efficiencies. The efficiency increased with increase the compression ratio to 5, then efficiency decreased with increased compression ratio, but in simple cycle the thermal efficiency always increase with increased in compression ratio. The increased in ambient temperature caused decreased thermal efficiency, but the increased in turbine inlet temperature increase thermal efficiency.

***Keywords*—**Gas turbine; power plant; thermal analysis; regeneration

I. INTRODUCTION

THE open-cycle gas turbines offered low capital costs, compactness, and efficiency close to that of the steam plants. Nevertheless, after the oil crisis in the 1970s the efficiency of power plants became the top priority, and combined-cycle plants, first in the form of existing steam plant repowering, and later, as specially-designed gas-and-steam turbine plants, have become a common power plant configuration [1]. Gas turbines that operate in simple cycles have low efficiencies because the turbine exhaust gases come out very hot and this energy is lost to the atmosphere. Better performance is reached with advanced cycles that take advantage of the energy contained in the turbine exhaust gases to improve the cycle or to transfer energy to combined cycles [2], [3]. In gas-turbine power plant, the temperature of the exhaust gas leaving the turbine is often considerably higher than the temperature of the air leaving the compressor. Therefore, the air leaving the compressor at high-pressure can be heated by transferring heat to it from the hot exhaust gases in a counter-flow heat exchanger, which is also known as a regenerator or recuperator [4]. Gas turbine regenerators are usually constructed as shell-and-tube type heat exchangers using very small diameter tubes, with the high pressure air inside the tubes and low pressure exhaust gas in multiple passes outside the tubes. The thermal efficiency of the Brayton cycle increases as a result of regeneration since the portion of energy of the exhaust gases that is normally rejected to the surroundings is now used to preheat the air entering the combustion chamber. This, in turn, decreases the heat input (thus fuel) requirements for the same net work output. Note, however, that the use of a regenerator is recommended only when the turbine exhaust temperature is higher than the compressor exit temperature. Otherwise, heat will flow in the reverse direction (to the exhaust gases), decreasing the efficiency. This situation is encountered in gas turbines operating at very high-pressure ratios [5].

A regenerator with a higher effectiveness will save a greater amount of fuel since it will preheat the air to a higher temperature prior to combustion [6]. However, achieving a higher effectiveness requires the use of a larger regenerator, which carries a higher price tag and causes a larger pressure drop because shaft horsepower is reduced. Pressure drop through the regenerator is important and should be kept as low as practical on both sides. Generally, the air pressure drop on the high-pressure side should be held below 2% of the compressor total discharge pressure. The effectiveness of most regenerators used in practice is below 0.85. The thermal efficiency of an ideal Brayton cycle with regeneration depends on the ratio of the minimum to maximum temperatures as well as the pressure ratio. Regeneration is most effective at lower pressure ratios and low minimum-to-maximum temperature ratios [7]. A parametric study of the effect of compression ratio, ambient temperature, turbine's inlet-temperature (TIT), the effectiveness of regenerator, compressor efficiency, and turbine efficiency on the performance of the regenerative gas turbine cycle and comparison with simple cycle [3].

II. MODEL DESCRIPTION AND PROBLEM FORMULATION

Figure 1 shows a gas turbine plant with regenerator, which is a single shaft turbine. Generally, the principle of the gas turbine cycle is that air is compressed by the air compressor, and transferred to combustion chamber (CC) in order to combine with fuel for producing high-temperature

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flue gas. Afterward, high-temperature flue gas will be sent to gas turbine, which connected to the shaft of generator for producing electricity [4]. The purpose of the single shaft turbine is to produce and supply the necessary power required to run the compressor, and is meant for producing the network output. In this regenerative cycle, air after compression enters in to a regenerator where it is heated by the exhaust gases coming from turbine. The preheated air then enters in to combustion chamber, after heated addition to maximum permissible temperature in the combustion chamber. The network output of the cycle is thus proportional to the temperature drop in the turbine.

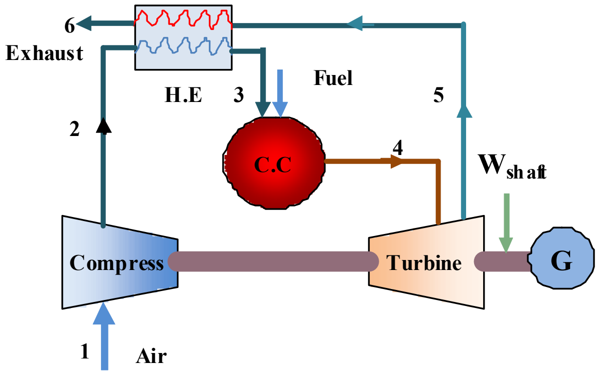

Fig. 1 The regenerative gas turbine cycle.

Figure 2 shows the T-S diagram for regenerative gas turbine cycle. The actual processes and ideal processes are represented in dashed line and full line respectively. The compressor efficiency (η_c), the turbine efficiency (η_t) and effectiveness of regenerator (heat exchanger) (ε) are considered in this study. These parameter in terms of temperature are defined as in (1) [8]:

$$\eta_c = \frac{T_{2s} - T_1}{T_2 - T_1}\ ; \quad \eta_t = \frac{T_4 - T_5}{T_4 - T_{5s}} \quad \text{and} \quad \varepsilon = \frac{T_3 - T_2}{T_5 - T_2} \tag{1}$$

The work required to run the compressor is expressed as in (2):

$$W_c = c_{pa} T_1 \left(\frac{r_p^{\frac{\gamma_a - 1}{\gamma_a}} - 1}{\eta_c} \right) \tag{2}$$

where the specific heat of air is expressed as in (3) [9].

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

The specific heat of flue gas is written as Eq. (4) [9].

$$c_{pg} = 1.8083 - 2.3127 \times 10^{-3} T + 4.045 \times 10^{-6} T^2 - 1.7363 \times 10^{-9} T^3 \tag{4}$$

The work developed by turbine is then rewrite as in (5):

$$W_t = c_{pg} T_4 \eta_t \left(1 - \frac{1}{r_p^{\frac{\gamma_g - 1}{\gamma_g}}} \right) \tag{5}$$

where turbine inlet temperature (TIT) = T_4
The net work is expressed as in (6)

$$W_{\text{net}} = c_{pg} \times TIT \times \eta_t \left(1 - \frac{1}{r_p^{\frac{\gamma_g - 1}{\gamma_g}}} \right) - c_{pa} T_1 \left(\frac{r_p^{\frac{\gamma_a - 1}{\gamma_a}}}{\eta_c} \right) \tag{6}$$

In the combustion chamber, the heat supplied by the fuel is equal to the heat absorbed by air, Hence,

$$Q_{\text{add}} = c_{pg} \times \left[\begin{matrix} TIT - T_1(1 - \varepsilon) \times \left(1 + \dfrac{r_p^{\frac{\gamma_a - 1}{\gamma_a}} - 1}{\eta_c} \right) \\ - \varepsilon \times TIT \times \left[1 - \eta_t \left(1 - \dfrac{1}{r_p^{\frac{\gamma_g - 1}{\gamma_g}}} \right) \right] \end{matrix} \right] \tag{7}$$

The power output is,

$$\text{Power} = \dot{m}_a \times W_{net} \tag{8}$$

where $\dot{m}_a$ = air mass flow rate ,
The air to fuel ratio is defined as in (9),

$$\text{AFR} = \frac{LHV}{Q_{\text{add}}} \tag{9}$$

The specific fuel consumption is expressed as (10):

$$\text{SFC} = \frac{3600}{\text{AFR} \times W_{\text{net}}} \tag{10}$$

Further the thermal efficiency of the cycle is then expressed as in (11).

$$\eta_{th} = \frac{W_{\text{add}}}{Q_{\text{net}}} \tag{11}$$

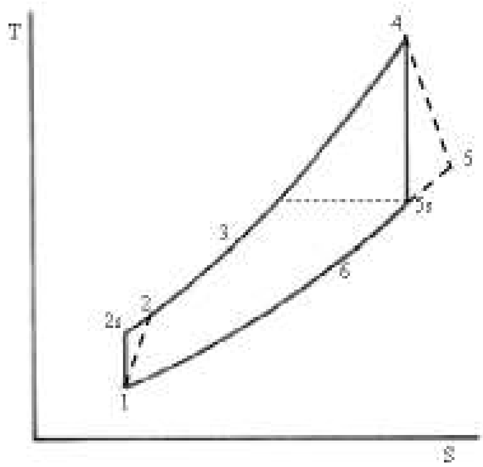

Fig. 2 T-S diagram for regenerative gas turbine cycle.

III. RSULTS AND DISCUSSION

The cycle was modeled using the thermodynamic analysis for the simple gas turbine and regenerative gas turbine. The pressure losses are assumed in this study. The effect of thermal efficiency, power and specific fuel consumption on operation conditions are analyzed in the following section.

A. Effect of Ambient Temperature (T1)

Figure 3 shows the effect of ambient temperature and regenerative effectiveness on thermal efficiency of gas turbine cycle. Turbine inlet temperature (r_p) and effectiveness are of 1450 K, 10 and 0.85 respectively. It can be seen that the thermal efficiency decreases with increases of ambient temperature while decreases of regenerative effectiveness. The specific work of the compressors increases as the ambient temperature increases [10]. Thus the thermal efficiency for the regenerative gas turbine cycles is reduced. It can be noticed that the gain of thermal efficiency increase of 12.6% with increases of regenerative effectiveness from (0.45-0.95). The density of air increases when ambient temperature decreases, which causes an increase in the air mass flow rate. The power and heat supplied to the combustion chamber increases with the gas mass flow rate increases however, the power increase is more than the increase in the heat supplied in the combustion chamber (Figure 3).

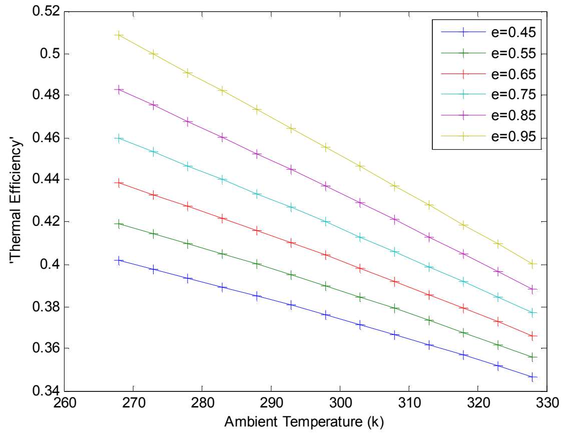

Fig. 3 Variation of thermal efficiency on ambient temperature and regenerative effectiveness.

Variation of thermal efficiency on inlet temperature of simple cycle and regenerative cycle is shown in Figure 4. It is observed that the thermal efficiency is higher for regenerative cycle than simple cycle. The variation of specific fuel consumption with ambient temperature is also shown in Figure 5. It shows that when the ambient temperature increases the specific fuel consumption increases too. 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 (AFR) is kept constant. The power increase is less than that of the inlet compressor air mass flow rate ($\dot{m}_f$); therefore, the specific fuel consumption increases with the increase of ambient temperature.

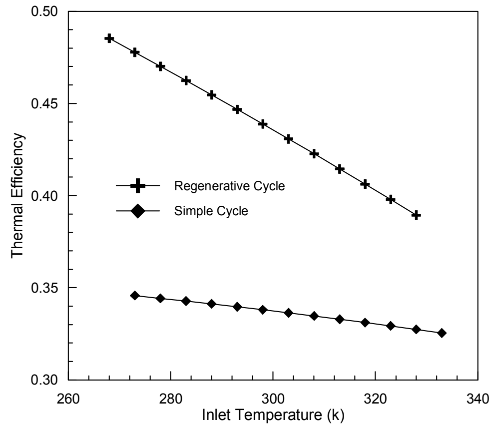

Fig. 4 Effect of ambient temperature on thermal efficiency for simple and regenerative cycle.

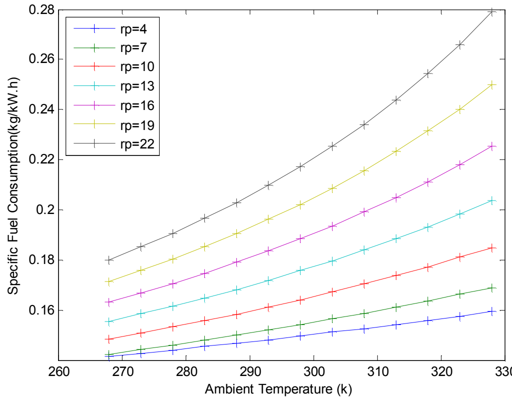

Fig. 5 Influence of ambient temperature on specific fuel consumption with deferent compression ratio (TIT is calculated).

B. *Effect of Compression Ratio (r_p)*

Figure 6 shows the variation of the thermal efficiency with compression ratio. The increase in compression ratio means an increase in power output, so the thermal efficiency must increase too. A direct effect of compression ratio on the standard air thermal efficiency and the thermal efficiency of regenerative cycle is shown in Figure 7. The thermal efficiency increases with increase of compression ratio for the same inlet temperatures since the compression ratio will raise the temperature of the air entering the combustion chamber which is decreases the heat added, i.e. increases the thermal efficiency. In regenerative cycle the thermal efficiency increase with compression ratio to 5 then return the thermal efficiency decrease with increase compression ratio.

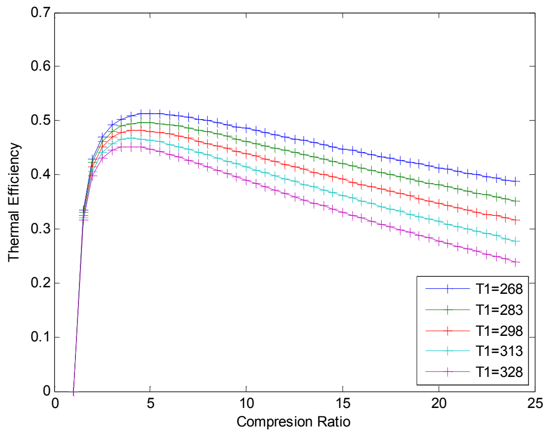

Fig. 6 Effect of compression ratio and ambient temperature on thermal efficiency (specified TIT).

Figure 6 also present a relation between regenerative gas turbine cycle thermal efficiency versus compression ratios for different ambient air temperatures, which reveals an opposite relation as the efficiency decreases as inlet air temperature increases, a comparison between the results from the present study and the results shown in [Gas Turbine Theory] which reveals an acceptable agreement as shown in Figure 7. Figure 8 shows the variation specific fuel consumption with compression ratio. The increase in compression ratio means an increase in power output, so the specific fuel consumption must increase too. The relation between specific fuel consumption versus compression ratios for regenerative gas turbine cycle at different effectiveness values for regenerator $(\epsilon = 0.45\ to\ 0.95)$ shown in Figure 9. The thermal efficiency increased with compression ratio at deferent values for regenerative effectiveness as shown in Figure 10. Also the thermal efficiency increased with increased compressor efficiency and turbine efficiency as shown in Figures 11 and 12.

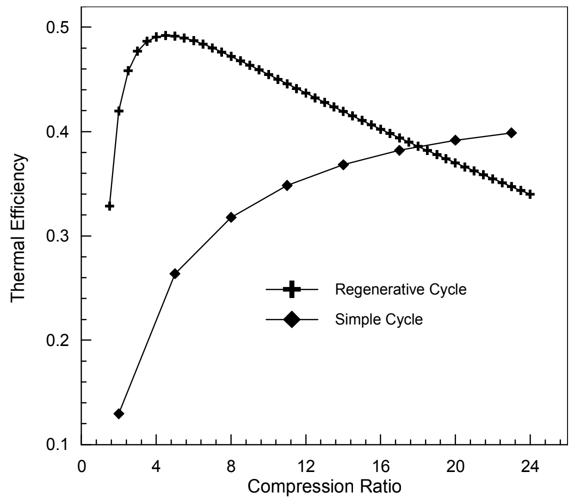

Fig. 7 Effect of compression ratio on thermal efficiency for simple and regenerative cycle.

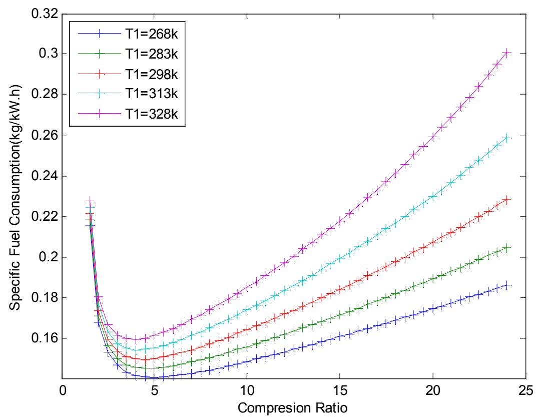

Fig. 8 Influence of compression ratio on specific fuel consumption with deferent ambient temperature (TIT is calculated).

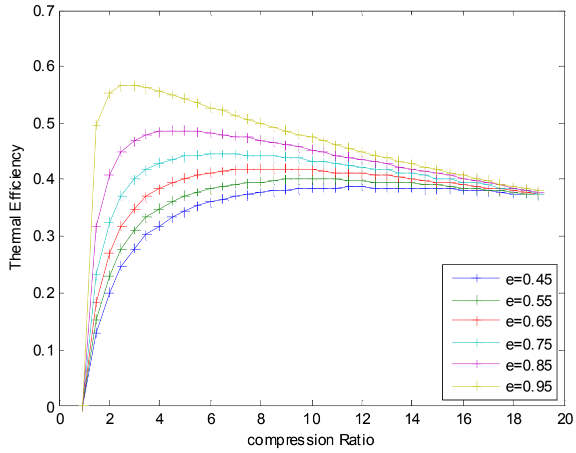

Fig. 9 Influence of compression ratio on specific fuel consumption (TIT is calculated).

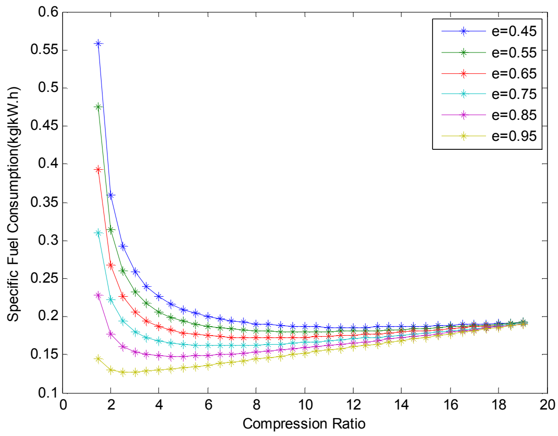

Fig. 10 Effect of compression ratio and reg. effectiveness on thermal efficiency (specified TIT).

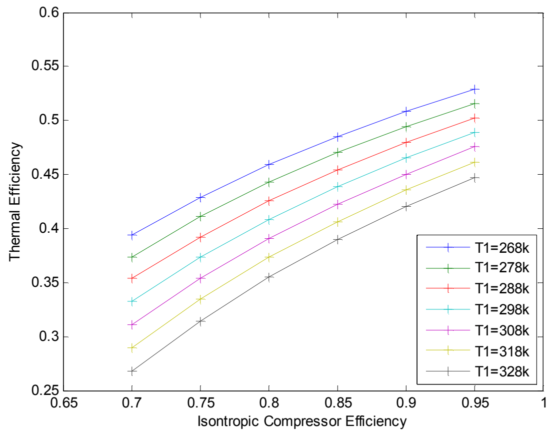

Fig. 11 Effect of isentropic compressor efficiency and ambient temperature on thermal efficiency.

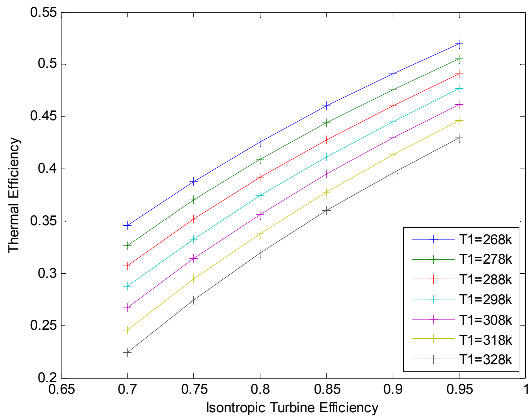

Fig. 12 Effect of isentropic turbine efficiency and ambient temperature on thermal efficiency.

The performance map of a regenerative gas turbine cycle is shown in Figure 13 Present a relation between power outputs versus thermal efficiency for regenerative cycle for different turbine inlet temperatures and different compression ratios. The power output increases as turbine inlet temperature increases, for a given compressor inlet temperature, turbine inlet temperature, compressor efficiency, and turbine efficiency, there is a compression ratio at which the thermal efficiency reaches a maximum value; if the compression ratio is increased beyond this value, the thermal efficiency and net work will slowly decrease as shown in Figure 14.

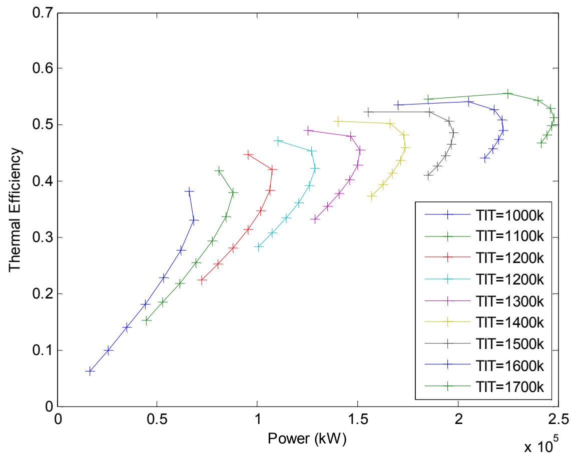

Fig. 13 Thermal efficiency-power dependence on compression ratio and TIT.

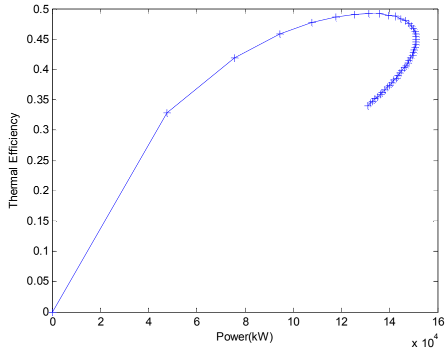

Fig. 14 Thermal efficiency-power dependence on compression ratio.

C. *Effect of Turbine Inlet Temperature (TIT)*

The relation between turbine inlet temperature and thermal efficiency for different values of ambient temperature is shown in Figure15. As the turbine inlet temperature is increased for the same exit temperature, the temperature drop will increase giving higher power potential. This increase in power leads to an increase in the thermal efficiency as shown in Figure 16.

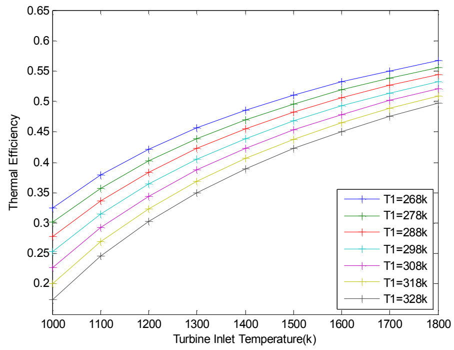

Fig. 15 Effect of turbine inlet temperature and ambient temperature on thermal efficiency.

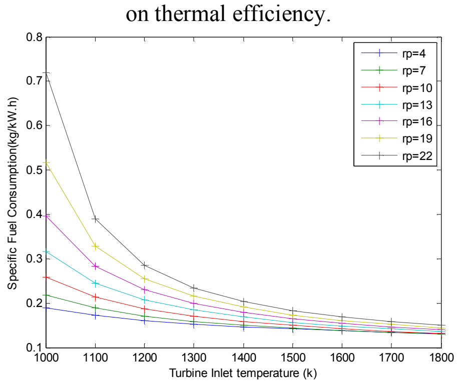

Fig. 16 Effect of turbine inlet temperature and compression ratio on specific fuel consumption.

IV. Conclusion

This paper has presented consideration that should be included in determining the performance of a regenerative gas turbine power plant. A design methodology has been developed for parametric study and performance evaluation of a regenerative gas turbine. Parametric study showed that rp, ambient temperature and TIT played a very vital role on overall performance of a regenerative gas turbine.

(i) The heat duty in the regenerator decreases with the pressure ratio but increases with the decreases ambient temperature and increases TIT this mean increased thermal efficiency.
(ii) The thermal efficiency of the simple gas-turbine cycle experiences small improvements at large pressure ratios as compared to regenerative gas turbine cycle.
(iii) In general, peak efficiency, power and specific fuel consumption occur at compression ratio (rp = 5) in the regenerative gas turbine cycle.
(iv) The thermal efficiency increases and specific fuel consumption decreases with the regenerator effectiveness.

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