EXERGY, ECONOMIC, AND ENVIRONMENTAL (3E) ANALYSIS OF A GAS TURBINE POWER PLANT AND OPTIMIZATION BY MOPSO ALGORITHM

by

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In this paper, exergy, exergoeconomic, and exergoenvironmental analysis of a gas turbine cycle and its optimization has been carried out by MOPSO algorithm. Three objective functions, namely, total cost rate, exergy efficiency of cycle, and CO_2 emission rate have been considered. The design variables considered are: compressor pressure ratio, combustion chamber inlet temperature, gas turbine inlet temperature, compressor, and gas turbine isentropic efficiency. The impact of change in gas turbine inlet temperature and compressor pressure ratio on CO_2 emission rate as well as impact of changes in gas turbine inlet temperature on exergy efficiency of the cycle has been investigated in different compressor pressure ratios. The results showed that with increase in compressor pressure ratio and gas turbine inlet temperature, CO_2 emission rate decreases, that is this reduction is carried out with a steeper slope at lower pressure compressor ratio and gas turbine inlet temperature. The results showed that exergy efficiency of the cycle increases with increase in gas turbine inlet temperature and compressor pressure ratio. The sensitivity analysis of fuel cost changes was performed on objective functions. The results showed that at higher exergy efficiencies total cost rate is greater, and sensitivity of fuel cost optimum solutions is greater than Pareto curve with lower total cost rate. Also, the results showed that sensitivity of changes in fuel cost rate per unit of energy on total cost rate is greater than the rate of CO_2 emission.

Key words: *gas turbine, optimization, multi-objective, CO_2 emission, exergy, environmental*

Introduction

In recent years, increased use of fossil fuels as well as increase in energy supply costs has led researchers and manufacturers looking for systems with higher efficiency more than ever. Also, with regard to environmental problems caused by emissions of fossil fuels and its effect on global warming and ozone layer, the use of systems with lower contamination is inevitable. Kopac and Hilalci [1] carried out an energy analysis for a thermal power plant in Turkey to investigate the effect of ambient temperature on the rate of irreversibility and overall exergy efficiency of power plant. Ehyaei and Mozafari [2] performed optimization of a micro turbine using exergy, economic, and environmental analysis, taking into account different fuels. Seyyedi *et al.* [3] car-

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ried out thermodynamic, economic, and environmental analysis and optimization of gas turbine cycle. They performed the impact of air preheater on thermodynamic cycle by examining the environmental effect. Ahmadi *et al.* [4] conducted a multi-objective optimization and exergy analysis for a combined heat and power (CHP) system. They carried out a sensitivity analysis on efficiency of the system for better understanding of design variables. Kaviri Ganjeh *et al.* [5] carried out thermodynamic modeling of a combined cycle power plant with dual pressure. They also performed its multi-objective optimization by genetic algorithm. Shirazi *et al.* [6] carried out energy, exergy, economic, and environmental analysis of a gas turbine – fuel cell combined cycle with internal reforming. Sanyeh and Katebi [7] carried out energy, exergy, economic, and environmental analysis as well as a multi-objective optimization of a hybrid fuel cell and gas turbine combined cycle for use in a CHP system. Ehyaei *et al.* [8] examined thermodynamic modeling of a combined cycle power plant as well as the effects of gas turbine inlet fogging system on the First and Second law efficiency and net output power. Khlijani *et al.* [9] performed a thermodynamic, exergy-economic, and environmental analysis of a gas turbine combined system and Rankine organic cycle. Khanmohammadi *et al.* [10] conducted thermodynamic and economic analysis of a gas turbine combined cycle and Rankine organic cycle with a biomass gasifier. Ahmadi Boyaqchi and Molaei [11] carried out advanced Exergy and optimization analysis of a real combined cycle with duct burners in Iran.

In this article, exergy, exergoeconomic, and exergoenvironmental analysis of a gas turbine cycle (Aliabad Katoul power plant, located in northern Iran) and its optimization has been done by multi-objective particle swarm optimization (MOPSO) algorithm. In this paper, three objective functions namely total cost rate, exergy efficiency of cycle and CO_2 emission rate have been considered. The main components of the cycle include air compressor, combustion chamber, gas turbine, and air preheater. The design variables considered in this study include: 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}. Also, sensitivity analysis of changes in fuel cost rate per unit of energy has been done on objective functions.

Energy analysis

In order to obtain optimum parameters of the system, gas turbine cycle modeling was performed in MATLAB. The following hypotheses were considered in analysis of the cycle:

- All processes are supposed to be steady-state.
- Air and combustion products are supposed to be ideal gas.
- Air compressor and gas turbine are supposed to be adiabatic.
- Heat loss from the combustion chamber has been considered equal to 8% of fuel low heating value.
- Pressure drop in air preheater has been considered to be 5% and 3% of pressure difference between input and output for air and combustion products, respectively.
- Air compressor inlet air temperature is 298 K and its pressure is intended to be equal to 1.013 bar.

The figure of Aliabad power plant cycle has been shown in fig. 1. Energy balance equations for various components of the cycle are as follows.

- Air compressor

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

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

where T [K] is the temperature, P [bar] – the pressure, η_{AC} [%] – the air compressor isentropic efficiency, $\dot{m}_a$ [kgs^{-1}] the air mass-flow rate, $c_{p,a}$ [kJkg^{-1}K^{-1}] – the specific heat capacity of air at constant pressure, and $\dot{W}_{AC}$ – the net-work of air compressor.

– Combustion chamber

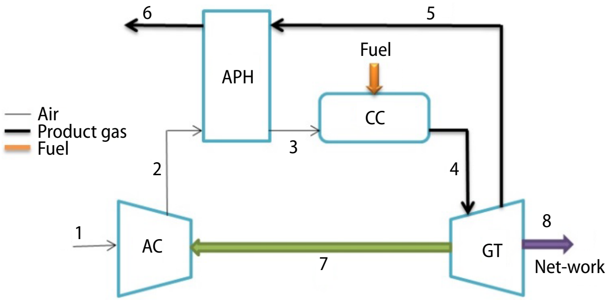

Figure 1. The gas turbine cycle of Aliabad Katoul power plant

$$\dot{m}_a h_3 + \dot{m}_f LHV = \dot{m}_g h_4 + (1 - \eta_{CC})\dot{m}_f LHV, \quad LHV = 50000 \text{ kJ/kg} \text{ and } \eta_{CC} = 0.92 \tag{3}$$

$$P_4 = P_3(1 - \Delta P_{CC}) \text{ with } \Delta P_{CC} = 0.05 \text{ bar} \tag{4}$$

where LHV [kJkg^{-1}] is lower heating value of fuel, $\dot{m}_f$ [kgs^{-1}] – the fuel mass-flow rate, η_{CC} [%] – the combustion chamber efficiency. The equation of reaction in the combustion chamber is:

$$fCH_4 + x_{O_2}^0 O_2 + x_{N_2}^0 N_2 + x_{CO_2}^0 CO_2 + x_{H_2O}^0 H_2O \rightarrow (f + x_{CO_2}^0)CO_2 + (2f + x_{H_2O}^0)H_2O +$$
$$+(x_{O_2}^0 - 2f)O_2 + x_{N_2}^0 N_2$$

where f is the molar ratio of fuel to air.

– Gas turbine

$$T_5 = T_4 \left\{ 1 - \eta_{GT} \left[1 - \left(\frac{P_4}{P_5} \right)^{\frac{1-\gamma_g}{\gamma_g}} \right] \right\} \tag{5}$$

$$\dot{W}_{GT} = \dot{m}_g c_{p,g}(T_4 - T_5) \tag{6}$$

$$\dot{m}_g = \dot{m}_a + \dot{m}_f \tag{7}$$

$$\dot{W}_{net} = \dot{W}_{GT} - \dot{W}_{AC} \text{ with } \dot{W}_{net} = 150 \text{ MW} \tag{8}$$

Here, $\dot{m}_g$ [kgs^{-1}] is combustion products mass-flow rate, $c_{p,g}$ [kJkg^{-1}K^{-1}] – the specific heat capacity of combustion products at constant pressure, η_{GT} [%] – the gas turbine isentropic efficiency, and $\dot{W}_{GT}$ [MW] and $\dot{W}_{net}$ [MW] – are net-work of gas turbine and cycle, respectively.

– Air preheater

$$\dot{m}_a c_{p,a}(T_3 - T_2) = \dot{m}_g c_{p,g}(T_5 - T_6) \tag{9}$$

$$P_3 = P_2(1 - \Delta P_{a,APH}) \text{ with } \Delta P_{a,APH} = 0.05 \text{ bar} \tag{10}$$

$$P_6 = P_5(1 - \Delta P_{g,APH}) \text{ with } \Delta P_{g,APH} = 0.03 \text{ bar} \tag{11}$$

By solving the previous equations, properties and thermodynamic values of the part and different parts of the cycle are obtained.

Exergy analysis

Exergy is divided into four parts: physical, chemical, kinetic, and potential exergy. In this study, kinetic and potential exergy are negligible [4]. Chemical exergy is related to the amount of system's chemical composition diversion from chemical equilibrium. Chemical exergy is one of the important parts of exergy in a combustion process.

$$\dot{E}x = \dot{E}x_{ph} + \dot{E}x_{ch} \tag{12}$$

Physical exergy per mass unit, in general, and considering the air and combustion products in a form of full gas, is defined:

$$ex_{ph} = (h - h_0) - T_0(s - s_0) \tag{13}$$

In the previous equation T is the temperature in terms of Kelvin and subscript 0 refers to ambient conditions. The mixed chemical exergy per mass unit is obtained [12]:

$$ex_{mix}^{ch} = \left[\sum_{i=1}^{n} X_i ex^{ch_i} + \mathrm{R}T_0 \sum_{i=1}^{n} X_i \ln X_i\right] \tag{14}$$

Considering the fact that for most of fuels the ratio of chemicals exergy to their low heating value is close to 1, for CH_4 can be written [13, 14]:

$$\zeta_{\mathrm{CH_4}} = 1,06$$

In tab. 1, the relations related to calculation of exergy destruction and exergy efficiency for each component have been shown.

Table 1. Exergy destruction rate and efficiency equations for gas turbine power plants components

Components	Exergy efficiency	Exergy destruction [MW]
Air compressor	$\eta_{ex,\mathrm{AC}} = \dfrac{\dot{E}_2 - \dot{E}_1}{\dot{W}_{\mathrm{AC}}}$	$\dot{E}_{D,\mathrm{AC}} = \dot{E}_1 - \dot{E}_2 - \dot{W}_{\mathrm{AC}}$
Combustion chamber	$\eta_{ex,\mathrm{CC}} = \dfrac{\dot{E}_4}{\dot{E}_3 + \dot{E}_9}$	$\dot{E}_{D,\mathrm{CC}} = \dot{E}_3 + \dot{E}_9 - \dot{E}_4$
Gas turbine	$\eta_{ex,\mathrm{GT}} = \dfrac{\dot{W}_{\mathrm{GT}}}{\dot{E}_4 - \dot{E}_5}$	$\dot{E}_{D,\mathrm{GT}} = \dot{E}_4 - \dot{E}_5 - \dot{W}_{\mathrm{GT}}$
Air preheater	$\eta_{ex,\mathrm{APH}} = 1 - \dfrac{\dot{E}_{D,\mathrm{APH}}}{\sum_{i,\mathrm{APH}} \dot{E}}$	$\dot{E}_{D,\mathrm{APH}} = (\dot{E}_2 + \dot{E}_5) - (\dot{E}_3 + \dot{E}_6)$

Economic analysis

Economic analysis is an important part of industrial projects. By combining economic and thermodynamic concepts, a new model for analysis and optimization of energy systems called exergoeconomic was presented for the first time by Valero *et al.* [12]. The purpose of this analysis is to determine cost flow and calculation of the cost per unit of flow exergy. The following equation is used to calculate values of investment cost including cost of equipment purchase and maintenance [4, 6, 12]:

$$\dot{Z}_k = \frac{Z_k CRF \varphi}{3600N} \tag{15}$$

The following equation was used to calculate the fuel cost rate [12]:

$$\dot{C}_f = c_f \dot{m}_f LHV \tag{16}$$

where Z_k is the purchase cost for k^{th} component in US$ that the relations related to various components of the cycle have been brought in tab. 2. Also, constant values related to relations of tab. 2 have been brought in tab. 3. The φ is the maintenance factor that it is considered equal to 1.06 in this paper [12, 15]. N is the number of power plant operation hours in a year (8000 hours), and CRF is return on capital coefficient that has been considered equal to 0.182 in this study [12]. Also, c_f, is fuel cost per unit of energy that has been considered equal to 0.004 US$/MJ [12]. Exergy destruction cost rate can be obtained from the following equation:

$$\dot{C}_{D,k} = c_{F,k} \dot{E}x_{D,k} \tag{17}$$

where $\dot{C}_{D,k}$ [$s^{-1}] is exergy destruction cost rate in the k^{th} part of the system, $c_{F,k}$ [$MJ^{-1}] – the exergy unit cost for k^{th} input line of the system, and $\dot{E}x_{D,k}$ is exergy destruction rate in k^{th} part of the system.

Table 2. Cost functions in terms of thermodynamic parameters for the system components [12]

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

Table 3. Constants used in the equations of tab. 2 [12]

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$/(kg/s), C_{32} = 0.92 C_{33} = 0.036 K^{-1}, C_{33} = 54.4
Air preheater	C_{41} = 2290 US$/(kg/s), U = 0.018 kW/m^{2}K

Exergoenvironmental analysis

In recent years, reduction in fuel consumption and GHG emissions has been one of the most important challenges among researchers. The most important GHG which has attracted the attention of researchers is CO_2. In this article, polluting gases namely CO_2, CO, and NO_x have been considered as the main pollutants. The amount of CO and NO_x produced in combustion chamber and combustion reaction changes greatly with adiabatic temperature of the flame. In order to determine the amount of pollution emission based on gram unit per kg of fuel, the following equation was used [16]:

$$\dot{m}_{\text{NOx}} = \frac{0.15 \cdot 10^{16} \tau^{0.5} \exp\left(-\frac{71100}{T_{pz}}\right)}{P_3^{0.05} \frac{\Delta P}{P}} \tag{18}$$

$$\dot{m}_{\mathrm{CO}} = \frac{0.179 \cdot 10^9 \exp\left(\dfrac{7800}{T_{pz}}\right)}{P_3^2 \tau \dfrac{\Delta P}{P}} \tag{19}$$

where τ is the residence time in the combustion zone that its constant value is considered to be 0.002 seconds [17, 18]. The P_3 is combustion chamber inlet temperature ($\Delta P/P$) is dimensionless pressure loss in the combustion chamber. Adiabatic flame temperature in the primary zone of the combustion chamber is obtained from the equation [16, 17]:

$$T_{pz} = A\sigma^{\alpha} \exp\left[\beta(\sigma+\lambda)^2\right] \pi^{x^*} \theta^{y^*} \psi^{z^*} \tag{20}$$

where π is dimensionless pressure, P/P_{ref}, θ – the dimensionless temperature, T/T_{ref}. Also, ψ is atomic ratio (H/C) that for $\varphi \leq 1$ we have $\sigma = \varphi$ (φ is the mass or molar ratio) and for $\varphi \geq 1$ we have $\sigma = \varphi - 0.7$. Moreover, x, y, and z are quadratic functions of the σ which are obtained from the relations:

$$x^* = a_1 + b_1\sigma + c_1\sigma^2 \tag{21}$$

$$y^* = a_2 + b_2\sigma + c_2\sigma^2 \tag{22}$$

$$z^* = a_3 + b_3\sigma + c_3\sigma^2 \tag{23}$$

In the previous relations A, α, β, λ, a_i, b_i, and c_i are parameters with constant values. These constant values have been brought in tab. 4 [3].

Table 4. Constants used in the eqs. (24)-(27) [3]

Constants	$0.3 \leq \varphi \leq 1.0$		$1.0 \leq \varphi \leq 1.6$	
	$0.92 \leq \theta \leq 2$	$2 \leq \theta \leq 3.2$	$0.92 \leq \theta \leq 2$	$2 \leq \theta \leq 3.2$
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

Three objective functions have been considered in this paper: total cost rate, exergy efficiency of the cycle, and CO_2 emission rate. The first objective function is total cost rate which includes fuel cost rate, cost of purchase and maintenance of equipment, cost of exergy destruction, and cost of environmental effects that are as follows:

$$\dot{C}_{\mathrm{Tot}} = \dot{C}_f + \sum \dot{Z}_k + \sum \dot{C}_{D,k} + \dot{C}_{\mathrm{env}} \tag{24}$$

where $\dot{C}_f$, $\dot{Z}_k$, $\dot{C}_{D,k}$, and $\dot{C}_{\mathrm{env}}$ are fuel cost, cost of purchase of equipment, exergy destruction cost and cost of environmental impacts, respectively. The relation of $\dot{C}_{\mathrm{env}}$ is:

$$\dot{C}_{\mathrm{env}} = C_{\mathrm{CO}}\dot{m}_{\mathrm{CO}} + C_{\mathrm{NOx}}\dot{m}_{\mathrm{NOx}} \tag{25}$$

In the previous equation, C_{CO} = 0.02086 \$/kgCO and C_{NOx} = 6.853 \$/kgNOx are unit damage costs [3]. Exergy efficiency of the cycle is the second objective function that is defined:

$$\eta_{Tot} = \frac{\dot{W}_{net}}{\dot{m}_f LHV \zeta} \tag{26}$$

Also, ζ for fuel with the formula C_xH_y is obtained from the relation:

$$\zeta = 1.033 + 0.0169 \frac{y}{x} - \frac{0.0698}{x} \tag{27}$$

The third objective is the amount of CO_2 emissions resulting from the combustion reaction in the combustion chamber that is defined:

$$\varepsilon = \frac{\dot{m}_{CO_2}}{\dot{W}_{net}} \tag{28}$$

Multi-objective optimization

Multi-objective particle swarm optimizer algorithm

This algorithm is a social search algorithm that has been modeled from gregarious behavior of birds. The MOPSO algorithm was introduced by Coelho [19]. In MOPSO algorithm, a concept called repository has been added into PSO algorithm. Choosing the best general answer and the best personal recollection for each particle is a crucial step in MOPS algorithm. When particles want to move, choose a member from repository as a leader. The leader must be a member of the repository and be non-dominate. Members of the repository represent Pareto front and contains non-dominate particles. So, instead of Gbest, a member of the repository is selected. For this reason, there is no repository in PSO. Because, there is only one target and a particle that is the best. But there are more particles in MOPSO which are non-dominate and are in the answer set.

Results

Design variables

The design variables considered in this article include: 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}. Given the different requirements of design variables in the optimization process, a reasonable range has been considered for each variable that has been brought in tab. 5.

Also, some restrictions and conditions must be determined in each optimization. Thus, for the cycle of fig. 1, following conditions have been intended for the heat exchanger:

$$T_3 > T_2, \quad T_5 > T_3, \quad T_4 > T_3, \quad T_6 > T_2$$

Figure 2 shows Pareto solution for two objective functions namely total cost rate and exergy efficiency. Three points (A, B, and C) have been specified on the figure. Point A has the lowest total cost rate and exergy efficiency and point C has the highest total cost rate

Table 5. Model constraints

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

and exergy efficiency. Since total cost rate must be minimal and exergy efficiency must be maximum and aim of the optimization is to optimize both objective functions (normalization), here, point B that is the closest point to the equilibrium point has been selected as a Pareto solution optimal point. From this figure, it is clear that with increase in total cost rate, exergy efficiency increases. From the figure, it is clear that from exergy efficiency of 45.1% up to about 48%, total cost rate has been increased with a low slope, from 1.91-2.21 US$/s. Whilst from exergy efficiency by 48% to 48.6%, total-cost rate has been increased steeply from 2.21-2.73 US$/s. Figure 3 shows Pareto solution for both objective functions namely total cost and CO_2 emission rate. Three points A, B, and C have been specified on the figure. Point A has the lowest total cost rate and the highest rate of CO_2 emission and point C has the highest total cost rate value and lowest rate of CO_2 emissions. Here, the goal is to minimize both objective functions. Here, nearest point to the balance point has been selected as the optimal point of Pareto solution (point B).

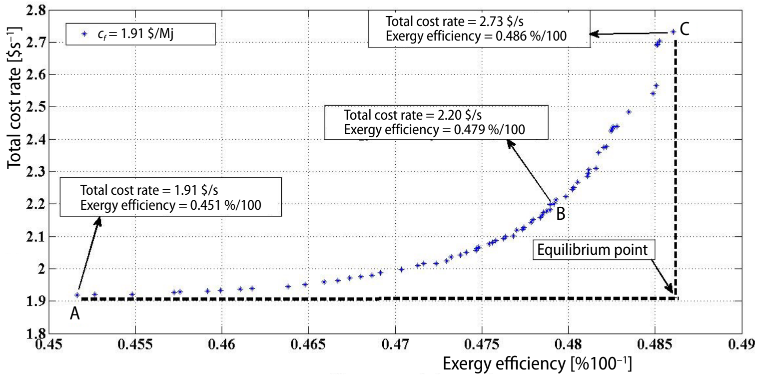

Figure 2. Pareto solution for total cost rate and exergy efficiency objective functions

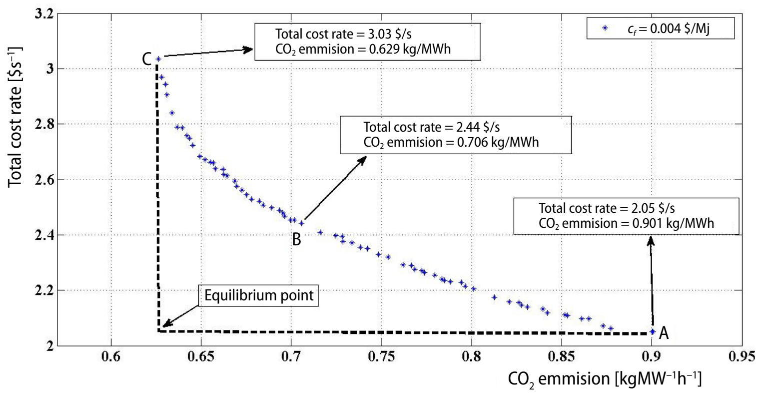

Figure 3. Pareto solution for total cost rate and CO_2 emission rate objective functions

Figure 4 shows changes in CO_2 emission rate into changes in compressor pressure ratio. Results show that with the increase in compressor pressure ratio, CO_2 emission has declined. From the figure it is clear that the rate of CO_2 emissions decreases with a steeper slope in the lower pressure ratios. With increasing in compressor pressure ratio from 6 to 12, the rate of CO_2 emissions has been reduced from 0.89 to 0.71 kg/MWh, whereas, in compressor pressure ratio from 12 to 16, CO_2 emission has been reduced from 0.71 to 0.68 kg/MWh.

Figure 5 shows changes in the rate of CO_2 emissions into turbine inlet temperature. From this graph it is clear that by increasing gas turbine inlet temperature, the rate of CO_2 emissions reduces. It is clear from the figure that by increasing gas turbine inlet temperature from 900 K to 1400 K, CO_2 emissions rate decreases with a steeper slope compared to higher temperatures.

Figure 6 shows changes in exergy efficiency of gas turbine cycle against changes in gas turbine inlet temperature for different compressor pressure ratios have been shown. This figure shows that exergy efficiency of the cycle increases by increasing of gas turbine inlet temperature. It is also obvious from the figure that by reducing compressor pressure ratio, exergy efficiency of the cycle is reduced. From the figure, it is clear that for different pressure ratios, exergy efficiency, at lower temperatures, increases with a steeper slope compared to higher temperatures. Figure 7 shows a sensitivity analysis for changes in total cost rate and exergy efficiency into fuel cost rate per unit of energy. From the figure, it is clear that the increase in fuel cost rate per unit of energy increases total cost rate. Also, in higher exergy efficiencies, that total cost rate is greater, sensitivity of fuel cost optimum solutions is more than Pareto curve with lower total cost rate. It can be said that sensitivity of changes in fuel cost rate per unit of energy on the total cost rate is more than exergy efficiency. Figure 8 shows the sensitivity analysis of total cost rate and the rate of CO_2 emissions into changes in fuel cost rate per unit of energy. From the figure, it is clear that the increase in fuel cost rate per unit of energy increases total cost rate. Moreover, the sensitivity of changes in fuel cost rate per unit of energy on total cost rate is greater than the rate of CO_2 emissions.

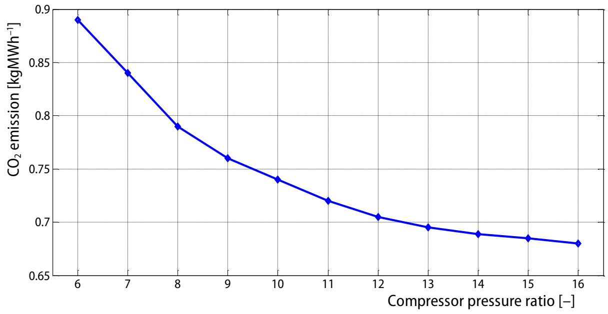

Figure 4. Changes in CO_2 emission rate against compressor pressure ratio changes

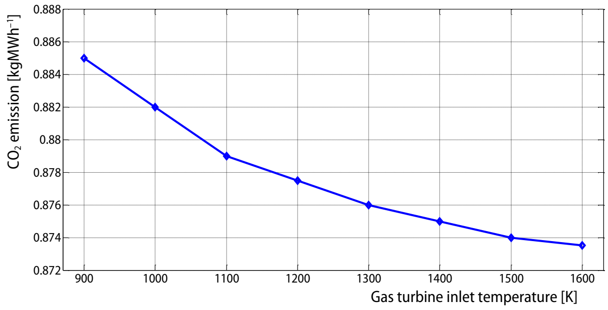

Figure 5. Changes in CO_2 emission rate against gas turbine inlet temperature changes

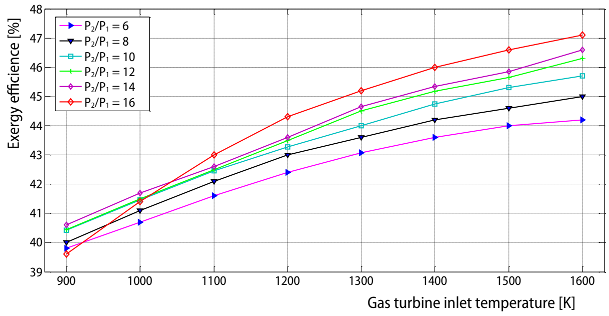

Figure 6. Changes in exergy efficiency against gas turbine inlet temperature changes for different values of compressor pressure ratio

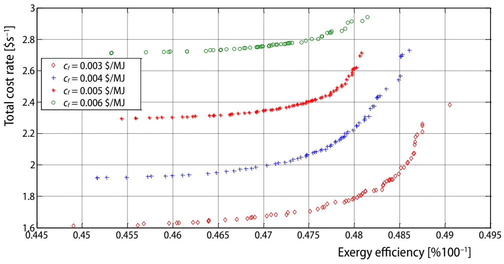

Figure 7. Sensitivity analysis for changes in total cost and exergy efficiency rate into fuel cost rate per unit of energy

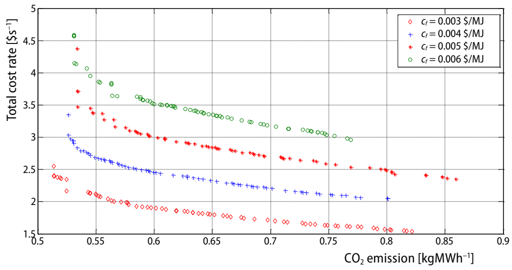

Figure 8. Sensitivity analysis of total cost rate and CO_2 emissions into changes in fuel cost rate per unit of energy

Conclusion

In this article, exergy, exergoeconomic, and exergoenvironmental analysis of a gas turbine cycle and its optimization was carried out by MOPSO algorithm. In this paper, three objective functions namely total cost rate, exergy efficiency of cycle, and CO_2 emission rate were considered. By considering effect of changes in compressor pressure ratio and gas turbine inlet temperature on the rate of CO_2 emissions, the results showed that with increasing compressor pressure ratio and gas turbine inlet temperature, the rate of CO_2 emissions decreases, and this reduction occurs with a steeper slope in lower compressor pressure ratios and gas turbine inlet temperatures. Also, the results showed that exergy efficiency of the cycle increases with increasing of gas turbine inlet temperature and compressor pressure ratio. Also, sensitivity analysis of changes in fuel cost rate per unit of energy on objective functions showed that in higher exergy efficiencies that total cost rate is greater, sensitivity of fuel cost optimum solutions is more than Pareto solutions with lower total cost rate. Also, sensitivity of changes in fuel cost per unit of energy on total cost rate is greater than the rate of CO_2 emissions.

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