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OPTIMIZATION OF GAS TURBINE POWER PLANT BY EVOLOUTIONARY ALGORITHM; CONSIDERING EXERGY, ECONOMIC AND ENVIRONMENTAL ASPECTS

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ABSTRACT

In this paper the exergy, economic and environmental analysis of Aliabad Katoul power plant as well as its multi-objective optimization have been done by NSGA-II algorithm. Two objective functions have been considered. The first objective function is the total cost rate and the second objective function is environmental impact cost. Optimization of objective functions has been done in two modes namely cycle with and without air preheater. The results showed that the existence of air preheater reduces both objective functions. So that in optimum point, for cycle without air preheater, the amount of total cost rate has been about 30% and environmental cost rate was about 33% higher than cycle with air preheater. Also, sensitive analysis of objective functions to fuel unit cost was conducted. At the lower environmental cost rate that the total cost rate was higher, sensitivity of Pareto solutions to the fuel unit cost was more than some parts of figure with smaller total cost rate. Also, exergy losses of various components were obtained that conclusions illustrated that combustion chamber has the maximum rate of exergy destruction (about 73%). Impact of ambient temperature variation on exergy losses and efficiency for different components was studied. The conclusions illustrated that with growing in ambient temperature, exergy efficiency of all parts decreased and exergy losses increased. Also, by rising the ambient temperature, exergy efficiency decreased, so that an increase in temperature from 293 Kelvin to 323 Kelvin, total exergy efficiency decreased from about 51% to 49%.

Keywords: *Gas Turbine, Exergy, Sensitive, Environmental, NSGA-II*

INTRODUCTION

In preceding years, according to the rising energy expenses and environmental damages, using of the systems with higher efficiency and lower pollution have attracted researchers' attention. Also, global warming and its side effects on environment is one of the major challenges confronting humanity. Gas turbine power plants have a considerable role in energy production for the industry. Therefore, a gas turbine cycle analysis in terms of thermodynamic, environmental and economic aspects is necessary. Kopac and Hilaci in 2007 the authors investigated an energy model for a thermal power plant in Turkey to consider the impact of ambient temperature on irreversibility and second law efficiency of the power plant components [1]. Sahoo in 2008 the author did exergy-economic analysis and optimization of a combined heat and power system. He studied the 50 MW of power plant which it produces 15 kg of saturated steam at a pressure of 2.5 Bars [2]. Ehyaei et al. in 2011 studied inlet fogging system effects on first and second law efficiencies for a gas turbine power plant located in Iran [3]. Ahmadi et al in 2011 conducted the exergy, exergoeconomic and environmental analyses and evolutionary algorithm based multi-objective optimization of combined cycle power plants [4]. Ganjeh Kaviri et al in 2012 performed thermodynamic analysis of a dual pressure CHP system [5]. Ahmadi et al. in 2012 conducted multi-objective optimization considering second law of thermodynamics for a cogeneration system [6]. Ahmadi et al. in 2012 studied energy modeling and multi-objective optimization of a polygeneration power plant [7]. Shirazi et al. in 2012 conducted energy, exergy, economic and environmental analysis of gas turbine cycle with fuel cell and internal reforming [8]. Ahmadi et al. in 2013 performed thermodynamic modeling and optimization of a new multi-generation energy system [9]. Memon et al. in 2013 conducted a gas turbine cycle modeling. They also studied the effects of major performance

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parameters on the overall cycle efficiency and CO_2 emissions [10]. Majdi Yazdi et al. in 2015 examined the use of a heat pump for reduction the gas turbine compressor inlet air temperature [11]. Ehyaei et al. in 2015 studied inlet air fogging system on the first and second law efficiency and net output power of a combined cycle power plant [12]. Khaljani et al. in 2015 carried out thermodynamic, exergy-economic and environmental aspects of a hybrid system included gas turbine and organic Rankine cycle [13]. Also, several papers about the exergy, economic and environmental analysis of power production system have been investigated in recent years [3, 11, 12, 14-45].

Up to now, no research has been done about the optimization and result comparison of a gas turbine power plant with and without air preheater. In previous studies that have been done by other researches, only one type of gas turbine power plant has been studied. Also, a real power plant (Aliabad Katoul) has been studied in this research.

In this paper, the thermodynamic, exergoeconomic and exergoenvironmental analysis of Aliabad Katoul gas turbine power plant (northern Iran) and its optimization by multi-objective genetic algorithm (NSGA-II) has been carried out in MATLAB software. Each unit of the power plant generates 150 MW of electricity. This power plant has six units and overall generates 900MW electricity. The weather (which the power plant is located) is moderate and wet region. Two objective functions have been intended in this research. The first objective function is the total cost rate including fuel cost rate, investment and maintenance cost rate and exergy destruction cost rate. The other objective function is cost of environmental impacts. The main components of the cycle include air compressor, combustion chamber, gas turbine and air preheater. The design variables considered in this study include: pressure ratio of air compressor (r_{AC}), combustion chamber inlet temperature (T_3), inlet temperature of gas turbine (T_4), air compressor isentropic efficiency (η_{AC}) and gas turbine isentropic efficiency (η_{GT}). Also, impact of air preheater presence on two objective functions has been investigated. The second intended case, cycle do not have air preheater that in this case, four design variables have been considered that are pressure ratio of air compressor, gas turbine inlet temperature, air compressor and gas turbine isentropic efficiency. Also, sensitivity analysis and the impact of fuel cost per unit of energy on objective functions have been considered. The effect of inlet air temperature change on exergy efficiency and destruction of each part as well as its impact on the exergy efficiency has been investigated. In summary, the following works have been done in this paper:

- Doing exergy, exergoeconomic and exergoenvironmental analysis of gas turbine cycle and its optimization with multi-objective genetic algorithm in MATLAB
- Comparing the values of objective functions for gas turbine cycle in both cases with air preheater and without air preheater and comparison of the results
- Sensitivity analysis of fuel cost per unit of energy and its impact on the objective functions
- Calculating the exergy destruction of various parts of the cycle
- Investigating the ambient temperature impact on exergy efficiency of each part, overall exergy efficiency and exergy destruction for each part.

MATHEMATICAL MODELING

ENERGY ANALYSIS

First, thermodynamic modeling of the cycle has been done. This modeling is obtained by writing the first law of thermodynamic and the balance of mass and energy equations for each component. In present analysis, the following assumptions have been assumed:

- The air and exhaust gases have been assumed to be ideal gas.
- The inlet air temperature of air compressor has been considered equal to 298 K and its pressure is 1.013 bar [6].
- All cycle parts have been assumed to be steady state.
- Pressure drop in air preheater for air has been considered to be 5% and 3% difference in pressure between input and output has been considered for combustion products [6].
- Heat loss from the combustion chamber has been considered equal to 5% low fuel heating value [6].
- The value of C_p is considered constant with temperature changes.

The figures of gas turbine cycle related to Aliabad Katoul power plant with and without air preheater have been illustrated in Figure 1 and Figure 2. In these figures, air is compressed in air compressor (AC). Then compressed air is reacted with natural gas in combustion chamber (CC). Exhaust hot gas from combustion chamber, rotates gas turbine (GT) and it generates electrical power. In cycle with air preheater (APH) exhaust hot gas from gas turbine heats compressed air before it enters the combustion chamber.

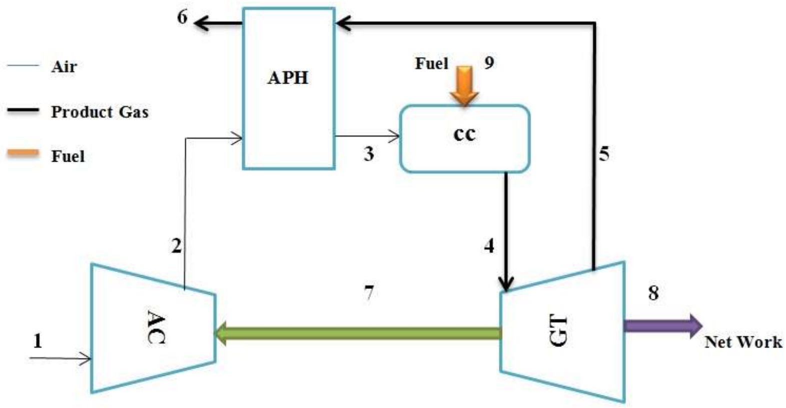

Figure 1. Aliabad Katoul gas turbine power plant

Energy equations for each component are as follows:
Air compressor:

$$T_2 = T_1\left\{1 + \frac{1}{\eta_{AC}}\left[\frac{P_2}{P_1}\right]^{\frac{\gamma_a - 1}{\gamma_a}} - 1\right\} \tag{1}$$

$$\dot{W}_{AC} = \dot{m}_a c_{p,a}(T_2 - T_1) \tag{2}$$

At the above equations, $\dot{W}_{AC}$ is air compressor net work.
Air preheater:

$$\dot{m}_a c_{p,a}(T_3 - T_2) = \dot{m}_g c_{p,g}(T_5 - T_6) \tag{3}$$

$$P_3 = P_2(1 - \Delta P_{\mathrm{a,APH}}) \tag{4}$$

$$P_6 = P_5(1 - \Delta P_{\mathrm{g,APH}}) \tag{5}$$

Combustion chamber:

$$\dot{m}_a h_3 + \dot{m}_f LHV = \dot{m}_g h_4 + (1 - \eta_{CC})\dot{m}_f LHV \;, \quad \eta_{CC} = 0.95 \tag{6}$$

$$P_4 = P_3(1 - \Delta P_{\mathrm{CC}}) \;\; with \;\; \Delta P_{\mathrm{CC}} = 0.05 \text{ Bar} \tag{7}$$

Here, LHV is fuel lower heating value that has been considered 50000 (kJ/kg) for methane. The chemical balance of combustion in chamber is as follows:

$$(0.81CH_4 + 0.079\ C_2H_6 + 0.042\ C_3H_8 + 0.047\ C_4H_{10} + 0.01\ N_2 + 0.012\ CO_2) + 2.412\frac{1}{f}(O_2 + 3.76\ N_2) \rightarrow$$
$$1.294CO_2 + 2.56\,H_2O + (2.412r_a - 2.562)O_2 + (0.01 + 9.06912r_a)N_2$$

In the above equation, f is fuel to air molar ratio.

$$f = \frac{n_{fuel}}{n_{air}} \tag{8}$$

By multiplying molar ratio into molar mass, the mass ratio obtains.
Gas turbine:

$$T_5 = T_4\left\{1 - \eta_{GT}\left[1 - \left[\frac{P_4}{P_5}\right]^{\frac{1-\gamma_g}{\gamma_g}}\right]\right\} \tag{9}$$

$$\dot{W}_{GT} = \dot{m}_g c_{p,g}(T_4 - T_5) \tag{10}$$

$$\dot{m}_g = \dot{m}_a + \dot{m}_f \tag{11}$$

$$\dot{W}_{net} = \dot{W}_{GT} - \dot{W}_{AC} \quad with \quad \dot{W}_{net} = 150\ MW \tag{12}$$

In the above equations, η_{GT} is the isentropic efficiency of gas turbine, $\dot{W}_{GT}$ and $\dot{W}_{net}$ are the gas turbine net-work (MW) and net-work of cycle (MW), respectively. By solving the above equations, properties and thermodynamic values of different parts are obtained. Figure 2 shows the second considered cycle (without air preheater) that is as follows:

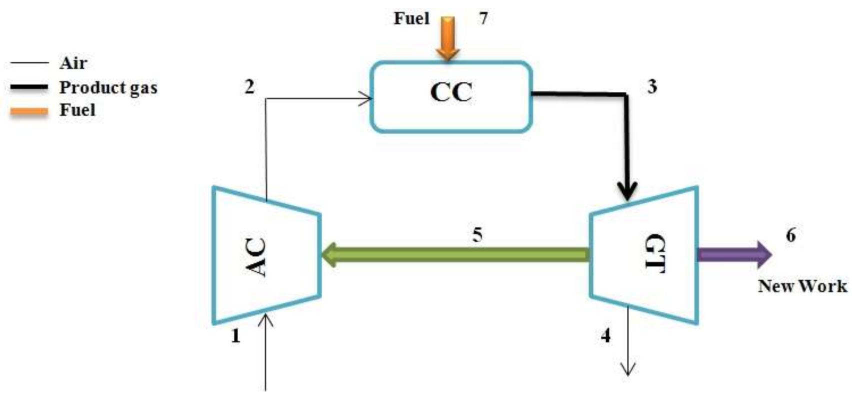

Figure 2. The gas turbine cycle of Aliabad Katoul power plant without air preheater

EXERGY ANALYSIS

Exergy is divided to four sections: Physical, Chemical, Kinetic and Potentials. Kinetic and potential exergies are neglected in this study although they have not any noticeable effects on system analysis. By applying the first and the second laws of thermodynamics, the following exergy balance is obtained. Formula for exergy balance is as the following [46]:

$$\dot{E}x = \dot{E}x_{ph} + \dot{E}x_{ch} \tag{13}$$

The equations of physical and chemical exergy per unit mass are as follows [46]:

$$ex_{ph} = (h - h_0) - T_0(s - s_0) \tag{14}$$

Also, for mixed chemical exergy per unit mass we have [46]:

$$ex_{mix}^{ch} = \left[\sum_{i=1}^{n} X_i ex^{ch_i} + RT_0 \sum_{i=1}^{n} X_i LnX_i\right] \tag{15}$$

The equations of exergy destruction and efficiency of different components of gas turbine cycle have been listed in Table 1.

Table 1. Exergy destruction and efficiency equations for whole parts

Components	Cycle	Exergy efficiency (%)	Exergy destruction (MW)
Air compressor	With APH	$\eta_{ex,AC} = \frac{\dot{E}_2 - \dot{E}_1}{\dot{W}_{AC}}$	$\dot{E}_{D,AC} = \dot{E}_1 - \dot{E}_2 - \dot{W}_{AC}$
	Without APH	$\eta_{ex,AC} = \frac{\dot{E}_2 - \dot{E}_1}{\dot{W}_{AC}}$	$\dot{E}_{D,AC} = \dot{E}_1 - \dot{E}_2 - \dot{W}_{AC}$
Combustion chamber	With APH	$\eta_{ex,CC} = \frac{\dot{E}_4}{\dot{E}_3 + \dot{E}_9}$	$\dot{E}_{D,CC} = \dot{E}_3 + \dot{E}_9 - \dot{E}_4$
	Without APH	$\eta_{ex,CC} = \frac{\dot{E}_3}{\dot{E}_2 + \dot{E}_7}$	$\dot{E}_{D,CC} = \dot{E}_2 + \dot{E}_7 - \dot{E}_3$
Gas turbine	With APH	$\eta_{ex,GT} = \frac{\dot{W}_{GT}}{\dot{E}_4 - \dot{E}_5}$	$\dot{E}_{D,GT} = \dot{E}_4 - \dot{E}_5 - \dot{W}_{GT}$
	Without APH	$\eta_{ex,GT} = \frac{\dot{W}_{GT}}{\dot{E}_3 - \dot{E}_4}$	$\dot{E}_{D,GT} = \dot{E}_3 - \dot{E}_4 - \dot{W}_{GT}$
Air preheater	With APH	$\eta_{ex,APH} = 1 - \left(\dot{E}_{D,APH} \Big/ \sum_{i,APH} \dot{E}\right)$	$\dot{E}_{D,APH} = (\dot{E}_2 + \dot{E}_5) - (\dot{E}_3 + \dot{E}_6)$
	Without APH	-	-

EXERGOECONOMIC ANALYSIS

In order to reach more affordable system with better performance, by combination of exergy and economic, a new concept was presented that is called exergo-economics. This concept first was presented by Valero and colleagues [47]. The purpose of exergo-economics analysis is calculation the cost flow and calculation of cost per unit of flow exergy. Exergy cost of products is used for economic cycle optimization. For a system, cost balance equation is as follows [47, 48]:

$$\sum_{e} \dot{C}_{e,k} + \dot{C}_{w,k} = \dot{C}_{q,k} + \sum_{i} \dot{C}_{i,k} + \dot{Z}_{k} \tag{16}$$

Using equation 16, we can write [47, 48]:

$$\sum \left(c_e \dot{E}x_e\right)_k + c_{w,k}\dot{W}_k = c_{q,k}\dot{E}x_{q,k} + \sum \left(c_i \dot{E}x_i\right)_k + \dot{Z}_k \tag{17}$$

$$\dot{C}_j = c_j E_j \tag{18}$$

At the above equations, c_i is input exergy unit cost (\$ / MJ), c_e is output exergy unit cost (\$ / MJ), $c_{w,k}$ is the cost rate for Kth flow line (\$ / MJ) and $c_{q,k}$ is exergy unit cost related to the heat for Kth flow line (\$ / MJ). Also, C_j and c_j are respectively, flow cost rate and exergy unit cost for the jth flow line. In Eq. 15, no term is directly related to exergy destruction rate. So, by combining exergy balance equation and exergo-economic equation, cost of exergy destruction rate can be calculated.

$$\dot{E}x_{F,k} = \dot{E}x_{p,k} + \dot{E}x_{D,k} \tag{19}$$

$$\dot{C}_{F,k} = c_{F,k}\dot{E}x_{D,k} \tag{20}$$

$$\dot{C}_{P,k} = c_{P,k}\dot{E}x_{D,k} \tag{21}$$

Where, $\dot{C}_{F,k}$ is the fuel cost rate (\$/s) and $\dot{C}_{P,k}$ is the products cost rate (\$/s). To solve cost balance equations and determine exergy rate of each system component, the component cost should be definite. In equation 16, $\dot{Z}_k$ is the total investment and maintenance cost rate of each component. For each line, a flow cost rate has been defined. Exergy destruction cost rate is computed from the following equation:

$$\dot{C}_{D,k} = c_{F,k}\dot{E}x_{D,k} \tag{22}$$

In this equation, $\dot{C}_{D,k}$ (\$/s) is the exergy destruction cost rate in kth part of the system (\$/s), $c_{F,k}$ is exergy unit cost for input routes of kth part of the system (\$/MJ) and $\dot{E}x_{D,k}$ is exergy destruction rate of kth part of the system. For calculation the investment cost including the cost of equipment purchase and maintenance the following equation has been used [47, 48]:

$$\dot{Z}_k = Z_k CRF\varphi/(N \times 3600) \tag{23}$$

In the above equation, Z_k is the purchase cost for kth part (US\$) that the equations related to each part has been brought in Table 2. Also, fixed values related to equations of Table 2 have been brought in Table 3. φ is the maintenance coefficient that in this article it is considered equal to 1.06 [48]. N is the hours of power plant operation in a year (8,000 hours) and CRF is the return on capital coefficient that has been considered equal to 0.182 in this study [47, 48]. The following equation has been used to calculate the fuel cost rate [47, 48]:

$$\dot{C}_f = c_f \dot{m}_f LHV \tag{24}$$

In the above equation $\dot{C}_f$ is fuel cost per unit of energy that is considered 0.004 (US$/MJ) [48]. $\dot{m}_f$ (kg/s) is fuel mass flow rate.

Table 2. Cost functions for each system component

System Components	Capital or investment cost functions
Air compressor	$Z_{AC} = \left(\frac{C_{11}\dot{m}_a}{C_{12} - \eta_{AC}}\right)\left(\frac{P_2}{P_1}\right)\ln\left(\frac{P_2}{P_1}\right)$
Combustion chamber	$Z_{CC} = \left(\frac{C_{21}\dot{m}_a}{C_{22} - \frac{P_4}{P_3}}\right)[1 + EXP(C_{23}T_4 - C_{24})]$
Gas turbine	$Z_{GT} = \left(\frac{C_{31}\dot{m}_g}{C_{32} - \eta_{GT}}\right)\ln\left(\frac{P_4}{P_5}\right)[1 + EXP(C_{33}T_4 - C_{34})]$
Air preheater	$Z_{APH} = C_{41}\left(\frac{\dot{m}_g(h_5 - h_6)}{(U)(\Delta TLM)}\right)^{0.6}$

Table 3. Constants used in the equations of Table 2

System Components	Constants
Air compressor	$C_{11} = 39.5\ US\$/(kg/s)$, $C_{12} = 0.9$
Combustion chamber	$C_{21} = 25.6\ US\$/(kg/s)$, $C_{22} = 0.995$ $C_{23} = 0.018\ K^{-1}$, $C_{24} = 26.4$
Gas turbine	$C_{31} = 266.3\ US\$/(kg/s)$, $C_{32} = 0.92$ $C_{33} = 0.036\ K^{-1}$, $C_{33} = 54.4$
Air preheater	$C_{41} = 2290\ US\$/m^{1.2}$, $U = 0.018\ kW/(m^2K)$

EXERGOENVIRONMENTAL ANALYSIS

In order to reduce environmental impacts, optimization of power generation systems and reducing fuel consumption and environmental impact have attracted the attention of researchers. Therefore, optimization of heating systems accordingly has been one of the most important issues in recent years. One of the main objects of this paper is to study the adverse impacts of CO and NOx emissions. Adiabatic flame temperature in the combustion primary zone is calculated by the following equation [8, 49]:

$$T_{pz} = A\sigma^{\propto} exp(\beta(\sigma + \lambda)^2)\pi^{x^*}\theta^{y^*}\psi^{z^*} \tag{25}$$

In this equation, π is dimensionless pressure (P/P_{ref}), θ is dimensionless temperature (T/T_{ref}). Also, ψ is atomic ratio (H/C) that for $\phi \le 1$, we have $\sigma = \phi$ (ϕ is the mass or molar ratio) and for $\phi \ge 1$, we have $\sigma = \phi - 0.7$. Moreover, x, y and z are quadric functions of σ.

$$x^* = a_1 + b_1\sigma + c_1\sigma^2 \tag{26}$$

$$y^* = a_2 + b_2\sigma + c_2\sigma^2 \tag{27}$$

$$z^* = a_3 + b_3\sigma + c_3\sigma^2 \tag{28}$$

At the above equations, A ،α ،β ،λ ،a_i ،b_i و c_i are constant values. These fixed values are shown in Table 4 [8, 49]. The product of carbon monoxide and nitrogen oxide in combustion chamber changes with adiabatic flame temperature. For calculation the amount of pollution (g/kg of fuel), the following equation is used [8, 49]:

$$\dot{m}_{NOx} = \frac{0.15 \times 10^{16} \times \tau^{0.5} \times exp(-71100/T_{pz})}{P_3^{0.05} \times (\Delta P/P)} \tag{29}$$

$$\dot{m}_{CO} = \frac{0.179 \times 10^{9} \times exp(7800/T_{pz})}{P_3^{2} \times \tau \times (\Delta P/P)} \tag{30}$$

At the above equations, τ is the residence time in the combustion zone that its amount has considered 0.002 seconds [8, 49]. P_3 is inlet pressure of combustion chamber and $(\Delta P/P)$ is dimensionless pressure loss in the combustion chamber.

Table 4. Constants used in the equations 24 to 27

Constants	$0.3 \le \phi \le 1.0$		$1.0 \le \phi \le 1.6$	
	$0.92 \le \theta \le 2$	$2 \le \theta \le 3.2$	$0.92 \le \theta \le 2$	$2 \le \theta \le 3.2$
A	2361.7644	2315.7520	916.8261	1246.1778
α	0.1157	-0.0493	0.2885	0.3819
β	-0.9489	-1.1141	0.1456	0.3479
λ	-1.0976	-1.1807	-3.2771	-2.0365
a_1	0.0143	0.0106	0.0311	0.0361
b_1	-0.0553	-0.0450	-0.0780	-0.0850
c_1	0.0526	0.0482	0.0497	0.0517
a_2	0.3955	0.5688	0.0254	0.0097
b_2	-0.4417	-0.5500	0.2602	0.5020
c_2	0.1410	0.1319	-0.1318	-0.2471
a_3	0.0052	0.0108	0.0042	0.0170
b_3	-0.1289	-0.1291	-0.1781	-0.1894
c_3	0.0827	0.0848	0.0980	0.1037

OBJECTIVE FUNCTIONS

In this paper, the two objective functions have been considered. The first objective function is the total cost rate which is included fuel, investment and maintenance and exergy destruction cost rate which is as follows[47, 48]:

$$\dot{C}_{Tot} = \dot{C}_f + \sum \dot{Z}_k + \sum \dot{C}_{D,k} \tag{31}$$

In this equation, $\dot{C}_f$ ،$\dot{Z}_k$ and $\dot{C}_{D,k}$ are fuel, equipment purchase and the exergy destruction cost rate, respectively.

Exergy destruction cost rate is computed from the following equation[47, 48]:

$$\dot{C}_{D,k} = c_{F,k}\dot{E}x_{D,k} \tag{32}$$

In this relation, $\dot{C}_{D,k}$ ($/s) is the exergy destruction cost rate in kth part of the system ($/s), $c_{F,k}$ is exergy unit cost for input routes of kth part of the system ($/MJ) and $\dot{E}x_{D,k}$ is exergy destruction rate of kth part of the system.

The second objective function is the cost of environmental impact which is calculated by multiplying the cost (US$/s) of CO and NOx emission in their values of unit damage cost. The values of unit damage cost are as follows [8, 49]:

$$C_{CO} = 0.02086 \quad US\$/kgCO \tag{33}$$

$$C_{NOx} = 6.853 \quad US\$/kgNOx \tag{34}$$

Therefore, the second objective function is as follows:

$$\dot{C}_{env} = C_{CO}\dot{m}_{CO} + C_{NOx}\dot{m}_{NOx} \tag{35}$$

Both the objective functions considered in this article should be minimized.

OPTIMIZATION METHOD

MULTI-OBJECTIVE OPTIMIZATION

Indeed, optimization problems are finding response or responses on a set of possible options with the aim of optimizing criterion or criteria of the problem. The purpose of multi-objective optimization is to find set of Pareto responses on the target function. Also, it is a subcategory from a set of multi-criteria decision-making methods that take place among an infinite set of possible solutions. In these types of problems, unlike the single-objective optimization problems and because of presence of several conflicting objectives, rather than just one solution, a set of solutions should be achieved. In multi-objective optimization, there are a set the solutions that the superior solutions are compared with other solutions in the search space. The remarkable point is that in multi-objective optimization no solution is superior to other one and solution for the problem can be considered regarding the need of designer of each of the Pareto solutions.

MULTI-OBJECTIVE GENETIC ALGORITHM (NSGA-II)

This algorithm has become a multi-objective algorithm by adding two essential operators to conventional single objective genetic algorithm that instead of finding the best solution, it gives a group of best solutions that is known as Pareto Front. Members of the population fall within the groups, such that members in the first group are a totally non-nominated set by other current members. Members in the second group are also dominated on the same basis only by members of the first group and this process will continue in the same way in other groups so that all the members in each group are assigned one rank based on the number of groups. The general flowchart of multi-objective genetic algorithm (NSGA-II) has been illustrated in Figure 3[50].

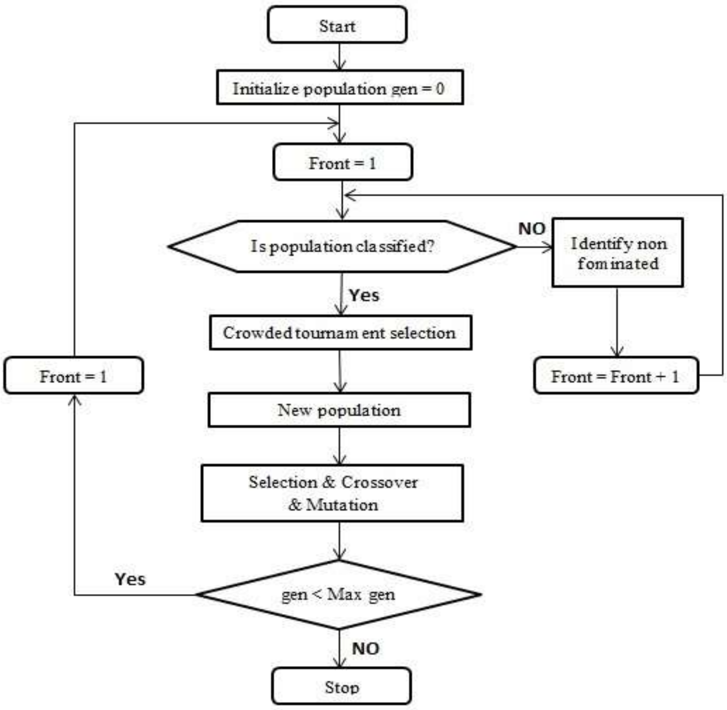

Figure 3. Flowchart of NSGA-II algorithm

RESULTS

DESIGN VARIABLES

The number of population and generation was selected 100 and 200 respectively. Mutation Probability and Crossover Probability was considered 0.01 and 0.9 respectively. In addition, the maximum number of iteration was considered 500, which if this number is reached without the optimization having reached convergence, iteration will stop.

The design variables considered in this paper for the first case cycle (gas turbine cycle with air preheater) are: air compressor pressure ratio (r_{AC}), combustion chamber inlet temperature (T_3), gas turbine inlet temperature (T_4), air compressor isentropic efficiency (η_{AC}) and gas turbine isentropic efficiency (η_{GT}). In another case, the cycle has been considered without air preheater that design variables in this state are: air compressor pressure ratio, gas turbine inlet temperature, air compressor and gas turbine isentropic efficiency. According to the different conditions of design variables in the optimization process, reasonable constraints have been considered for each variable which is shown in Table 5.

Table 5. Model constraints

Constraints	Reason
$6 \leq r_{AC} \leq 16$	Commercial availability
$800\ K \leq T_3 \leq 1100\ K$	Material limitation
$1200\ K \leq T_4 \leq 1600\ K$	Material limitation
$0.7 \leq \eta_{AC} \leq 0.9$	Commercial availability
$0.7 \leq \eta_{GT} \leq 0.92$	Commercial availability

In order to validate results of this simulation, the conclusions of this research are compared with the real Aliabad Katoul power plant. The comparison of results is presented in Table 6.

Table 6. Comparison between the power plant real data and simulation

Parameter	Power plant data	Simulation Code	Difference (%)
$\dot{C}_{Tot}\ (US\$/s)$	2.82	2.98	4.6
$T_2\ (K)$	606	612	1.0
$T_5\ (K)$	864	879	1.7
$T_6\ (K)$	672	695	3.4

THE RESULTS OF MULTI-OBJECTIVE OPTIMIZATION BY GENETIC ALGORITHM

Figure 4 shows Pareto solution for Aliabad Katoul gas turbine power plant by multi-objective genetic algorithm. It concludes that with increasing in the environmental cost rate, total cost rate decreases. From the figure, it is clear that for the environmental cost rate values from 0.06 (US$/s) up to 0.1 (US$/s), total cost rate decreases with a steeper slope. From 0.1 (US$/s) onwards, the total cost rate decreases slightly while environmental cost rate increases with a steeper slope. In Pareto solution, each solution can be as the optimal answer. Choosing an optimal solution depends on the designer's perspective and importance of each objective function. In the figure, the three points A, B and C are specified. The point A has the maximum point of total cost rate and the lowest environmental cost. Also, the point C has the lowest total cost rate and the highest rate of environmental cost. In this study, point B is selected as an optimal point because the goal is optimizing both objective functions simultaneously.

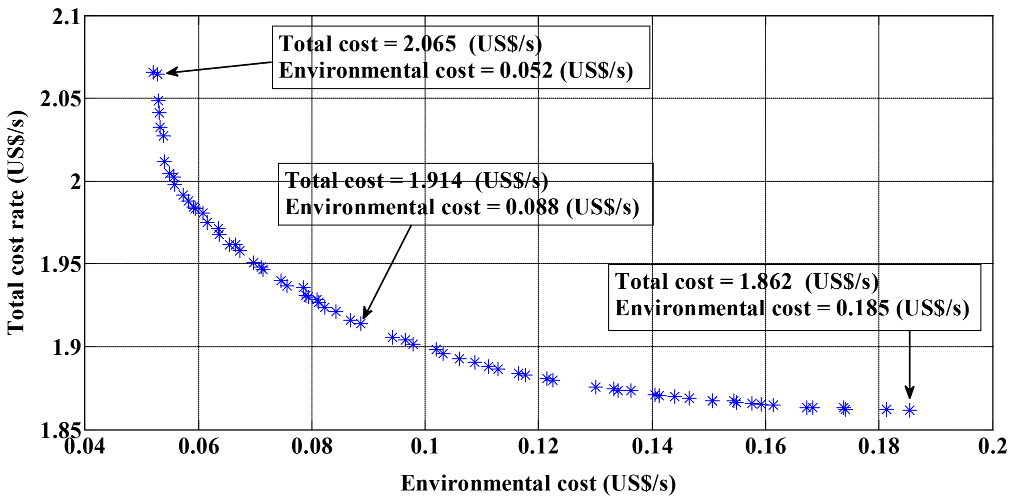

Figure 4. Pareto solution of Aliabad Katoul gas turbine power plant by NSGA-II algorithm

To investigate the effect of air preheater on objective functions, in the second case, the air preheater is removed from Aliabad Katoul power plant cycle so that its effect on objective functions could be studied. In Figure 5, Pareto solution for the studied cycle by eliminating the air preheater has been shown. As it can be seen, the three points A, B and C are specified. Like Figure 4, the point A has the highest total cost rate and the lowest environmental cost rate. Also, point C has the lowest total cost rate and highest environmental cost rate. The results show that by removing of air preheater, values of both objective functions increase. Only at the point C, environmental cost rate is lower than the value of point C in Figure 4, but this point has higher total cost rate. According to the results, it is observed that air preheater existence in the system reduces both objective functions. The values of points A, B and C for both cases are presented in Table 7. The results demonstrate that at the optimum point (point B), for cycle without air preheater, total cost rate is about 30% and environmental cost rate is about 33% higher than the cycle with air preheater.

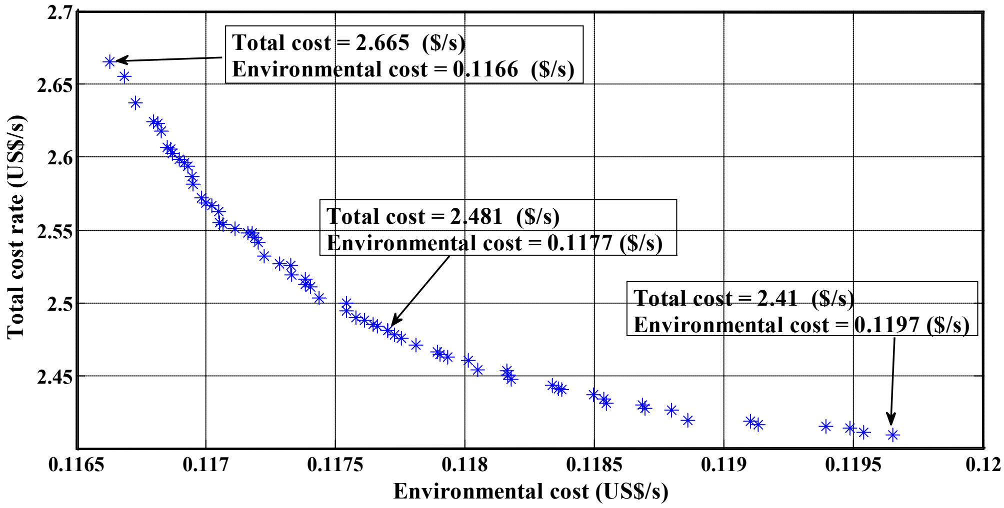

Figure 5. Pareto solution of Aliabad Katoul gas turbine power plant without air preheater by NSGA-II algorithm

Table 7. The objective function values at selected points for two considered cycles

Cases	Objective function	A point	B point	C point
Aliabad power plant cycle	Total cost rate $(US\$/s)$	2.065	1.914	1.862
	Environmental cost $(US\$/s)$	0.052	0.088	0.185
Aliabad power plant cycle without air preheater	Total cost rate $(US\$/s)$	2.665	2.481	2.41
	Environmental cost $(US\$/s)$	0.1166	0.1177	0.1197

DISTRIBUTION OF DESIGN VARIABLES

In Figures 6a to 10e, distribution of design variables is shown. Upper and lower limits of design parameters are presented by dash lines. Figure 6a shows distribution of Pareto solutions for compressor pressure ratio variable. This distribution shows that the result of changes in this variable within the specified range is in contradiction with both objective functions. Figures 6b and 6c, respectively, show distribution of Pareto solutions for inlet temperature of the combustion chamber and gas turbine. As can be seen, distribution of Pareto solutions is close to the specified upper limit which indicates the higher values of these two variables have improved the solution in both objective functions. Most of the solutions for the combustion chamber inlet temperature are about 1005 Kelvin and for the gas turbine inlet temperature is about 1470 Kelvin. Also, Figures 6d and 6e, respectively, show distribution of design variables for isentropic efficiency of compressor and gas turbine. It can be seen from these two figures that for the compressor isentropic efficiency, most of the solutions are about 87% and for the gas turbine isentropic efficiency are about 90%, which indicates that the values of these efficiencies in this range have improved both objective functions.

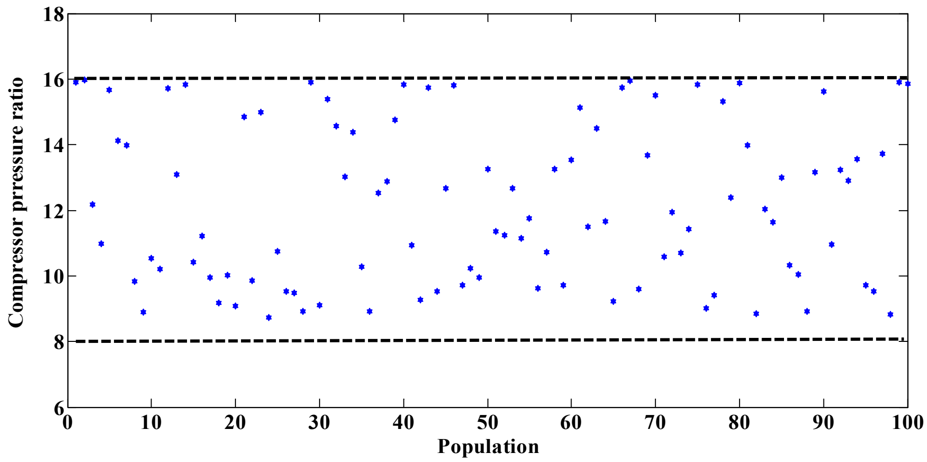

Figure 6a. Distribution of compressor pressure ratio values in Pareto solution

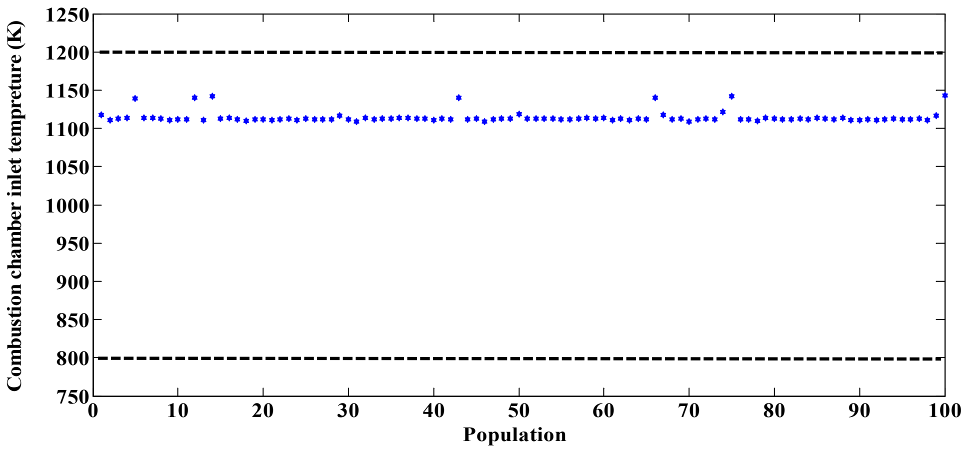

Figure 6b. Distribution of combustion chamber inlet temperature values in Pareto solution

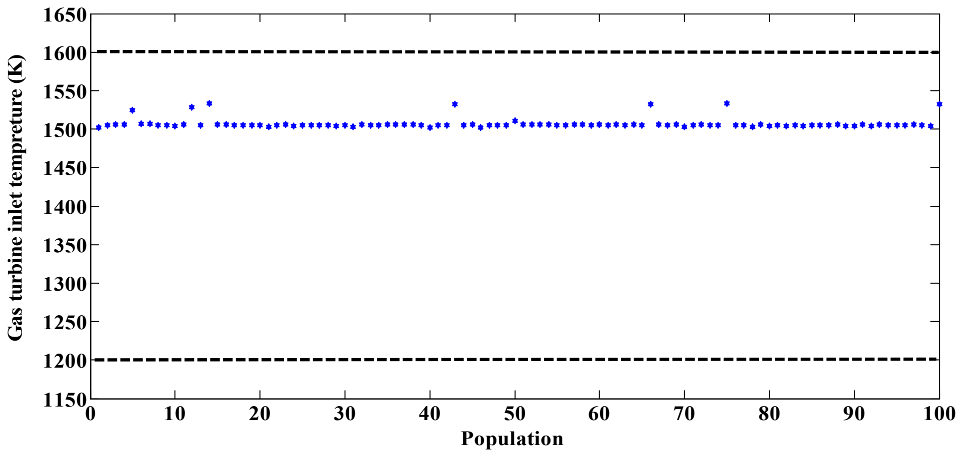

Figure 6c. Distribution of gas turbine inlet temperature values in Pareto solution

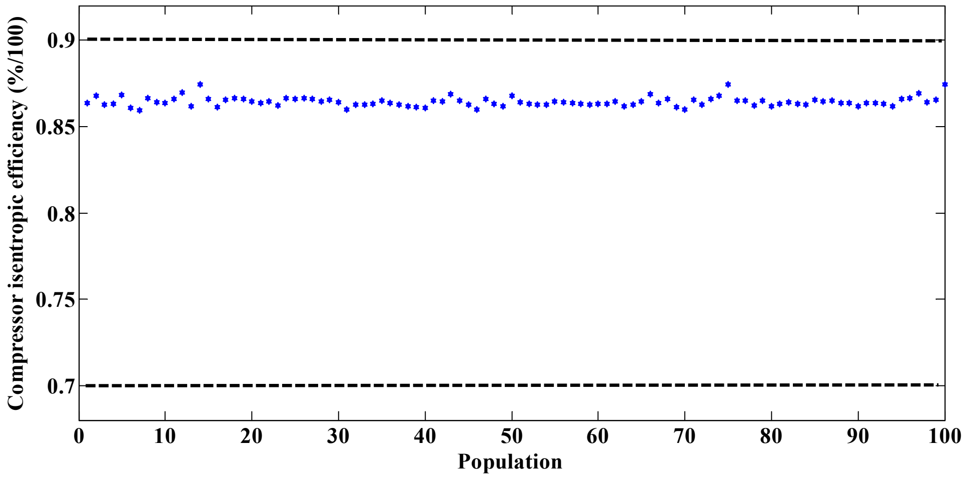

Figure 6d. Distribution of air compressor efficiency values in Pareto solution

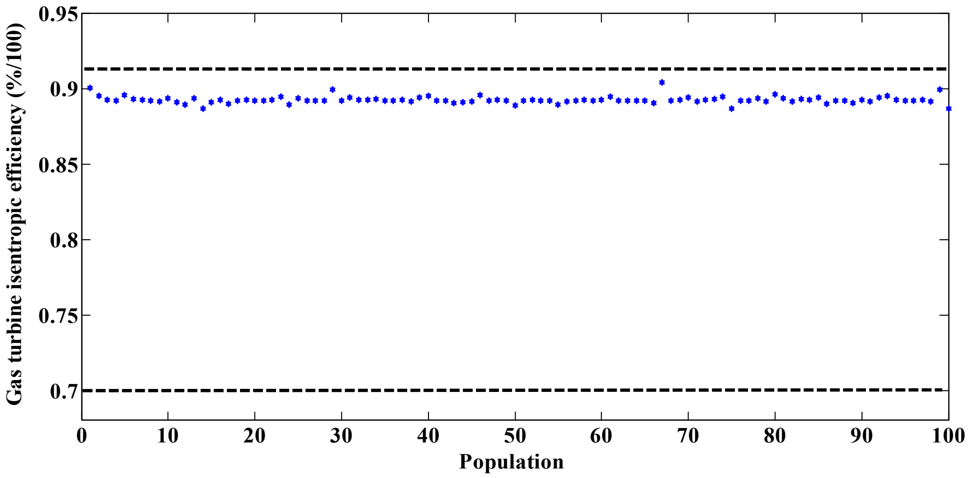

Figure 6e. Distribution of gas turbine efficiency values in Pareto solution

Table 8. The value of design parameter for points A, B and C

Parameter	Point A	Point B	Point C
r_{AC}	12.1	9.3	11.6
T_3	1119	1121	1128
T_4	1511	1504	1505
η_{AC}	88.1	87.4	87.2
η_{GT}	89.8	89.1	89.3

SENSITIVITY ANALYSIS

In Figure 7 the sensitivity of objective functions changes to fuel cost per unit of energy is shown. From this figure, it is clear that at lower environmental cost rate, that total cost rate is higher, the sensitivity of Pareto solutions to the fuel unit cost is more than some parts of figure with lower total cost rate. In other words, we can say that sensitivity of fuel unit cost parameter does not have too much effect on cost of environmental impacts.

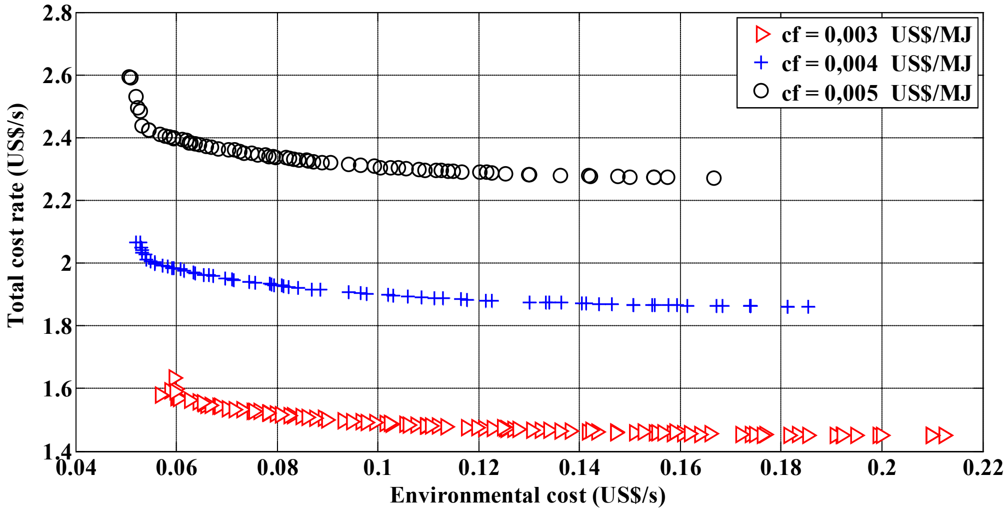

Figure 7. Pareto solution sensitivity to the fuel cost per energy unit

EXERGY DESTRUCTION

Figure 8 shows exergy destruction values for different parts of the cycle. From this figure it is clear that the maximum rate of exergy destruction is related to the combustion chamber. Exergy destruction is because of three irreversibility factors, which include heat transfer, friction and chemical reaction. Figure 9 shows exergy destruction percentage for different cycle parts. This figure shows that about 73% of the total exergy destruction is related to the combustion chamber. It decreases by optimizing the air to fuel ratio, reducing exergy destruction and preheating the air before entering to combustion chamber.

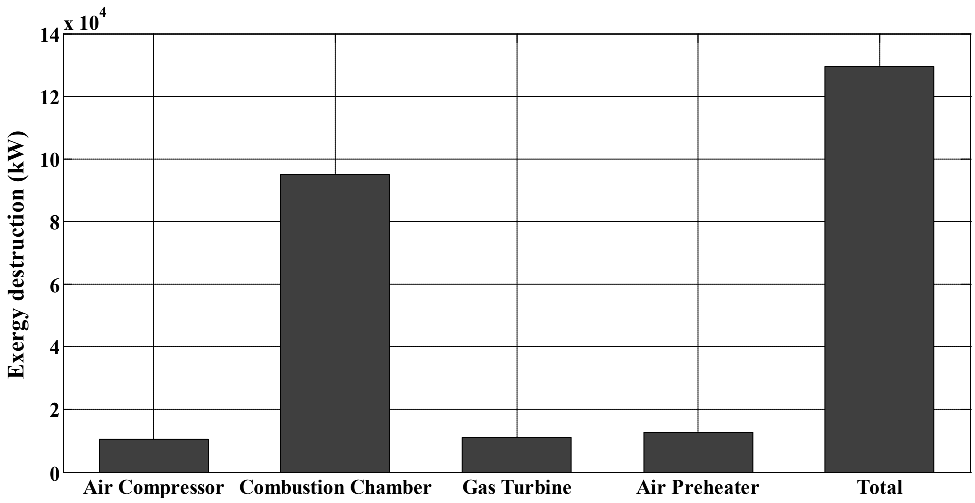

Figure 8. Exergy destruction values for diverse parts

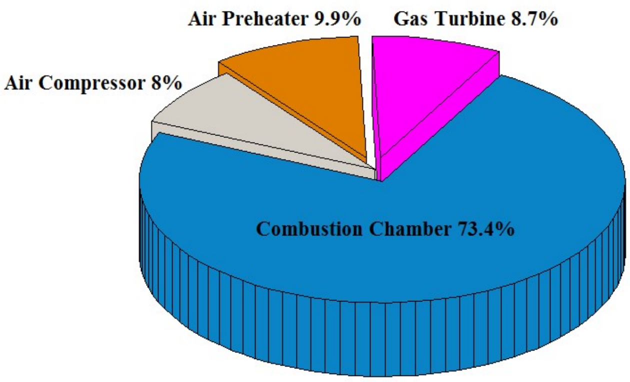

Figure 9. Exergy destruction percentage for diverse cycle parts

Figure 10 shows exergy efficiency changes for different components versus variations in ambient temperature. It is clear that with increasing the ambient temperature, exergy efficiency of all components decreases. By increasing ambient temperature from 293 to 323 K, exergy efficiency of air compressor has decreased from 90% to 87.7%, exergy efficiency of combustion chamber from 51.9% to 48.6%, exergy efficiency of gas turbine from 85.4% to 81.4% and exergy efficiency of air preheater from 93.9 % to 90%.

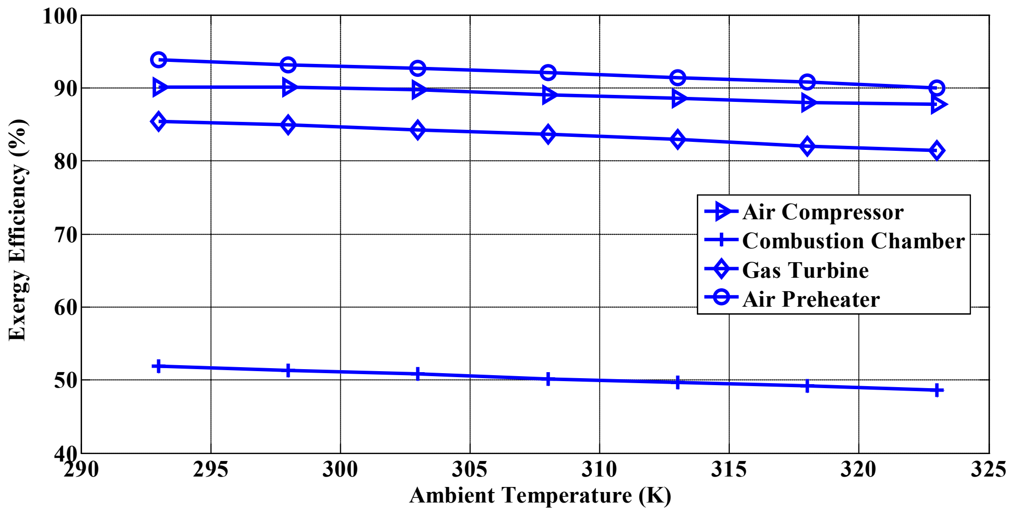

Figure 10. Changes in exergy efficiency for various parts against ambient temperature changes

Figure 11 shows changes in total exergy efficiency against changes in ambient temperature. A growth in ambient temperature diminishes total exergy efficiency. So that with increase of temperature from 293 Kelvin to 323 Kelvin, total exergy efficiency has decreased approximately from 51% to 49%. It indicates that increasing in ambient temperature has had an adverse impact on exergy efficiency.

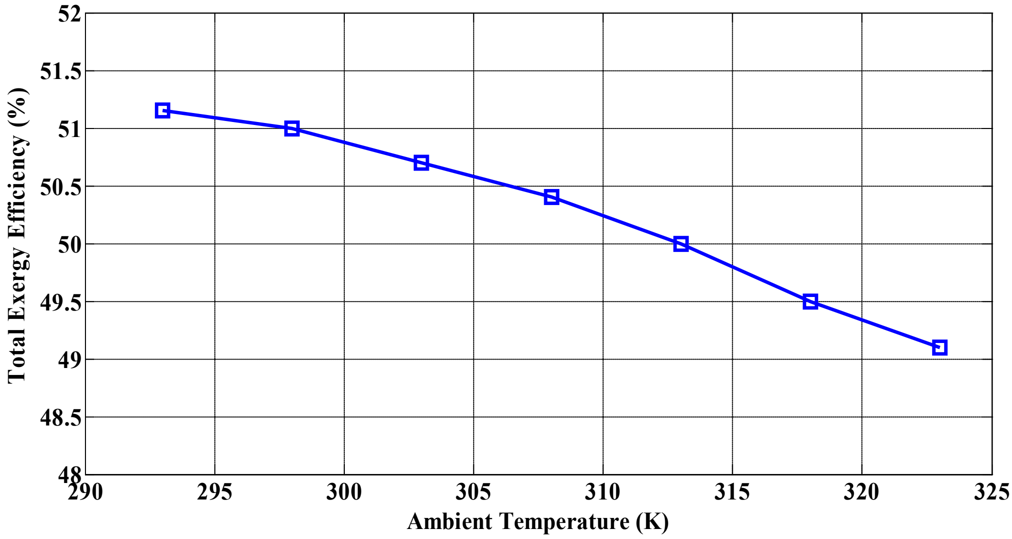

Figure 11. Changes in exergy efficiency against ambient temperature changes

Figure 12 shows changes in exergy destruction for various sectors against changes in ambient temperature. This figure shows that increase in ambient temperature causes exergy destruction of whole parts. So, by increasing the ambient temperature from 293 K to 303 K, exergy destruction of air compressor, combustion chamber, gas turbine and air preheater have increased 14%, 0.6%, 18% and 10%, respectively.

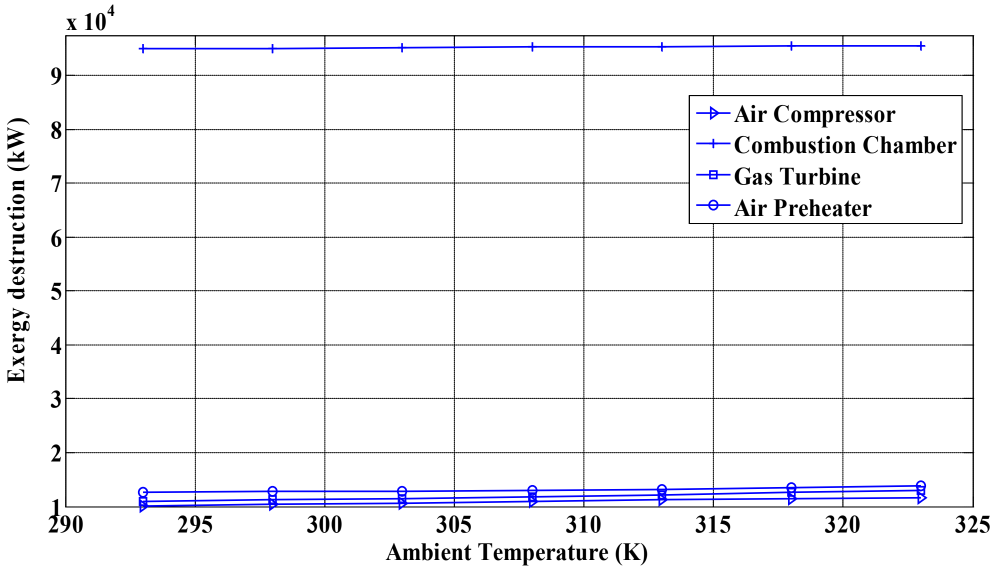

Figure 12. Exergy destruction changes for diverse parts of the cycle against ambient temperature changes

CONCLUSION

In this paper, Aliabad Katoul gas turbine power plant (northern Iran) was considered thermodynamically, economically environmentally aspects and as well as its optimization by NSGA-II has performed in MATLAB software. The two objective functions considered were: total cost rate and cost of environmental impact. Also, optimization of this cycle has performed in two cases, with air preheater and without it. Also, sensitive analysis of objective functions was carried out into changes in fuel cost per unit of energy. Furthermore, the impact of change in ambient temperature on exergy efficiency of each part, also, total exergy efficiency of the cycle was investigated. Briefly following results have concluded:

- Air preheater reduced both objective functions particularly total cost rate.
- In selected optimal point in Pareto solution (point B), for the cycle with air preheater, the total cost rate about 30% and the environmental cost rate about 33% were lower than the cycle without air preheater.
- In lower environmental costs, that total cost rate was higher, sensitivity of Pareto solutions to fuel price was more than some parts of the graph with lower total cost rate.
- The highest exergy destruction was related to the combustion chamber.
- With increasing temperature, exergy efficiency of all components was decreased.
- By increasing the ambient temperature, destructions and irreversibility of different components increased.

DECLARATION ON CONFLICT OF INTEREST

No conflict of interest in this paper existed.

NOMENCLATURE

c	Exergy unit cost $(US\$/MJ)$
c_f	Fuel exergy unit cost $(US\$/MJ)$
C	Cost flow rate $(US\$/s)$
c_p	Constant pressure heat $(kJ/kg.K)$
LHV	Lower heating value (kJ/kg)
R	Gas constant $(kJ/kg.K)$
h	Enthalpy (kJ/kg)
f	Fuel/air molar ratio
$\dot{E}x$	Exergy flow rate (MW)
$\dot{E}x_D$	Exergy destruction rate (MW)
ex	Specific exergy (kJ/kg)
CRF	Capital recovery factor
P	Pressure (bar)
T	Temperature (K)
ΔP	Pressure loss
r_{AC}	Compressor pressure ratio
$\dot{m}$	Mass flow rate (kg/s)
s	Specific entropy $(kJ/kg.K)$
T_{pz}	Adiabatic temperature in the primary zone of combustion chamber (K)
$\dot{W}_{net}$	Net power output (MW)
X_i	Molar fraction
N	Number of hours of plant operation per year
Z	Capital cost of a component ($)
$\dot{Z}$	Capital cost rate $(\$/s)$

Greek symbols

γ	Specific heat ratio
η	Efficiency
φ	Maintenance factor
θ	Dimensionless temperature
π	Dimensionless pressure

ψ	H/C atomic ratio
ϕ	Equivalent fuel to air ratio

Subscripts

a	Air
g	Combustion gases
ch	Chemical
ph	Physical
AC	Air Compressor
CC	Combustion Chamber
GT	Gas Turbine
APH	Air Preheater
D	Destruction
k	Component
Tot	Total
env	Environmental
0	Reference environment condition
f	Natural gas fuel
Ref	Reference
i	Inlet condition
e	Exit condition

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