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Thermo-Economic Analysis of Simple Cycle Steam Power Plant

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Abstract

Thermal steam power plants represent the most important and dependable type for supplying the base load of electricity around the world. The thermos-economic analysis is an important tool for improving the performance of thermal steam power plants. In the present study, a thermo-economic analysis of a simple steam power plant for different boiler pressure was performed. The analysis comprises the energy, exergy, entropy, economics, and exergy-economic of a simple cycle steam power plant for different boiler pressure. The analysis was performed for a simple steam power plant with the constant output power of 10 MW and the boiler pressure is varied from 10 bar to 100 bar by a step of 10 bar. For each boiler pressure and constant output power, firstly, the fuel mass flow rate, steam flow rate, energy and exergy efficiency, and cost of electricity were calculated. Secondly, entropy generation, exergy destruction, and exergy efficiency for each component were calculated. Finally, exergy destruction economics for each component of the plant was performed. The results reveal that increasing the boiler pressure from (10 to 100 bar) for constant output power reduces the cost of electricity from (0.135 to 0.1025 $/kWh) due to a decrease in the fuel mass flow rate and an improvement in the thermal cycle and exergy efficiency. Also, when the boiler pressure increases, the exergy destruction for the pump increases, the exergy destruction for the boiler decreases, the exergy destruction for the turbine increases, and the exergy destruction for the condenser decrease.

Keywords: Thermo-economic analysis, Exergy analysis, Energy analysis, Steam power plant efficiency.

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1. Introduction

Thermal steam power plants represent the most important and dependable type for supplying the base load of electricity around the world. A thermos-economic analysis is an important tool for improving the performance of thermal steam power plants. In this review, a general survey of literature on steam power plant analysis will be viewed. This review was divided into two sections. The first section focused on the studies dealing with exergy, entropy, and energy analysis are included in the first section. The second section focused on the studies dealing with economic analysis.

1.1. Exergy and energy analysis

Elhelw and Al Dahma, [2] performed an exergy analysis for a 650 MW steam power plant. The relationship between power plant exergy and thermal efficiency is illustrated for two distinct loads. Their results showed that the maximum exergy destruction is occurring in the boiler, followed by the turbine, then the condenser. It was also discovered that lowering the condenser pressure from 0.067 bar to 0.049 may save 0.5725 percent of the electricity at full load and 0.5878 percent at half load.

Khrebish and Hussien, [5] analyzed the thermal-economic impact of heat lost to the atmosphere by gas turbine power plants (GTPPs) under different ambient temperatures. Results show that the output power and thermal efficiency decrease with each rise in ambient temperature by 0.97 MW and 0.0726 %, respectively. Based on the economic analysis, HRB generates 75757 dollars per month in economic gains.

Faisal et al. [8] both energy and exergy analyzed and carried out on GE's gas turbine units found at the Khor Al-Zubair gas turbine power plant in Basra, Iraq. Based on the ISO (International Standards Organization) operating conditions as well as actual operating data during the hot season of July 2016, the analysis was performed. Based on energy and exergy analyses, a vapor compression cycle could enhance Khor Al-Zubair GE unit by 20 % and 27 % when operated at part and full loads, respectively

Ahmadi et al. [1] Performed an analysis of energy and exergy for a 200 MW steam power plant in Isfahan. Using mass, exergy, and energy balance equations. The EES (Engineering Equation Solver) software is used for performing the theoretical analyses. Their results showed that 69.8 % of the total lost energy in the cycle occurs in the condenser, while exergy wasting in the boiler is 85.66 % of the total exergy entering the system.

Osueke et al. [4] the energy and exergy analyzed of the simple steam power plant in Nigeria. The study is focusing on the losses that occur in the energy and develops a model that will improve the efficiency of the power plant. The researchers have used energy analysis and determined the efficiency and energy losses of all plant components collected from the Sapele power plant in Nigeria. They found that energy losses greatly in the boiler, with approximately 105 kW to the environment while only 15.7 kW was lost from the condenser only. The boiler system was found to have the greatest rate of energy destruction (105.7 %) followed by the turbine (86.53 %), and finally the condenser (62.5 %).

Jamel et al. [7] Basrah steam power plant simulations were conducted for 200 MW of gas-fueled power. A simulation is used to estimate the thermodynamic performance of the power plant under consideration. This study uses a flow-sheet computer program called "Cycle-Tempo". There are illustrations of the exergy losses and temperature profiles for the main components of the plant. Their results showed, there were many suggestions for improving the performance of the plant based on the results.

Mitrović et al. [3] Performed energy and exergy of Kostolac power plant in Serbia. The major objective of the researcher is an analysis of the system component separately and which one has the greatest energy and exergy losses. The researchers calculate energy and exergy efficiency at various loads ranging from 60 % to 100 %. According to their results, the majority of energy losses occurred in the condenser, where 421 MW was lost to the environment, while the boiler lost just 105.78 MW. The boiler system had the highest percentage ratio of exergy destruction to total exergy destruction 88.2 %, followed by the turbines 9.5 %. Furthermore, the computed thermal efficiency based on the lower heating value of fuel was 39 %, while the power cycle exergy efficiency was 35.77 %.

Aljundi [6] the energy and exergy analysis of Jordan's Al-Hussein power plant is described. The primary goal of the researcher is to analyze each system component independently and determine which one has the biggest energy and exergy losses. In addition, an analysis of the effects of altering the reference environment condition will be presented. Their result showed that there was a loss of 134 MW in the condenser while only 13 MW was lost from the boiler system. In the boiler system, the percentage of exergy destroyed to the total exergy destruction was maximum (77 %) followed by the turbine (13 %), and then by the forced draft fan condenser (9%). Using the lower heating value of fuel, the calculated thermal efficiency was 26 %, while the energy efficiency of the power cycle was 25 %.

1.2. Economic and exergoeconomic analysis

Ogorure et al. [9] performed energy, exergy, and economics for the 5.22 MW Nigerian power plant. Their results showed the exergy efficiency is 85.64 % and energy efficiency is 63.63 %. In the combustion chamber, the rate of exergy destruction was the highest, contributing 15 % to the total exergy destroyed. An estimated cost of electricity is 0.0109 $ per kWh.

Kumar et al. [12] investigated the economics of coal-fired power plants in north India for electricity generation based on 210 MW of steam power plant. According to the results of a literature search, capacity data has been fitted with a power law. Based on the total capital investment, operating cost, and revenue of the plant, a cost analysis was conducted. Power plant live data was used for 34 years. This plant had a monthly cost of 25,858.4 (INR).

Bolatturk et al. [14] studied the energy and thermos-economics of the Çayırhan thermal power plant in Turkey. Using the EES package program, the thermodynamic properties of each unit in a thermal plant have been specified. Their results showed thermal power plant with efficiencies of 38 % and 53 % was found through the analysis. The cost of exergy losses ($/h) was 758.32, 172.94, and 75.48 for boiler, turbine, and condenser respectively.

Kumar et al. [10] described the economic and thermal performance of a 210 MW coal-fired power station. Equipment cost, fuel cost, operation and maintenance expenses, income, and the net present value of the plant are all analyzed as part of the economic analysis. They found shows the cost of electricity is 4000 (Rs/MW-hr).

Gupta and Kumar [15] analyzed exergy-economically the performance of a boiler in a coal-fired thermal power plant. In developing his model, the researchers based on the second law of thermodynamics. The analysis for 55 MW power plant Show the cost flow rate was C (Rs/hr) = 99135.72, Cost of exergy destruction and CD (Rs/hr) = 505409.4.

Anozie and Odejobi [13] carried out a study on the effect of reference temperature on the exergy and exergy-economic performance parameters of a thermal plant. They used HYSYS software (2003) was used to simulate the plant and Microsoft Excel spreadsheets to estimate exergy and economics. When the temperature is increased by 20 degrees then exergy efficiency decreased from 11.7 % to 11.5 % and exergy cost decreased from 6650.78 MW to 6055.40 MW and monetary cost from (75,343.84/h to 68,430.19/h) $.

Sharma and Tewari [11] used operational availability and the net present value index to predict the steady-state performance and economics of thermal power plants. By the Laplace transformation, the differential equation system obtained are solved. Based on the economic evaluation module, they found that plant availability and power generation capacity are determined.

Rosen and Dincer [16] related capital costs to thermodynamic losses of power plants operating on various fuels. Their results showed may (a) describe the relationship between thermodynamics and economics for electrical generating stations, both in general and in detail (b) Show the benefits of second-law analysis. For the 512 MW oil Lennox plant, Energy efficiency was 37 %, and Exergy efficiency was 34 %. The exergoeconomics of the boiler, condenser, and pump were 13.47, 12.64, and 4.39, respectively. The aims of the study, from the previous viewed studies, the energy, exergy, and economic analysis were performed for specific power plant with constant boiler pressure and turbine inlet temperature.

1. perform energy, exergy, economic and exergy-economic analysis for simple cycle steam power plant for different values of boiler pressure and turbine inlet steam temperature.
2. The effect of varying the boiler pressure on the energy losses, exergy losses and the related economic losses will be explained.

2. Theoretical analysis

The theoretical analysis comprises five parts. A complete thermodynamics (energy analysis) study for a basic steam power plant cycle is described in the first part. The second part describes a comprehensive thermodynamics study (exergy analysis) for the steam power plant cycle. The third part describes a general entropy analysis (Second Law of Thermodynamics). The fourth part that describes economic analysis of steam power plant. Finally, a comprehensive economic study of a basic steam power plant is presented in the third part.

2.1. Energy and exergy analysis

The following are general equations for the energy and exergy balances of the fluid streams in an open system experiencing a steady-state flow process for all components.

2.1.1. General energy analysis (first law of thermodynamics)

There are three forms of energy in an open system. Heat acts as a means of transporting energy and storing energy in the fluid. The energy balance equation for a steady-state open system is provided by [17]:

$$\dot{Q}_k + \dot{m}_i\left(h_i + \frac{c_i^2}{2} + gZ_i\right) = \dot{m}_e\left(h_e + \frac{c_e^2}{2} + gZ_e\right) + \dot{W}_{net} \qquad (1)$$

Where:

$\dot{m}_i$, $\dot{m}_e$: is the mass flow rate at inlet and exit respectively in (kg/s).

$\left(h_i + \frac{c_i^2}{2} + gZ_i\right)$: is the total energy of the flowing stream.

$\frac{c_i^2}{2}$: is the kinetic energy.

gZ_i : is the potential energy.

$\dot{W}_{net}$: is the network produced by the system in (kW).

The thermal efficiency of the system is defined as the ratio of network to the energy input as shown in equation (2):

$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_k} \qquad (2)$$

2.1.2. General exergy analysis (second law of thermodynamics)

Physical exergy $\dot{Ex}^{ph}$, kinetic exergy $\dot{Ex}^{KN}$, potential exergy $\dot{Ex}^{PT}$, chemical exergy $\dot{Ex}^{CH}$, heat exergy, and work exergy are the components of a system's total exergy at any state [18], [19]. The first four components are possessed exergies, whereas heat and work are transmitted exergies.

$$\dot{Ex} = \dot{Ex}^{Ph} + \dot{Ex}^{KN} + \dot{Ex}^{PT} + \dot{Ex}^{CH} \qquad (3)$$

The total physical exergy is:

$$\dot{Ex}^{ph} = \dot{m}[(h - h_\circ) - T_\circ(s - s_\circ)] \qquad (4)$$

Kinetic exergy is:

$$\dot{Ex}^{KN} = \dot{m}\frac{c_i^2}{2} \qquad (5)$$

Chemical exergy for natural gas [7] is:

$$\dot{Ex}^{CH} = 1.06 \times LHV \qquad (6)$$

And the potential exergy is:

$$\dot{Ex}^{PT} = \dot{m}\, g\, Z \qquad (7)$$

The exergy balance for an open system is given by equation (8):

$$\dot{Ex}_{in} - \dot{Ex}_{out} - \dot{Ex}_D = \Delta\dot{Ex}_{system} \qquad (8)$$

Where $\dot{Ex}_{in}$ and $\dot{Ex}_{out}$ are the exergy input and output for the open system.

For a steady-state, the exergy balance becomes:

$$\dot{Ex}_{in} - \dot{Ex}_{out} - \dot{Ex}_D = 0 \qquad (9)$$

A steady flow system requires the exergy entering the system in all forms (heat, work, and mass transfer) to equal the exergy leaving the system plus the exergy destroyed. Then the exergy balance equation is given in below [20], [21]:

$$\sum_{k=1}\left(1 - \frac{T_o}{T_k}\right)\dot{Q}_k - \dot{W} + \sum_i \dot{m}\,Ex - \sum_e \dot{m}\,Ex = 0 \qquad (10)$$

Where:

$\dot{W}$: is the rate of work (exergy transfer of work).

$\left(1 - \frac{T_o}{T_k}\right)\dot{Q}_k$: is the exergy due to heat transfer $\dot{Q}_k$

T_k : Temperature at which heat is transferred, *K*.

T_k : Reference temperature and equal to 293.5 *K*.

The physical exergy for a given pressure (*P*) and temperature (*T*) is given by [21]:

$$Ex = (h - h_\circ) - T_\circ(s - s_\circ) \qquad (11)$$

For every point, all of the following parameters are calculated using a steam table.

$h_\circ$: Is enthalpy at reference temperature and pressure.

$s_\circ$: Is entropy at reference temperature and pressure.

h, s : Properties that can be found in steam tables.

Exergy destruction, energy, and exergy efficiency for each component of a power plant are included in the Table 1 [3]-[7].

Table 1. Exergy destruction, energy, and exergy efficiency equation for each component.

Component	Equation	Exergy destruction	Exergy efficiency	Equation
Boiler	12	$\dot{E}_{D,B} = \left(1 - \frac{T_o}{T_k}\right)\dot{Q}_i + \sum_{i,B}\dot{E} - \sum_{e,B}\dot{E}$	$\eta_{e,B} = \left(\dot{E}_{e,B} - \dot{E}_{i,B}\right)/\dot{E}_f$	16
Steam turbine	13	$\dot{E}_{D,T} = \sum_{i,T}\dot{E} - \sum_{e,T}\dot{E} - \dot{W}$	$\eta_{e,T} = 1 - \frac{\dot{E}_{D,T}}{\dot{E}_{i,T} - \dot{E}_{e,T}}$	17
Pump	14	$\dot{E}_{D,P} = \dot{E}_{i,P} - \dot{E}_{E,P} + \dot{W}_P$	$\eta_{e,P} = 1 - \frac{\dot{E}_{D,P}}{\dot{W}_P}$	18
Condenser	15	$\dot{E}_{D,C} = \sum_{i,C}\dot{E} - \sum_{e,C}\dot{E}$	$\eta_{e,C} = 1 - \frac{\dot{E}_{D,C}}{\dot{E}_{i,C}}$	19

2.2. General entropy analysis (second law of thermodynamics)

Entropy analysis for the steam power plant will be performed in this part. According to the second law of thermodynamic (irreversibility or lost work). In the power plant, there are four main components (boilers, turbines, condensers, and pumps). The irreversibility losses of the plant are calculated as follow.

The entropy balance for an open system is given by equation (20).

$$S_{in} - S_{out} + S_{generation} = \Delta S_{system} \tag{20}$$

Where S_{in} and S_{out} are the entropy input and output for the open system.

For a steady-state, the entropy balance becomes:

$$S_{in} - S_{out} + S_{generation} = 0 \tag{21}$$

A steady flow system requires the entropy entering the system in all forms (heat and mass transfer) to equal the entropy leaving the system plus the entropy generation. Then the entropy balance equation is given in below [22].

$$\left(\frac{\dot{Q}_k}{T_k}\right) + \sum_i S - \sum_e S + S_{generation} = 0 \tag{22}$$

Where:

$\left(\frac{\dot{Q}_k}{T_k}\right)$: is the entropy due to heat transfer $\dot{Q}_k$.

(Clausius inequality)

T_k : Temperature at which heat is transferred, K.

S : Properties that can be found in steam tables.

2.3. Economic analysis of steam power plant

The following components must be included in the life cycle cost model:

1. **Total capital cost** includes the cost of the steam boiler, the turbine, the condenser, the generator, and the pump.
2. **Operating cost** includes the, maintenance cost, insurance and general cost.
3. **Annual fuel cost** from sale of produced electric energy.

The following models will now be used to compute the electric cost [11], [23], [24], [25], [32]:

2.3.1. Total capital cost (I_C)

The total capital cost in dollar is given by:

$$I_C = 1.87\ (S_C + T_C + CON_C + G_C + P_C) \tag{23}$$

Where:

S_C: steam boiler cost.
T_C: turbine cost.
CON_C: condenser cost.
G_C: generator cost.
P_C: pump cost.

Each cost of component S_C, T_C, CON_C, G_C, and P_C can be calculated by equation (24):

$$C = a\, M_w^b \tag{24}$$

Where:

a, b : is constant calculate from Table 2.

M_W : is plant capacity in (MW).

Table 2. the constant a and b for each component.

Equipment	a	b
Steam boiler (S)	1340000	0.694
Turbine (T)	633000	0.398
Condenser (C)	398000	0.333
Condensate extraction pump (P_h)	9000	0.4425
Feed pump (P_b)	35000	0.6107
Generator (G)	138300	0.3139

The initial capital cost is in ($) unit is multiplied by the commission factor (β) to become in ($/year) unit.

Where:

β : The commission is based on the capital and depends on discount rate and the life of the station.

$$\beta = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{25}$$

i = interest rate 10 % and n = equipment life = 20 year. Then, by using these values, β = 0.11764.

Now:

$\beta \times I_C$: Annual cost of capital ($/year).

2.3.2. Operating cost (O_C)

The operating cost that includes, operating labour cost (L_C), maintenance cost (MAN_C), insurance and general cost (IG_C). The operating cost in ($/year) is given by equation (26).

$$O_C = L_C + MAN_C + IG_C + F_C \tag{26}$$

Where:

$L_C = C_P$ (employed personnel average fee 29.68 $/year) [30].

n = total annual working personnel has been varied in the range 12–36 [31].

$$MAN_C = 0.015\ \mathrm{I_C} \tag{27}$$

$$IG_C = 0.01\ \mathrm{I_C} \tag{28}$$

2.3.3. Annual fuel cost (F_C)

Using the lower heating value of fuel, we have calculated the following annual fuel consumption:

$$MF = (MW \times 3600 \times hr\text{-}up)/(\eta\text{-}ov \times lhv\text{-}F) \tag{29}$$

Where:

η-*ov* : Overall thermal efficiency.

lhv-F : Lower heat value.

hr-up: The annual operating plant period (8000 hours).

Now, fuel cos (F_C) can be calculated from equation (30):

$$\text{Annual fuel cost } (F_C) = \text{fuel price} \times MF \tag{30}$$

Finally, the cost of electric can be calculated from:

$$\text{Electric cost (\$/kWh)} = \frac{I_C + O_C + F_C}{\text{plant capacity in (kW)} \times \text{running hours } \left(\frac{H}{yr}\right)} \tag{31}$$

2.4. Exergoeconomic analysis of steam power plant

Exergoeconmics is designed to find the economic losses in each component by the results of exergy analysis to determine how much money each component losses in a year. The model employed in the following computation [26], [29]:

$$\dot{C}_{D,k} = c_F \times \dot{E}_k^D \tag{32}$$

Where:

$\dot{C}_{D,k}$: Exergy destruction cost for any component *k*.

c_F : Denote average costs per unit of exergy in dollars per gigajoule (1.1 \$/GJ)

$\dot{E}_k^D$: Exergy destruction for any component *k*.

3. Results and discussion

In this part the results of the energy, exergy and economic analysis for simple steam power plant for different boiler pressure and turbine inlet steam temperature will be viewed.

The specifications for simple steam power plant analyzed in Table 3.

Table 3. specifications for simple steam power plant.

Component	Value	Unit
Condenser pressure	20	kPa
Boiler pressure	10 - 100	bar
Turbine inlet temperature	$T_{saturated}$ + 100	°C
Plant capacity	10	MW
Isentropic pump efficiency	83	%
Isentropic turbine efficiency	80	%
Ambient temperature	25	°C
Fuel type	Natural gas	

3.1. Steam flow rate

The effect of variation of boiler pressure on steam flow rate $\dot{M}s$ (kg/s) required for constant power output is explained in Fig. 1. The results indicate that, as the boiler pressure increase steam mass flow rate decrease for constant power output. This reduction is due to decreasing the latent heat required for evaporation with increasing the pressure. The percentage decrease in steam mass flow rate is 55.79 %.

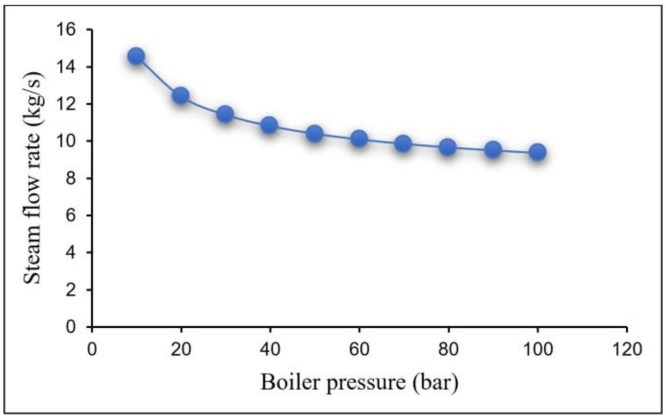

Fig. 1 variation of steam flow rate with boiler pressure.

3.2. Pump work

The power required for the boiler feed water pump increase with increasing the boiler pressure due to increasing the head of the pump, as shown in Fig. 2. The percentage increase in pump work (*WP*) is 90.19 %.

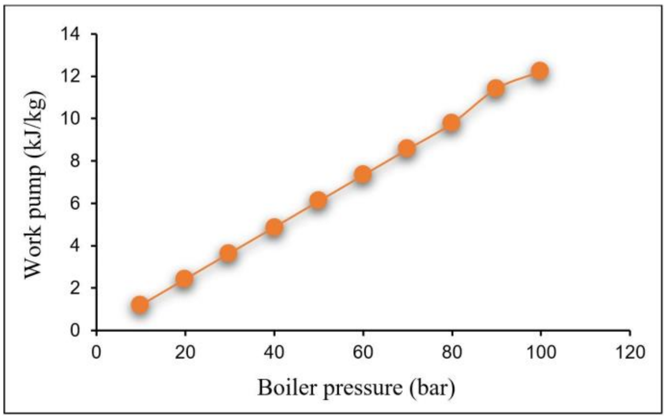

Fig. 2 variation of feed water pump work with boiler press.

3.3. Turbine work

The power required for the Turbine Work (*WT*) increase with increasing the boiler pressure due to increasing the energy that inlet to turbine, as shown in Fig. 3. The percentage increase in Turbine Work is 35.81 %.

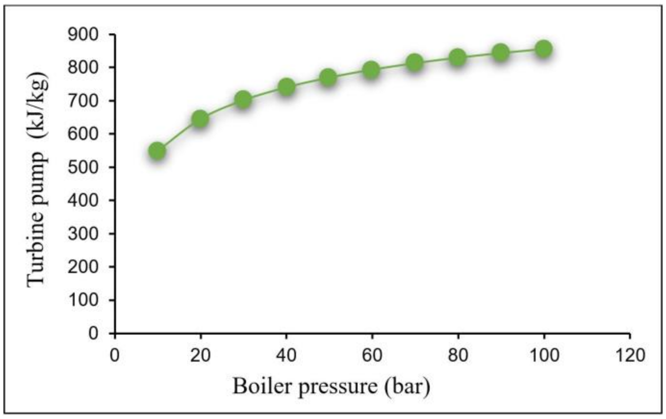

Fig. 3 variation of Turbine Work with boiler press.

3.4. Thermal plant efficiency

The variation of power plant thermal efficiency with boiler pressure is given in Fig. 4. The figure indicates that, thermal efficiency increases with increasing the boiler pressure due to decreasing the heat input required for same power. The percentage increase of thermal efficiency is 32.02 %.

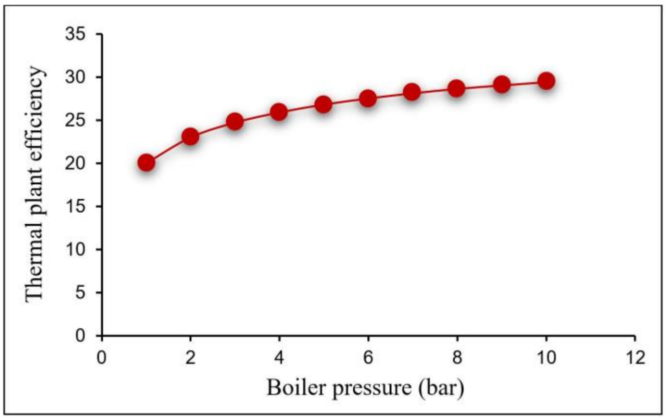

Fig. 4 variation of thermal efficiency with boiler pressure.

3.5. Exergy cycle efficiency (based on boiler heat gain exergy)

Figure 5 shows the variation of exergy efficiency (based on boiler heat gain exergy) with boiler pressure. The behavior is that, the exergy efficiency increases with increasing the boiler pressure due to decreasing the exergy destruction. The percentage increase in exergy efficiency is 32.65 %.

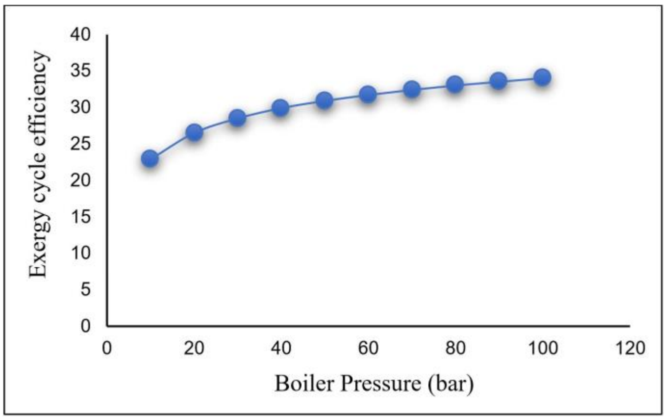

Fig. 5 variation of exergy efficiency with boiler pressure.

3.6. Exergy cycle efficiency (based on chemical fuel exergy)

Figure 6 shows the variation of exergy efficiency (based on the chemical fuel exergy) with boiler pressure. The increase of exergy efficiency with increasing boiler pressure is clear from the figure, and this increasing is due to decreasing the exergy destruction. Also, the exergy efficiency based on heat gained is greater than that based on the chemical fuel exergy. This difference is due to different input exergy. The percentage increase in exergy efficiency is 32.40 %.

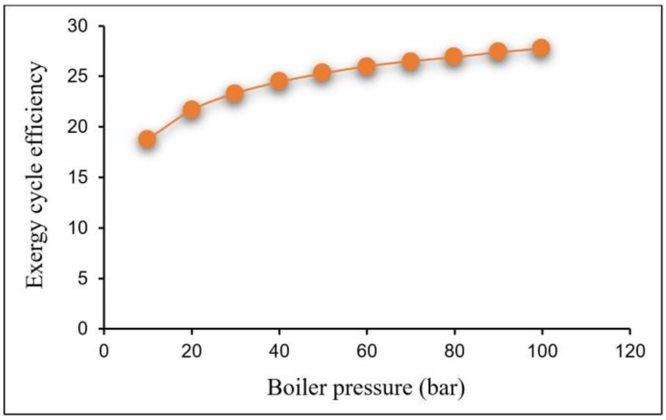

Fig. 6 variation of exergy efficiency with boiler pressure.

3.7. Fuel mass flow rate

The variation of fuel mass flow rate ($\dot{M}_f$) with boiler pressure for constant output power is shown in Fig. 7. The fuel flow rate is decreased with increasing boiler pressure due to decreasing the required heat input for constant power output. The percentage decreased in fuel flow rate is 49.72 %.

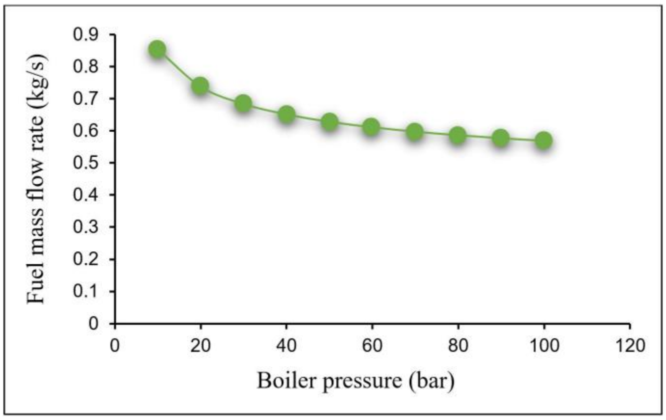

Fig. 7 variation of fuel mass flow rate with boiler pressure.

3.8. Electric cost

Figure 8 shows the variation the cost in ($/kWh) of electricity with boiler pressure. The cost or electricity is decreased with increasing boiler pressure, due to decreasing the operating cost which is results from decreasing the fuel flow rate for constant output power. The percentage reduction in electricity cost is -31.63 %.

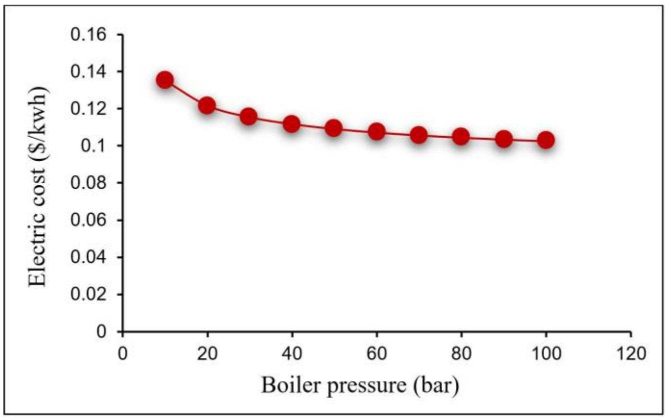

Fig. 8 variation of cost of electricity with boiler pressure.

3.9. Exergy destruction economic

The effect of exergy destruction on the economic losses CD ($/h) is explained in Fig. 9. The exergy destruction economic losses are decreased with increasing the boiler pressure due to decreasing the exergy destruction. The percentage decreased of economic losses is 74.62 %.

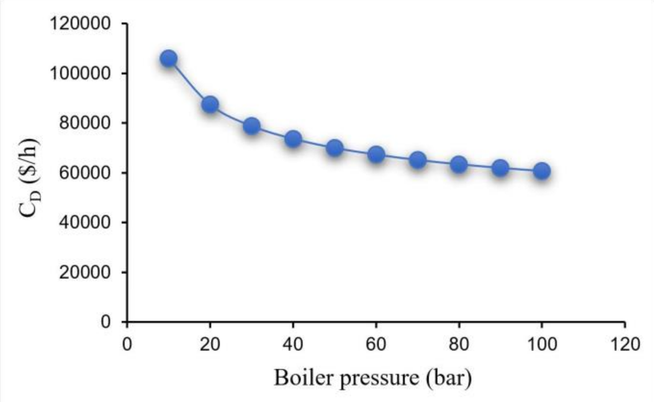

Fig. 9 variation of cost of electricity with boiler pressure.

4. Conclusions

The present results are show, increasing the boiler pressure led to:

1. Improve the performance of the power plant and consequently decreasing the cost of electricity generated.
2. The percentage increase in power plant thermal efficiency is 32.02 %.
3. The percentage increase in Pump Work is 90.19 %.
4. The percentage increase in Turbine Work is 35.81 %.
5. The percentage decrease in Fuel mass flow rate is 49.72 %.
6. The percentage decrease in Exergy destruction cos is 74.62 %.
7. The decreasing in the cost of electricity generated is 31.63 %.

Nomenclature		
Symbol	**Description**	**Unit**
$\dot{Q}_k$	Thermal energy	kW
$\dot{m}$	Mass flow rate	kg/s
$\dot{m}_f$	Fuel mass rate	kg/s
h_i	Enthalpy	kJ/kg
$\dot{W}_{net}$	Network	kW
E_x	Exergy	kJ/kg
S	Entropy	kJ/kg.K
T_k	Temperature	K
$\beta \times IC$	Total capital cost	$/year
O_C	Operating cost	$/year
F_C	Annual fuel cost	$/year
$\dot{C}_{D,k}$	Exergy destruction	$/h

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