Exergo-economic analysis of performance of a gas turbine power generation system with a solar air preheater

Masoud Valizadeh*[1]

[1] *Department of Energy Engineering, College of Environment and Energy, Science and Research Branch, Islamic Azad University, P.O. Box 14515-775, Tehran, Iran.*

Abstract

The power generation sector, especially the gas turbine, is one of the most critical sources in order to eliminate greenhouse gases worldwide. In a thermo-dynamic system, exergo-economic analysis is utilized as a means to specify the inefficient thermo-dynamic points, where the highest loss of exergy arises. In this paper, engineering equation solver (EES) software and exergo-economic analysis, which uses both the second-law of thermodynamics and economic principles, are utilized to evaluate the economical and exergetical performance of the gas turbine with solar air preheater. The gas turbine without preheating of the air entering the combustion chamber is first investigated. Then, based on three concepts including relative difference, exergo-economic coefficient and exergetic efficiency, a comparison study is performed between the gas turbine with and without solar air preheater. The results clearly reveal that by increasing the inlet temperature of the combustion chamber from 620˚K to 820˚K, the exergy factor increases from 0.41% to 0.68%. Also, the consumption of gas turbine with solar air preheater is reduced from 8.99 kg/s to 7.84 kg/s by raising the inlet temperature of the combustion chamber. As a result, it is noteworthy to express that the exergetic efficiency is increased from 58.4% to 63.4%.

Keywords: Exergo-economic analysis; Solar air preheater; Gas turbine; EES software.

1. Introduction

Nowadays, the use of renewable energy sources is rapidly progressing. The researchers believe that supply of energy using renewable sources such as water, wind and sun should be a priority

* Corresponding author: m.masoud.valizadeh@gmail.com

instead of oil. Among them, sun has become more appealing to the researchers. Generally, hybrid power plants use a fossil fuel such as diesel or gas, supplemented with a renewable energy source such as solar and wind. As shown in Fig. 1, a solar power plant is a set of facilities which collect radiation energy from the sun, or by focusing it gives high temperature. The energy collected through a heat exchanger, turbines or steam engines will be converted into electrical energy, leading to reduction in cost as any other conventional plant [1-3].

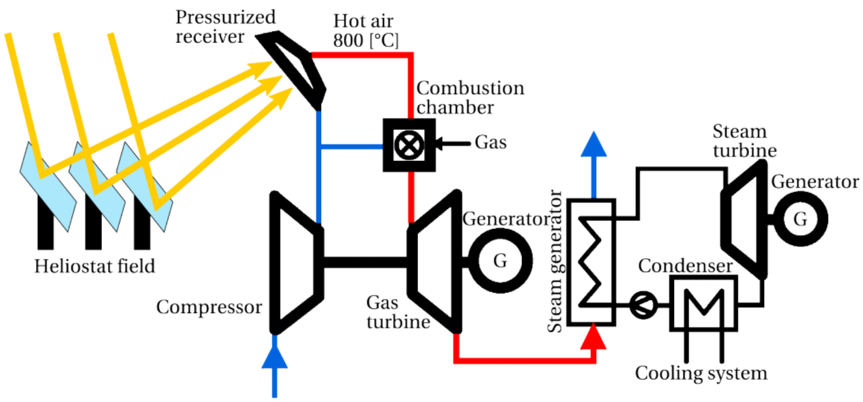

Fig. 1 Schematic of a solar power plant, [4, 5].

In general, solar power plants correspond to the concept of focusing solar radiation to produce steam or hot air which can then be utilized for electricity generation. There are mainly four known solar power plant based on the receiver, and among them only one that is investigated in this paper. In solar tower power plant, also known as central receiver systems, sunrays are concentrated by a field consisting of reflectors, called heliostats, on a receiver which stands on the top of the tower. Heliostats are flat or slightly concave mirrors which follow the sun in a two axis tracking. The central receiver at the top of the tower converts solar energy into thermal energy and transfer the heat generated to the fluid flowing through it. The fluid becomes steam after receiving heat which generates electricity. Moreover, the use of heliostats and placing a receiver prior to the combustion chamber results in increasing the temperature of the intake air into the combustion chamber and thus reduction in the fuel consumption. However, the use of solar energy in the gas turbine cycle is one of the new methods for increasing efficiency [4-7].

Optimization is one of the most important issues for design of energy systems. In large thermal systems, which have many design variables, conventional mathematical optimization methods are not efficient. In recent decades, due to the rise in energy costs and restrictions of non-renewable energy, the optimal performance of the system has attracted special importance from the point of view of energy and production costs. Thus, the combination of the second law of thermodynamics with the economic concept has led to the formation of a powerful tool known as exergo-economic analysis in order to optimize the thermal systems and design efficient and cost-effective systems [8-10]. Such concept of optimization became popular among researchers, with studies performed by Antonio Valero [11], Richard Gaggioli [12], and El-sayed [13].

In recent times, comprehensive works have been performed on the application of exergo-economic concept for analysis and optimization of energy systems [14-20]. The purpose of work done by Khaljani and his associates [21] was thermodynamic, exergo-economic and environmental evaluation of heat and power cycle. In their work, the three objective functions of first and second law efficiencies and the total cost rates of the system were considered. The main result of their assessment was that combustion chamber, and heat recovery steam generator and gas turbine had the most exergy destruction rate, respectively. The exergetic sustainability indicators were extended by Aydin [22] in order to analyze gas turbine engine based power plant and specify sustainability aspects of it. Mousafarash et al. [23, 24] investigated energy, exergy and exergo-economic analyses of a gas turbine power generation system. The results obtained from this study represented that the combustion chamber, where the high temperature difference is the main source of the irreversibility, had the greatest exergy destruction rate. In order to evaluate the cost rate related to all the exergy streams at cycle state points, engineering equation solver software and exergo-economic methods were employed to analyze a 100 MW gas turbine power plant at Ughell, Nigeria [25]. In another work, exergo-economic assessment of solar hybrid power generation systems combining with thermo-chemical fuel conversion was studied by Yue and Lior [26]. A Gas Turbine power plant was simulated by Ahmadi and Dincer [27] according to thermodynamic and exergo-economic approaches, in which the results were compared with one of the largest gas turbine power plants in Iran in order to verify their thermodynamic model.

2. Exergo-economic analysis of gas turbine with solar air preheater

The gas turbine mechanism with gas and solar air preheaters discussed in this study is depicted in Fig. 2. In this section, using the air thermodynamic table and the EES library functions, enthalpy and entropy values are calculated at each point of the flow path (points 1-10) of Table 1. Following Eq. (1):

$$Ex = (h - h_0) - T_0(S - S_0) \qquad (1)$$

h_0, S_0 and $T_0 = 298\ K$ are enthalpy, entropy and temperature at the reference point, respectively. Also, h and S are enthalpy and entropy at considered points, respectively. After identifying the exergy of products, Ex_p, and fuel exergy, Ex_f, the exergy loss, Ex_D, is evaluated as follows:

$$Ex_D = Ex_f - Ex_p \qquad (2)$$

By determining the exergy of each stream, the actual energy loss or, in other words, the thermodynamic inefficiencies of exergy loss and exergetic efficiency are determined for each component of the system.

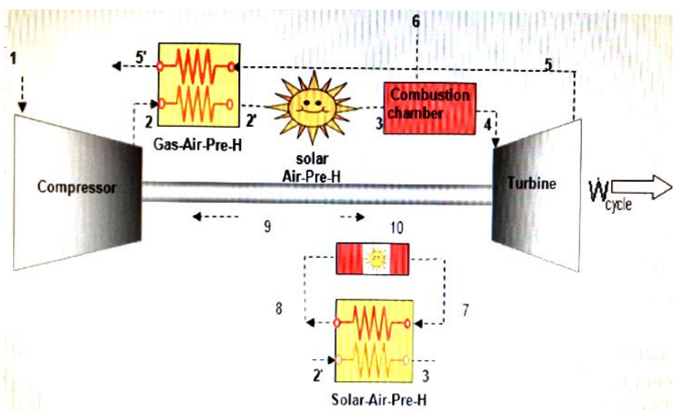

Fig. 2 Schematic of a gas turbine with gas and solar air preheaters

Table 1 Calculation of exergy values for gas turbine with solar air preheater

Position	Fluid mat.	Pressure (Bar)	Mass (kg/s)	Temperature (K)	Exergy (MW)	Exergy Destroid
1	Air	1.013	427	298	0	0
2	Air	10.47	427	620	130.98	25.2

2'	Air	10.15	427	720	155.15	9
3	Air	9.84	427	810	163	73.23
4	Gas-Pro	9.54	436	1320	365	259.9
5	Gas-Pro	1.08	436	810	100.84	38.62
5'	Gas-Pro	1.032	436	700	67.67	-
6	Fuel	30	8.99	308	462.2	-
7	Molten Salt	1.013	120	820	135.1	-
8	Molten Salt	1.013	120	298	46.2	-

3. GE-F9 gas turbine model

In our case study, the GE-F9 gas turbine (100 MW) is considered with solar air preheating system. There are important variables as exergo-economic parameters, discussed as follows:

- The pressure ratio $r_p = P_2/P_1$ (output pressure of compressor on inlet pressure of compressor), which depends on the position of the gas turbine installation and varies from 10.5 to 12, which is assumed to be 11 in this study.
- Isentropic efficiency of compressor and turbine, which according to the documentation of power plant was calculated 88% and 89%, respectively [5, 25].
- The outlet temperature of the solar air preheater is assumed to be 820 K.
- The outlet temperature of the combustion chamber and the inlet temperature entering the turbine are considered 1400 K.

4. Economic analysis

It is necessary to examine each component of the turbine in order to determine the economic situation of a gas turbine. These costs include the cost of ownership and exploitation, and each of them depends on the factors such as unit life, investment conditions, and financing structure, calculated for each component according to following.

6.1. Purchased equipment cost (PEC) calculation

The cost of purchasing and investing for an equipment is calculated based on the following model.

a) Cost evaluation for compressor

$$PEC_{ac} = \left(\frac{71.1\ m_a}{0.9 - \eta_{ac}}\right).\left(\frac{P_2}{P_1}\right).ln(\frac{P_2}{P_1}) \quad (3)$$

b) Cost evaluation for combustion chamber

$$PEC_{cc} = \left(\frac{46.08\ m_a}{0.995 - \frac{P_3}{P_2}}\right).(1 + exp(0.081T_3 - 26.4)) \quad (4)$$

c) Cost evaluation for gas air preheater

$$PEC_{aph} = 4122\left(\frac{m_g(h_5 - h_5')}{U\Delta T_{m,aph}}\right)^{0.6} \quad (5)$$

d) Cost evaluation for gas turbine

$$PEC_{gt} = \left(\frac{479.34\ m_g}{0.92 - \eta_{gt}}\right).\left(\frac{P_3}{P_4}\right).(1 + exp(0.036T_3 - 56.4)) \quad (6)$$

Table 2 Calculation of PEC

Components of gas turbine	**PEC (M$)**
Purchase cost of compressor	19
Purchase cost of gas air preheater	0.46
Purchase cost of heliostat	70.318
Purchase cost of tower and receiver construction	13.104
Purchase cost of concrete tower construction	3.7306
Purchase cost of tank	14.7347

Purchase cost of combustion chamber	0.83
Purchase cost of turbine	15.18

6.2. Calculation of $\dot{C}_k$

Using the equilibrium equation and the effect of the inflation rate i = 13%, and the time period of depreciation of n = 20 years, $\dot{C}_k$ is calculated based on the following relation:

$$\dot{C}_k = \left(\frac{PEC - 0.1}{(i+1)^n}\right)\left(i - \frac{1}{(i+1)^n}\right) \quad (7)$$

6.3. Calculation of Z_k

In order to calculate Z_k, which includes repair and maintenance costs, the coefficient $\phi_k = 1.06$ and H are respectively considered as the cost correction factor and the unit operating hours per year (approximately $H = 24 \times 365 \times 0.85 = 7446$ hours).

$$Z_k = \frac{\phi_k \dot{C}_k}{H} \quad (8)$$

Table 3 Economic calculation of gas turbine with solar air preheater

Component	**Purchased Equipment Cost PEC ($)**	**Annual Levelized Cost $\dot{C}_k$ ($)**	**Capital Cost Rate $\dot{Z}_k$ ($/h)**
Air compressor	19×10^6	2.66×10^6	378.6
Air preheater	0.46×10^6	0.0641×10^6	9.11
Solar air preheater	101.8×10^6	9.6×10^6	1367
Combustion chamber	0.83×10^6	0.12×10^5	16.5
Gas turbine	15.18×10^6	2.12×10^6	302

6.4. Exergo-economic analysis

Given that the cost analysis in each system and in each component of the system is different, we use an equilibrium equation of exergy flow.

$$\sum_{out} \dot{C}_{O,k} = \sum_{in} \dot{C}_{i,k} + Z_k \tag{9}$$

Using equation (11), the exergo-economic relations of the gas turbine with preheater are determined in accordance with Table 4.

Table 4 Exergo-economic equations for gas turbine with solar air preheater

Components	**The main equations of energy balance**	**The equivalent equations of energy balance**
Air compressor	$\dot{C}_1 + \dot{C}_9 + \dot{Z}_{comp} = \dot{C}_2$	$C_1 = 0$; $C_{w,9} = C_{w,10}$; $\dot{C}_9/\dot{Ex}_9 = \dot{C}_{10}/\dot{Ex}_{10}$
Combustion chamber	$\dot{C}_3 + \dot{C}_6 + \dot{Z}_{cc} = \dot{C}_4$	
Gas turbine	$\dot{C}_4 + \dot{Z}_{gt} = \dot{C}_5 + \dot{C}_{w,9} + \dot{C}_{w,10}$	$C_4 = C_5$; $\dot{C}_4/\dot{Ex}_4 = \dot{C}_5/\dot{Ex}_5$
Gas air preheater	$\dot{C}_2 + \dot{C}_5 + \dot{Z}_{ap} = \dot{C}_{2'} + \dot{C}_{5'}$	$C_5 = C_{5'}$; $\dot{C}_5/\dot{Ex}_5 = \dot{C}_{5'}/\dot{Ex}_{5'}$
Solar air preheater	$\dot{C}_{2'} + \dot{C}_7 + \dot{Z}_{sap} = \dot{C}_3 + \dot{C}_8$	$C_7 = C_8$; $\dot{C}_7/\dot{Ex}_7 = \dot{C}_8/\dot{Ex}_8$

According to Table (4), which is presented for 12 exergy streams of the gas turbine with a preheating system based on Eq. (10), we need to solve these equations. Each component of the system consists of multi-input and multi-output. Therefore, the use of equivalent equations is necessary in order to solve the mentioned equations, which is obtained a 12×12 matrix.

$$[A][C] = [Z] \tag{10}$$

in which

$$[C] = \{\dot{C}_i = 1, 2, 2', 3, 4, 5, 5', 6, 7, 8, 9, 10\} \tag{11}$$

$$[Z] = \{\dot{Z}_i = 1, 2, 2', 3, 4, 5, 5', 6, 7, 8, 9, 10\}$$

The matrix $[A]$, which is the coefficient matrix, is adjusted according to the following matrix.

$$\begin{vmatrix}
1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1 & -1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 & 1 & -1 \\
0 & 1 & -1 & 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1/Ex_9 & -1/Ex_{10} \\
0 & 0 & 0 & 0 & 1/Ex_4 & -1/Ex_5 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1/Ex_7 & -1/Ex_8 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1/Ex_5 & -1/Ex_{5'} & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0
\end{vmatrix}$$

$\dot{C}_i$ is calculated as follows:

$$[C] = [A]^{-1}[Z] \tag{12}$$

c_k is evaluated according to $c_k = \dot{C}_k / \dot{E}x_k$.

Table 5 Calculation of $\boldsymbol{c_k}$

Position	$\boldsymbol{\dot{C}_k}$ **($)**	$\boldsymbol{c_k}$ **($/kwh)**	$\boldsymbol{c_k}$ **($/Gj)**
1	0	0	0
2	1938.6	0.0148	4.11
2’	2191.93	0.0141	3.92

3	6988.25	0.0428	11.89
4	2704.75	0.0074	2.05
5	737.66	0.0073	1.03
5’	493.43	0.00729	2.02
6	4300	0.0093	2.58
7	5167.46	0.0038	10.6
8	1738.15	0.0376	10.44
9	1560	0.01	2.77
10	2269.09	0.01	2.77

5. Results and discussion

The results of all calculations performed in exergy analysis are recorded in Tables 6 and 7 for gas turbine with and without solar air preheater. $\dot{C}_p$ and $\dot{C}_f$ are the average cost of the exergy of products and fuel of each component of the gas turbine, respectively. According to the data of tables 6 and 7 and the exergo-economic evaluation method, the highest value of $\dot{C}_{D,k} + \dot{Z}_k$ is related to the solar air preheater, combustion chamber and gas turbine, which are the most important units to examine and optimize from the point of view of exergo-economic.

Table 6 Calculation of exergo-economic parameters of gas turbine with preheater

Component	$\dot{E}x_f$ **(Mj/s)**	$\dot{E}x_p$ **(Mj/s)**	$\dot{E}x_D$ **(Mj/s)**	y_d **(%)**	$\dot{C}_p$ **($/GJ)**	$\dot{C}_f$ **($/GJ)**	$\dot{C}_D$ **($/h)**	$\dot{Z}_k$ **($/h)**	$\dot{C}_D + \dot{Z}_k$ **($/h)**	r_k **(%)**	ε **(%)**	f_k **(%)**
Air compressor	156.2	130.98	25.2	6	4.11	2.77	251.3	378.6	629.9	48.3	83.8	60.1

Air preheater	33.17	24.17	9	2.2	3.92	1.03	33.37	9.11	42.48	28	72.8	21.4
Solar air preheater	88.9	7.65	81.05	19.6	11.89	10.6	3092.8	1367	4459.8	12.2	8.6	30.6
Combustion chamber	625.23	365.26	259.9	63	2.05	2.58	2413.9	16.5	2430.4	20.5	63.4	0.68
Turbine	264.42	225.8	38.6	9.3	2.77	2.05	284.8	302	586.8	35.1	84.1	51.5
Total	1167.72	753.86	413.7	100	24.74	19.03	6040.2	2073.2	8149.3	30.1	64.6	47.3

Table 7 Calculation of exergo-economic parameters of gas turbine without preheater

Component	$\dot{E}x_f$ **(Mj/s)**	$\dot{E}x_p$ **(Mj/s)**	$\dot{E}x_D$ **(Mj/s)**	y_d **(%)**	$\dot{C}_p$ **($/GJ)**	$\dot{C}_f$ **($/GJ)**	$\dot{C}_D$ **($/h)**	$\dot{Z}_k$ **($/h)**	$\dot{C}_D + \dot{Z}_k$ **($/h)**	r_k **(%)**	ε **(%)**	f_k **(%)**
Compressor	156.2	130.98	25.2	8.8	2.75	1.672	151.7	378	529.7	64.6	83.8	71.4
Combustion chamber	593.18	376.26	216.8	76	4.05	5.28	4120.9	17	4137.9	23.3	58.4	0.41
Turbine	268.56	225	43.56	15.3	1.68	3.969	622.4	310.9	933.3	57.7	85.4	33.3
Total	1017.9	732.24	285.26	100	8.43	10.92	4895	705.9	1480.2	22.3	71.9	44.5

7.1. Solar air preheater

From the exergo-economic point of view, and Tables 7 and 6, the highest $\dot{C}_{D,k} + \dot{Z}_k$ occurs in solar air preheater due to high cost of investment and loss of exergy. The efficiency of the system should be investigated with regard to the high exergo-economic factor, $f_k = 30.6$. Also, it is merely a reduction in the investment cost regarding the lowness of $r_k = 12\%$ in solar air preheater. As a solution, it is proposed to replace the molten salt with a new composition which has the capability of absorption temperature above 860 K, (decomposition point of the molten salt structure). This method reduces the flow rate (molten salt) and finally the dimensions of the facilities include storage tanks, heat exchangers, tower and receiver, etc., which results in a reduction in the cost of solar air preheater investment.

7.2. Combustion chamber

According to Tables 6 and 7, the exergo-economic factor of the combustion chamber in two conditions with solar air preheater ($f_k = 0.68$) and without solar air preheater ($f_k = 0.41$) indicates that the change in cost of combustion chamber depends on exergy loss variation. Increasing the inlet temperature of the combustion chamber is one of the factors which reduces the loss of exergy.

It is observed from Tables 6 and 7 that the cost of exergy loss without solar air preheater is 4120.9 $/h which is reduced to 2413.9 $/h by using solar preheater. In other words, the cost of exergy loss is reduced 41% by utilizing solar preheater.

Table 8 Results of $\dot{C}_D$ for combustion chamber

Unit	**T_3 (K)**		**$\dot{C}_D$ ($/h)**	
Combustion chamber	Without preheater	With preheater	Without preheater	With preheater
	620	820	4120.9	2413.9

The computational values of Tables 6 and 7 show that the highest values of $\dot{C}_{D,k} + \dot{Z}_k$ are related to combustion chamber with and without solar air preheater, which is the most important unit for the examination and optimization. In the exergo-economics analysis, when f_k is a small number, it should be tried to improve the efficiency of the components by increasing the cost of investment. In this study, f_k is very small for combustion chamber either with solar air preheater or without solar air preheater.

Table 9 Results of f_k for combustion chamber

Unit	**T_3 (K)**		**f_k**	
Combustion chamber	Without preheater	With preheater	Without preheater	With preheater
	620	820	0.41	0.68

In addition to increase of inlet temperature of the combustion chamber, which improves the exergo-economical factor, other methods such as improved fuel nozzle spraying, improved fuel feedback control systems, and control of fuel / air ratio can be used.

7.3. Gas turbine

The gas turbine with compressors and solar preheating has the least amount of exergy loss. The gas turbine needs to be optimized about 38.6 \$/h due to high $\dot{C}_{D,k} + \dot{Z}_k$ and $r_k = 35.1\%$. Tables 6 and 7 show that increasing the inlet temperature of the combustion chamber reduces the cost of exergy loss to 54%. Also, the cost of exergy loss without solar air preheater is 622.4 \$/h which is reduced to 284.8 \$/h by using solar air preheater. Therefore, the use of solar air preheater improves the exergo-economic factor from 33.3% to 51.5%. It should be tried to reduce the cost of investment and maintenance regarding the high exergo-economics factor $f_k = 51.5\%$ and $r_k = 35.1\%$ for gas turbine with solar air preheater, which depends on inlet flow rate of gas turbine considering the relations of the cost of investment. Therefore, reducing the inlet flow rate of the turbine will reduce the cost of exergy of products for gas turbine, which is obtained as follows:

$$C_{p,gt} = (\frac{\dot{C}_4 - \dot{C}_5 + \dot{Z}_{total}}{W_{gt}}) \quad (13)$$

As a second method to reduce the investment cost based on the following equation, a decrease in isentropic efficiency of the turbine (η_{gt}) will diminish investment costs.

$$PEC_{gt} = \left(\frac{79.34\, m_g}{0.92 - \eta_{gt}}\right).\left(\frac{P_3}{P_4}\right).(1 + exp(0.036T_3 - 56.4)) \quad (14)$$

7.4. The effect of using pre-regulator to reduce fuel consumption

The fuel exergy in this study, which is considered methane gas, contains two parts of the chemical exergy and physical exergy. However, total fuel exergy is determined based on the following equation.

$$Ex_f = m_f \left[c_p\left(T_f - T_0\right) - T_0 c_p ln\left(T_f/T_0\right) + \sum_{k=1}^{N} (x_k \bar{e}_k^{CH}) + \bar{R}T_0 \sum_{k=1}^{N} \left(x_k ln(x_k)\right) \right] \tag{15}$$

It should be pointed out that the fuel exergy of methane gas is directly related to the mass flow rate of fuel. Furthermore, assuming that the output exergy of combustion chamber remains constant, and according to the exergy changes in the combustion chamber, the fuel flow rate decreases from 8.99 to 7.84 Kg/s. Also, it can be observed from Tables (6) and (7) that the exergy efficiency (ε) of combustion chamber is increased from 58.4% (without preheater) to 63.4% (with preheater) in the non-progressive state with a pre-igniter.

6. Conclusion

In this research, engineering equation solver (EES) software and exergo-economic analysis were employed to investigate the economical and exergetical performance of the gas turbine with and without solar air preheater The inlet air entering to the combustion chamber was initially heated by exhaust gas and then used at the stage of a solar power plant, which utilized molten salt to store the extracted energy from the sun. In this mechanism, the air was preheated using a heat exchanger prior to entering the combustion chamber up to 820 K. The results obtained from this study show that by increasing the inlet temperature of the combustion chamber from 620˚K to 820˚K, the exergy factor increases from 0.41% to 0.68% and the cost of exergy loss decreases from 4120.9 $/h to 2413.9 $/h. Also, the consumption of gas turbine with solar air preheater is reduced from 8.99 kg/s to 7.84 kg/s by raising the inlet temperature of the combustion chamber. As a result, the exergetic efficiency is enriched from 58.4% to 63.4%. Therefore, due to the variety of gas turbines used in the power plants, all available turbines can be assessed based on exergo-economic analysis in order to examine the inefficient points and the sources of exergy loss.

References

[1] Kribus, A., Zaibel, R., Carey, D., Segal, A., and Karni, J., 1998, "A solar-driven combined cycle power plant," Solar energy, 62(2), pp. 121-129.

[2] Buck, R., Abele, M., Kunberger, J., Denk, T., Heller, P., and Lüpfert, E., 1999, "Receiver for solar-hybrid gas turbine and combined cycle systems," Le Journal de Physique IV, 9(PR3), pp. Pr3-537-Pr533-544.

[3] Buck, R., Brauning, T., Denk, T., Pfänder, M., Schwarzbözl, P., and Tellez, F., 2002, "Solar-hybrid gas turbine-based power tower systems (REFOS)," Journal of Solar Energy Engineering, 124(1), pp. 2-9.

[4] Ávila-Marín, A. L., 2011, "Volumetric receivers in Solar Thermal Power Plants with Central Receiver System technology: A review," Solar Energy, 85(5), pp. 891-910.

[5] Augsburger, G., 2013, "Thermo-economic optimisation of large solar tower power plants."

[6] Zhang, H. L., Baeyens, J., Degrève, J., and Cacères, G., 2013, "Concentrated solar power plants: Review and design methodology," Renewable and Sustainable Energy Reviews, 22, pp. 466-481.

[7] Lozano, M., and Valero, A., 1993, "Thermoeconomic analysis of gas turbine cogeneration systems," ASME, NEW YORK, NY,(USA). 30, pp. 311-320.

[8] Gorji-Bandpy, M., and Ebrahimian, V., 2006, "Exergoeconomic analysis of gas turbine power plants," International Energy Journal, 7(1).

[9]Tsatsaronis, G., 2007, "Definitions and nomenclature in exergy analysis and exergoeconomics," Energy, 32(4), pp. 249-253.

[10] Gorji-Bandpy, M., Goodarzian, H., and Biglari, M., 2010, "The cost-effective analysis of a gas turbine power plant," Energy Sources, Part B: Economics, Planning, and Policy, 5(4), pp. 348-358.

[11] Valero, A., Lozano, M., Serra, L., and Torres, C., 1994, "Application of the exergetic cost theory to the CGAM problem," Energy, 19(3), pp. 365-381.

[12] Gaggioli, R., and El-Sayed, Y., 1989, "A critical review of second law costing methods—II: calculus procedures," Journal of Energy Resources Technology, 111(1), pp. 8-15.

[13] El-Sayed, Y., and Gaggioli, R., 1989, "A critical review of second law costing methods—I: background and algebraic procedures," Journal of Energy Resources Technology, 111(1), pp. 1-7.

[14] Baghernejad, A., and Yaghoubi, M., 2011, "Exergoeconomic analysis and optimization of an Integrated Solar Combined Cycle System (ISCCS) using genetic algorithm," Energy conversion and Management, 52(5), pp. 2193-2203.

[15] Bagdanavicius, A., and Jenkins, N., 2014, "Exergy and exergoeconomic analysis of a Compressed Air Energy Storage combined with a district energy system," Energy Conversion and Management, 77, pp. 432-440.

[16] Elsafi, A. M., 2015, "Exergy and exergoeconomic analysis of sustainable direct steam generation solar power plants," Energy conversion and Management, 103, pp. 338-347.

[17] Mohammadkhani, F., Shokati, N., Mahmoudi, S., Yari, M., and Rosen, M., 2014, "Exergoeconomic assessment and parametric study of a Gas Turbine-Modular Helium Reactor combined with two Organic Rankine Cycles," Energy, 65, pp. 533-543.

[18] Cavalcanti, E. J. C., and Motta, H. P., 2015, "Exergoeconomic analysis of a solar-powered/fuel assisted Rankine cycle for power generation," Energy, 88, pp. 555-562.

[19] Ahmadi, R., Pourfatemi, S. M., and Ghaffari, S., 2017, "Exergoeconomic optimization of hybrid system of GT, SOFC and MED implementing genetic algorithm," Desalination, 411, pp. 76-88.

[20] Lee, Y. D., Ahn, K. Y., Morosuk, T., and Tsatsaronis, G., 2018, "Exergetic and exergoeconomic evaluation of an SOFC-Engine hybrid power generation system," Energy, 145, pp. 810-822.

[21] Khaljani, M., Khoshbakhti Saray, R., and Bahlouli, K., 2015, "Comprehensive analysis of energy, exergy and exergo-economic of cogeneration of heat and power in a combined gas turbine and organic Rankine cycle," Energy Conversion and Management, 97, pp. 154-165.

[22] Aydin, H., 2013, "Exergetic sustainability analysis of LM6000 gas turbine power plant with steam cycle," Energy, 57, pp. 766-774.

[23] Mousafarash, A., and Ahmadi, P., 2014, "Exergy and exergo-economic based analysis of a gas turbine power generation system," Progress in Sustainable Energy Technologies Vol II, Springer, pp. 97-108.

[24] Mousafarash, A., and Ameri, M., 2013, "Exergy and exergo-economic based analyses of a gas turbine power generation system," Journal of Power Technologies, 93(1), p. 44.

[25] Igbong, D., and Fakorede, D., 2014, "Exergoeconomic analysis of a 100 MW unit GE Frame 9 gas turbine plant in Ughelli, Nigeria," International Journal of Engineering and Technology, 4(8), pp. 463-468.

[26] Yue, T., and Lior, N., 2017, "Exergo economic analysis of solar-assisted hybrid power generation systems integrated with thermochemical fuel conversion," Applied Energy, 191, pp. 204-222.

[27] Ahmadi, P., and Dincer, I., 2011, "Thermodynamic and exergoenvironmental analyses, and multi-objective optimization of a gas turbine power plant," Applied Thermal Engineering, 31(14), pp. 2529-2540.