Parametric Performance of Gas Turbine Power Plant with Effect Intercooler

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Abstract

A cycle model of a gas turbine power plant with effect intercooler along with a detailed parametric study is presented in this paper. The effects of parameter (design and operation condition) on the power output, compression work, specific fuel consumption and thermal efficiency are evaluated. In this study, the implementation of intercooling increases the power generating efficiency of the suggested gas turbine power plant when compared to the non-intercooled gas turbine power plant, configurations. Intercooler gas turbine cycle is analyzed and a new approach for improvement of their thermodynamic performances based on first law of thermodynamics is presented. Different effected parameters are simulated, including different compressor pressure ratios, different ambient temperature, air fuel ratio, turbine inlet temperature, and cycle peak temperature ratio were analyzed. The obtained results are presented and analyzed. Further increasing the cycle peak temperature ratio and total pressure ratio can still improve the performance of the intercooled gas turbine cycle.

Keywords: Gas turbine, Intercooler, Performance, Pressure ratio, Peak temperature ratio

1. Introduction

The world's energy demand, especially in developing countries, is growing steadily. Global energy use is expected to grow by 75 percent by 2020. The development allows us to be witnesses to the technological progress. Engineers are working to make good use of their knowledge and available materials to produce efficient, cheap and reliable machines. Over the past decade, gas turbines have turned out to be one of the most interesting techniques for electric power production (June, et al., 2009). Today, the gas turbine can be used in several different modes in critical industries such as power generation, oil and gas, process plants, transport, and smaller related industries, as well. Compressor, combustor and turbine modules are linked in a group called gas turbine generator. The last 20 years represent a large growth for gas turbine technology. This development is spear headed by the increase in compressor pressure ratio, advanced combustion techniques, improved technology for materials, the appearance of new coatings and new cooling schemes. As for the increase in gas turbine efficiency it dependents on two basic parameters enhanced efficiency in (a) pressure ratio, (b) cycle peak temperature ratio (Lingen, et al., 2011).

The gas turbine has been successfully employed in large scale to generate the electricity, whereas gas turbine ensures better production power. 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 used to reduced the temperature at the high-pressure compressor, causing reduce consumption power on compressor and lower output temperature at high pressure (Maria and Jinyue, 2005). **G**as-turbines power plant with high pressure ratios can use an intercooler to cool the air between stages of compression, allowing you to burn more fuel and generate more power. Remember, the limiting factor on fuel input is the temperature of the hot gas created, because of the metallurgy of the first stage nozzle and turbine blades. With the advances in materials technology this physical limit is always climbing.

The intercooled used to increasing the overall efficiency of a gas turbine power plant is to decrease the work input to the compression process. These effects increase of the net specific work outputs. In this process the air is compressed in the first compressor (low pressure compressor) to some intermediate pressure and so it is passed across an intercooler, where it is cooled off to a lower temperature at fundamentally constant pressure. It is suitable that the lower temperature is as low as possible. The cooled air is directed to high pressure compressor, where its pressure is further raised and then it is directed to the combustion chamber and later to the expander. A multistage compression processes is also possible. The overall result is a lowering of the net specific work input required for a given pressure ratio. However, intercooling used without reheating causes decrease of the efficiency leastways for small pressure ratios. It is explained by the drop of air temperature after the compressor, which is compensated by the increase of the temperature in the combustion chamber (Law and Reddy, 2009).

Intercooling provides significant benefits to the Brayton cycle gas turbine power plant through decreasing the work of compression for the high pressure compressor (HPC), which allows for higher pressure ratios, thus increasing overall efficiency. The cycle pressure ratio is 42:1. The reduced inlet temperature for the HPC allows increased mass flow resulting in higher specific power. The lower resultant compressor discharged temperature provides colder cooling air to the turbines, which in turn allows increased firing temperatures at metal temperatures equivalent to the LM6000™ gas turbine producing increased efficiency. The LMS100™ system is a 2550°F (1380°C) firing temperature class design(Michael, et al., 2005).

In this paper, a parametric study for performance of gas turbine power plant with intercooled compression process. The effects of ambient temperature, pressure ratio, cycle peak temperature ratio, turbine inlet-temperature, air fuel ratio and the effectiveness of the intercooler on the gas turbine cycle performance is investigated

2. Description of the Plant and Thermal Analysis

The power output of gas turbine can be increased by inter-cooling. The compressed air from low pressure compressor during delivery to high pressure compressor is cooled in the intercooler. Therefore the compression is preformed in two stages. The compressed cooled air has lesser volume, enabling air to be compressed in a smaller compressor with less expenditure of energy. Clearly the work required for compression is reduced with intercooler. The heat supplied with inter-cooling is more than that with the heat supplied in single stage compression. The net output is also increased but thermal efficiency falls due to increased heat supply.

The system diagram, which was analyzed, is depicted in figure 1. The system consists of a low-pressure compressor, intercooler, high-pressure compressor, combustion chamber and turbine (Wenhua, et al., 2005). Consider Figure 2 and assume that the compressor is working between the thermodynamic states 0 and 1. If the air is cooled from state 1 to 2 the required compressor power is decreased and the net cycle power delivered is increased if the inlet temperature is reduced, (Cengel and Boles, 2008). Efficient compression of large volume of air is essential for a successful gas turbine power plant. It is assumed that the turbine efficiency (η_t), compressor efficiency (η_c) and effectiveness of intercooler is ε. The actual processes and ideal processes are represented in dashed line and full line, respectively, on the T-S diagram figure 2 (Horlock, et al., 2003).

$$T_1 = T_0 \left(1 + \frac{r_{LPC}^{\frac{\gamma-1}{\gamma}} - 1}{\eta_{LPC}} \right) \tag{1}$$

The work required to run the low pressure compressor is:

$$w_{LPC} = c_p T_0 \left(\frac{r_{LPC}^{\frac{\gamma-1}{\gamma}} - 1}{\eta_{LPC}} \right) \tag{2}$$

The specific heat of air is given by (Ulizar, 1998):

$$\begin{aligned} c_p = 4185.787(((((((1.0116\times10^{-25}\times T - 1.4527\times10^{-21})T + \\ 7.6216\times10^{-18})T - 1.5128\times10^{-14})T - 6.7178\times10^{-12})T \\ + 6.5519\times10^{-8})T - 5.1537\times10^{-5})T + 0.2502) \end{aligned} \tag{3}$$

The effectiveness for intercooler can be defined as:

$$\varepsilon = \frac{T_2 - T_1}{T_1 - T_0} \tag{4}$$

Therefore T_2 can be calculated from above equation.

The work relations of the components involved in the intercooler gas turbine power plant can be given by:

The work required to run the high pressure compressor is:

$$w_{HPC} = c_p T_2 \left(\frac{r_{HPC}^{\frac{\gamma-1}{\gamma}} - 1}{\eta_{HPC}} \right) \quad (5)$$

The work of gas turbine is:

$$w_t = c_p T_4 \eta_t \left(1 - \frac{1}{r_t^{\frac{\gamma-1}{\gamma}}} \right) \quad (6)$$

The combustion energy balance equation used:

$$f = \frac{m_f^{\cdot}}{m_a^{\cdot}} = \frac{t - r_{HPC}^{\frac{\gamma-1}{\gamma}}}{\frac{LHV}{c_p T_0} - t} \quad (7)$$

$$t = \frac{T_4}{T_0} \quad (8)$$

where is the fuel mass flow.

Having described all the components of the cycle its specific work can be stated:

$$W_n = w_t - w_{LPC} - w_{HPC} \quad (9)$$

For the ideal case when we neglected the pressure losses it is valid that:

$$r_t = r_{LPC} \times r_{HPC} \quad (10)$$

The thermal efficiency can be calculated from this formula:

$$\eta_{th} = \frac{W_n}{f \times LHV} \quad (11)$$

3. Result and Discussions

The simulation result from the analysis of the influence of parameter showed that total pressure ratio, turbine inlet temperature and ambient temperature effect on performance of gas turbine cycle with intercooler. The effects of various parameters influencing the gas turbine main characteristics are examined and the results of the case studied are compared based on different criteria such as power, specific fuel consumption, and thermal efficiency.

3.1 Effect of Total Pressure Ratio

Figure 3 shows the effect of total pressure ratio on total compressor work for various values of intercooler effectiveness. The work required to run the compressor increased with increased the total pressure ratio but the work of compressor will decreased with increased the effectiveness for intercooler. Also the turbine inlet temperature decreases with increases the intercooler effectiveness and increases with increased the total pressure ratio as shown in figure 4, because decreases the work required to run the compressor and increases the turbine inlet temperature the power output increases with increases the total pressure ratio as shown in figure 5.

The relation between specific fuel consumption versus total pressure ratios for intercooler gas turbine cycle at different effectiveness values for intercooler $\varepsilon = 0.5$ to 1 shown in figure 6. The specific fuel consumption decreases about 50% when the total pressure ratio increases from 6 to 40. The thermal efficiency increased with total pressure ratio at deferent values for intercooler effectiveness as shown in figure 7. Also the thermal efficiency increased about 40% when the total pressure ratio increased from 6 to 40.

3.2 Effect of Ambient Temperature

The variation of total compressor work with ambient temperature for various values of intercooler effectiveness is shown in Figure 8. It shows that when the ambient temperature increases the total compressor work increases too. This is because, the air mass flow rate inlet to compressor increases with decrease of the ambient temperature. So, the total compressor work will increase, since air fuel ratio is kept constant. The power increase is less than that of the inlet compressor air mass flow rate; therefore, the total compressor work increases with the increase of ambient temperature but the total compressor work will decreases with increases the intercooler effectiveness. The turbine inlet temperature increased with increased ambient temperature and decreased with increased intercooler effectiveness as shown in figure 9.

Figure 10 shows the effect of ambient temperature on the power output of intercooler gas turbine cycle. It is clear from the figure that decreasing the ambient temperature increases the gain in power output. As the ambient temperature increases, the total work of the compressors increases (Horlock, 2003), thus reducing cycle efficiency for the intercooler gas turbine cycles. It can be noticed from Figures 11 that the gain in efficiency because of decreases intercooler effectiveness from (1- 0.5) could reach 8.2%. Therefore the specific fuel consumption will increases with increases the ambient temperature as shown in figure 12. It is clear from the figure that decreasing the ambient temperature increases the gain in power output. A direct effect of inlet temperature on the standard air power output for simple gas turbine and the power output of gas turbine cycle with intercooler is shown in figure 13.

3.3 Effect Air Fuel Ratio

Figure 14 shows the effect of ambient temperature on thermal efficiency for various values of air fuel ratio and fixed total pressure ratio. The thermal efficiency will increases about 2.4% when the air fuel ratio decreases form 50 to 30. Also figure 15 represented the relation between the thermal efficiency and total pressure ratio for various values of air fuel ratio and fixed ambient temperature. The thermal efficiency will increases about 3.9% when the air fuel ratio decreases form 50 to 30.

3.4 Effect Cycle Peak Temperature Ratio

Figure 16 represented the relation between the thermal efficiency and the cycle peak temperature ratio for six total pressure ratios (6-36). The thermal efficiency increased from 30% t0 47% when the total pressure ratio increases from 6 to 36. It is clear from the figure that increasing the cycle peak temperature ratio increases the gain in thermal efficiency. As the cycle peak temperature ratio increases, the total work of the compressors decreases.

5. Conclusions

The result from the analysis of the effect of parameter showed that total pressure ratio, cycle peak temperature ratio, air fuel ratio and ambient temperature effect on performance of gas turbine cycle with intercooler. The results were summarized as follows.

1) The cycle calculation used in the intercooler gas turbine power plant analysis is correct. The examination of effect of varying parameters on the cycle performance is reliable.

2) Comparatively an intercooled gas turbine power plant can offer a fuel consumption of 8% better than that of a simple cycle gas turbine, with a 5-9 % increase in power.

3) As expected the higher total pressure ratio and cycle peak temperature ratio result in better performance.

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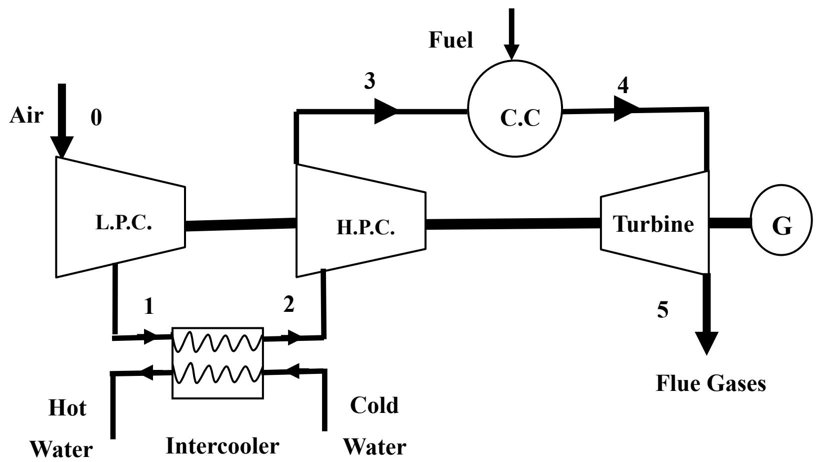

Figure 1. Schematic layout for the intercooled gas turbine

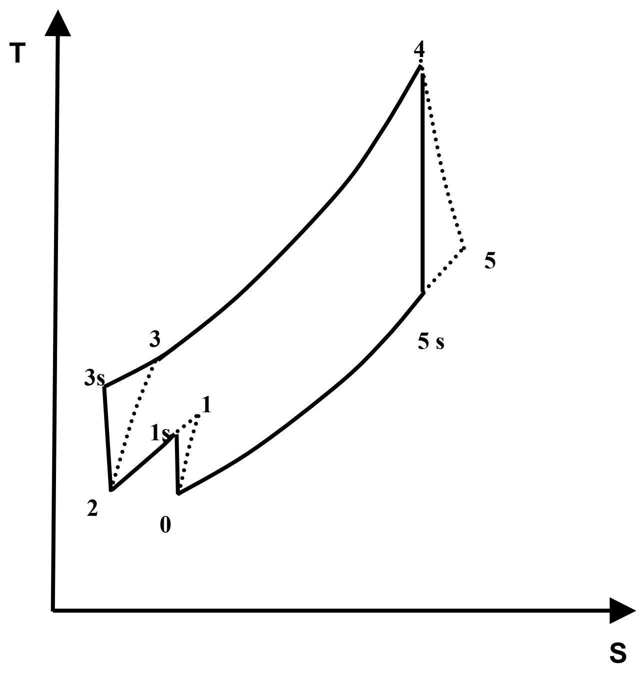

Figure 2. T-S diagram for intercooler gas turbine

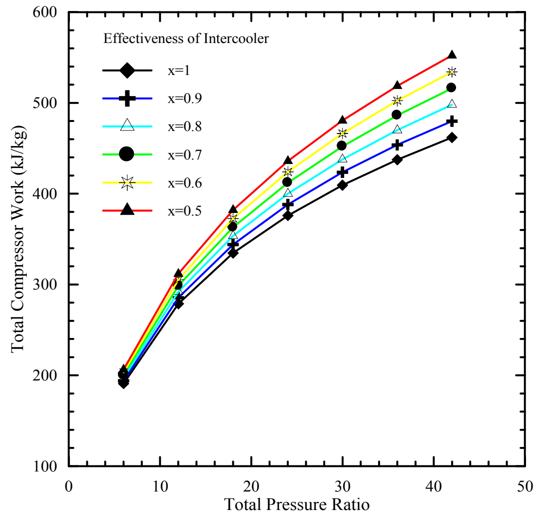

Figure 3. Effect of total pressure ratio on total compressor work for various values of intercooler effectiveness

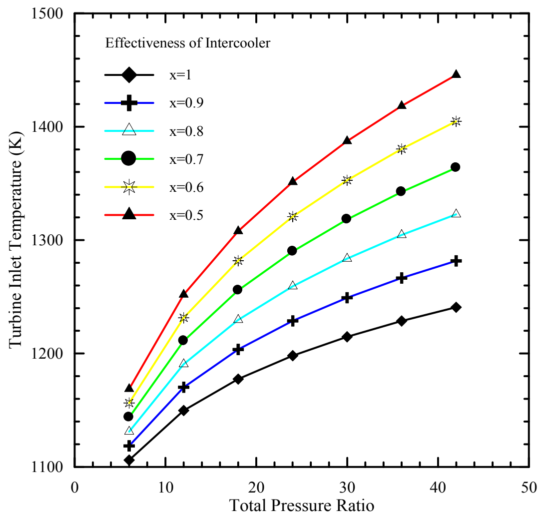

Figure 4. Effect of total pressure ratio on turbine inlet temperature for various values of intercooler effectiveness

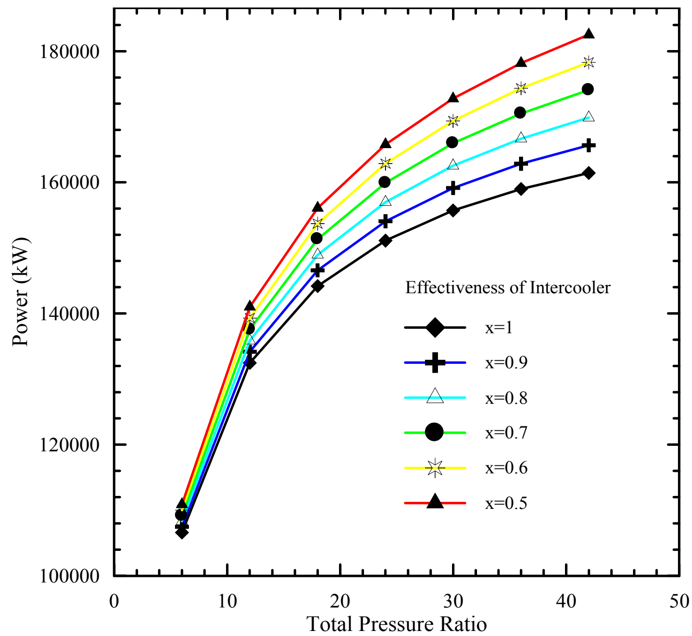

Figure 5. Effect of total pressure ratio on power for various values of intercooler effectiveness

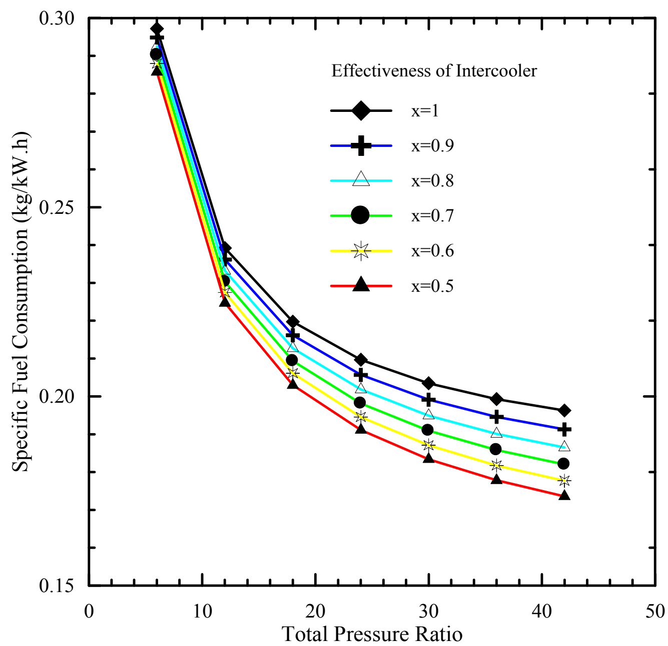

Figure 6. Effect of total pressure ratio on specific fuel consumption for various values of intercooler effectiveness

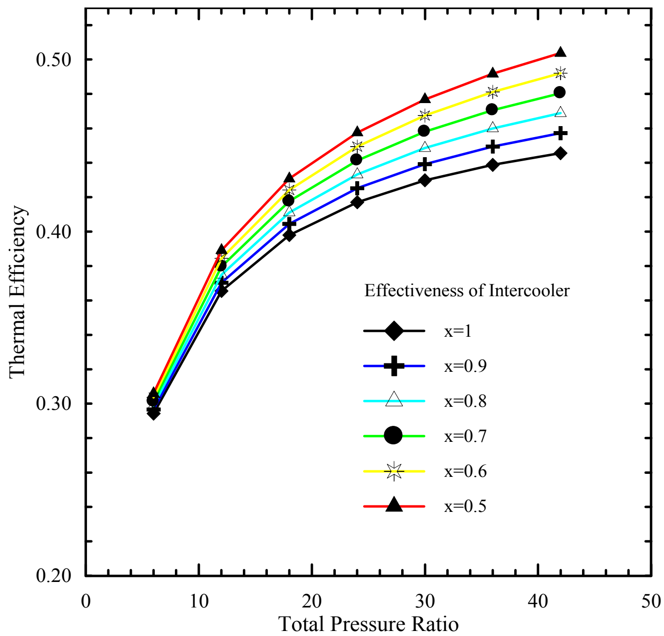

Figure 7. Effect of total pressure ratio on thermal efficiency for various values of intercooler effectiveness

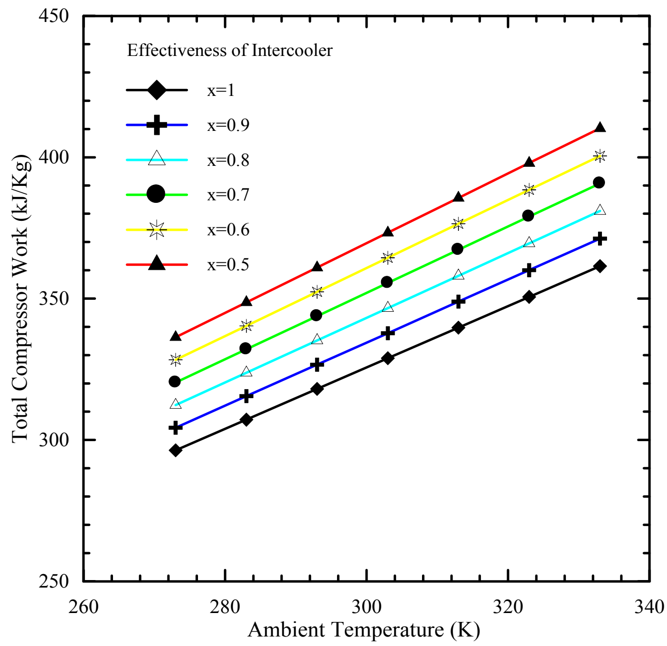

Figure 8. Effect of ambient temperature on total compressor work for various values of intercooler effectiveness

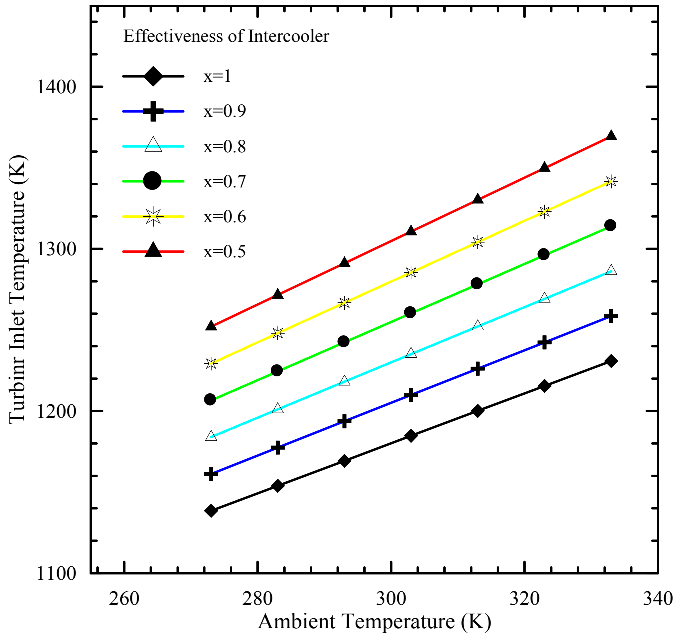

Figure 9. Effect of ambient temperature on turbine inlet temperature for various values of intercooler effectiveness

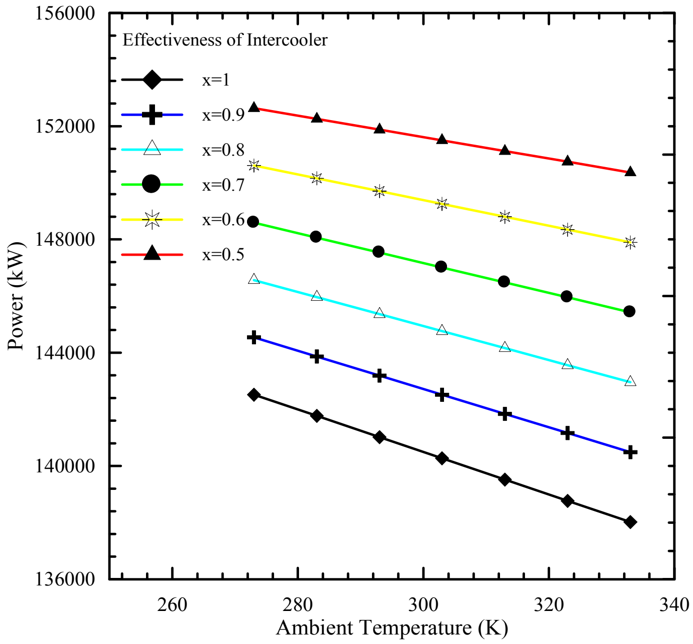

Figure 10. Effect of ambient temperature on power for various values of intercooler effectiveness

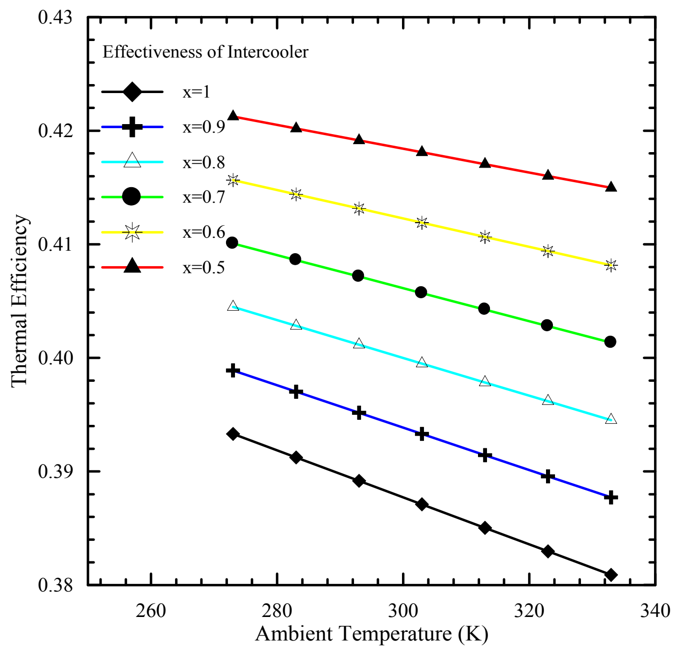

Figure 11. Effect of ambient temperature on thermal efficiency for various values of intercooler effectiveness

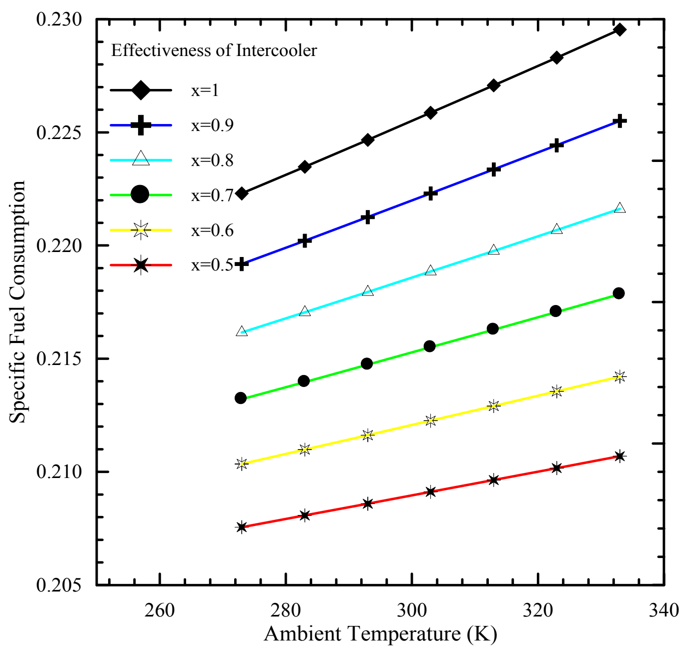

Figure 12. Effect of ambient temperature on specific fuel consumption for various values of intercooler effectiveness

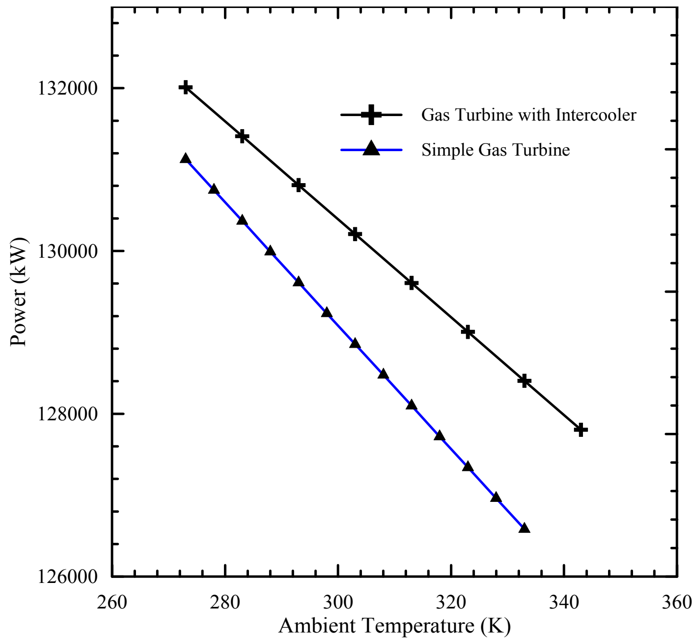

Figure 13. Effect of ambient temperature on power output for simple and intercooler gas turbine

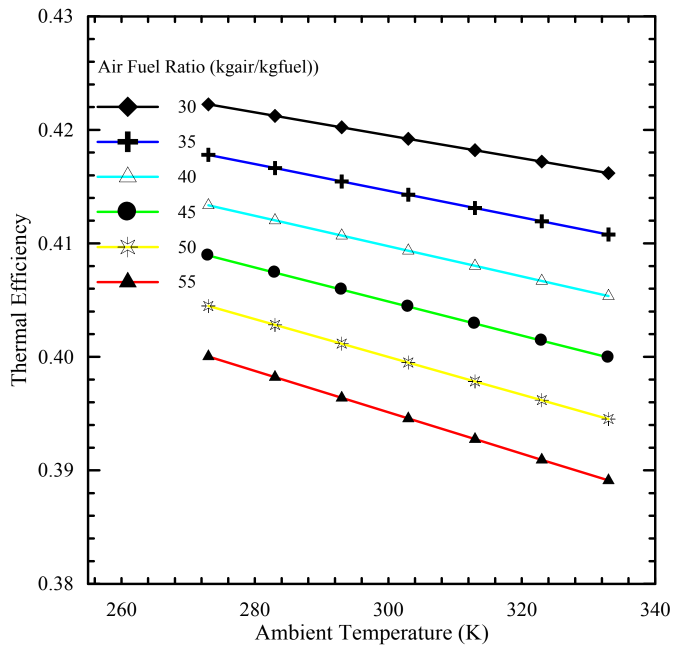

Figure 14. Effect of ambient temperature on thermal efficiency for various values of air fuel ratio

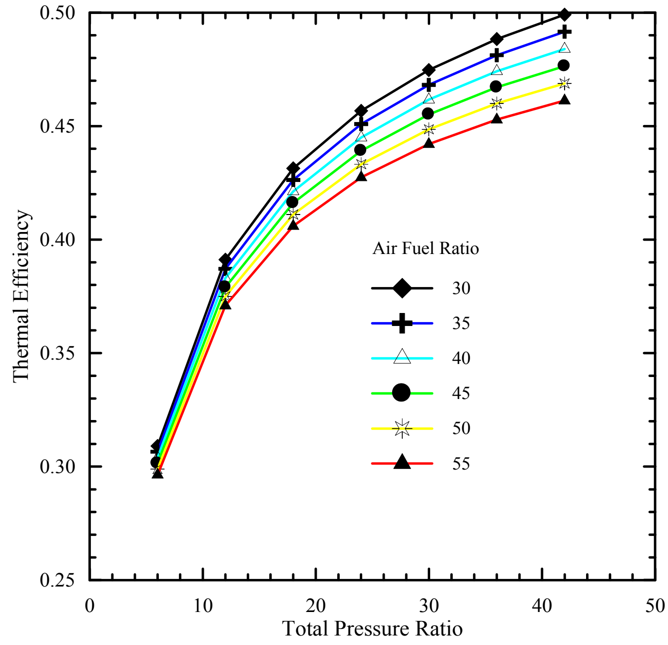

Figure 15. Effect of total pressure ratio on thermal efficiency for various values of air fuel ratio

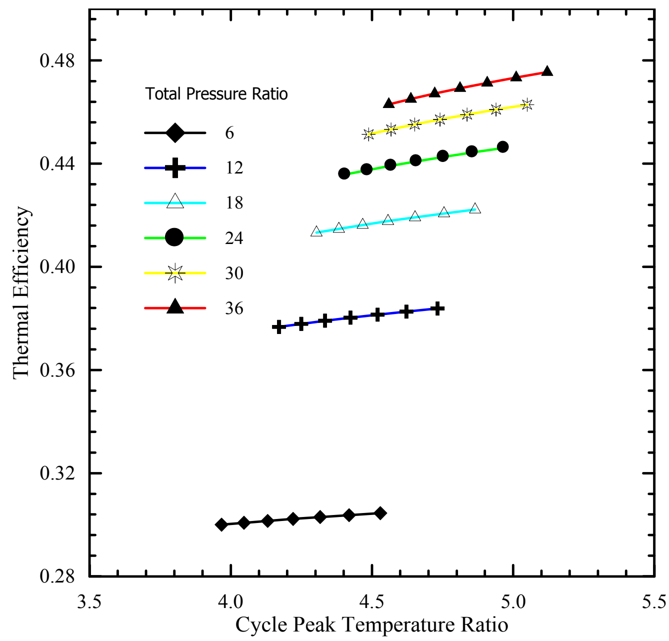

Figure 16. Effect of cycle peak temperature ratio on thermal efficiency for various values of total pressure ratio