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Sensitivity analysis of combined cycle parameters on exergy, economic, and environmental of a power plant

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Abstract
In this paper, a typical combined cycle power generation unit in Iran is simulated by a mathematical method in order to perform sensitivity analysis on environmental emission and electricity price. The results of this study demonstrate that the efficiency of the power plant depends on both gas turbine design parameters such as gas turbine inlet temperature, compressor pressure ratio and steam cycle design parameters such as HRSG pinch point temperature, condenser pressure. The results demonstrate that an increase in TIT and compressor pressure ratio have a significant effect on exergy efficiency and destruction.

Keywords Exergy efficiency · Cycle optimization · Environmental emission · Combined cycle

List of symbols

c	Cost per exergy unit (\$ MJ^{-1})
c_f	Cost of fuel per energy unit (\$ MJ^{-1})
$\dot{C}$	Cost flow rate (\$ s^{-1})
c_p	Specific heat at constant pressure (kJ kg^{-1} K^{-1})
CRF	Capital recovery factor
E	Exergy MJ kg^{-1}
f	Exergoeconomic factor
$\dot{E}$	Exergy flow rate (MW)
$\dot{E}_D$	Exergy destruction rate (MW)
$\dot{E}_W$	Exergy rate of work (MW)
e	Specific exergy (kJ kg^{-1})
e_f	Chemical exergy of the fuel (kJ kg^{-1})
i	Annual interest rate (%)
h	Specific enthalpy (kJ kg^{-1})
h_0	Specific enthalpy at environmental state (kJ kg^{-1})
LHV	Lower heating value (kJ kg^{-1})
$\dot{m}$	Mass flow rate (kg s^{-1})
n	Number of years
N	Number of hours of plant operation per year
PP	Pinch point
$\dot{Q}$	Heat transfer rate (kW)
r_{AC}	Compressor pressure ratio
s	Specific entropy (kJ kg^{-1} K^{-1})
s_0	Specific entropy at environmental state (kJ kg^{-1} K^{-1})
T_0	Absolute temperature (K)
$\dot{W}_{net}$	Net power output (MW)
Z	Capital cost of a component (\$)
$\dot{Z}$	Capital cost rate (\$ s^{-1})

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Greek letters

η	Isentropic efficiency
ξ	Coefficient of fuel chemical exergy
σ	Standard deviation
Φ	Maintenance factor
π	Dimensionless pressure values
θ	Dimensionless temperature values

Subscripts

a	Air
AC	Air compressor
CC	Combustion chamber

ch	Chemical
Cond	Condenser
D	Exergy destruction
f	Fuel
GT	Gas turbine
HP	High pressure
HRSG	Heat recovery steam generator
i	ith trial vector
k	kth component
LP	Low pressure
ph	Physical
tot	Total
ST	Steam turbine
sys	System
w	Water

Introduction

In today's world, there is an increasing demand for energy which has an adverse effect on earth resources and environment [1–3]. Numerical analysis of energy, exergy and energy optimization of a power generating cycle is one of sustainable solutions to alleviate adverse effects of power generation due to their key factor on resource consumption [4–8]. In order to evaluate performance of heat and power plants, exergy analysis of components and process plays a key role to identify the most exergy casualties. Unfortunately, in most cases improving exergy efficiency may effect on financial payback of plants and decrease desirability of an investment which should be tackled with compromise.

Ahmadi and Dincer [9–11] analyzed a combined cycle power plant (CCPP) with a supplementary firing system through energy and exergy to find optimally the design parameters by applying a generic algorithm. In this study, an objective function demonstrating the sum of the cost of exergy destruction and the fuel cost as well as electricity price is considered and minimized by genetic algorithm method. Khalilarya et al. [12] employed an exergy analysis for a gas turbine plant as well. These results show that increasing exergy efficiency enhances the emission of carbon dioxide moderately.

By using an evolutionary algorithm, Sahoo evaluated a cogeneration system economically and exergetically. The results demonstrate that for a cogeneration plant 50 MW of electricity and 15 kg s^{-1} of steam production, the base cost of the system can fall approximately 9.9% by analysis of economic exergy [13].

Boyaghchi et al. [14, 15] employed sensitivity analysis to study TIT and compressor pressure ratio effects based on advanced exergy method and concluded that the thermal and exergy efficiencies increase when TIT and compressor pressure ratio rise.

There are various measures and approaches in thermoeconomics analysis that include: exergy cost theory [16–18], the theory of explicit exergetic cost method [19–23], analysis of thermoeconomic functions [24–27], the applied intelligent approach, the principle of last in first out, the individual cost approach [28–30], the functional analysis of engineering and optimization problems [31–33]. In this study, a particular cost approach is applied.

This research consists of three major parts. In the first place, using the individual cost approach, the cost of exergy is calculated on streamline. In the second part of this research, the optimization of the performance of this system is based on the cost function and exergy efficiency and the amount of power plant emissions. Finally, the impact of the parameters affecting the system's performance is studied separately.

Theory and modeling

In this research, a typical combined cycle power plant (CCPP) has been studied. Configuration of this power plant as shown in Fig. 1 consists of two gas turbine units and a two pressure steam turbines.

Regarding mathematical simulation of this combined cycle power plant, other assumptions are considered as well. All processes in this research are stable. The air and exhaust gases from the combustion chamber are considered to be entirely gaseous. The kinetic and potential changes in energy and exergy are neglected. Turbine, compressor, and pump are assumed to be adiabatic. The environment temperature and pressure are considered as input conditions into the compressor. The fuel used in this modeling is assumed to be the methane gas.

The econometric exergy analysis refers to the cost associated with the exergy of each streamline. Therefore, to analyze the exergy economic and the exergy rates of each of the input and output lines to the various components should be specified. Exergy rates are determined at different points in the power plant by applying the balance of mass, energy, and exergy formulations. The reference state in this research is T_0 = 299.15 K and $P_0 = 1$bar.

The balance of mass, energy, and exergy for various components of the power plant can be calculated by considering their appropriate control volume applying the following equations, respectively:

$$\sum_{I} \dot{m}_{\mathrm{i}} = \sum_{e} \dot{m}_{\mathrm{e}} \quad (1)$$

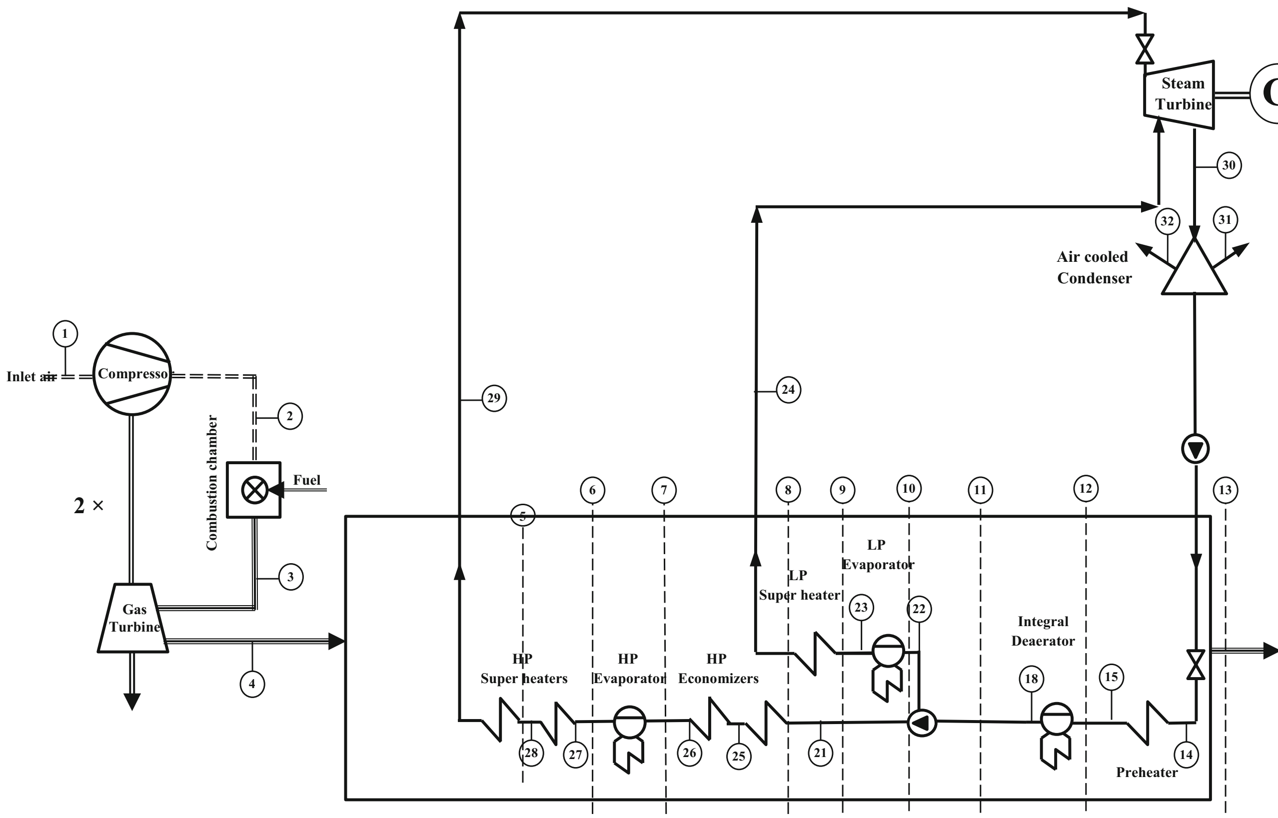


Fig. 1 Combined cycle power plant scheme

$$\sum_{I} \dot{m}_i h_i + \dot{Q} = \sum_{e} \dot{m}_e h_e + \dot{W} \quad (2)$$

$$\dot{E}_Q + \sum_{i} \dot{m}_i e_i = \sum_{e} \dot{m}_e e_e + \dot{E}_W + \dot{E}_D \quad (3)$$

$\dot{E}_D$ in (3) represents the rate of exergy destruction. Also, the exergy rate of work ($\dot{E}_W$) and the exergy rate of heat transfer at temperature T are calculated from the following relationships, respectively:

$$\dot{E}_Q = \left(1 - \frac{T_0}{T_i}\right)\dot{Q}_i \quad (4)$$

$$\dot{E}_W = \dot{W} \quad (5)$$

The exergy of each of the flow lines at the points shown in Fig. 1 can be obtained by the following relations:

$$\dot{E} = \dot{m}e \quad (6)$$

$$\dot{E} = \dot{E}_{ph} + \dot{E}_{ch} \quad (7)$$

$$\dot{E}_{ph} = \dot{m}[(h - h_0) - T_0(s - s_0)] \quad (8)$$

$$\dot{E}_{ch} = \dot{m}e^{ch}_{mix} \quad (9)$$

$$e^{ch}_{mix} = \left[\sum_{i=1}^{n} X_i e^{ch}_i + RT_0 \sum_{k=1}^{n} X_k \mathrm{Ln} X_k\right] \quad (10)$$

In Eqs. 6–10, $\dot{E}$ expresses the exergy flux, $\dot{E}_{ph}$ the physical exergy flux, $\dot{E}_{ch}$ the chemical exergy flux, h the specific enthalpy, T_0 the absolute temperature, s the specific entropy and X is the molar ratio of fuel.

Equation (10) cannot be used to calculate the fuel exergy. Therefore, the fuel exergy is extracted from the following equation that ξ represents the corresponding chemical fuel exergy ratio:

$$\xi = \frac{e_f}{\mathrm{LHV}_f} \quad (11)$$

The ratio of the chemical exergy of the fuel e_f to the lower heating value LHV_f is usually close to 1 for gaseous fuels.

$$\xi_{CH_4} = 1.06 \quad (12)$$

$$\xi_{H_2} = 0.985 \quad (13)$$

For hydrocarbon fuels C_xH_y, the following empirical relation is used to compute ξ:

$$\xi = 1.033 + 0.0169\frac{y}{x} - \frac{0.0698}{x} \quad (14)$$

In the present research, the exergy of each line and the exergy changes in each component are calculated for the exergy analysis of the power plant.

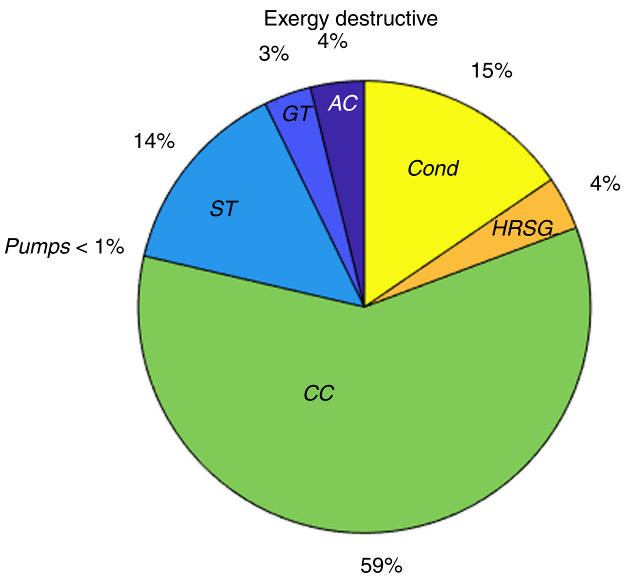


Fig. 2 Exergy destruction of each component of the power plant in percent

The thermoeconomic calculations of each system are based on the cost of components. Here, we use the cost function proposed by Rosen et al. [34, 35]. However, improvements have been made in order to achieve regional conditions in Iran. To convert the cost of investment into cost per unit time, the following relation can be used:

$$\dot{Z}_k = \frac{Z_k \mathrm{CRF} \Phi}{(3600N)} \quad (15)$$

Z_k is the cost of purchasing equipment in dollars. The cost-return factor (CRF) in this equation depends on the estimated interest rate and estimated lifetime for equipment. CRF is calculated according to the following equation:

$$\mathrm{CRF} = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (16)$$

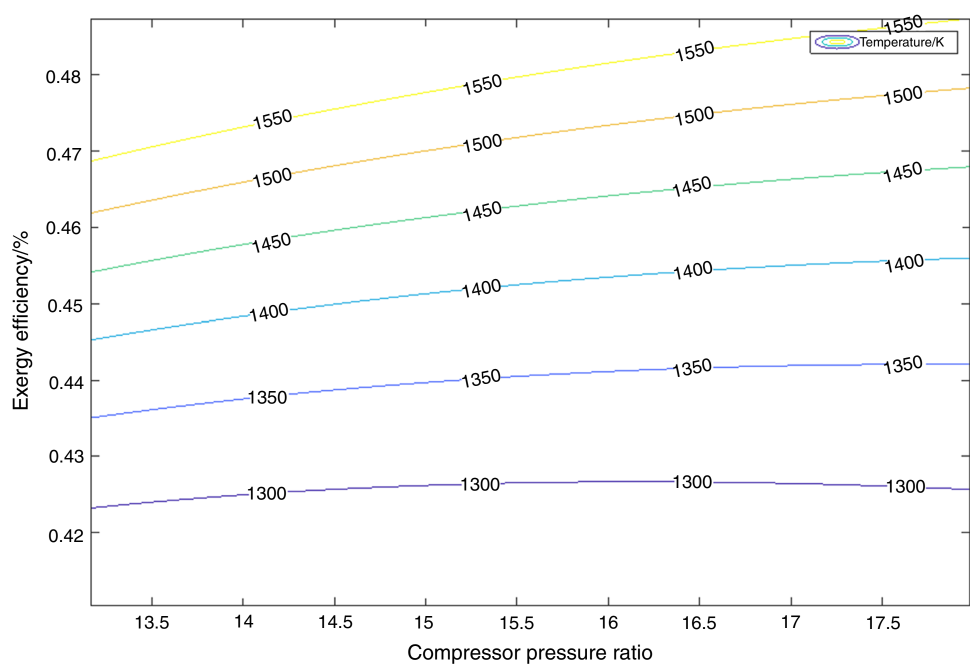
here i is the interest rate, and n is the sum of system operation years. In Eq. (14), N is the number of hours of operation of the power plant in one year, and Φ is the maintenance factor, which is equal to 7446 and 1.06, respectively.

Result

Sensitivity analysis is performed on some part of plant, to understand the effect of various variables on cycle better; Fig. 2 shows the magnitude of exergy degradation in each of the plant's components. In this chart, the most significant exergy destruction occurs in the combustion chamber by about 59% of total exergy destruction and the lowest exergy destruction (merely $< 1\%$) happens in the pumps. Furthermore, condenser and steam turbine account for 15% and 14% exergy destruction of plant, respectively.

As mentioned before, two most cycle parameters which have significant effects in power plants are turbine inlet temperature and compressor pressure ratio which are demonstrated in Fig. 3. Generally, by increasing turbine

Fig. 3 The effect of TIT and R_c on exergy efficiency



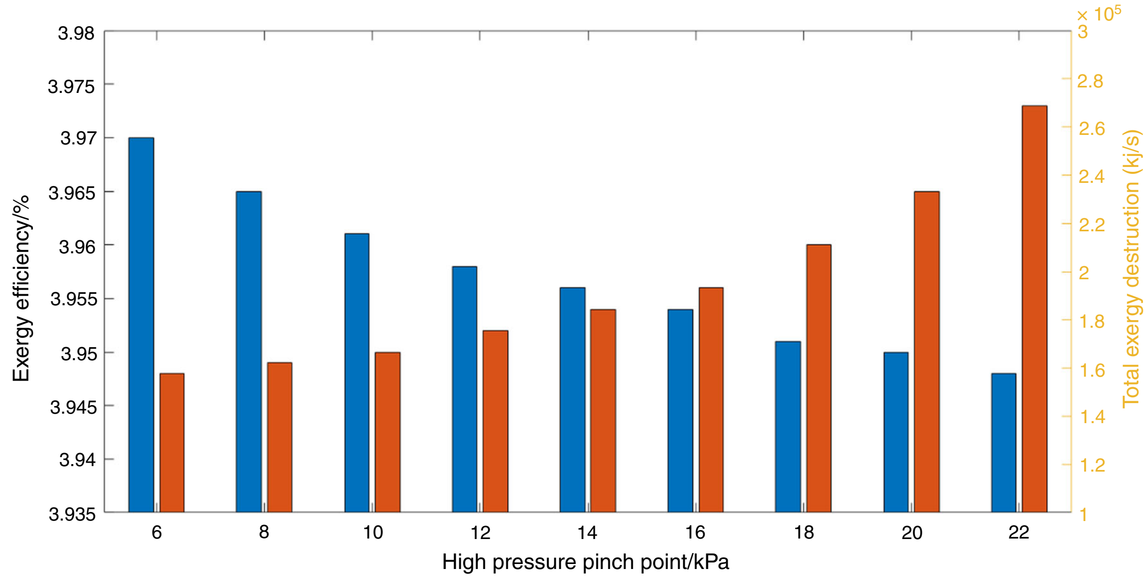


Fig. 4 Exergy degradation rate of the power plant effect of change in pinch point on the exergy efficiency and the amount of exergy destruction of the entire power plant

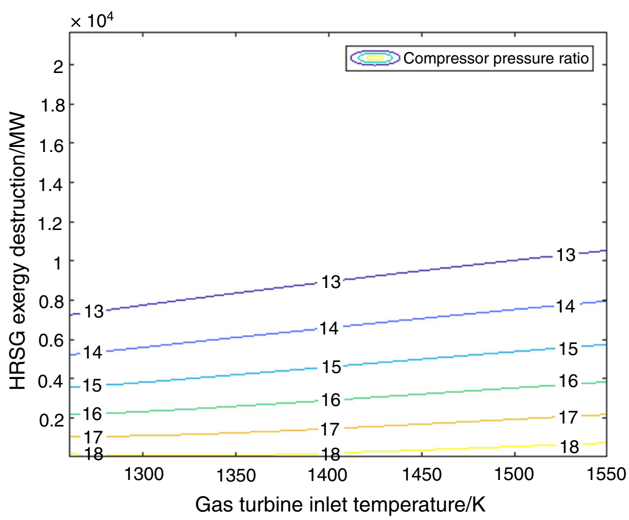


Fig. 5 Exergy degradation of HRSG

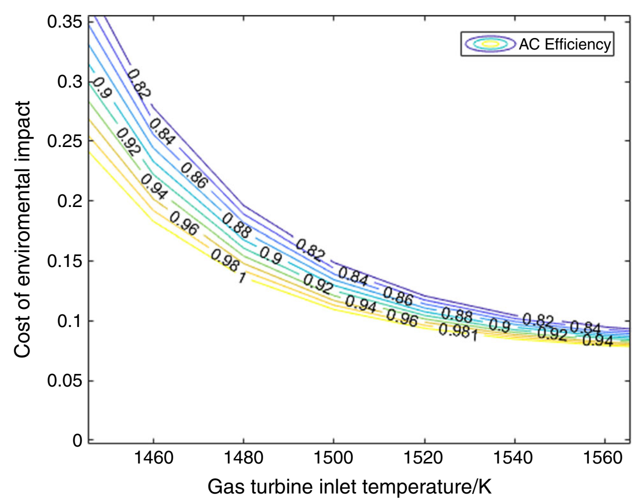


Fig. 6 Power plant the effect of changing the temperature of the input to the gas turbine on the amount of power plant effluent effects

inlet temperature from 1300 to 1500 K, the exergy efficiency increases approximately 7% depending on compressor pressure ratio. It is observed that at higher TIT, rising compressor pressure ratio increases exergy efficiency while in lower TIT and higher PR, exergy destruction falls moderately which is due to higher required work in compressor.

Figure 4 shows that by changing the temperature of the high-pressure pinch point, both the parameters of the exergy efficiency and the destruction rate of exergy change. Also, it is observed that by increasing the temperature of the pinch point, the effectiveness of the exergy decreases, which means lower energy supply for the steam line and will reduce the output power of the steam turbine. Meanwhile, the increase in the exergy rate of destruction indicates an increase in irreversibility in the recovery boiler, and the increase in the rate of exergy destruction increases with this change.

As demonstrated in Fig. 5, turbine inlet temperature and compressor pressure ratio impact on exergy destruction of heat recovery steam generation as well. Increasing turbine inlet temperature from 1300 to 1550 increases at least 10% exergy destruction depending on compressor pressure ratio. The effect of turbine inlet temperature plays an important role in lesser compressor pressure ratio.

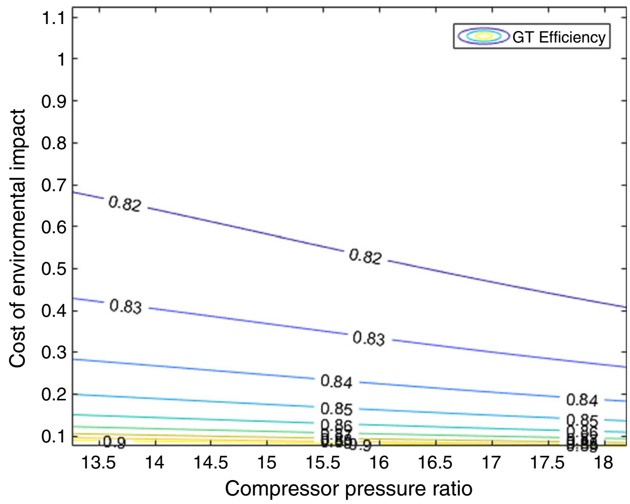


Fig. 7 Effect of compressor compression coefficient change on cost of pollutant effects

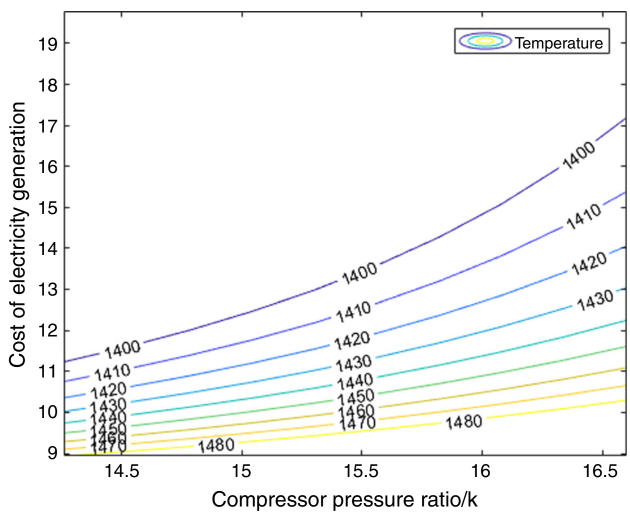


Fig. 8 Effect of compressor compression coefficient change on cost of pollutant effects

Also, with the increase in the input temperature to the gas turbine, the amount of pollutant emissions in the combined cycle power plant will be reduced by about 0.003$ per second, which is significant in Fig. 6, and, finally, with the reduction of the gas turbine efficiency, the amount of pollution also increases the amount of pollution.

Figure 7 shows that by increasing the compressor pressure, the cost of the power plant's emissions decreases. This is because the fuel injection rate inside the combustion chamber decreases and the pollutant emissions increase by decreasing the gas turbine efficiency.

Finally, the cost of electricity generation depending on compressor pressure ratio and turbine inlet temperature was estimated. According to Fig. 8, increasing compressor pressure ratio has a negative effect on electricity price in which increase the cost of electricity generation by about 10 to 50% depending on turbine inlet temperature. Moreover, by increasing turbine inlet temperature, the effect of compressor pressure ratio becomes negligible.

Conclusions

The influence of design variables such as compressor compression ratio, gas turbine input temperature; pinch point temperature on real combined cycle has been investigated. Accordingly, with increasing turbine inlet temperature, the exergy efficiency of the combined cycle increases.

Furthermore, according to the contents expressed, it can be concluded that the sensitivity analysis of various parameters on exergy economic is an extraordinarily useful tool for identifying and evaluating inefficiencies concerning cost and efficiency.

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