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THERMAL ANALYSIS OF OPEN-CYCLE REGENERATOR GAS-TURBINE POWER-PLANTS

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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

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 (Nag, 2008). 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 (Mahmood and Mahdi, 2009), that take advantage of the energy contained in the turbine exhaust gases to improve the cycle or to transfer energy to combined cycles (Saravanamuttoo et al., 2009). 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

(Moran and Shapiro, 2008). 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 (Mahmoudi et al., 2009).

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 (Maria and Jinyue, 2005). 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 (Dellenback, 2002). 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 at (Saravanamuttoo et al., 2009).

MODEL DESCRIPTION

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 flue gas. Afterward, high-temperature flue gas will be sent to gas turbine, which connected to the shaft of generator for producing electricity (Moran and Shapiro, 2008). 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.

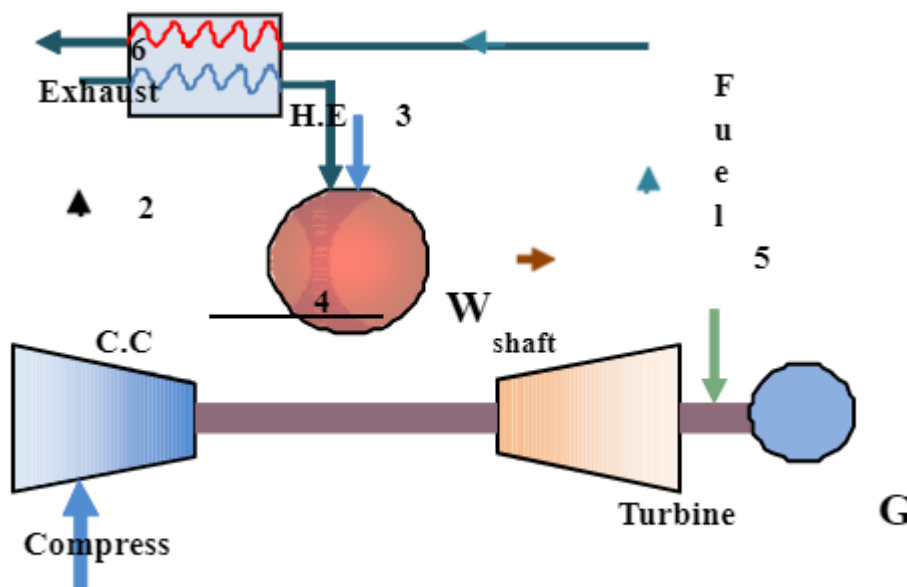


Figure 1: The regenerative gas turbine cycle.



PROBLEM FORMULATION

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 Eq. (1) (Al-Sayed, 2008):

$$\eta_c = \frac{T_4 - T_5}{T_3 - T_2} \quad \eta = \frac{T_{2s} - T_1}{T_2 - T_1}$$

$$\epsilon = \frac{T_4 - T_{5s}}{T_5 - T_2}$$

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

$$W = c_p \gamma_a \left(\frac{\gamma_a - 1}{\gamma_a} \right) \left(\frac{r_p}{c} - 1 \right) \quad (2)$$

where the specific heat of air is expressed as Eq. (3) (Naradasu et al., 2007)

$$c_{p,a} = 1.0189 \times 10^3 - 0.13784 T_a + 1.9843 \times 10^{-4} T_a^2 + 4.2399 \times 10^{-7} T_a^3 - 3.7632 \times 10^{-10} T_a^4$$

The specific heat of flue gas is written as Eq. (4) (Naradasu et al., 2007)

$$c_{p,g} = 1.8083 - 2.3127 \cdot 10^{-3} T + 4.045 \cdot 10^{-6} T^2 - 1.7363 \cdot 10^{-9} T^3$$

Figure 2: T-S diagram for regenerative gas turbine cycle.

RESULTS 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.

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 (Dellenback, 2005). 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).

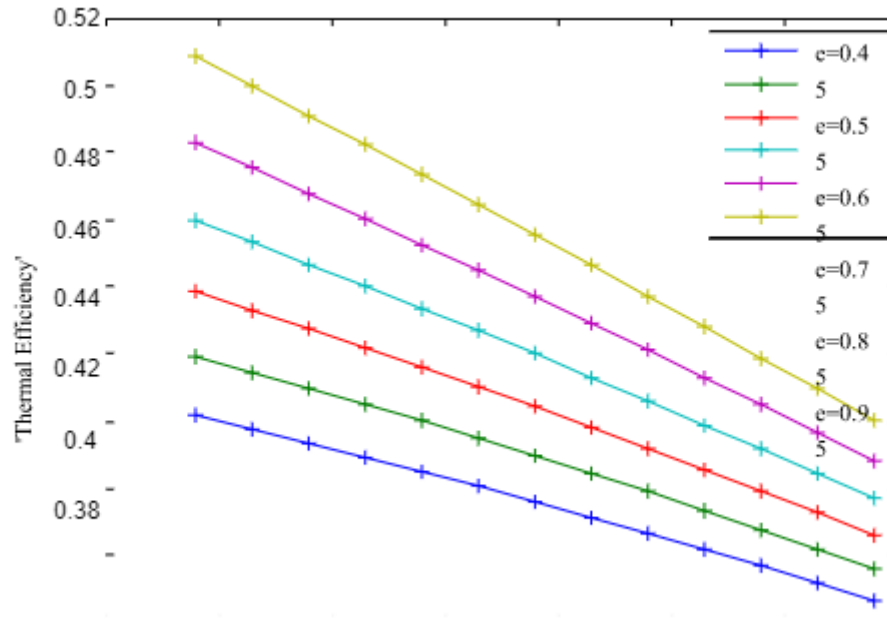


Figure 3: Variation of thermal efficiency on ambient temperature and regenerative effectiveness.

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.

Effect of Turbine Inlet Temperature (TIT)

The relation between turbine inlet temperature and thermal efficiency for different values of ambient temperature 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.

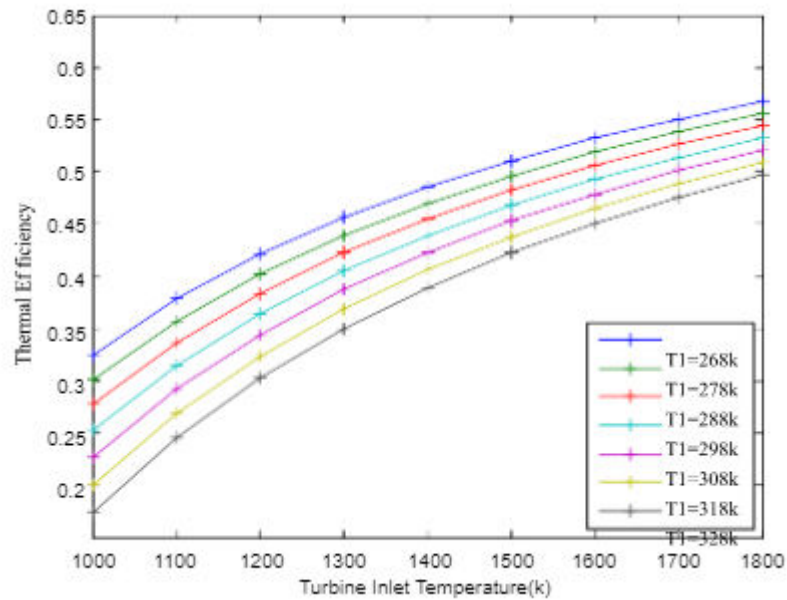


Figure 15: Effect of turbine inlet temperature and ambient temperature on thermal efficiency.

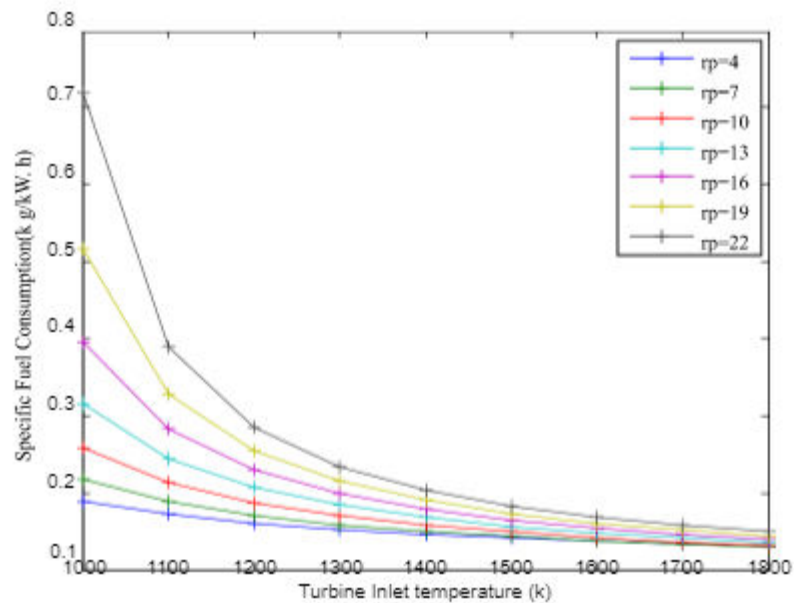


Figure 16: Effect of turbine inlet temperature and compression ratio on specific fuel consumption.

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.

1. 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.
2. The thermal efficiency of the simple gas-turbine cycle experiences small improvements at large pressure ratios as compared to regenerative gas turbine cycle.



3. In general, peak efficiency, power and specific fuel consumption occur at compression ratio ($r_p = 5$) in the regenerative gas turbine cycle.
4. The thermal efficiency increases and specific fuel consumption decreases with the regenerator effectiveness.

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