

*Full Length Research Paper*

# Study on the effective parameter of gas turbine model with intercooled compression process

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**In this paper parametric study of a gas turbine cycle model power plant with intercooler compression process was proposed. The power output and the efficiency are simulating with respect to the cycle temperatures and pressure ratio for a typical set of operating conditions. Simple gas turbine cycle calculations with realistic parameters are made and confirm that increasing the turbine inlet temperature no longer means an increase in cycle efficiency, but increases the work done. The analytical study is done to investigate the performance improvement by intercooling. The analytical formula for specific work and efficiency are derived and analyzed. The simulation results shows that increasing turbine inlet temperature and pressure ratio can still improve the performance of the intercooled gas turbine cycle.**

**Key words:** Gas turbine, power plant, performance, intercooler.

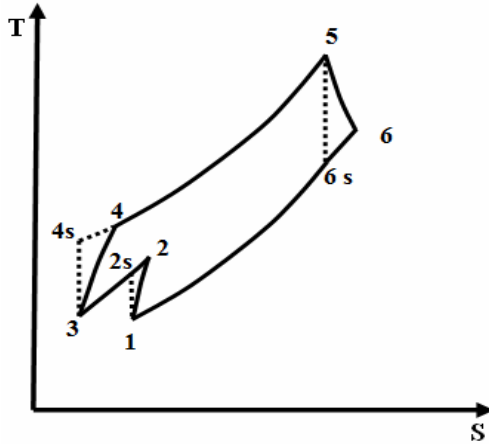
## INTRODUCTION

Over the past decade, gas turbines have turned out to be one of the most interesting techniques for electric power production (Mahmood and Mahdi, 2009). Therefore, enhancing the performance of Gas turbine was successfully through raising the turbine inlet temperature (TIT) and the compressor pressure ratio and advances in cooling technology and material science caused high turbine inlet temperature conceivable. The challenge of constantly enhancing the gas turbine performance has got to a critical moment as Horlock et al. (2003) looked into the limits of raising the combustor outlet temperature. Highest performance is suggested to be achieved at TIT much lower than the stoichiometric combustion temperature due to the increase in losses affiliated with the cooling flows. Unless new materials and improved heat transfer mechanisms can confine the increase in the requirement cooling air flow rates, it will not be valuable raising the TIT much boost. Saidi et al. (2002) made a careful study on the gas properties as a limit on performance in the absence of cooling. It was shown that

real gas effects cause the peaks in cycle performance, even without cooling. Higher fuel/air ratios give higher water contents, which hint to higher values of specific heat capacitances  $c_v$  and  $c_p$ . Wang et al. (2008) arrived at an overview of their investigations about the effect of the cooling on cycle performance. They conclude that enhancement allowable blade metal temperature and film cooling effectiveness are salutary, but not as important as enhancing the turbomachinery aerodynamic performance.

Various means have been employed by many researchers to improve the power product of the turbines, particularly the gas turbine. One of the means is to use intercooler. The intercooler is used to reduced the temperature at the high-pressure compressor, causing reduce consumption power on compressor and lower output temperature at high pressure (Canie`re et al., 2006). The overall result is a lowering of the net work input wanted for a given pressure ratio. According to Yadav and Jumhare (2004) the intercooling is especially effective when used in a cycle with heat recovery. Even so, intercooling used without reheating causes decrease of the efficiency at least for low pressure ratios. It is explicated by the drop of temperature after the

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**Figure 1.** T-S diagram for gas turbine with intercooler.

compressor, which is compensated by the increment of the temperature in the combustion chamber. The range of power output that is concerned when talking about "mid-size" plants is typically 30-200 MW (Saravanamuttoo et al., 2009).

This paper focuses on investigating the effective parametric such as ambient temperature, compression ratio, turbine inlet-temperature, and the effectiveness of the intercooler to improve the performance of gas turbine power plant with intercooled compression process. In the process the fluid is compressed in the first compressor to some average pressure and then it is passed across an intercooler, where it is chilled to a lower temperature at basically constant pressure. It is suitable that the lower temperature is as low as possible. The cooled fluid is directed to second compressor, where it increases in the pressure and then it directs the fluid to the combustion chamber and later to the expander.

## MODEL DESCRIPTION

Intercooling is a way to reduce the power consumption for compression of an air. Thus, the inlet temperature of the second compressor stage can be kept low. For a given compression ratio, the power consumed in a compressor is directly proportional to the inlet temperature. Consider Figure 1 and assume that the compressor is working between the thermodynamic states 1 and 2. If the air is cooled from state 2 to 3 the required compressor power is decreased and the net cycle power delivered is increased if the inlet temperature is reduced (Cengel and Boles, 2008). Figure 2 shows a gas turbine power plant with intercooler has a single shaft gas turbine. In this gas turbine cycle with intercooler, air after compression in the first stage compressor enters into an intercooler where it is cooled. The cooled air then enters into second stage compressor to compress to

required pressure, and then goes to combustion chamber, after additional heating to maximum permissible temperature in the combustion chamber. The network output of the cycle is thus proportional to the temperature drop in the turbine (Bassily, 2004).

## PROBLEM FORMULATION

It is assumed that the effectiveness of intercooler (heat exchanger) is  $x$ , the compressor efficiency in  $\eta_c$ , and the turbine efficiency is  $\eta_t$ . The ideal processes and actual processes are represented in dashed line and full line, respectively, on the T-S diagram (Figure 1). These parameters in terms of temperature are defined as (Al-Sayed, 2008):

$$\eta_c = \frac{T_{2s} - T_1}{T_2 - T_1} = \eta_{clp} = \eta_{chp} = \frac{T_{4s} - T_3}{T_4 - T_3}$$

$$\eta_t = \frac{T_5 - T_6}{T_5 - T_{6s}}, \quad x = \frac{T_2 - T_3}{T_2 - T_1}$$

Where  $\eta_{clp}$  and  $\eta_{chp}$  represent low and high pressure compressor efficiency respectively.

The work required to run the compressor is,

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

Where the specific heat of air is given by (Naradasu et al., 2007),

$$c_{pa} = 1.0189 * 10^3 - 0.13784 T_a + 1.9843 * 10^{-4} T_a^2 + 4.2399 * 10^{-7} T_a^3 - 3.7632 * 10^{-10} T_a^4$$

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

$$c_{pg} = 1.8083 - 2.3127 * 10^{-3} T + 4.045 * 10^{-6} T^2 - 1.7363 * 10^{-9} T^3$$

The work developed by turbine is given by,

$$W_t = c_{pg} T_5 \left[ \eta_t \left( 1 - \frac{1}{\left( \frac{\gamma_s - 1}{(r_p^2)^{\gamma_s}} \right)} \right) \right]$$

Where  $TIT = T_5$  (turbine inlet temperature)

$$W_t = c_{pg} TIT \left[ \eta_t \left( 1 - \frac{1}{\left( \frac{\gamma_s - 1}{(r_p^2)^{\gamma_s}} \right)} \right) \right]$$

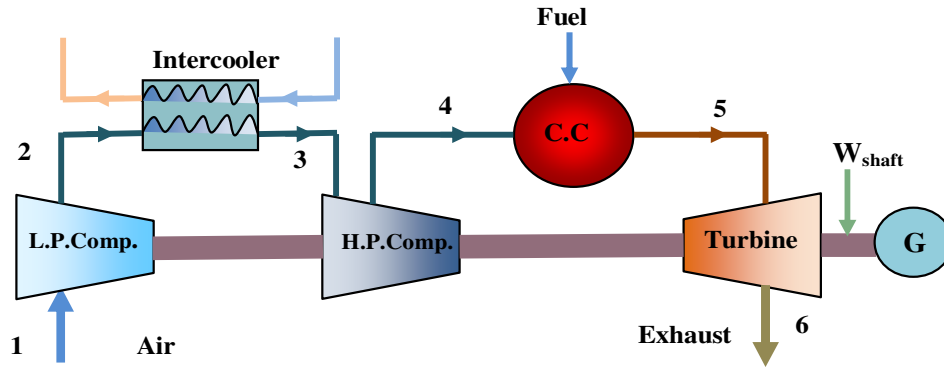


Figure 2. Block diagram for gas turbine with intercooler.

The network is,

$$W_n = c_{pg} TIT \left[ \eta_t \left( 1 - \frac{1}{\left( \frac{r_p^2}{r_p^2} \right)^{\frac{\gamma_a-1}{\gamma_a}}} \right) - c_{pd} T_1 \left( \frac{r_p^{\frac{\gamma_a-1}{\gamma_a}} - 1}{\eta_c} \right) \right] + (1-x) \left( \frac{r_p^{\frac{\gamma_a-1}{\gamma_a}} - 1}{\eta_c} \right)$$

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

$$Q_{add} = c_{pgm} \left[ TIT - T_1 + T_2 \left( \frac{r_p^{\frac{\gamma_a-1}{\gamma_a}} - 1}{\eta_c} \right) \left( (2-x) + (1-x) \left( \frac{r_p^{\frac{\gamma_a-1}{\gamma_a}} - 1}{\eta_c} \right) \right) \right]$$

The power output is (Saravanamuttoo et al., 2009),

$$Power = m_a \cdot W_{net}$$

Where  $\dot{m}_a$  = air mass flow rate, also air to fuel ratio is,

$$AFR = \frac{LHV}{Q_{add}}$$

The specific fuel consumption is determined by the formula:

$$SFC = \frac{3600}{(AFR \cdot W_{net})}$$

Further the thermal efficiency of the cycle,

$$\eta_{th} = \frac{c_{pg} TIT \left[ \eta_t \left( 1 - \frac{1}{\left( \frac{r_p^2}{r_p^2} \right)^{\frac{\gamma_a-1}{\gamma_a}}} \right) - c_{pd} T_1 \left( \frac{r_p^{\frac{\gamma_a-1}{\gamma_a}} - 1}{\eta_c} \right) \right] + (1-x) \left( \frac{r_p^{\frac{\gamma_a-1}{\gamma_a}} - 1}{\eta_c} \right)}{c_{pgm} \left[ TIT - T_1 + T_2 \left( \frac{r_p^{\frac{\gamma_a-1}{\gamma_a}} - 1}{\eta_c} \right) \left( (2-x) + (1-x) \left( \frac{r_p^{\frac{\gamma_a-1}{\gamma_a}} - 1}{\eta_c} \right) \right) \right]}$$

## RESULT

In this paper, the effects of pressure ratio across the compressor  $rp$ , turbine inlet temperature (TIT), ambient temperature and the effectiveness of intercooler ( $x$ ) on the first-law efficiency and power are obtained by the energy-balance approach or the first-law analysis of the cycle programming using matlab software.

The results of the above analysis are shown in Figures 3 to 15. Figure 3 shows the effect of ambient temperature on the efficiency of gas turbine cycle with intercooler. For that figure,  $TIT=1450$  K,  $rp=12$ ,  $\eta_c = 0.85$  and  $\eta_t = 0.89$ . It is clear from the figure that decreasing the ambient temperature increases the gain in efficiency. A direct effect of inlet temperature on the standard air thermal efficiency and the thermal efficiency of regenerative cycle is shown in Figure 4. As the ambient temperature increases, the specific work of the compressors increases (Nag, 2008), thus reducing cycle efficiency for the intercooler gas turbine cycles as shown in Figure 5. Also in Figure 3, if the effectiveness for intercooler changes from  $x = 0.5$  to  $x = 1$ , the efficiency will decrease from 43.8 to 42.5%. This is because the entry air to the combustion chamber with low temperature causes increasing fuel consumption as shown in Figure 6, thus reducing the efficiency in spite of the increased power output from the gas turbine as shown in Figure 7.

Figure 8 shows the effect of compression ratio and intercooler effectiveness on the thermal efficiency. Note that the thermal efficiency is increased with compression ratio, but the effect of intercooler effectiveness is very low to increase the thermal efficiency compared with pressure ratio.

Figure 9 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. Also, the effect of decreasing ambient temperature has low effect on thermal efficiency for gas turbine with intercooler. A direct effect of compression ratio on the simple gas turbine

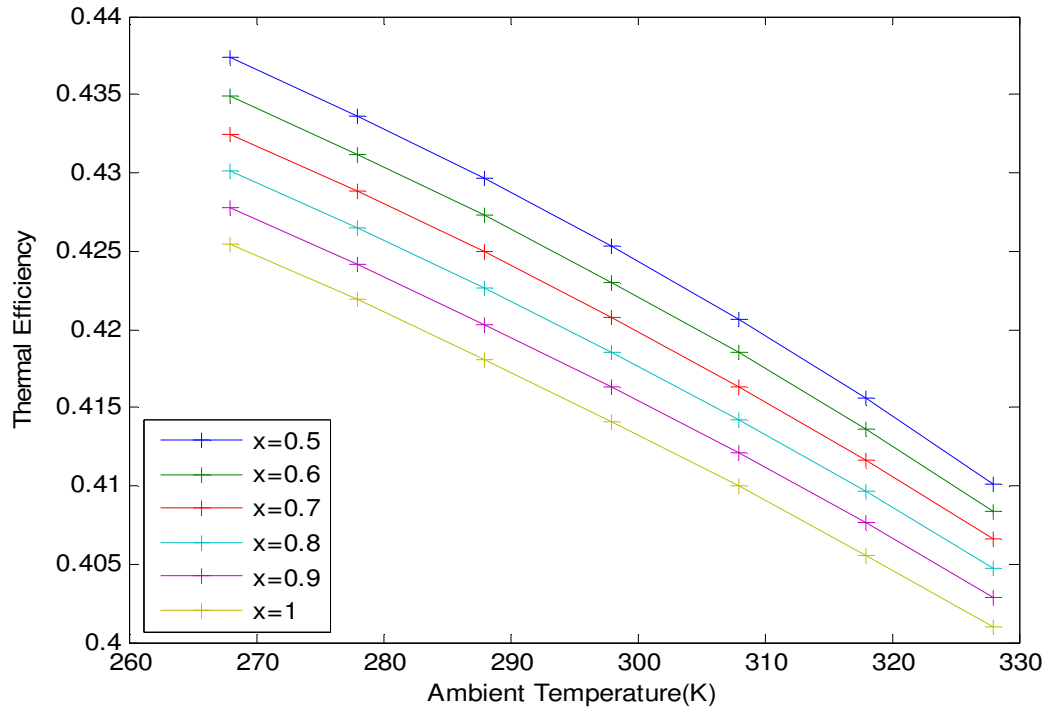


Figure 3. Effect of ambient temperature and intercooler effectiveness on thermal efficiency.

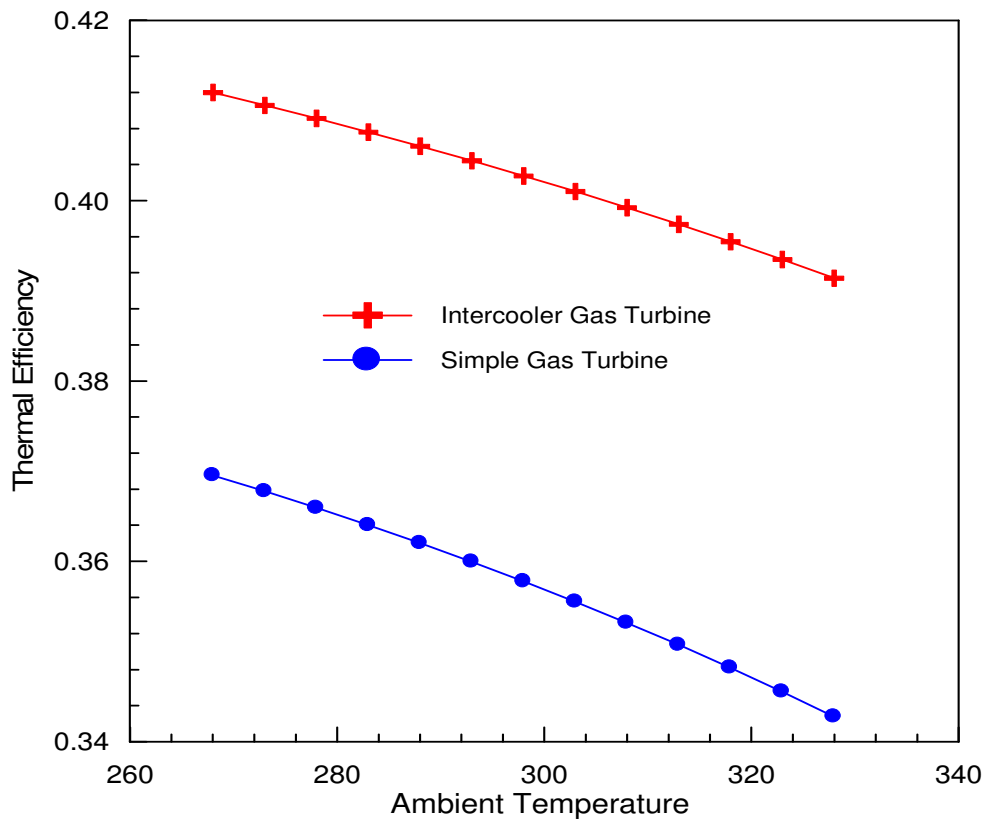


Figure 4. Effect of ambient temperature on thermal efficiency for simple and gas turbine cycle with intercooler.

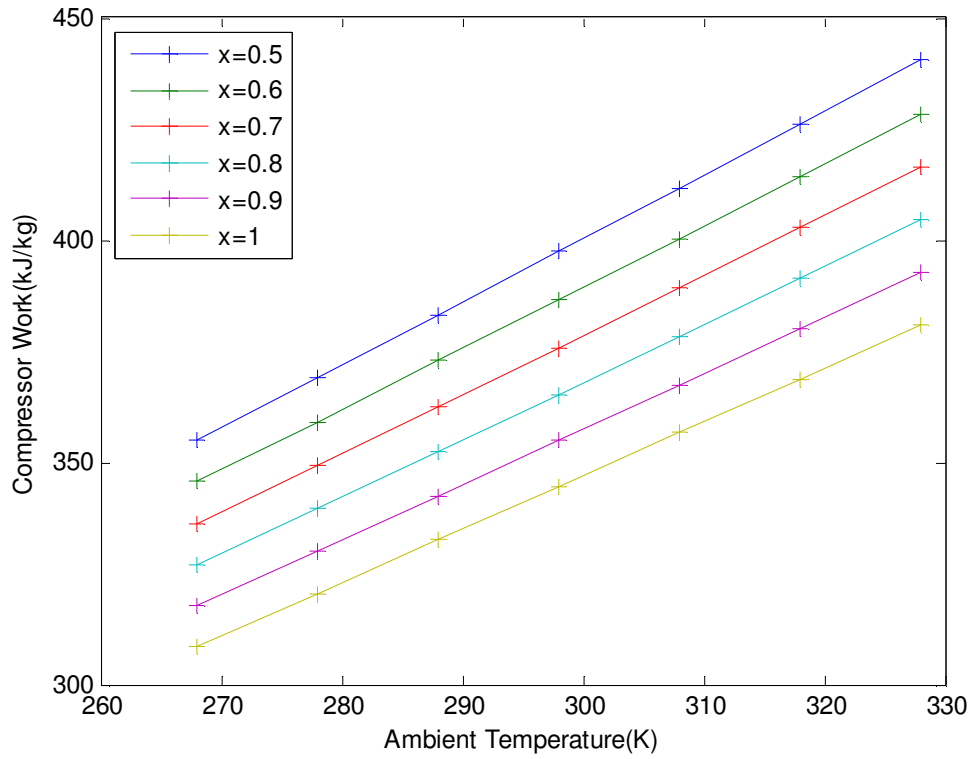


Figure 5. Effect of ambient temperature and intercooler effectiveness on compressor work.

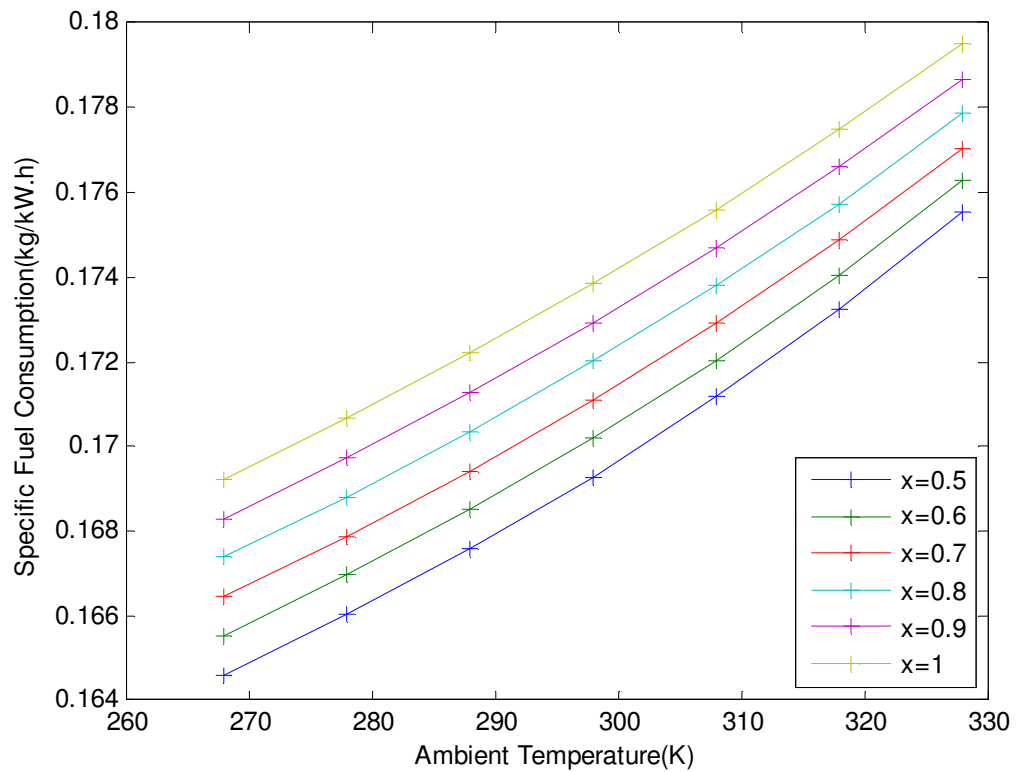
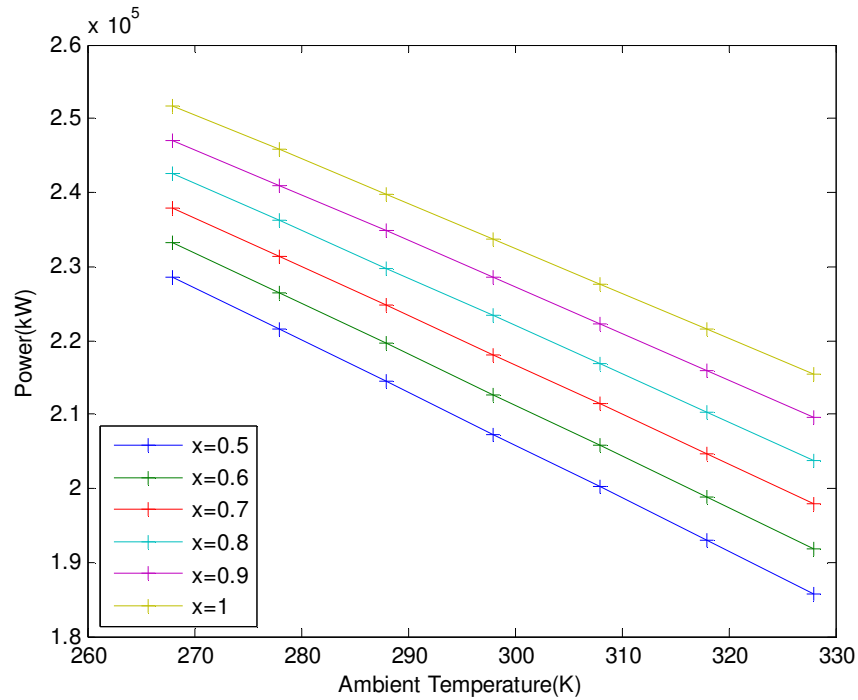
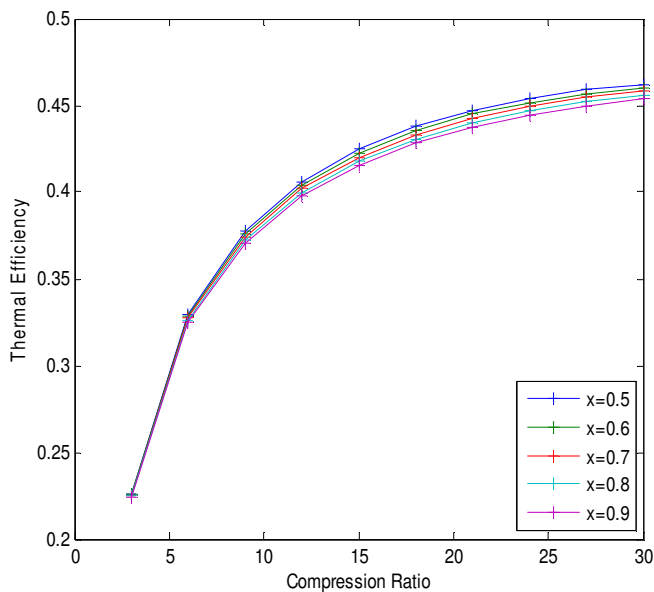


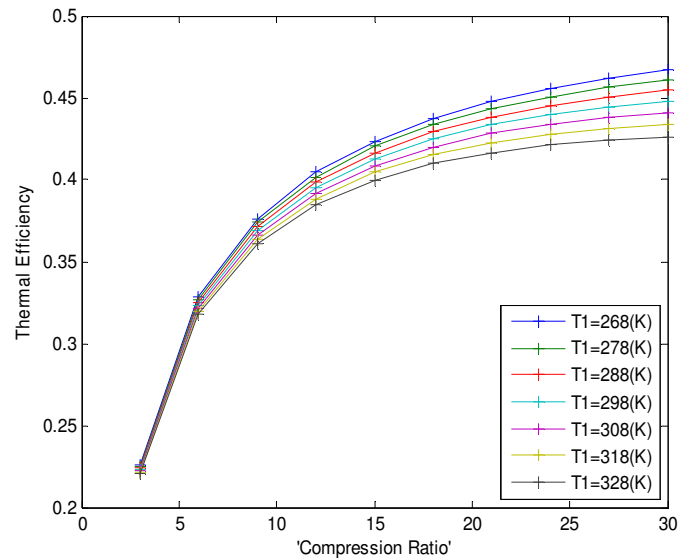
Figure 6. Effect of ambient temperature and intercooler effectiveness on specific fuel consumption.



**Figure 7.** Effect of ambient temperature and intercooler effectiveness on power output.



**Figure 8.** Effect of pressure ratio and intercooler effectiveness on the thermal efficiency.



**Figure 9.** Effect of compression ratio and ambient temperature on thermal efficiency.

cycle thermal efficiency and the thermal efficiency of gas turbine cycle with intercooler is shown in Figure 10. 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 decreases the heat added, that is, increases the thermal efficiency. In gas turbine cycle with intercooler the thermal efficiency increases with compression ratio.

Figure 11 shows the relation between turbine inlet temperature and thermal efficiency for different values of

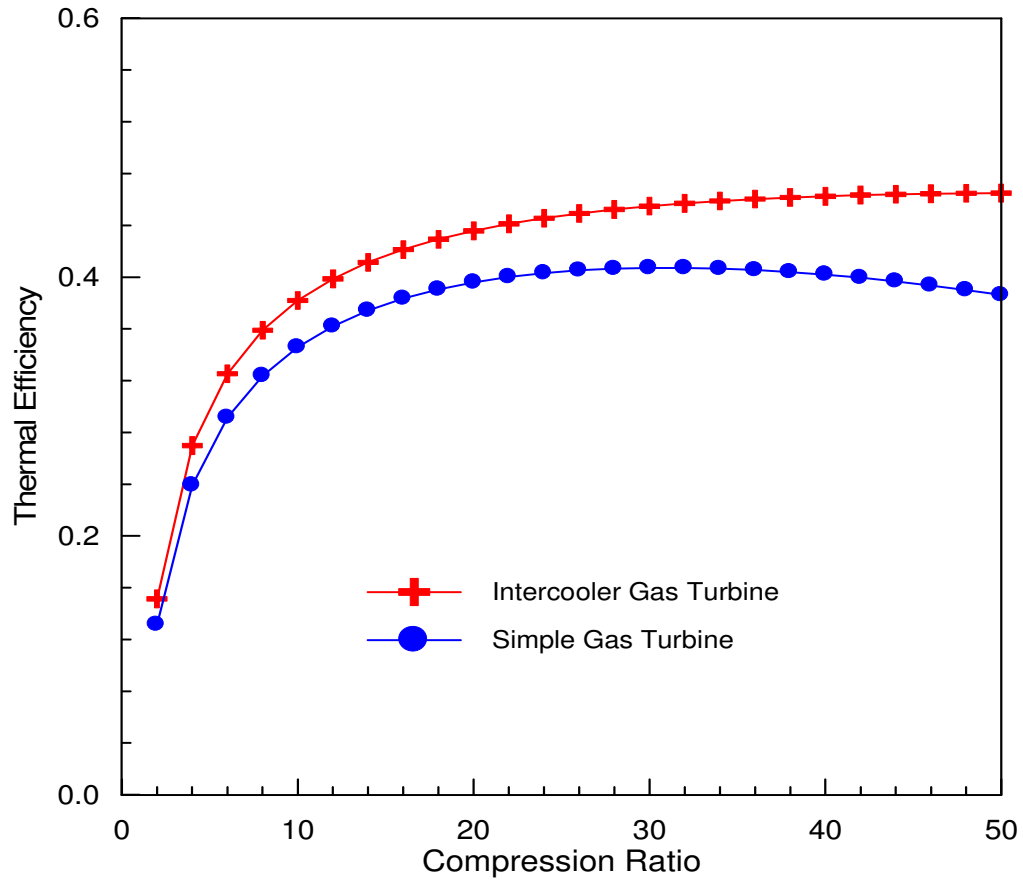


Figure 10. Effect of compression ratio on thermal efficiency for simple and intercooler gas turbine.

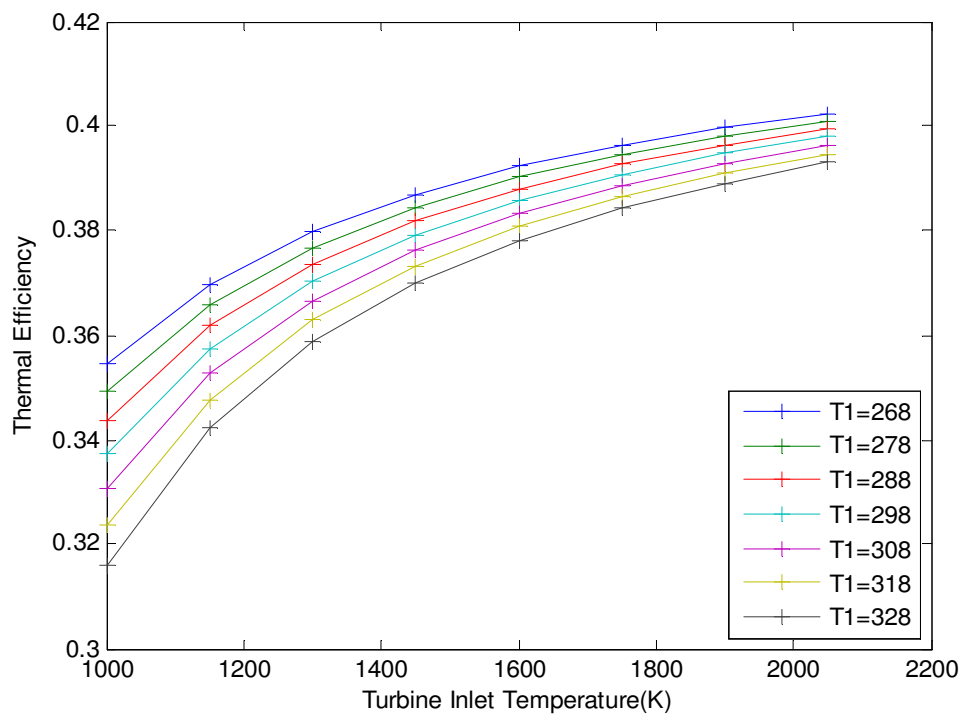
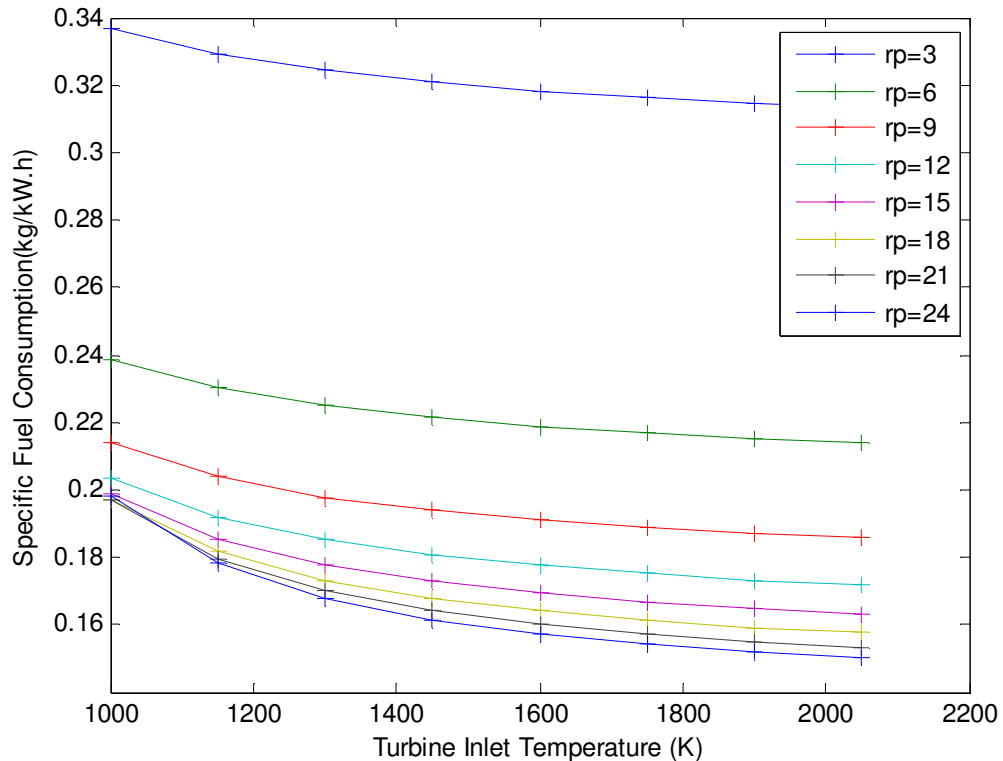


Figure 11. Effect of turbine inlet temperature and ambient temperature on thermal efficiency.



**Figure 12.** Effect of turbine inlet temperature and compression ratio on specific fuel consumption.

ambient temperature. 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, then the increase in the thermal efficiency about (6 to 8%) increases the turbine inlet temperature from 1000 to 2050K.

The relation between specific fuel consumption versus turbine inlet temperature for gas turbine cycle with intercooler at different compression ratios values is shown in Figure 12. The specific fuel consumption decreases with increase in the turbine inlet temperature and increase in compression ratio. Also the power output increases with increase in the turbine inlet temperature and compression ratio as shown in Figure 13.

Figure 14 represented the relation between the thermal efficiency and power output for eight turbine inlet temperatures (1000-2050K) and twelve pressure ratios (2-24). The compression ratio for maximum power for the turbine inlet temperatures is selecting a compression ratio of 9.3 for a turbine inlet temperature of 1000K which will result in a higher thermal efficiency, but for the turbine inlet temperature (2050K), the maximum power output was at compression ratio of 24 and that yielded the highest thermal efficiency.

The effect of isentropic compressor efficiency and intercooler effectiveness on thermal efficiency is shown in Figure 15. The thermal efficiency increased with increase

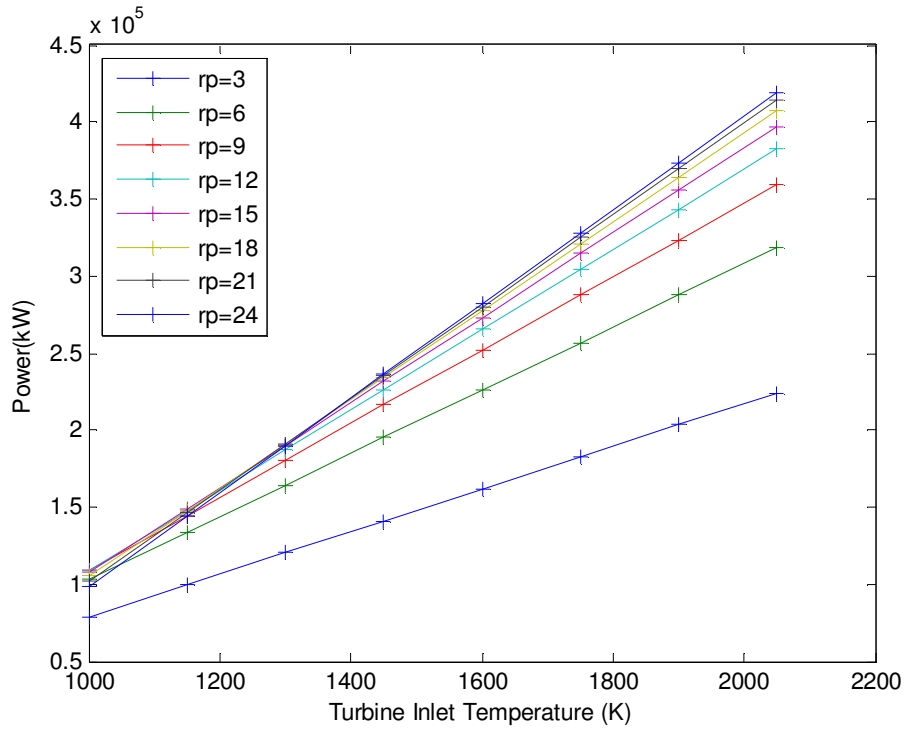
in the isentropic compressor efficiency and intercooler effectiveness but the effect of isentropic compressor efficiency is more than the effect of intercooler effectiveness. Also the thermal efficiency increased with increase in the isentropic turbine efficiency and intercooler effectiveness as shown in Figure 16.

## DISCUSSION

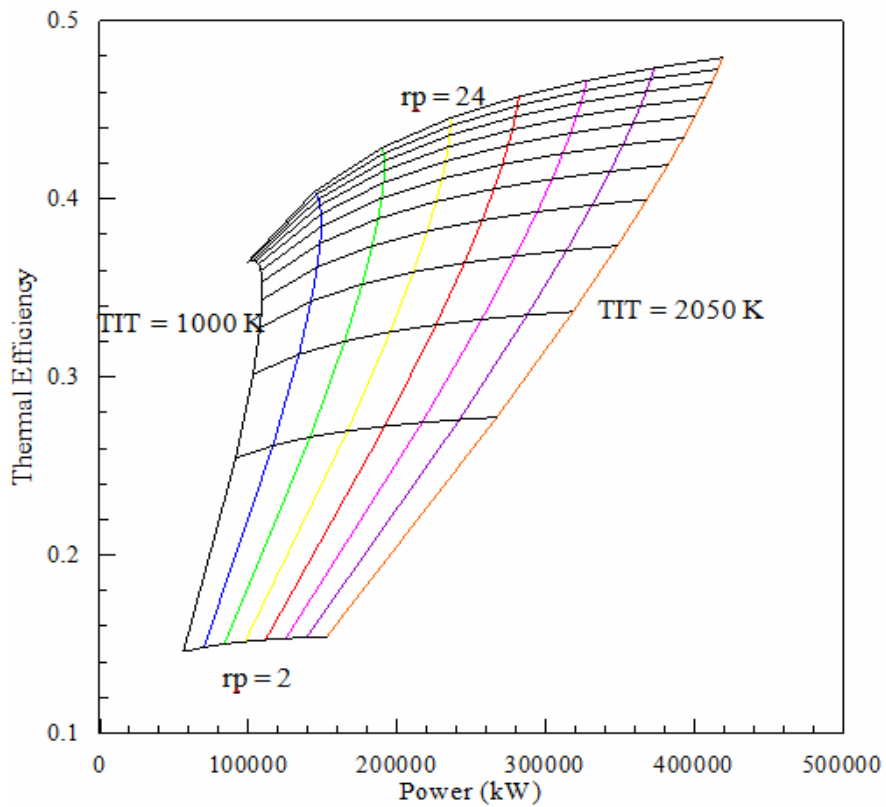
Efficiencies of the simple-cycle early gas turbines were practically increased by incorporating intercooling. The output power of a gas-turbine cycle improves as a result of intercooling. The efficiency of gas turbine with intercooler depends on the operation conditions; with full load operation giving the highest efficiency. The necessary derivation of output power and efficiency for gas turbine with intercooler were made. Results show the effect of intercooler on performance of the gas turbine power plant. The effect of increase of ambient temperature leads to decreased efficiency and that is identical to all previous studies. Also the increase in compression ratio for gas turbine with intercooler leads to a continuous increase in the thermal efficiency and this result runs counter to simple cycle for gas turbine that reaches the highest efficiency and then begins to decrease.

Therefore, the overall impact of intercooling on

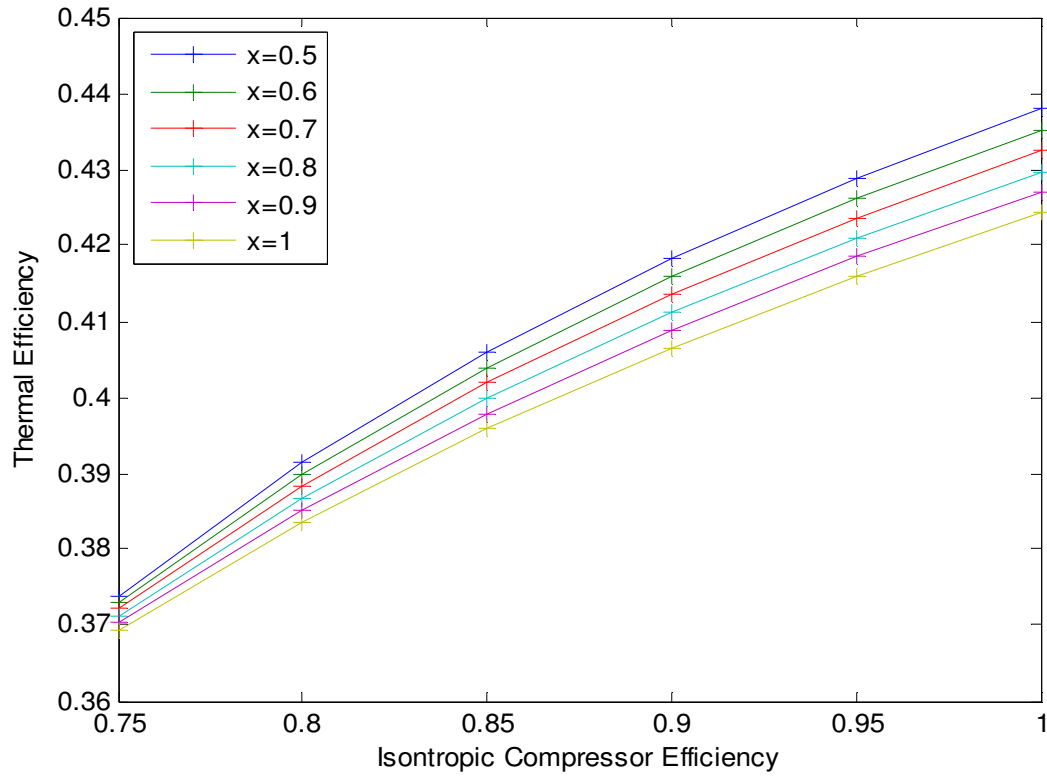




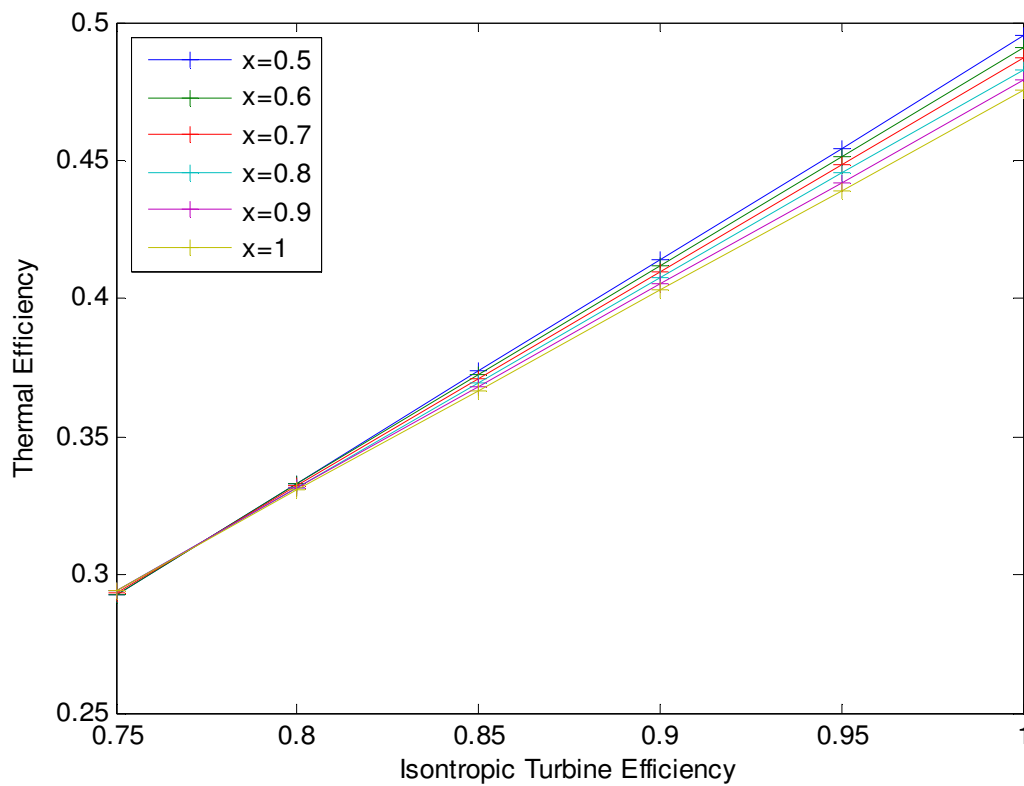
**Figure 13.** Effect of turbine inlet temperature and compression ratio on power output.



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



**Figure 15.** Effect of isentropic compressor efficiency and intercooler effectiveness on thermal efficiency.



**Figure 16.** Effect of isentropic turbine efficiency and intercooler effectiveness on thermal efficiency.

efficiency of gas turbine can be highly positive, especially when considering the possibility to take advantage of lower intercooler effectiveness to increase TIT, and then increase the output power and the thermal efficiency.

### Conclusion

The simulation result from the analysis of the influence of parameter showed that compression ratio, turbine inlet temperature and ambient temperature effect on performance of gas turbine cycle with intercooler can be summarized as follows:

1. The thermal efficiency decreases and specific fuel consumption increases with increase in the intercooler effectiveness.
2. The thermal efficiency of the simple gas-turbine cycle experiences small improvements at large compression ratios as compared to gas turbine cycle with intercooler.
3. The peak efficiency, power and specific fuel consumption occur when compression ratio increases in the gas turbine cycle with intercooler.
4. Maximum power for the turbine inlet temperatures is selecting a compression ratio of 9.3 for a turbine inlet temperature of 1000K which will result in a higher thermal efficiency.

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