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Air Excess Coefficient and Irreversibility Value Analysis of Gas Turbines

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Abstract

Gas turbines used in natural gas cycle power plants have been researched in terms of energy efficiency. Gas turbines used in power generation plants have a very complex structure because they contain many components. In order to determine the thermodynamic performance of this system, the efficiency of each component and the increase in entropy of each component were calculated using exergy analysis. Irreversibility was chosen as the main parameter and used for thermodynamic optimization of production. The system consists of many components. An increase in the irreversibility of a single component causes an increase in the irreversibility of other components. The effect of gas turbine pressure ratio and excess air percentage on fuel consumption, fuel exergy, combustion chamber exergy change and irreversibility change was investigated. It was observed that the increase in compressor pressure ratio increased irreversibility. Maximum irreversibility was observed in the combustion chamber. Irreversibility was compared with the excess air used in the combustion chamber. The air excess coefficient was examined as percentages of 100%, 200%, and 300%, respectively. The compression pressure ratio was examined for air excess coefficient percentage values from 3 to 40.

Keywords

gas turbines, combined power cycle, irreversibility, exergy analysis

1 Introduction

Combined cycle power plants, which are used for electrical energy generation, consist of important components such as, gas turbine running on Brayton-cycle, excess heat utilization unit and steam-turbine running according to Rankine-cycle. Energy losses arise because of energy transfers occurring from one component to another during the operation. And these losses are analyzed by applying laws of thermodynamics [1].

When we look at the studies on irreversibility of combined cycle power plants in the literature, it is seen that Alconhelelji applied exergy analysis to a Teruel thermal power plant with 3 units, each with a power ratio of 350 MW. They had determined the irreversibility sources by performing an exergy analysis between power and fuel. So that they had clarified the losses in energy flow for any operation condition [2].

Tsatsaronis and Moran had performed a minimum cost analysis in an cogeneration system by examining the thermo-economical aspects such as exergy performance, lost exergy amount, exergy loss ratio, cost of lost exergy, exergy economical factor and first investment cost [3].

Exergy balance is mostly used in analysis of thermal systems. Exergy balance is similar to energy balance, but there are certain fundamental differences. Energy conversion is based on energy conversion laws, and exergy balance is based on irreversibility law of the energy [4]. Analysis of power systems according to the second law of thermodynamics is called exergy analysis. Irreversibilities and energy losses are determined via this analysis [5].

Torres and Gallo had been calculated irreversibilities occurred in the units by calculating the first law and exergy efficiencies in a cogeneration power plant, which generates 200 MW of electric power and 2100 tons of steam in an hour, and had found that 9.62% of energy efficiency and 8.96% of exergy efficiency only for energy production, and 88.4% of energy efficiency and 38.75% of exergy efficiency for the cogeneration case [6].

In order to determine the exergy of different energy systems, the basic theory of exergy analysis has been developed and introduced [7].

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Marrero et al. [8] had optimized the combined power cycle and had determined the effects of irreversibility of combustion chamber on system performance. And they had determined by using these that the irreversibility occurs mainly in the combustion chamber.

Some scientists have defined the energy of systems as follows. As a result of energy losses in the system, efficiency decreases. According to the second law of thermodynamics, there is no efficient energy conversion process. Therefore, there is definitely a decrease in energy quality [9–12].

Sinha et al. investigated the simple gas turbine, single-stage and double-stage waste heat recovery hybrid system in their study. At a pressure ratio of 10 and a turbine inlet temperature of 1250 K, they determined the energy and exergy efficiencies as 65.33% and 61.639%, respectively [13].

Han et al. studied the double stage intercooled and recuperative gas turbine system. They developed Thermoflex software to determine the energetic and exergetic. It was found that the system net energy efficiency/exergy efficiency/specific work increased from 43.88%/41.80%/567 kJ kg_{air}^{-1} and 57.21%/54.49%/684 kJ kg_{air}^{-1} to 62.48%/59.52%/745 kJ kg_{air}^{-1}, respectively [14] .

Khan, Alarifi I.M., Tlili I. have done extensive research on the determination of energy and exergy of gas turbine power cycles and improving their performance [15–17].

Gholizadeh et al. in their study, investigated the organic Rankine cycle combined with a gas turbine cycle operating on biogas containing 60% methane + 40% carbon dioxide. The combined system produces 1368 kW net output electricity. They achieved 41.83% thermal efficiency, 38.91% exergy efficiency and 17.2 $/GJ overall product cost respectively [18].

This performed study had investigated a gas turbine, which has 256 MW of power, and consuming approximately 52000 kg of natural has per hour. Compressor inlet and outlet temperatures are examined together with the exergy change according to air excess state of the combustibility capacity. Irreversibilities occurring in the combustion chamber had been identified. It is seen here that the irreversibility occurs mainly in the combustion chamber.

2 Gas turbine cycle

Gas turbine cycle is called Brayton cycle. Compression and expansion are designed as compressors and turbines in the Brayton cycle. Gas turbines operate generally in open cycle.

Atmospheric air is sucked and compressed by the compressor, and pressure and temperature of the compressed air increases. The high pressure air enters into the combustion chamber, where the fuel is consumed with a steady pressure later. The high temperature gases formed after the combustion performs a work when they expand to the atmospheric pressure in the turbine. Exhaust gases from the turbine are sent to excess heat boiler. Thus the necessary open cycle for the Brayton cycle is formed.

2.1 Compressor work

The air coming into the compressor in atmospheric conditions is compressed through the combustion chamber and its temperature increases as a result. Compressor work related to entering air mass and enthalpies:

$$W_{comp} = \dot{m}_{air} \left(h_{out} - h_{in} \right) = \dot{m}_{air} c_{p_{air}} \left(T_{out} - T_{in} \right) \quad (1)$$

is determined. And, incoming and outgoing energy flow are expressed as in Fig. 1. Irreversibility ($\dot{I}_{comp}$) occur because of the compressor work (Fig. 2). By taking incoming and outgoing air mass equal, the energy equation

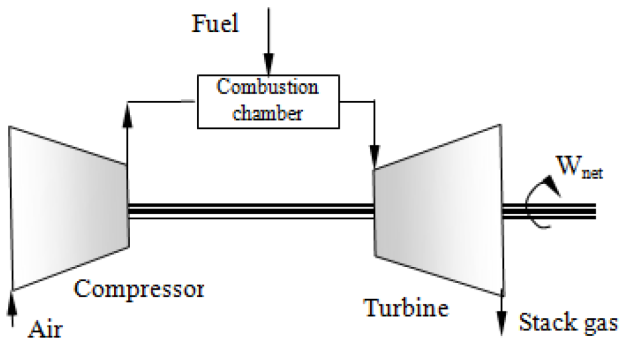

Fig. 1 Gas turbine cycle

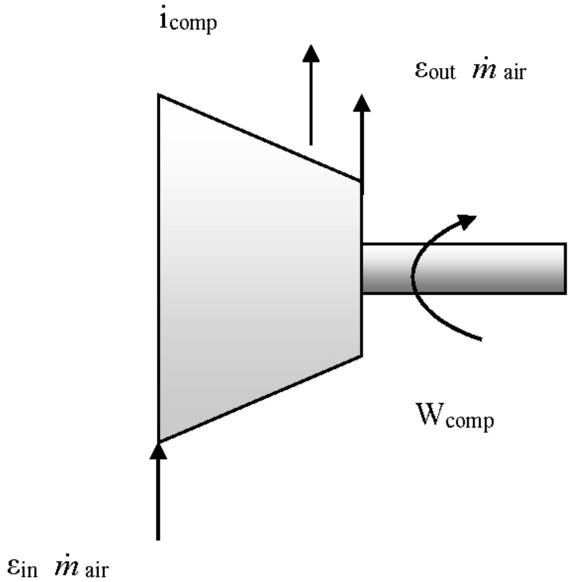

Fig. 2 Gas turbine compressor

$$W_{\text{comp}} = \dot{I}_{\text{comp}} - \dot{m}_{\text{air}} \left(\varepsilon_{\text{out}} - \varepsilon_{\text{in}} \right) \tag{2}$$

is formed with the Eq. (2). And the efficiency according to exergy exchange is formed with the Eq. (3).

$$\psi_{\text{comp}} = \frac{\dot{m}_{\text{air}} \left(\varepsilon_{\text{in}} - \varepsilon_{\text{out}} \right)}{W_{\text{comp}}} \tag{3}$$

Change in the compressor pressure ratio (PR) will affect the gas turbine outlet temperature (T_2) during the operation of gas turbine.

$$T_2 = T_1 \left[1 + \frac{PR^{(k-1)/k} - 1}{\eta_{kizv}} \right] \tag{4}$$

2.2 Fuel exergy

95% of the gas turbine fuel is methane (CH_4) [19]. Exergy of the methane gas gives approximately the exergy of fuel. To determine the fuel exergy (E_{fuel}) it is necessary to determine physical specific exergies and standard chemical specific exergy of the methane, which forms the fuel. And this is determined via Eqs. (6) and (7) [7].

$$\varepsilon_{\text{fuel}} = \varepsilon_{\text{cim}} + \varepsilon_{\text{phys}} \tag{5}$$

$$\varepsilon_{\text{chem}} = \varepsilon_{\text{chem}}^{\text{st}} \frac{T_o}{T_n} - \Delta H \frac{T_n - T_o}{T_n} \tag{6}$$

$$\varepsilon_{\text{phys}} = R\, T_o \ln \frac{P_{\text{fuel}}}{P_o} \tag{7}$$

2.3 Fuel amount

First law of thermodynamics and chemical energy of the fuel should be considered while calculating the net heat formed during the combustion in the system. The air sent to the combustion chamber via compressor is consumed here by mixing with fuel. Flue gas amount exhausted because of the combustion equals to sum of masses of incoming air and fuel.

$$\dot{m}_{\text{egas}} = \dot{m}_{\text{air}} + \dot{m}_{\text{fuel}} \tag{8}$$

Amount of fuel and air entering into the combustion chamber determines the combustion capacity in the chamber [20]. The total amount of fuel and air mass mixture is given by the Eq. (8).

$$\dot{m}_{\text{fuel}} = \dot{m}_{\text{air}} \left[\frac{c_{p_{\text{gas}(T3)}} \cdot T_3 - c_{p_{\text{air}(T2)}} \cdot T_2}{Hu \cdot \eta_b - c_{p_{\text{gas}(T3)}} \cdot T_3} \right] \tag{9}$$

Here, changes in specific heats of air and fuel related to temperature are given in Eq. (9) [20].

$$\begin{aligned} C_{p_{air(T)}} &= 1.04841 - 0.000383719 \cdot T + \left(\frac{9.45378 \cdot T^2}{10^7} \right) \\ &- \left(\frac{5.49031 \cdot T^3}{10^{10}} \right) + \left(\frac{7.92981 \cdot T^4}{10^{14}} \right) (kJ/kgK) \end{aligned} \tag{10}$$

$$\begin{aligned} C_{p_{\text{gas}(T)}} &= 0.991615 + \left(\frac{6.99703 \cdot T}{10^5} \right) \\ &+ \left(\frac{2.71298 \cdot T^2}{10^7} \right) - \left(\frac{1.22442 \cdot T^3}{10^{10}} \right) (kJ/kgK) \end{aligned} \tag{11}$$

The $c_{p_{\text{air}}}$ and $c_{p_{\text{gas}}}$ denotes specific heat capacities of air and gas under constant pressure, respectively.

2.4 Combustion equation

Fuel enters into the gas turbine combustion chamber at a certain temperature. In the methane gas consuming process, the air-fuel mixture ratio is very importing in determining energy and exergy from the combustion equations. The minimum air amount for a complete combustion of a fuel is called stoichiometric or theoretical air amount. Free oxygen does not present in combustion yields when the fuel is consumed with theoretical air amount. Combustion is a chemical process. Therefore, chemical energy turns into thermal energy. Generally, a combustion event is:

$$\text{Fuel} + \text{Air}(\text{oxygen}) \rightarrow \text{Reaction Products Heat} \tag{12}$$

It is determined with above equation. In a controlled volume combustion chamber, the air-fuel ratio is determined in terms of moles. In this case, the combustion equation is performed with this.

$$\begin{aligned} &\text{CH}_4 + \text{HE}(2)\left[\text{O}_2 + 3.76\text{N}_2\right] \rightarrow \\ &\text{CO}_2 + 2\text{H}_2\text{O} + (2\text{HE} - 2)\text{O}_2 + 7.52\ \text{HE}\ \text{N}_2 \end{aligned} \tag{13}$$

Here, air excess coefficient (AE) affects the combustion energy substantially. Fuel air ratio and amount of combustion yields should be known for calculation of irreversibility and exergy occurred during the combustion. Systems efficiency depends on fuel's combustion performance [7].

2.5 Combustion chamber exergy

It is determined by sum of incoming and outgoing exergy values, including all irreversibilities, by taking a control volume into account. In this case, the exergy balance can be written like this:

$$\sum \Delta E_{\text{in}} = \sum \Delta E_{\text{out}} + I . \tag{14}$$

Exergy terms in the Eq. (14), can be consist of exergy amounts in heat transfer and mass transfer, or they can refer to exact exergy exchange amount of a fluid passing through a heat exchanger [7].

Exergy of combustion chamber is determined with physical and chemical exergies of combustion yields. Exergy of combusted gas is expresses by the sums of chemical and physical exergies.

$$E_{\text{egas}} = E_{\text{phys}} + E_{\text{chem}} \tag{15}$$

It's provided with this Eq. (15). Environment is a very important factor in exergy calculation. Exergy is defined as the maximum useful work that a limited system can do under environmental conditions. Therefore, temperature, pressure and chemical composition of gases % N_2, % O_2, % CO_2, % H_2O are important factors according to environmental conditions. Chemical compositions of these gases are determined by using Gibbs function and specific heats of materials. Specifications of these materials are given in Table 1. The h_0 and s_0 are determined by using Eqs. (16) and (17) [7, 21–23].

$$h_0 = 10^3 \left(H + ay + \frac{b}{2} y^2 - cy^{-1} + \frac{d}{2} y^3 \right) \tag{16}$$

$$s_0 = s + a \ln T + by - \frac{c}{2} y^2 + \frac{d}{2} y^2 \tag{17}$$

Here $y = 10^{-3}\ T$ are equal.

2.5.1 Chemical exergy

When calculating the chemical exergies of materials, standard chemical exergies of surrounding material are calculated and added in principal. Equation (18) can be applied to all gas mixtures and can also be expanded to non-ideal gas mixtures.

$$E_{\text{chem}} = n \left[\sum x_i \ \varepsilon^{\text{chem}} + \bar{R}\, T_0 \sum x_i \ \ln \ x_i \right], \tag{18}$$

where n is sum of moles, x_i is i^{th} mole ratio of the mixture [7, 21–23]. It equals to ratio of gas moles to sum of gas moles. The formation is also considered as Gibbs function formation enthalpy. In environmental conditions, by taking Gibbs functions of certain materials zero, the reaction equation becomes this:

$$\varepsilon^{\text{chem}} = \bar{R} T_0 \ln \frac{P_0}{P_{00}} . \tag{19}$$

Here, P_{00}: is the partial pressure of the gas. R: universal gas constant (kJ/kmol K) to determine chemical exergy of each gas in mole the Eq. (19) is used. Total chemical exergy of excess gas is found by using molar chemical exergy Eq. (18).

$$\begin{aligned} \varepsilon^{\text{chem}} &= \sum x_i \ \varepsilon_{N_2} + x_i \ \varepsilon_{O_2} + x_i \ \varepsilon_{CO_2} + x_i \ \varepsilon_{H_2O} \\ &+ \bar{R} T_0 \sum x_i \ \ln \ x_i \end{aligned} \tag{20}$$

$$E_{\text{chem}} = \dot{m} \cdot \varepsilon_{\text{chem}} \tag{21}$$

Under the conditions that the ambient pressure and temperature are accepted as P_0 = 100 kPa, T_0 = 291 K, respectively. P_{00} partial pressure of the gas change x_i and n values are given in Table 2.

2.5.2 Physical exergy

There are air, combustion yields and fuel in the system as working fluids. Since the working fluid is not a raw material, chemical composition of every point should be identified in addition to thermodynamic characteristics [15]. Total exergy of a material in mass flow is determined with the Eq. (22) [7, 21–23]:

Table 2 Thermodynamic values of each gas

State	N_2	CO_2	O_2	H_2O
P_{00} (kPa)	76.26	0.03	20.27	1.44
x_i	0.7424	0.04	0.11	0.076
n	7.663	0.403	1.721	0.178

Table 1 Chemical compositions of certain gases

Material	Formula	h+	s+	a	b	c	d
Nitrogen	N_2	−9.98	16.203	30.415	2.544	−0.238	0
Oxygen	O_2	−9.58	36.116	29.154	6.477	−0.184	−1.017
Carbondioxide	CO_2	−413.88	−87.078	51.128	4.368	−1.467	0
Water builing	H_2O	−253.87	−11.750	34.376	7.841	−0.423	0
Water	H_2O	−289.93	−67.147	20.355	109.198	2.033	0

$$E_{\text{phys}} = \dot{m}_{\text{fuel}} \left[\frac{h_{\text{mixture}} - h^0 - T_0 \left(s_{\text{mixture}} - s^0 \right)}{M} \right], \tag{22}$$

where M is the weight of combustion yields per kmole. To determine the physical exergy of the gas, which is formed in gas turbine combustion chamber by consuming fuel, mixture enthalpy and entropy values in the Eq. (22) are determined from total mixture enthalpy and entropy values and Eqs. (23) and (24) by using mole fractions of each gas.

$$h_{\text{mixture}} = x_1 h_{N_2} + x_2 h_{O_2} + x_3 h_{CO_2} + x_4 h_{H_2O} \tag{23}$$

$$s_{\text{mixture}} = x_1 s_{N_2} + x_2 s_{O_2} + x_3 s_{CO_2} + x_4 s_{H_2O} \tag{24}$$

In Eqs. (23) and (24), enthalpy and entropy values of the gases N_2, O_2, CO_2, H_2O are determined by the Eqs. (16) and (17).

To determine h^0 and s^0 in the Eq. (22), specifications of these gases in atmospheric conditions and entropy and enthalpy values according T_0 Gibbs function are taken as in Table 3 [7].

By using Table 3, enthalpy and entropy values of combustion yields are determined by using mole fractions from Eqs. (25) and (26), and h^0 and s^0 mixture values are determined.

$$h^0 = x_1 N_2 + x_2 O_2 + x_3 CO_2 + x_4 H_2O \tag{25}$$

$$s^0 = x_1 N_2 + x_2 O_2 + x_3 CO_2 + x_4 H_2O \tag{26}$$

Physical exergy of the excess gas is determined by the Eq. (22) with these calculated values. Since total exergy does not depend on temperature changes of combustion yields, it gives the same value for each operation.

Total exergy of consumed gas in the combustion chamber is defined as below:

$$E_{\text{combustion}} = E_{\text{phys}} + E_{\text{chem}} . \tag{27}$$

2.6 Gas turbine

Exhaust gases from the combustion chamber are expanded in the turbine and results in a work. Certain amount of this is the exact work, and remaining is used for driving the compressor. Turbine's exergy equals to net work. Compressor work related to entering air mass and enthalpies is determined:

Table 3 Enthalpy and entropy specifications of gases in atmospheric conditions

	N_2	O_2	CO_2	H_2O
h^0 kJ/kmol	0	0	−393954.44	−242122.27
s^0 kJ/kmol-K	190	203.6	212	187

$$\dot{W}_{GT} = \dot{m}_{\text{egas}} \left(h_{\text{in}} - h_{\text{out}} \right) = \dot{m}_{\text{egas}} c_{p_{\text{egas}}} \left(T_{\text{in}} - T_{\text{out}} \right), \tag{28}$$

where h_{in} and h_{out} are enthalpies of incoming and outgoing combustion yields in the gas turbine. And, incoming and outgoing energy flow to the turbine is expressed as in Fig. 3. Irreversibilities ($\dot{I}_{GT}$) occur because of the compressor work. By taking incoming and outgoing combustion gases' mass equal, the energy equation

$$\dot{I}_{GT} = \dot{m}_{\text{egas}} \left(\varepsilon_{\text{in}} - \varepsilon_{\text{out}} \right) - \dot{W}_{GT} \tag{29}$$

is formed with the above Eq. (29). Exergy efficiency is determined according to the second law of thermodynamics.

$$\psi_{GT} = \frac{\dot{W}_{GT}}{\dot{m}_{\text{egas}} \left(\varepsilon_{\text{in}} - \varepsilon_{\text{out}} \right)} \tag{30}$$

Here, in determining the exergy efficiency, $\dot{m}_{\text{egas}} = 14.706$ kJ/kg is taken as an average, $\dot{W}_{GT} = 256000$ kW. The ε_{in} and ε_{out} specific exergies are calculated according to the properties of the fuel gas.

3 Conclusion

Studies have evaluated in a computer program and numerical results have been obtained. Numerical results, which are changing according to changing parametric values of the system, are explained by graphics. When the obtained graphs are evaluated numerically, in general, in all three air percentage rate change values, efficiency and irreversibility values show more change in low pressure ratios between 3 and 8. In pressure ratios between 8 and 40, the efficiency change remains routine and stable.

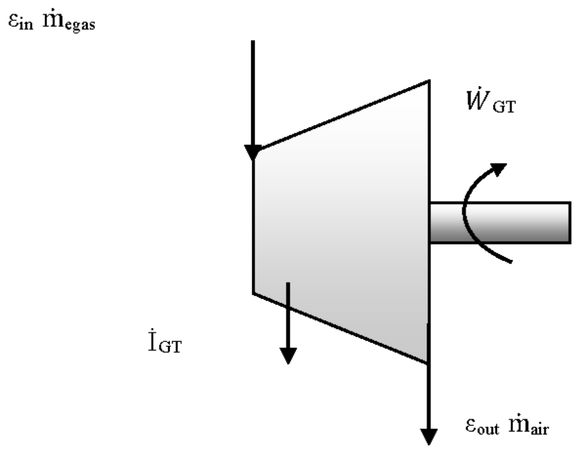

Fig. 3 Gas turbine

As it is seen in Fig. 4, irreversibility value of combustion chamber in excess air ratio change for different compressor pressure values has been obtained. It's also seen that, when the pressure ratio increases the irreversibility decreases, and in parallel when air percentage coefficient increases the irreversibility also increases.

And in Fig. 5 efficiency of combustion chamber has been determined via second law in excess air percentage change for different compressor pressure values. It's seen that, when the pressure ratio increases the efficiency also increases, and in parallel when air percentage coefficient increases the efficiency decreases.

In Fig. 6, total irreversibility of the gas turbine has been determined in excess air percentage change for different compressor pressure values. It's seen that, when the pressure ratio increases the irreversibility of gas turbine decreases and in parallel when air percentage coefficient increases the irreversibility also increases.

In Fig. 7, efficiency of gas turbine has been determined via first law in excess air percentage change for different compressor pressure values. It's seen that, when the pressure ratio increases the efficiency of gas turbine also increases, and in parallel when air percentage coefficient increases the efficiency decreases. Although excess air coefficient does not affect the efficiency much in low pressure ratios, the efficiency decreases at high pressures.

In Fig. 8, efficiency of gas turbine has been determined via second law in excess air percentage change for different compressor pressure values. It's seen that, when the

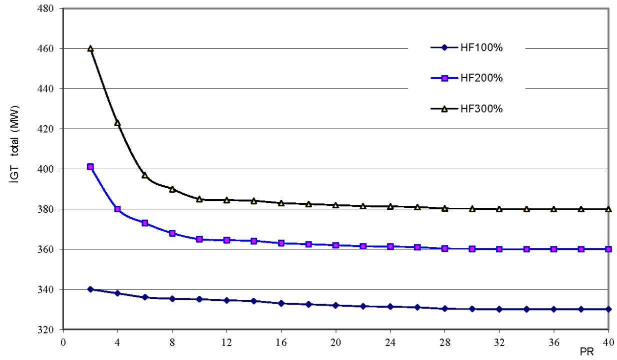

Fig. 6 Irreversibility values related to excess air percentage, for different pressure scales of compressor

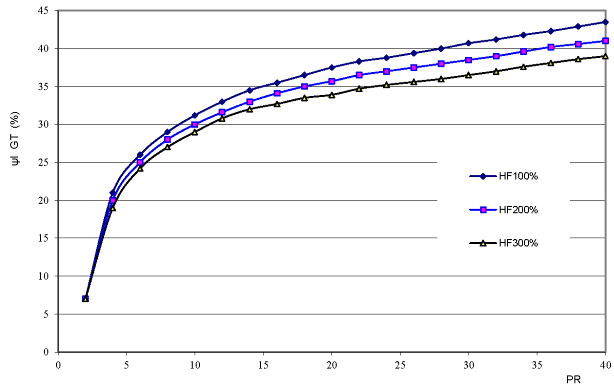

Fig. 7 Irreversibility values related to excess air percentage, for different pressure scales of compressor

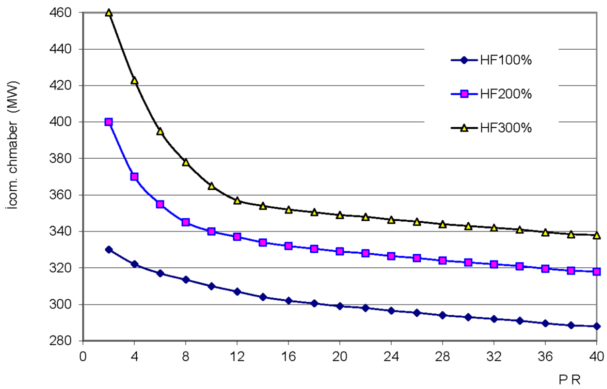

Fig. 4 Irreversibility values related to excess air percentage, for different pressure scales of compressor

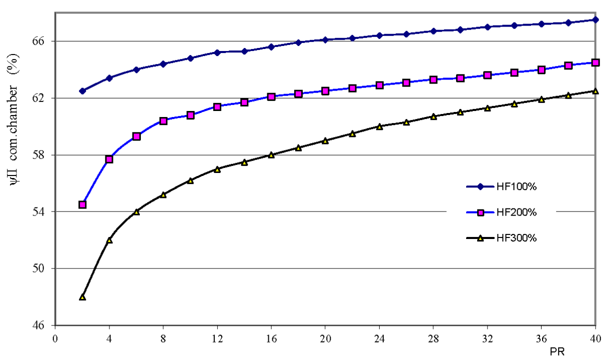

Fig. 5 Irreversibility values related to excess air percentage, for different pressure scales of compressor

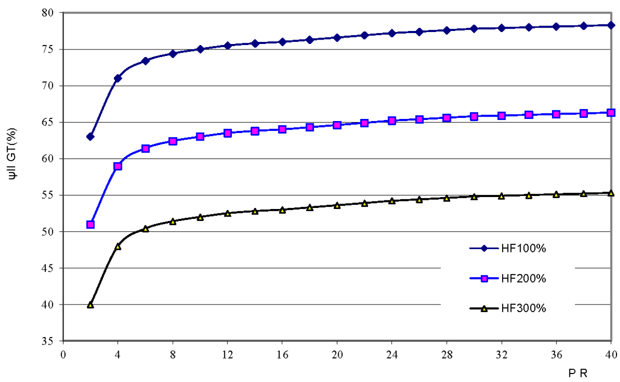

Fig. 8 Efficiency values of gas turbine related to second law, for different pressure scales of compressor

pressure ratio increases the efficiency of gas turbine also increases, and in parallel when air percentage coefficient increases the efficiency decreases. For every three air percentage increase, the efficiency increase increases rapidly at low pressure ratio values between 3 and 8. The efficiency increase remains lower at pressure ratios between 8 and 40.

4 Result

The reason for the frequent choice of exergy analysis in thermodynamically analysis of thermal systems is to make it possible to obtain much more clear performance analysis of the system. With this method, loss ratio of components in total losses of the system is determined by obtaining irreversibility of the components more clearly, and a solution is chosen according to findings.

The irreversibility occurs mainly in the combustion chamber. It is seen that total irreversibility decreases related to compressor pressure increase. Total irreversibility increases in parallel to increased incoming air percentage ratio in the combustion chamber. It is observed that gas turbine irreversibility is greater for a low pressure compressor case. Also, an increase in excess air coefficient increases gas turbine irreversibility.

Nomenclature

E	exergy (kW)
$\dot{I}$	irreversibility (kW)
T	temperature (K)
T_n	reaction temperature (K)
$\dot{W}$	power (kW)
H	enthalpy (kJ/kg)
S	entropy (kJ/kg K)
R	universal gas constant (kJ/kmol.K)
P_0	environmental pressure (kPa)
P_{00}	partial pressure of the gas.
PR	pressure rate
ΔH	standard combustion enthalpy (kJ/kmol)
M	the weight of combustion yields per kmole (kg/kmol)
n	sum of moles (kmol)
$\dot{m}$	measure of mass flow (kg/s)
Hu	fuel under heat value
η_b	fuel combustion efficiency
ε	specific exergy (kJ/kg)
ψ	exergy efficiency
η	second law efficiency
c_p	specific heat (kJ/kg.K)
k	specific heat ratio
x_i	mole ratio of the mixture

Abbreviations

chem	chemical
phys	physical
st	standard
comp	compressor
egas	egsos gas

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