EXERGOECONOMIC ANALYSIS OF A FLUIDIZED BED COAL COMBUSTION STEAM POWER PLANT

by

N. Filiz TUMEN OZDIL * ***and Atakan TANTEKIN***

Department of Mechanical Engineering, Adana Science and Technology University, Adana, Turkey

Original scientific paper
https://doi.org/10.2298/TSCI151210056T

In this study, extensive exergoeconomic analysis is performed for a 6.5 MW steam power plant using the data obtained from running system. The role and impact of the each system component on the first and second law efficiencies are analyzed to understand the individual performance of sub-components. Moreover, the quantitative exergy cost balance for each component is considered to point out the exergoeconomic performance. The analysis shows that the largest irreversibility occurs in the fluidized bed coal combustion (FBCC), about 93% of the overall system irreversibility. Furthermore, it is followed by heat recovery steam generator and economizer with 3% and 1%, respectively. In this study, the capital investment cost, operating and maintenance costs and total cost of FBCC steam plant are calculated as 6.30, 5.35, and 11.65 US$ per hour, respectively. The unit exergy cost and fuel exergy cost, which enter the FBCC steam plant, are found as 3.33 US$/GJ and 112.44 US$/h, respectively. The unit exergy cost and exergy cost of the steam which is produced in heat recovery steam generator are calculated as 16.59 US$/GJ and 91.87 US$ per hour, respectively. This study emphasizes the importance of the exergoeconomic analysis based on the results obtained from the exergy analysis.

Key words: *exergy, fluidized bed, exergoeconomic*

Introduction

Exergy is a measure of the potential of a stream for causing a change, as a consequence of not being completely stable relative to the reference environment. It is defined as the maximum amount of work that can be produced by a stream of matter, heat, or work as it comes into equilibrium with a reference environment. This information is much more effective in determining the plant and operation costs, the fuel versatility, and the pollution. By using exergy analysis method, magnitudes, and locations of exergy destructions (irreversibility) in the whole system can be identified, while potential for the first law efficiency improvements can be introduced [1-5].

The exergoeconomic analysis is a method that comes out with the combination of both the exergy and economic analysis. The exergoeconomic method has a huge potential to optimize the systems using effectiveness of energy and exergy. The aims of the exergoeconomic are listed:
- calculate separately the cost of each product generated by a system having more than one product,
- understand the cost formation process and the flow of costs in a system,
- optimize the specific variables in components separately, and
- optimize the overall system.

*Corresponding author, e-mail: fozdil@adanabtu.edu.tr

Eskin *et al.* [6] presented the thermodynamic analysis for a FBCC power plant in Turkey. The analysis was performed for the system and subsystem separately and a model of the FBCC was generated. Based on their results for the developed and validated model, FBCC had the major irreversibility. Moreover, they found out that as the excess air increased, the first and second law efficiencies of the FBCC decreased. Furthermore, when the ambient temperature increased, the first and second law efficiencies of the FBCC increased in their study. Lian *et al.* [7] demonstrated the evaluation of the thermoeconomic potential of a steam turbine plant for a trigeneration system. The principal objective of this study was to derivate a calculation process using the second law of thermodynamics. The plant employed waste wood as biomass for energy source. The cost effectiveness of the four different configurations was evaluated varying economic and operating parameters such as the fuel price and electricity price. For all configurations, the highest exergy destruction occurred in the furnace, about 60%. The steam drum followed the furnace with the value ranging from 11% to 16%. The overall production cost decreased with increasing steam pressure while it increased with increasing steam temperature. Aljundi [8] examined the energy and exergy analysis of a power plant which was located in Jordan. In this study, the system components were analyzed separately and identified the major energy and exergy losses of power plant. Moreover, the effect of different ambient temperature on the system efficiency was performed in this study. As a result, minor change of the ambient temperature had no major effect on performance of the power plant.

There is a limited data about exergoeconomic analysis of FBCC power plant in literature [9]. The main objectives of this study are the demonstration of the comprehensive exergoeconomic analysis of an FBCC steam plant and economic performance of the FBCC steam plant with the help of a method of exergoeconomic analysis which is called as SPECO [10]. This study is implemented to fulfill and improve the economic point of view for the FBCC power plant using the real operation data. The exergetic performance assessment for the system components and exergy-cost relations were done in parts in order to demonstrate the relationship between thermodynamics and economic assessments of the FBCC steam plants for industrial areas.

System description

The plant has a 6.5 MW capacity including a bubbling type FBCC, a heat recovery steam generator (HRSG), an economizer (ECO), a cyclone (CY), two induced draft fan as ventilation fan (VF), a forced draft fan as air fan (AF), a chimney (CH), and two pumps (P) as components. The schematic diagram of the examined FBCC steam plant is demonstrated in fig. 1. The Sirnak asphaltite [11, 12] is used in FBCC power plant as solid fuel of which components are demonstrated in tab. 1. The operating conditions for the FBCC plant data are given in tab. 2. In the FBCC steam plant, the feed water first pumps into the ECO and then goes into the HRSG where steam generation occurs through the heat exchanger tubes placed inside the HRSG. The inspection of the feed water and the steam production are provided by the HRSG which includes the saturated steam in its top zone and the saturated water in its bottom zone. Meanwhile, the water level remains constant in the HRSG. When the feed water enters in HRSG, the water temperature contained in the HRSG achieves the saturation temperature. Several assumptions are made in this research which can be listed:

- the plant operation is in a steady-state condition,
- for the air and combustion gas the ideal gas principles are considered,
- owing to minor contribution of the exergy of the ash compared with the exergy of coal, the exergy of the ash is neglected, and
- the pressure losses in piping and ducts are also neglected.

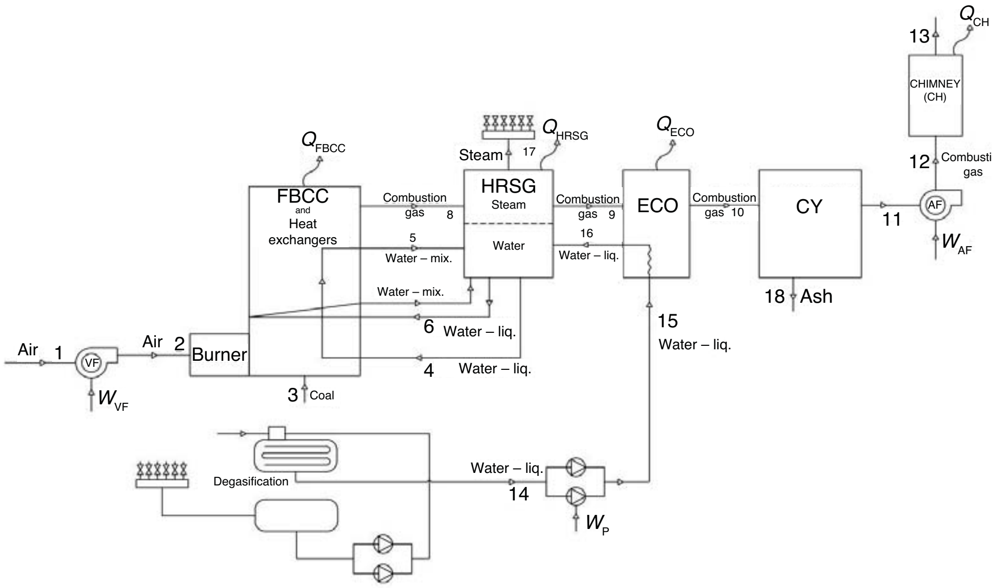

Figure 1. Schematic diagram of the power plant

Table 1. The properties of the Sirnak asphaltite

Moisture [%]	8.15
Ash [%]	36.67
Volatile matter [%]	20.03
Sulphur [%]	5.36
Hydrogen [%]	4
Oxygen [%]	2
Nitrogen [%]	1
Carbon [%]	22.79
GCV or HHV [kcal/kg]	4637
LHV [kcal/kg]	4426

Analysis

The purpose of this study is to implement an exergo-economic analysis in order to figure out and demonstrate the relationship between economic and exergetic parameters. To be understood of the cost based performance for the FBCC steam plants on real running system.

The thermodynamic properties of water, steam, and combustion gases are provided from thermodynamic tables and EES program. Moreover, the thermodynamic properties of reference environment are accepted as T_0 = 25 °C, P_0 = 101.3 kPa. The mole fraction of the combustion gases obtained from the equipment and the mole fraction of the reference environment are shown in tabs. 3 and 4, respectively.

Table 2. Operating conditions of the power plant

Mass flow rate of coal	0.45 kg/s
Steam flow rate	2 kg/s
Steam pressure	700 kPa
Steam temperature	165 °C
Combustion gas flow rate	1.21 kg/s
Air flow rate	1.34 kg/s
Water flow rate	2 kg/s

Table 3. Mole fraction of the combustion gas

Combustion gas	Mole fraction [%]
SO_2	81.60
H_2	0.42
CO	11.16
O_2	6.82
λ	48

Table 4. Mole fraction of the component of the reference ambient

Reference component	Mole fraction [%]
SO_2	0.20E-03
H_2	0.05E-03
CO	0.70E-03
O_2	20.35

Thermodynamic analysis

Energy can not be produced or destroyed that the first law of thermodynamics refers to this idea. Mass and energy balance equations for energy analysis can be given as eqs. (1) and (2):

$$\text{Mass input} = \text{Mass output}\ \left(\Sigma \dot{m}_{\text{in}} = \Sigma \dot{m}_{\text{out}}\right) \tag{1}$$

$$\text{Energy input} - \text{Energy output} = \text{Net energy}\ \left(\dot{Q} + W = \Sigma \dot{m}_{\text{out}} h_{\text{out}} - \Sigma \dot{m}_{\text{in}} h_{\text{in}}\right) \tag{2}$$

Because of the minor change of kinetic and potential energy, they are neglected for this study. The exergy indicates the work potential of the system. Exergy is destructed while it is not preserved as energy. Exergy destruction is expressed as irreversibility which refers to the performance of system.

General balance equations for exergy analysis (tab. 5) can be written as eq. (3):

Exergy input – Exergy output – Exergy consumed reversibility – Exergy destruction = Net exergy (3)

Table 5. Exergy balance equations for the subsystem of FBCC steam plant

Components	Exergy balance equations
VF	$Ex_1 + \dot{W}_{\text{VF}} = Ex_2 + Ex_{\text{Q}}^{\text{VF}} + \dot{E}x_{\text{D}}$
FBCC	$Ex_2 + Ex_3 + Ex_4 + Ex_6 = Ex_5 + Ex_7 + Ex_8 + Ex_{\text{Q}}^{\text{FBCC}} + \dot{E}x_{\text{D}}$
HRSG	$Ex_5 + Ex_7 + Ex_8 + Ex_{16} = Ex_4 + Ex_6 + Ex_9 + Ex_{17} + Ex_{\text{Q}}^{\text{HRSG}} + \dot{E}x_{\text{D}}$
ECO	$Ex_9 + Ex_{15} = Ex_{10} + Ex_{16} + Ex_{\text{Q}}^{\text{ECO}} + \dot{E}x_{\text{D}}$
CY	$Ex_{10} = Ex_{11} + Ex_{18} + \dot{E}x_{\text{D}}$
AF	$Ex_{11} + W_{\text{AF}} = Ex_{12} + Ex_{\text{Q}}^{\text{AF}} + \dot{E}x_{\text{D}}$
CH	$Ex_{12} = Ex_{13} + Ex_{\text{Q}}^{\text{CH}} + \dot{E}x_{\text{D}}$
P	$Ex_{14} + W_{\text{P}} = Ex_{15} + Ex_{\text{Q}}^{\text{P}} + \dot{E}x_{\text{D}}$

Thermoeconomic analysis

The thermoeconomic analysis combines exergy analysis and economic analysis to provide information that is not accessible with general energy and exergy analysis. In general economic analysis, a cost balance can be formulated for the steady-state system below for each control volume *i*:

$$\sum \dot{C}_{\text{in},i} + \dot{Z}_i^T = \sum \dot{C}_{\text{out},i} + \dot{C}_i^W + \dot{C}_i^Q \tag{4}$$

$$\dot{C}_{\text{i}} = c_{\text{i}} Ex_{\text{i}} \tag{5}$$

$$\dot{C}_i^W = c_i W_i \tag{6}$$

$$\dot{C}_i^Q = c_i Ex_i^Q \tag{7}$$

$$\dot{Z}_i^T = \dot{Z}_i^{\text{CI}} + \dot{Z}_i^{\text{OM}} \tag{8}$$

where $\dot{C}_i$, $\dot{C}_i^W$, and $\dot{C}_i^Q$ are the exergy costs of the flows, power, and heat, respectively, c – the unit exergy costs of the flows, power, and heat, Ex_i, W_i, and Ex_i^Q – the exergy of flow, power and heating entering and leaving control volume, respectively $\dot{Z}_i^{\text{CI}}$, $\dot{Z}_i^{\text{OM}}$, and $\dot{Z}_i^T$ – the hourly leveled costs of the capital investment, operating and maintenance and the total cost of equipment inside the control volume.

The capital recovery factor (CRF):

$$\mathrm{CRF} = \frac{i\left(i+1\right)^n}{\left(i+1\right)^n - 1} \tag{9}$$

The hourly leveled capital investment cost of i^{th} component $\dot{Z}_i^{\mathrm{CI}}$:

$$\dot{Z}_i^{\mathrm{CI}} = \frac{\mathrm{CRF}}{\tau}\,\mathrm{PEC}_i \tag{10}$$

The cost rate (CR_i) of the subsystems:

$$\mathrm{CR}_i = \frac{\mathrm{PEC}_i}{\sum \mathrm{PEC}_{\mathrm{FBC,CSD}}} \tag{11}$$

where i, n, τ, and PEC are the interest rate, the life time of the plant, total annual number of hour of the system operated at a full road, and the purchased equipment cost, respectively. For this system i, n, and τ are taken as 0.1, 10 year, and 8400, respectively.

$$\dot{Z}_i^{\mathrm{OM}} = \dot{Z}_i^{\mathrm{CI}}\varphi \tag{12}$$

where the maintenance and operating costs are considered with the factor $\varphi = 0.85$ for the steam plant and its auxiliary components.

The total investment price of the examined FBCC steam plant is 325 000 US$ and the subsystem costs are calculated using the cost rates given by the manager of the plant, as listed in tab. 9. The unit exergy cost of the coal c_3^{coal},

$$\mathrm{c}_3^{\mathrm{coal}} = \frac{Pr^{\mathrm{coal}}}{ER\,LHV 10^{-6}[\mathrm{GjkJ^{-1}}]} \tag{13}$$

where Pr^{coal}, ER, and LHV are called as the coal sell price in the Turkish Lira [TL], the exchange rate [TLUS^{-1}], and the LHV of the coal, respectively. The unit exergy cost of the electricity $c_{19}^W = c_{20}^W = c_{21}^W$:

$$c^W = \frac{Pr^W}{ER\,360010^{-6}[\mathrm{sh^{-1}}][\mathrm{GjkJ^{-1}}]} \tag{14}$$

where Pr^W and ER are called as the electricity sell price in the Turkish Lira [TL] and the exchange rate [TLUS^{-1}], respectively.

The exergoeconomic analysis intends that the better and detailed comprehension the cost formation process and calculations of the cost rate for each product generated by steam plant.

The cost balance and auxiliary equations for the each component are shown in tab. 6. The exergoeconomic factor provides detailed information regarding the combination of non-exergy costs (capital investments, operating, and maintenance costs), exergy destruction and exergy loss.

The exergetic fuel is defined as the consumed resource for generating product:

$$f_i = \mathrm{Z}_i T / \left\{\dot{Z}_i^T + \left[c_{f,i}\left(\dot{E}x_{D,i} + Ex_{L,i}\right)\right]\right\} \tag{15}$$

Table 6. Exergoeconomic balance equations for the subsystem of FBCC steam plant

Components	Exergoeconomic balance equations
VF	$C_1 + C_{19} + Z_{VF}^T = C_2$ $C_1 = 0$ (Assumption)
FBCC	$(C_6 - C_7) + (C_4 - C_5) + C_2 + C_3 + Z_{FBCC}^T = C_8 + C_{22}^Q$ $(C_6 - C_7) / (Ex_6 - Ex_7) = (C_4 - C_5) / (Ex_4 - Ex_5)$ $c_8 = c_3$
HRSG	$(C_8 - C_9) + (C_7 - C_6) + (C_5 - C_4) + C_{16} + Z_{HRSG}^T =$ $= C_{17} + C_{23}^Q$ $C_8 / Ex_8 = C_9 / Ex_9$, $(c_8 = c_9)$ $C_4 / Ex_4 = C_6 / Ex_6$, $(c_4 = c_6)$ $c_4 = c_6 = c_{16}$ (Assumption)
ECO	$(C_9 - C_{10}) + (C_{15} - C_{16}) + Z_{ECO}^T = Ex_{24}^Q$ $C_9 / Ex_9 = C_{10} / Ex_{10}$, $(c_{10} = c_{11})$
CY	$C_{10} + Z_{CY}^T = C_{11} + C_{18}$ $C_{18} = 0$ (Assumption) $C_9 = C_{10}$ (Assumption)
AF	$C_{11} + C_{21}^W + Z_{AF}^T = C_{12}$
CH	$C_{12} + Z_{CH}^T = C_{13} + Ex_{25}^Q$
P	$C_{14} + C_{20}^W + Z_P^T = C_{15}$

Results and discussions

In this study, the exergoeconomic analysis is performed using first and second law of thermodynamics and economic parameters to provide the relationship between thermodynamics and economic performance of components for the FBCC steam plant. Using the given and measured parameters in tabs. 1 and 2, exergy rates for the steam plant are calculated as can be seen in tab. 7 with respect to state numbers. Exergy destruction, the first and second law efficiencies are calculated using the values shown in tab. 7 as can be seen in tab. 8.

Table 7. The exergy rate and other properties*

State No *	Fluid type	Mass flow rate [kgs^{-1}]	Temperature [K]	Pressure [kPa]	$\dot{E}x$ [kW]
1	Air	1.34	291	101,32	0,60
2	Air	1.34	319	110	1.52
3	Coal	0.45	291	0	9362.33
4	Water-liquid	1.67	438	700	180.02
5	Water-mix	1.67	438	700	1061.58
6	Water-liquid	1.41	438	700	152.26
7	Water-mix	1.41	438	700	972.48
8	Comb. gas	1.21	1049	101,32	1074.82
9	Comb. gas	1.21	663	101,32	791.24
10	Comb. gas	1.21	393	101,32	673.73
11	Comb. gas	1.21	388	101,32	671.71
12	Comb. gas	1.21	413	101,32	678.12
13	Comb. gas	1.21	410	101,32	677.40
14	Water-liquid	2	373	950	69.44
15	Water-liquid	2	374	950	71.28
16	Water-liquid	2	403	950	128.74
17	Steam	2	438	700	1538.17
18	Coal (ash)	0.13	393	0	0
FBCC	E_{LOSS}	-	-	-	1693.12
HRSG	E_{LOSS}	-	-	-	422.77
ECO	E_{LOSS}	-	-	-	7.35
CH	E_{LOSS}	-	-	-	0.78

* for state numbers refer to fig. 1 for the FBCC system while dead state temperature and pressure values are 298.15 K and 101.32 kPa

Table 8. The exergy destruction, the first and second law efficiency values of the main components in FBCCSP

Components	$\dot{E}x_D$ [kW]	η_I [%]	η_{II} [%]
FBCC	4894. 19	63.78	20.53
HRSG	153.16	90.85	99.38
ECO	52.68	88.61	48.90
CY	2.02	93.79	99.70
CH	0	97.36	100
VF + AF + P	79.88	75.19	16.68
FBCC SP	5181.95	55.60	15.53

Table 9. The distribution of the cost rate, the purchased equipment cost, the leveled capital investment, operating and maintenance costs and total costs of the components

Com-ponent	CR_i	PEC [US$]	$\dot{Z}_i^{CI}$ [US$ per hour]	$\dot{Z}_i^{OM}$ [US$ per hour]	$\dot{Z}_i^{T}$ [US$ per hour]
VF	0.03	9 750.00	0.19	0.16	0.35
FBCC	0.4	130 000.00	2.52	2.14	4.66
HRSG	0.2	65 000.00	1.26	1.07	2.33
ECO	0.14	45 500.00	0.88	0.75	1.63
CYC	0.09	29 250.00	0.57	0.48	1.05
AF	0.04	13 000.00	0.25	0.21	0.46
CH	0.07	22 750.00	0.44	0.37	0.81
P	0.03	9 750.00	0.19	0.16	0.35
TOTAL	1	325 000.00	6.30	5.35	11.65

According the results that are shown in tab. 8, the first law efficiencies of FBCC, HRSG, ECO, CYC, and CH are calculated as 63.78%, 90.85%, 88.61%, 93.79%, and 97.36%, respectively. The second law efficiencies of FBCC, HRSG, ECO, CY, and CH are calculated as 20.53%, 99.38%, 48.90%, 99.70%, and 100%, respectively. The first and second law efficiencies of the FBCC steam plant are to be 55.60% and 15.53%, respectively. The highest exergy destruction occurs in the FBCC with 4894.19 kW between the components of the FBCC steam plant. The exergy destruction of the whole FBCC steam plant is found as 5181.95 kW.

The purchased equipment cost, the hourly leveled capital investment, operating, and maintenance cost, and the total costs of the FBCC steam plant with its auxiliary systems are shown in tab. 9. The distribution of the cost rates, the purchased equipment costs and the total investment costs of the auxiliary equipments are also presented in figs. 2-4, respectively. As can be seen in figs. 2-4, the highest values of the cost rate, the purchased equipment cost and the total investment cost are occurred in FBCC component. With the combination of the values given in tab. 9, the cost balance equations demonstrated in tab. 6 while the exergy rate values shown in tab. 7.

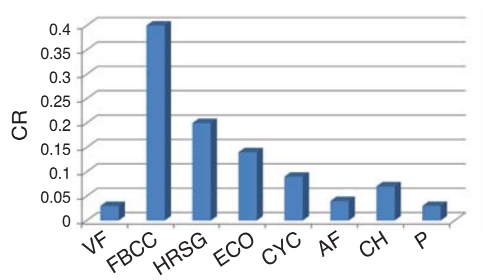

Figure 2. Distribution of the cost rates for equipment

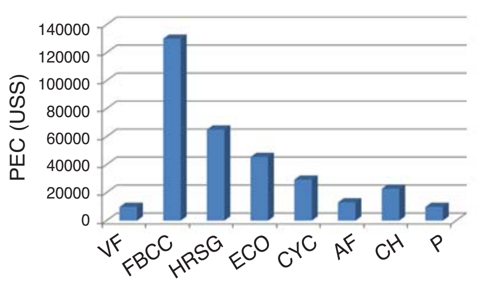

Figure 3. Distribution of the purchased equipment costs of the equipments

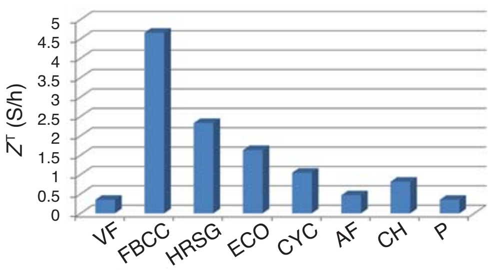

Figure 4. Distribution of the total investment costs of the equipments

Moreover, unit exergy cost, and exergy cost of the components on FBCC steam plant are calculated as shown in tab. 10 with respect to state numbers. Based on the results which are shown in tab. 10, the unit exergy cost and exergy cost of the fuel, which is entering the FBCC steam plant, are calculated as 3.33 US$/GJ and 112.44 US$ per hour, respectively. The unit exergy cost and exergy cost of the steam, which is produced in HRSG, are calculated as 16.59 US$/GJ and 91.87 US$ per hour, respectively. The capital investment cost, operating and maintenance costs and total cost of FBCC steam plant are found to be 6.30, 5.35, and 11.65 US$ per hour, respectively.

The exergy destruction cost rates of the equipments are demonstrated in fig. 5. The highest cost rate value occurs in FBCC. Moreover, FBCC is the most important component in exergoeconomic point of view. The exergoeconomic factors of the equipments are shown in fig. 6. FBCC has the lowest exergo-

Table 10. The distribution of the exergy rate, unit exergy cost and exergy cost at different locations of the FBCC steam plant (for state numbers refers to fig. 1)

State No.	Ex [GJ/h]	c [US$/GJ]	C [US$/h]
1	0,22E-02	0	0
2	0,55E-02	811,47	4,44
3	33,70	3,33	112,44
4	0,65	6,29	4,08
5	3,82	13,03	49,82
6	0,55	6,29	3,45
7	3,50	13,14	46,00
8	3,87	3,33	12,91
9	2,85	3,33	9,50
10	2,42	3,33	8,09
11	2,42	3,33	8,07
12	2,44	4,87	11,90
13	2,44	5,21	12,70
14	0,25	0	0
15	0,26	5,26	1,35
16	0,46	6,29	2,92
17	5,54	16,59	91,87
18	0	0	0
VF - 19	0,16	25,25	4,09
P - 20	0,04	25,25	1
AF - 21	0,13	25,25	3,36
FBCC - 22	6,09	3,33	20,33
HRSG - 23	1,52	3,33	5,08
ECO - 24	0,03	3,33	0,09
CH - 25	0,28E-02	3,33	0,01

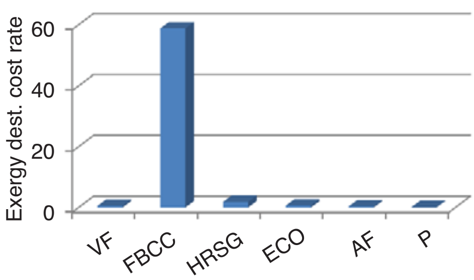

Figure 5. Exergy destruction cost rates of the equipments

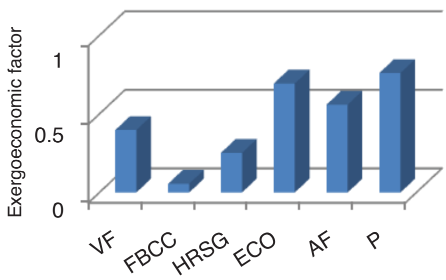

Figure 6. The exergoeconomic factors of the equipments

economic factor rate due to the high exergy destruction rate. In order to decrease the exergy destruction rate in FBCC, excess air ratio and rate of the heat loss can be decreased and exhaust gas can be preheated. The high exergoeconomic factor rate in ECO and pump means a decrement in the investment costs of these components.

Conclusions

This study introduces a detailed exergoeconomic analysis for a FBCC steam plant. The second law efficiencies and exergy destruction rates are calculated to show the performance and effectiveness of the FBCC steam plant in exergetic point of view. Exergy cost and unit exergy cost terms are calculated to indicate the evaluation of the exergoeconomic analysis. Some observations obtained from the investigations and results of this study can be listed as follows.

- The first and second law efficiencies of the FBCC steam plant are found as 55.60% and 15.53%, respectively. The exergy destruction rate for the overall system is 5181.95 kW. The major exergy destruction occurs in the FBCC component with approximately 4894.19 kW due to high amount of excess air and low combustion efficiency. Combustion process in the FBCC is the main source of irreversibility that can be decreased through preheating combustion gas before FBCC. The first and second law efficiencies of the FBCC are found as 63.78% and 20.53%, respectively.
- The capital investment cost, operating and maintenance costs and total cost of FBCC steam plant are calculated to be 6.30, 5.35 and 11.65 US$ per hour, respectively. The unit exergy cost and exergy cost of the fuel, which is entering the FBCC steam plant, are calculated as 3.33 US$/GJ and 112.44 US$ per hour, respectively. The unit exergy cost and exergy cost of the steam, which is produced in HRSG, are calculated as 16.59 US$/GJ and 91.87 US$ per hour, respectively. FBCC component has the lowest exergoeconomic factor rate due to the high exergy destruction rate. The high exergoeconomic factor rate in ECO and pump means a decrement in the investment costs of these components.

Nomenclature

$\dot{C}$ – exergy cost, [US$ per hour]
CR – cost rate
CRF – capital recovery factor
c – unit exergy cost, [US$/GJ]
$\dot{E}x_D$ – exergy destruction, [Kw]
ex – specific exergy, [kJkg^{-1}]
f – exergoeconomic factor
h – specific enthalpy, [kJkg^{-1}]
LHV – lower heating value of coal, [kJkg^{-1}]
$\dot{m}$ – mass flow rate, [kgs^{-1}]
P – pressure, [Pa]
Q – rate of heat transfer, [W]
s – specific entropy, [kJkg^{-1}K^{-1}]
T – temperature, [K]
W – rate of work, [W]
$\dot{Z}$ – hourly levelized cost of investment, [US$ per hour]

Greek symbols

η_I – first law efficiency
η_{II} – second law efficiency
λ – excess air

Subscripts and Superscripts

AF – air fan
CH – chimney
CI – capital investment
CSP – coal steam production
CY – cyclone
comb. – combustion gas
destr. – destruction
ECO – economizer
FBC – fluidized bed combustion
FBCC – fluidized bed coal combustor
HRSG – heat recovery steam generator
OM – operating and maintenance
P – pump
VF – ventilation fan
0 – reference state

References

[1] Kaushik, S. C., *et al*., Energy and Exergy Analyses of Thermal Power Plants, *A Review, Renew Sustain Energy Rev., 15* (2011), 4, pp. 1857-1872
[2] Bejan, A., *et al*., *Thermal Design & Optimization*, A Wiley-Interscience Publication, New York, USA, 1996
[3] Kotas, T. J., *The Exergy Method of Thermal Plant Analysis,* Krieger Publishing Company, London, 1995
[4] Dincer, I., Rosen M. A., *Exergy, Energy, Environment and Sustainable Development,* Elsevier, London, 2007
[5] Tumen Ozdil, N. F., *et al*., Thermodynamic Analysis of an Organic Rankine Cycle (ORC) Based on Industrial Data, *Appl Therm Eng, 91* (2015), Dec., pp. 43-52
[6] Eskin, N., *et al*., Thermodynamic Analysis of a FBCC Steam Power Plant, *Energy Convers Manage., 50* (2009), 9, pp. 2428-2438
[7] Lian, Z. T., *et al*., A Thermoeconomic Analysis of Biomass Energy for Trigeneration, *Appl Energy, 87* (2010), 1, pp. 84-95
[8] Aljundi, I., Energy and Exergy Analysis of a Steam Power Plant in Jordan, *Appl Therm Eng., 29* (2009), 2-3, pp. 324-328
[9] Ozdemir, K., *et al*., Exergoeconomic Analysis of a Fluidized-Bed Coal Combustor (FBCC) Steam Power Plant, *Appl Therm Eng., 30* (2010), 13, pp. 1621-1631
[10] Lazzaretto, A., Tsatsaronis, G., SPECO: A Systematic and General Methodology for Calculating Efficiencies and Costs in Thermal Systems, *Energy, 31* (2006), 8-9, pp. 1257-1289
[11] Gyul'maliev, A. M., Shpirt, M. Ya., Calculation of the Enthalpy of Formation of Coal Organic Matter, *Solid Fuel Chemistry*, *42* (2008), 5, pp. 263-267
[12] Ballice, L., Classification of Volatile Products Evolved from Temperature-Programmed Pyrolysis of Soma-Lignite and Şırnak-Asphaltite from Turkey, *Journal of Analytical and Applied Pyrolysis, 63* (2002), 2, pp. 267-281

Paper submitted: December 10, 2015
Paper revised: February 1, 2016
Paper accepted: February 5, 2016