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Thermodynamic Analysis of a Gas Turbine

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ABSTRACT

This study involves analyzing of a natural gas turbine system by using the first and second laws of thermodynamics. As a result of the study, the optimal operating conditions of a gas turbine were determined and some information was given on what needs to be done to increase the efficiency. It was determined that an average of 81.1% of the energy produced in the gas turbine was consumed in the compressor while the compressor compression ratio was 10:1; also an average of 78% while the compressor compression ratio was 15:1, an average of 76.2% while the compressor compression ratio was 20:1 and an average of 75.7% while the compressor compression ratio was 25:1 at compressor air inlet temperatures between 270 and 303 K. A 33^{o}C increase in compressor inlet temperature leads to a 6% reduction in thermal efficiency when the compressor pressure ratio is 10:1, and leads to a 4.8% reduction when the compressor pressure ratio is 25:1. The increase in the compressor inlet air temperature reduces the thermal efficiency at all compressor pressure ratios. However, the effect of reducing the thermal efficiency of the increase in compressor inlet air temperature is reduced as the compressor pressure ratio increases. Also the reversible work and the second law efficiency of the compressor of the gas turbine system were calculated at different compressor pressure ratios for different compressor air inlet temperatures.

Keywords: Gas turbine; Compressor; Thermodynamic analysis; Optimal operating conditions.

1. INTRODUCTION

According to other energy sources, natural gas, which is easy to use and has less impact on the environment, is increasingly used as primary energy source in Turkey. Due to its advantages such as high efficiency and short time operation, natural gas-fired gas turbines have been used increasingly in recent years in electricity generation in our country. Natural gas fueled gas turbines can be operated in a shorter period of time with lower installation costs than thermal, nuclear and hydroelectric power plants using other fossil fuel sources. In addition to providing high efficiency and power, gas turbines have working characteristics that are suitable for flexible operating conditions, can be quick-actuated, can be easily adapted to full load and variable load conditions, and change their efficiency according to ambient temperature and compressor pressure ratio. Gas turbines are used worldwide for power generation in many regions. The place of installation of such systems is very important. The interest of the gas turbines in the generation of electricity is very much related to the environmental temperature. The average environmental temperature and humidity from different geographical locations affect power generation and turbine efficiency.

The first law of thermodynamics relates to the quantity of energy and refers to the conservation of energy. The first law does not make any assessment of the nature of the energy. The second law of thermodynamics makes it possible to make evaluations on the quality of the energy. The second law analysis is based on entropy or available energy.
There is considerable work in the literature on the performance of gas turbines. Ünver and Kılıç (2009) studied thermodynamic analysis of a combined cycle power plant. In the study, the changes of the performance parameters of a natural gas-fired combined cycle power plant were investigated with the help of first and second law analysis of thermodynamics [1]. Çetin (2006) has conducted a study on the optimal performance analysis of gas turbines. They theoretically calculated according to the working conditions of gas turbines. As a result of the calculations made, he has interpreted and suggested the optimal performance analyzes of the working conditions of the gas turbines [2]. Alhazmy and Najjar (2004) have conducted a study to improve the gas turbine performance by cooling the compressed air. They used two different types of coolers in their work. These are water-sprayed and cooling coils [3]. Basrawi *et al.* (2011) examined the effect of ambient temperature on the performance of a micro gas turbine system in cold climatic conditions [4].

2. MATERIAL AND METHODS

2.1. Gas turbine system

As a gas turbine, a natural gas-operated system was examined in the Caterpilar Tarus 5.7 MW power plant, which is shown in Figure 1. The characteristics of the gas turbine is shown in Table 1.

Table 1. Characteristics of the gas turbine considered in the study [5].

Brand Mark	Installed power (MW)	Length (m)	Width (m)	Height (m)	Weight (kg)
Caterpilar Tarus	5.7 MW	9.8	2.5	2.9	32800

In the Caterpilar Tarus gas turbine, the pressure and temperature of the air taken by the filter are raised by the rotors in the compressor. The pressure and temperature of the compressor are mixed with the natural gas, and the gas is sent to the combustion chamber of the turbine by the manifold. The combustion air, which is the result of combustion, is propelled by the gas turbine shaft. The shaft of the gas turbine begins to rotate with this drive and performs the electricity generation by rotating the shaft of the gas turbine generator connected to it. The gases produced as a result of combustion are discharged to the atmosphere through the exhaust outlet system.

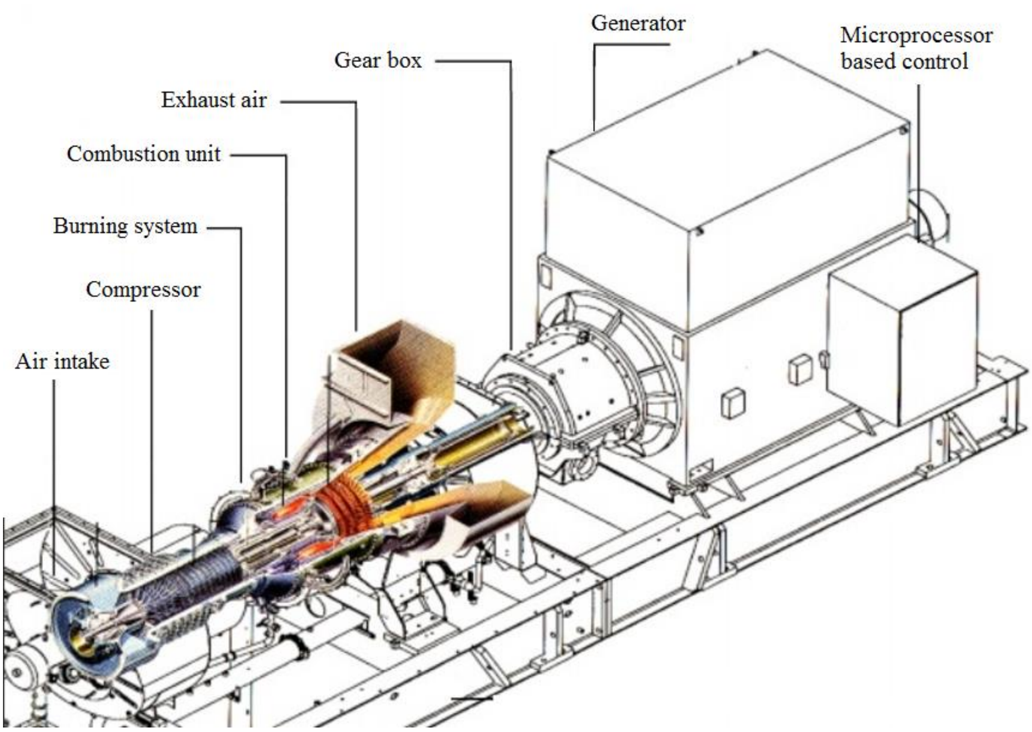

Figure 1. Schematic view of the gas turbine system [5].

2.2. Formulation

Thermodynamic analysis was carried out by taking temperature and pressure values at different compressor pressure ratios. The assumptions made for the analysis are: Air and products of combustion are assumed to be ideal gases. It is thought to be a complete combustion reaction. Each of the components that constitute the system is considered as a steady-flow control volume. The combustion gases are considered to be air. First, inlet temperatures and turbine combustion chamber temperatures were taken by the plant during the year at different compressor pressures. The ideal gas table for the air was used in solutions. Figure 2 shows the main components of the gas turbine cycle and the points considered in calculations. The principle of conservation of energy, in other words first law of thermodynamics for a steady-flow open system is expressed as follows [6]:

$$\dot{Q} - \dot{W} = \sum \dot{m}_{out}\left(h_{out} + \frac{V_{out}^2}{2} + gz_{out}\right) - \sum \dot{m}_{in}\left(h_{in} + \frac{V_{in}^2}{2} + gz_{in}\right) \quad (1)$$

where $\dot{Q}$ (kW) is heat transfer rate, $\dot{W}$ (kW) is power, $\dot{m}$ (kg/s) is mass flow rate, h (kJ/kg) is enthalpy, V (m/s) is velocity of the fluid related to the kinetic energy, g (m/s^2) is acceleration of gravity and z (m) is elevation related to the potential energy. Also, the subscripts *in* and *out* denotes the fluid entering and leaving the control volume respectively.

The kinetic and potential energy changes between compressor input and output, and the heat transfer at the compressor can be neglected. In this case, according to Figure 2, compressor work w_c (kJ/kg) can be written as;

$$-w_c = h_2 - h_1 \quad (2)$$

The heat given to the system in the combustion chamber is q_{in} (kJ/kg);

$$q_{in} = h_3 - h_2 \tag{3}$$

Turbine work is w_t (kJ/kg);

$$w_t = h_3 - h_4 \tag{4}$$

Net work of the system is w_{net} (kJ/kg);

$$w_{net} = w_t - w_c \tag{5}$$

Thermal efficiency of the cycle is;

$$\eta_{th} = \frac{w_{net}}{q_{in}} \tag{6}$$

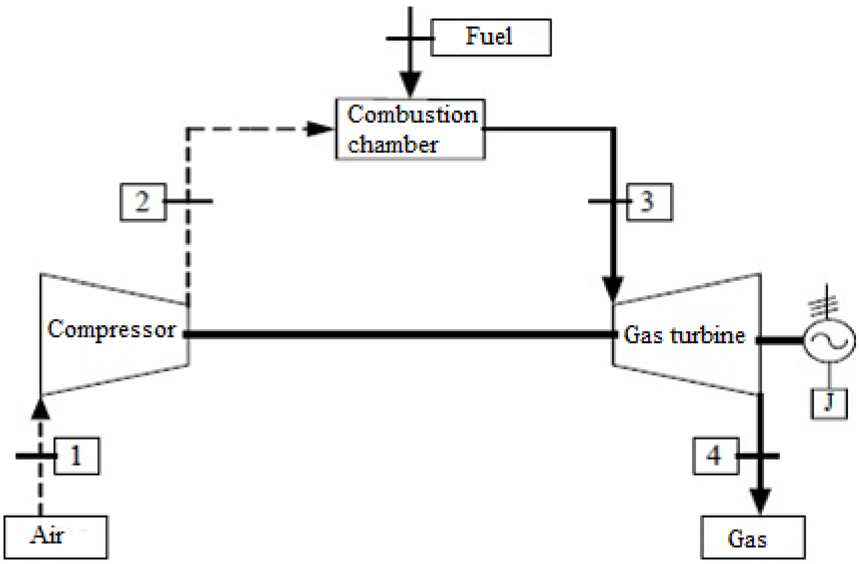

Figure 2. Gas turbine cycle.

The second law of thermodynamics for a steady-flow open system is expressed as follows:

$$\dot{S}_{pro} = \sum \dot{m}_{out}\, s_{out} - \sum \dot{m}_{in}\, s_{in} + \frac{\dot{Q}_o}{T_o} \tag{7}$$

where $\dot{S}_{pro}$ (kW/K) is entropy production, $\dot{m}$ (kg/s) is mass flow rate, s (kJ/kg·K) is specific entropy, $\dot{Q}_o$ (kW) is heat transfer rate between the system and the environment, T_o (K) is temperature of the environment.

Reversible work w_{rev} (kJ/kg) for the compressor is;

$$w_{rev} = (h_1 - h_2) - T_o(s_1 - s_2) \tag{8}$$

When calculating the entropy change for an ideal gas considering the variable specific heat, the following relation can be used taking into account both the effect of temperature and pressure on the entropy;

$$s_1 - s_2 = (s_1^o - s_2^o) - R \cdot ln\frac{P_1}{P_2} \tag{9}$$

where R (kJ/kg·K) is ideal gas constant and P (kPa) is pressure. Second law efficiency for the compressor is as follows:

$$\eta_{c,II} = \frac{w_{rev}}{w_u} \tag{10}$$

where w_{rev} (kJ/kg) is reversible work and w_u (kJ/kg) is useful work.

3. RESULTS AND DISCUSSION

In this study the effect of ambient temperature and the compressor compression ratio on the performance of the gas turbine was determined by using thermodynamic analysis. Specific net work, thermal efficiency of the system, reversible work and second law efficiency of the compressor were calculated. Figure 3 shows the variation of the energy consumed in the compressor according to the pressure ratio in the compressor. When the figure is examined, the energy consumed in the compressor is also increased in proportion to the ambient temperature and compressor pressure ratio.

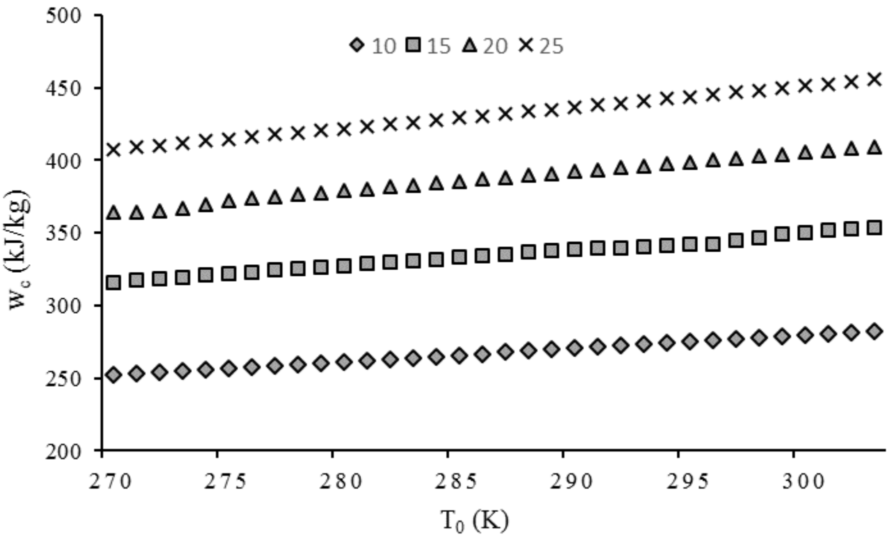

Figure 3. Energy consumed in compressor for different compressor pressure ratio and inlet air temperature values.

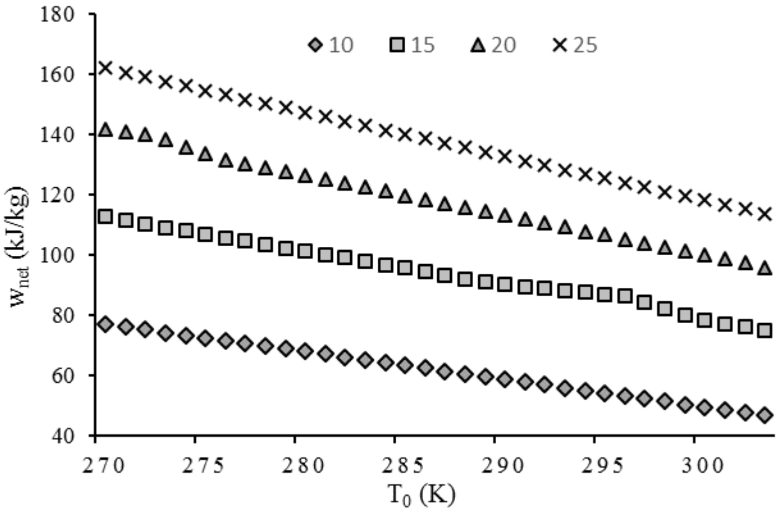

Figure 4. Net work values for different compressor pressure ratio and inlet air temperature values.

Figure 4 shows w_{net} values at different compressor pressure ratios according to T_0 temperature. For example, the pressure ratio is 10:1, w_{net}=77.3 kJ/kg at T_0=270K, and w_{net}=46,7 kJ/kg at T_0=303K. However, when the pressure ratio is 25:1, w_{net}=162.1 kJ/kg at T_0=270K and w_{net}=113.8 kJ/kg at T_0=303K. As can be seen from the calculation results, the net work is increasing as the compressor pressure ratio decreases and the ambient temperature decreases.

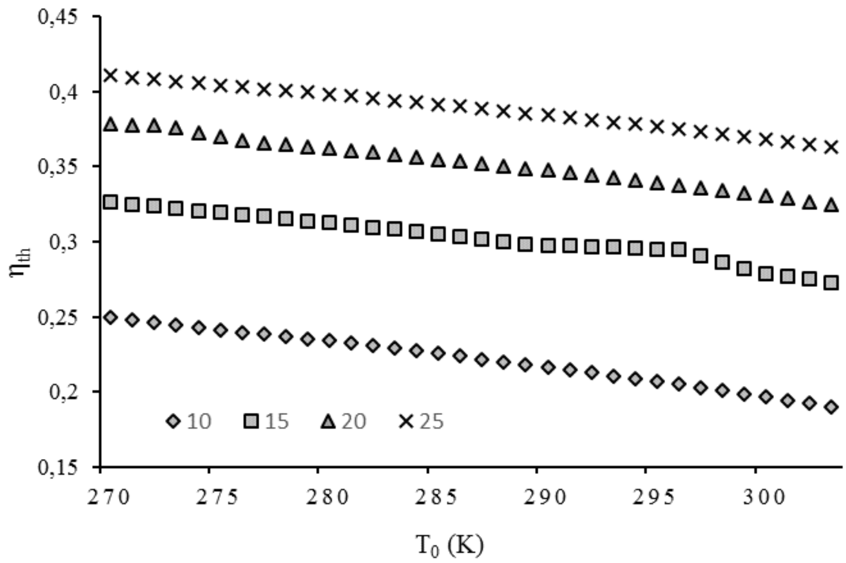

Figure 5. Thermal efficiency for different compressor pressure ratio and inlet air temperature values.

The effect of ambient temperature on thermal efficiency at different pressure ratios can be seen in Figure 5. At any compressor pressure ratio value, as the ambient temperature increases, the thermal efficiency decreases while the decrease in the pressure ratio causes the tendency to decrease at the thermal efficiency. For example, for a 10:1 pressure ratio, the thermal efficiency at T_0=270 K is 24.9% and the thermal efficiency at T_0=303K is 18.9%. While the pressure ratio is 10:1, an increase of 33^{o}C at ambient temperature reduces the thermal efficiency by 6%. For a 25:1 pressure ratio, the thermal efficiency at T_0=270K is 41% and the thermal efficiency at T_0=303K is 36.2%. While the pressure ratio is 25:1, an increase of 33^{o}C at ambient temperature reduces the thermal efficiency by 4.8%. As the compressor pressure ratio increases, the effect of the ambient temperature on the thermal efficiency decreases.

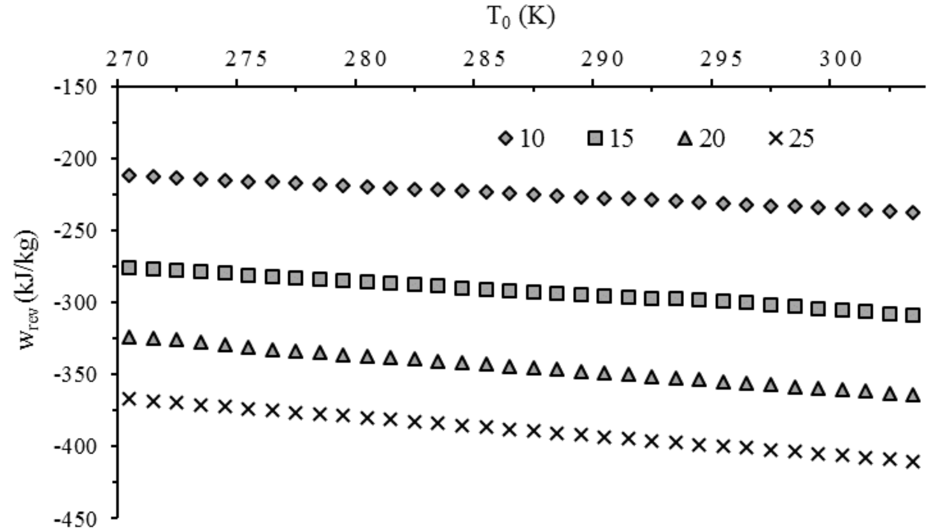

Figure 6. Reversible work of compressor for different compressor pressure ratio and inlet air temperature values.

Figure 6 shows the reversible work of the compressor depending on the air inlet temperature at different compressor pressure ratios. Reversible work represents the most useful work that can be obtained from a system. This happens when the system is totally reversible. In other words, the heat transfer between the system and environment is reversible and there is no irreversibility in the system. As can be seen in this figure, the reversible work is considerably reduced with increasing in the compressor pressure ratio and ambient temperature.

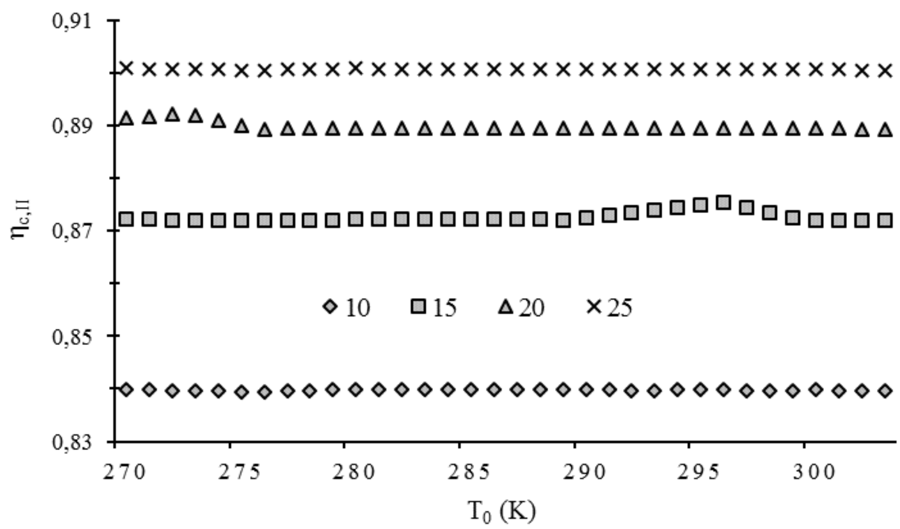

Figure 7. Second law efficiency of the compressor for different compressor pressure ratio and inlet air temperature values.

Figure 7 shows the second law efficiency values calculated for the compressor depending on inlet air temperature at different compressor pressure ratios. The second law is about how much of the business potential is being used. The second law is the ratio of useful work to the least (reversible) work required for compressors. As can be seen from this figure, the second law efficiency increases with increase in compressor pressure ratio. When the compressor pressure ratio is 10, the second law efficiency is approximately 84%, when it is 15, it is between 87-88%, when it is 20 it is about 89% and when the pressure ratio is 25, second law efficiency is slightly over 90%. On the other hand, the second law efficiency does not change considerably depending on the inlet temperature of the compressor inlet air.

4. CONCLUSION

As can be seen from the results obtained, at any pressure ratio value, the net work and thermal efficiency decreases as the ambient temperature increases. As the compressor pressure ratio increases, the energy, net work and thermal efficiency of the compressor is increased. That is, the thermal efficiency and net work are directly proportional to the compressor pressure ratio, while the energy consumed in the compressor is inversely proportional to the compressor pressure ratio.

As the ambient temperature increases, the mass flow of air entering the gas turbine decreases, which causes the net work value to be reduced by affecting the entire system. It is also seen that the pressure ratio of the compressor is higher than the ambient temperature of the effect of the system on the thermal efficiency.

As a result, it is very important to determine the compressor pressure ratio during the first stage of the system installation. Because, as the net work of the system decreases at low pressure ratios, it is necessary to increase the mass load, that is, to design a larger system, in order to obtain the desired power. A larger system may not be economical. Therefore, the most economical system should be determined by the relationship between compressor pressure ratio, ambient temperature change and desired net work. The best choice for this plant is to use a 25:1 compressor. Once the compressor selection has been completed, the annual temperature data at which the system is to be installed should be inspected, and the systems to be used to reduce the temperature of the compressor air entering must be investigated. The cost of the pre-cooling systems should be determined by comparing the income from the increase in the efficiency of the system.

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