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Thermoeconomic optimization of the steam power plant

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Abstract
In this study, thermoeconomic optimization of the steam power plant with Levelized-cost method was carried out. Aim of thermoeconomy is to minimize exergy cost. With this aim, the first law and the second law of thermodynamics to each component of system were performed. Irreversibility and exergy values were obtained. Economic analysis by using exergy values was carried out. Unit electric cost for each component of system was calculated. Optimum design and operating conditions for minimum exergy cost were obtained.

Keywords: Thermoeconomic optimization, Levelized-cost method, Thermodynamic analysis, Steam power plant, Exergy.

1. Introduction

Many factors should be taken into consideration about what type of energy will be used to increase the efficiency of energy systems. The energy type to be used should be economical. Another effective factor in increasing the efficiency is the cost conditions. Moreover, energy cost is an important factor which affects the total cost. Unit price is rather significant in the use of energy. The most important factor in setting the price is the production plant and the fuel to be used. The higher the efficiency of the producing plants, the more energy from the used fuel will be able to produce. Thus, the unit cost of energy will be minimized accordingly. By means of exergy analysis, it is possible to increase the efficiency by localizing and decreasing the irreversibility in the system. By adding the new elements to the system or increasing the exergy efficiency of existent elements it is quite possible to enhance the efficiency of the system. But this addendum may affect the cost of system elements. As a result of this, it increases the unit energy cost. Some precautions to decrease the cost of unit energy should be taken. In this condition, maximum exergy efficiency may not to be acquired but not only the possible top value of the efficiency, but also the minimum value of the cost can be determined. Such method of analysis has been named as thermoeconomic analysis [1]. In Figure 1, the steam thermal power cycle which works according to ideal Rankine cycle and T-s diagram has been seen [2, 3].
In this study, thermoeconomic optimization of actual steam power plant using Levelized-Cost method has been carried out. The optimum operating values which minimize the exergy cost in the system was determined.

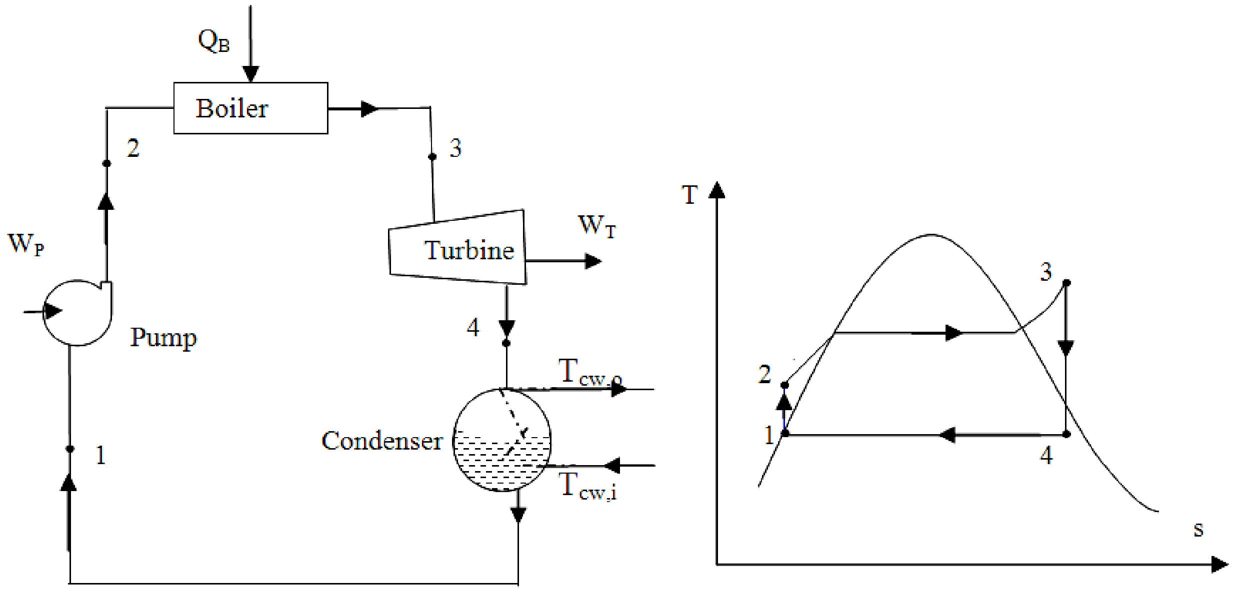

Figure 1. The steam plant cycle and T-S diagram

2. First and second law analysis of steam thermal power cycle

Energy is saved and never and never disappears according to the first law. But the exergy is saved only in reversible processes and decreases in irreversible processes [4-7]. In exergy analysis of steady state steady flow system, the basic equation below is used in all the components.

$$\dot{E}_Q - \dot{E}_W = \sum_{\text{outlet}} \dot{m}\,\varepsilon - \sum_{\text{inlet}} \dot{m}\,\varepsilon + T_0 S_{\text{production}} \quad (1)$$

The irreversibility value of each component in the system is calculated as follows:

$$I = T_0 S_{\text{production}} \quad (2)$$

Thermomechanical exergy is determined by neglecting the chemical exergy terms based on reactions.

$$\varepsilon = (h - T_0 s) + \frac{1}{2}V^2 + gZ - (h_0 - T_0 s_0) \quad (3)$$

If the potential and kinetic energy terms in Equation 3 are neglected, specific exergy is follows:

$$\varepsilon = (h - T_0 s) - (h_0 - T_0 s_0) \quad (4)$$

The total irreversibility of thermal power cycle can be written as follows.

$$I_{Top} = I_P + I_B + I_T + I_C \quad (5)$$

The design parameters for first and second law analysis of the system can be seen in Table 1. The system design parameters have been defined by analyzing the common thermal power plant applications and they are the most frequently seen parameters. Then, the optimum working values of the designed system have been determined.

3. Levelized-cost method and thermoeconomic optimization

In levelized-cost method, firstly, the system parameters to be used in optimization process are chosen. Then, the irreversibility equations and at last the relationships between each component are obtained thermoeconomically [8,9]. In the thermoeconomic analysis of a system, the calculation is started from the point where power fluid enters the system. Because the output of an element is the input for another. In the cost balance equations of each element, the necessary assumptions are received by the way of one missing from the unknown number. So the input cost of another element can be calculated. If this calculation is applied to all the elements in order, the cost of the last element can be found [10]. Water

and fuel enters the steam thermal power plant cycle. Annual maintenance and operating costs is shared with in the elements. Recycling time in investment cost accounts has been taken for 10 years and cost method and investment cost has been calculated. Continuous flow conditions have been taken and analysis has been done starting from the pump.
The total cost belonging to a system element is calculated as follows: ($TM = K_{burning} + K_{maintenance} + K_{staff}$)
The cost equations belonging to the system elements that compose steam thermal power plant is given in Ref. [11].

Table 1. The design parameters to be used in the first and second law analysis

Parameter	**Value**
Power of steam plant	500 MW
Environmental temperature, T_0	20 ^oC
Boiler temperature, T_B	400-1300 ^oC
Inlet cooling water temperature, $T_{cw,i}$	15–20 ^oC
Outlet cooling water temperature, $T_{cw,o}$	25–32 ^oC
Reference pressure, P_0	101,325kPa
Condenser pressure, P_C	2,5-10 kPa
Boiler pressure, P_B	12500 kPa
Stream mass flow rate, $\dot{m}$	200–300 kg/s
Pump efficiency, η_P	0,75-0,8
Turbine efficiency, η_T	0,8-0,85

3.1 Cost balance equation
In order to determine the cost of last products produced by the system, the investment cost, management and maintenance cost and fuel cost should be taken into consideration. The equation which includes the actual valves is called cost equation and it is written as follows.

$$M_u = M_y + Y + IB \tag{6}$$

M_u : Product Cost ($\$/MW_e$)
M_y : Fuel Cost ($\$/MW_e$)
Y : Investment Cost ($\$/MW_e$)
IB : Management and Maintenance Cost ($\$/MW_e$)

As the annual investment cost varies according to depreciation method, the present valves should be calculated. The costs are dealt in years with the method of Levelized-cost. Annual depreciation cost and management and maintenance cost are handled together as they are the characteristic features of the system.

$$K = Y + IB \tag{7}$$

$$M_u = M_y + K \tag{8}$$

3.2 Thermoeconomic balance equation
The aim in writing the thermoeconomic balance equation is to determine the exergy cost. The exergy cost is related to exergy flow. The exergy of the system or its component is written according to the input and output exergy values. System is in interaction with its environment in terms of heat and function. There are several irreversibilities and they cause exergy losses in this interaction. These losses are important for determining specific electricity production. In exergy cost, the interaction of system and its environment and the effect of the irreversibilities in the system on cost are investigated. For this aim, the exergy cost equation can be written as follows [12]:

$$\sum M_o + M_w = \sum M_i + M_Q + K \tag{9}$$

$$\dot{M}_o = c_o E_o = c_o \left(\dot{m}_o \dot{\varepsilon}_o \right) \quad (10)$$

$$\dot{M}_i = c_i E_i = c_i \left(\dot{m}_i \dot{c}_i \right) \quad (11)$$

$$\dot{M}_w = c_w \dot{W} \text{ (The exergy cost of work)} \quad (12)$$

$$\dot{M}_Q = c_q E_Q \text{ (The exergy cost of heat)} \quad (13)$$

$$\sum (c_o E_o) + \left(c_W \dot{W} \right) = \sum (c_i E_i) + (c_Q E_Q) + K \quad (14)$$

In Equation 15, the place of work and heat can change as production or input according to system conditions. For instance, as the function is called as input in the pump, it should be on the right of the equation. The unit c in equation is the exergy cost. In the analysis as the input exergy cost of each component is the output rate of previous component it is seen as known. As a result, the unknown quaintly in the equation is the exergy cost of the product.

4. Results and discussion

The first and second law analysis of thermodynamics is applied to the examined steam power plant. According to the results of the first law analysis, the variation of turbine power according as fluid mass flow rate and boiler temperature was given in Figure 2. With the rise in boiler temperature and mass flow rate values, the amount of power gained from the turbine has risen as well.

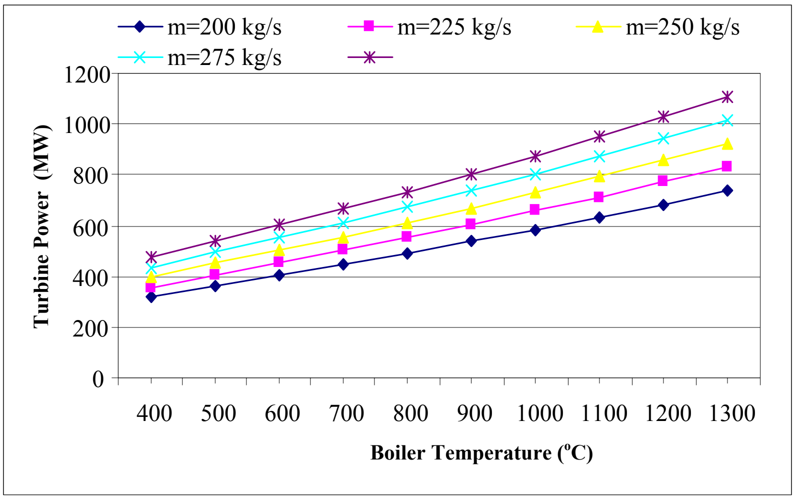

Figure 2. Variation with boiler steam temperature depending on fluid mass flow rate of turbine power

In Figure 3, the total irreversibility rate of the system depending on steam turbine inlet temperature and mass flow rates of fluid has been given. It has been seen that the irreversibility of the system has increased due to the rise in boiler temperature and mass flow rates.

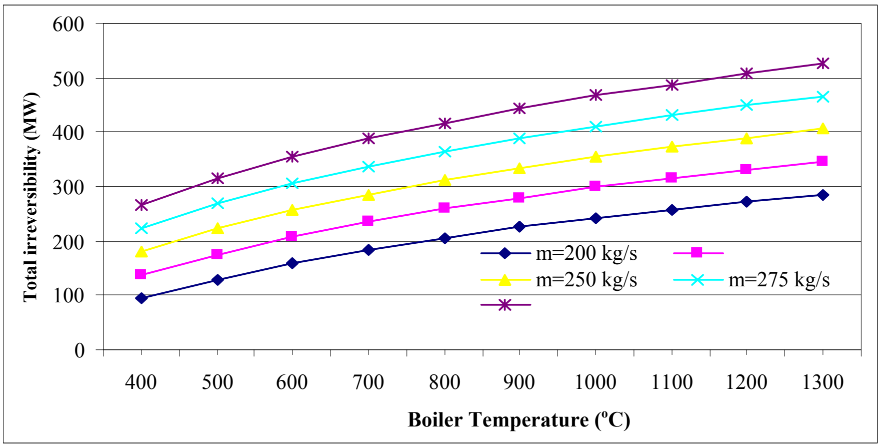

Figure 3. Variation with boiler temperature depending on different fluid mass flow rate of total irreversibility

In Figure 4, the variations of total irreversibility rates according as steam temperature and cooling water inlet temperature have been given. It has also been seen that the irreversibility of the system has risen due to the rise in boiler temperature and cooling water inlet temperature.

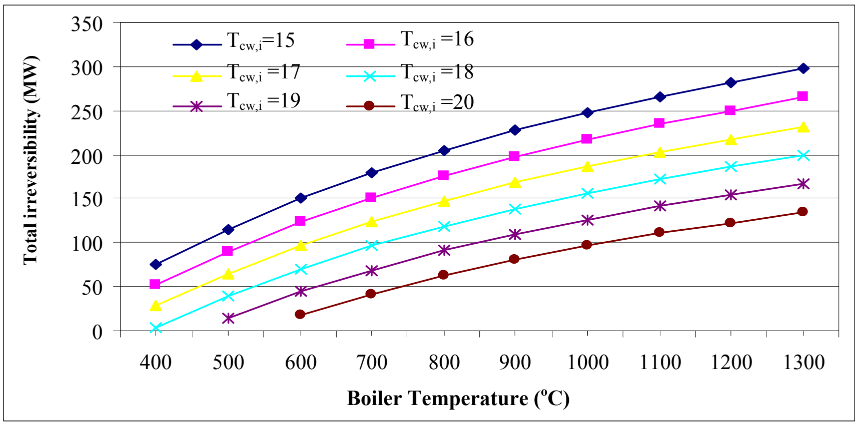

Figure 4. Variation with steam temperature depending on different cooling water inlet temperature of total irreversibility

In Figure 5, the variation in steam cost due to the boiler superheat steam temperature has been given. It is seen that the more the boiler temperature is, the more the steam cost is.

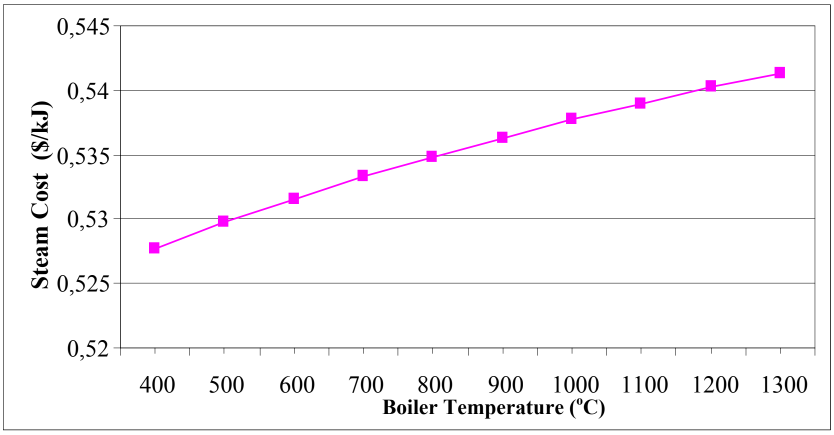

Figure 5. Variation with boiler temperature of steam cost

In Figure 6, the variation in electricity cost according as boiler superheated steam temperature has been given and the more the boiler temperature is, the more the electricity cost is.

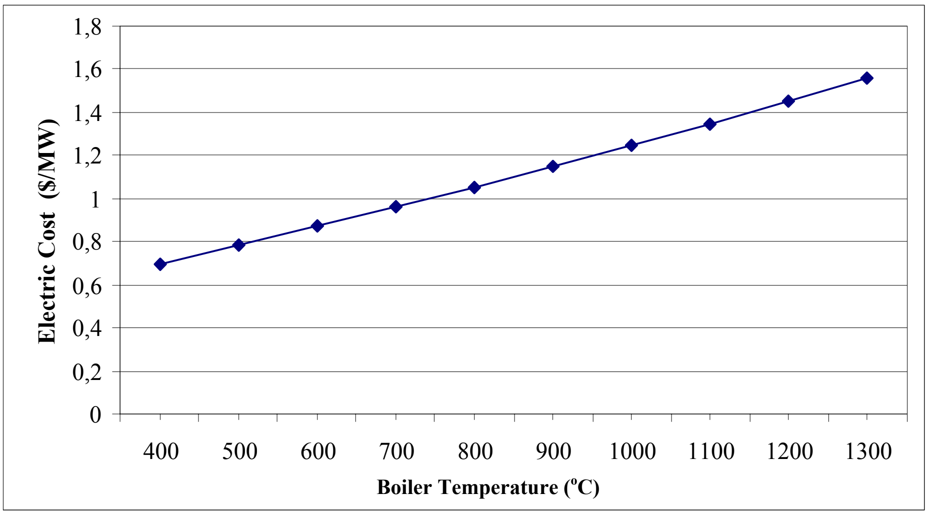

Figure 6. Variation with boiler temperature of electric cost

The optimum operating values have been carried out with the application of thermoeconomic optimization equation for steam power plant system in the range of design parameters. Obtained results have been given in Table 2.

Table 2. Optimum operating values of steam power plant

	Unit Cost of Electricity 1.18 $/MW						
Operating Values	T_B (^{0}C)	m (kg/s)	P_B (MPa)	P_C (kPa)	$T_{cw,i}$ (^{0}C)	$T_{cw,o}$ (^{0}C)	η_P
	900	250	12.5	5	15	32	0.75

The optimum operating values for a 500 MW plant are; in 20 ^{o}C ambient temperature and 0.1 MPa atmospheric pressure, in 12,5 MPa pump pressure, 900 ^{o}C boiler temperature, 250 kg/s steam flow, 0,75 pump efficiency, 15 ^{o}C cooling water inlet, 32 ^{o}C cooling water output and 5 kPa condenser pressure. With these operating values, the unit cost of steam is 0.538 $/MW and unit cost of electricity is 1.18 $/MW.

5. Conclusion

In this study, thermoeconomic analysis has been applied to a steam power plant. The analysis has been done with MATLAB computer program. The optimum operating values for a 500 MW steam power within the stated design parameters has been defined as 900 ^{o}C boiler temperature and 250 kg/s steam flow. With these values, the unit cost of steam is 0,538 $/MW and the unit cost of electricity is 1,18 $/MW. The cost of electricity is approximately twice more than steam cost. Besides, it has also been seen that due to the rise in boiler temperature, the unit cost of steam and the unit of electricity has increased.
The results obtained from this study will significantly contribute to the application of an actual steam power plant to be practiced.

Nomenclature

c	Exergy cost
E	Exergy
h	Enthalpy
I	Irreversibility

K	Cost within year of component
M	Cost
$\dot{m}$	Mass flow rate
IB	Management and maintenance cost
Q	Heat transfer rate
s	Entropy
W	Work
V	Flow velocity
Z	Reference altitude
ΔT	Temperature difference
η	Efficiency
Y	Investment cost

Subscripts

B	Boiler
C	Condenser
cw	Cooling water
i	inlet
o	outlet
P	Pump
T	Turbine

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