EXERGOECONOMIC ANALYSIS OF A FBCC STEAM POWER PLANT

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In this study, comprehensive exergoeconomic analysis is implemented in a 6.5 MW fluidized- bed coal combustor steam power plant (FBCCSP) 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 cost of exergy 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 combustor, about 93% of the overall system irreversibility. Furthermore, it is tracked by steam generator (HRSG) and economizer (ECO) with 3% and 1%, respectively. In this study, the capital investment cost, operating and maintenance costs and total cost of FBCCSP are obtained as 6.30, 5.35 and 11.65 US$/h, respectively. The cost of unit exergy and cost of fuel exergy, which enter the FBCCSP, are found as 3.33 US$/GJ and 112.44 US$/h, respectively. The cost of unit exergy and cost of exergy of the steam which is generated in heat recovery steam generator are calculated as 16.59 US$/GJ and 91.87 US$/h, respectively. This study emphasizes the importance of the exergoeconomic analysis connected to the results provided from the exergy analysis.

Key words: Exergy, Fluidized bed, Exergoeconomic.

1. Introduction

Exergy is a scale of the potential of a flow for causing a change, as a result of not being stable compare with the ambient condition. It is described as the maximum amount of work which can be produced by a flow of work or heat because it is stable with the reference environment. This information is much more efficient for determining the operation and plant costs, the pollution and fuel versatility. With the help of exergy analysis, locations and magnitudes of exergy destructions in the whole system can be specified [1-5].

The exergoeconomic analysis is a technique, which emerges with the joining of economic and thermodynamic analyses. The exergoeconomic analysis has an enormous capacity to optimize the systems. The main goals of the thermoeconomic analysis are stated as;

i. estimation of the price of each output produced within a process
ii. grasp formation of costs within a system
iii. certain component optimization

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iv. overall system optimization

Eskin et al. [6] implemented the thermodynamic analysis for a FBCCSP in Turkey. The analysis was done for the all process and auxiliary equipments separately and a FBCC model was generated. Based on their results for the developed and validated model, FBCC had the major irreversibility. Moreover, they observed that there are inversely proportional relationship between excess air and efficiency of the system. Furthermore, as the temperature of the reference ambient increased, the energy and exergy efficiencies of the FBCC increased in their study. Lian et al. [7] demonstrated the evaluation of the exergoeconomic potential of a steam turbine plant for a trigeneration system. The objective of this study was to derivate a calculation process using the second law of thermodynamic. The plant employed waste wood as biomass for energy source. The cost effectiveness of the four different configurations was evaluated ranging from 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 thermodynamic assessment of a power station. The equipments of the station were analyzed separately and the main energy and exergy losses of the plant were identified. 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 thermoeconomic analysis of FBCCSP in literature [9]. The major objectives of this study are to be demonstration of the intensive exergoeconomic analysis of an fluidized-bed coal combustor steam plant and economic assessment of the 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-economic relations were done to demonstrate the relation between thermodynamic and economic assessments of the FBCC steam plants for industrial areas.

2. System Definition

The plant has a bubbling type fluidized bed coal combustor, a heat recovery steam generator, an economizer , a cyclone, two induced draft fan as ventilation fan, a forced draft fan as air fan, a chimney and two pumps as components. Its capacity is 6.5 MW. The figural representation of the examined FBCC steam system is demonstrated in Fig. 1. The Şırnak Asphaltite [11-12-14] is used in FBCC power plant as solid fuel of which components are demonstrated in Tab. 1. The operating conditions [14] for the FBCC plant are given in Tab. 2. According to the working principal of the system, firstly the water comes into the economizer with the help of pumps and then goes into the HRSG where steam generation occurs through the heat exchanger tubes placed inside the HRSG. The control and formation of the steam are ensured by the HRSG that contains both saturated water and saturated vapor. At the same time, the water level in the HRSG maintains constant. The temperature of the water within the HRSG reaches the saturation temperature whenever the feed water goes into HRSG. Several assumptions are made in this research which can be listed as;

i. the system operation is in a steady state case,

ii. due to minor change of the kinetic and potential energy, kinetic and potential energy are neglected.

iii. for the air and combustion gas the ideal gas principles are considered,

iv. owing to minor contribution of the exergy of the ash compared with the exergy of fuel, the exergy of the ash is neglected

v. the losses of pressure in system are disregarded.

Tab. 1
The data of the coal. [14]

Ash [%]	36,67
Carbon [c, %]	22,79
Hydrogen [h, %]	4
Moisture [w, %]	8,15
Nitrogen [n, %]	1
Oxygen [o, %]	2
Sulphur [s, %]	5,36
Volatile Matter [%]	20,03
LHV [kcal/kg]	4426
GCV/HHV [kcal/kg]	4637

Tab. 2
Power plant operating parameters.

Water flow rate	2 kg/s
Steam flow rate	2 kg/s
Steam temperature	165 ^{o}C
Steam pressure	700 kPa
Air flow rate	1,34 kg/s
Comb. gas flow rate	1,21 kg/s
Mass flow rate of coal	0,45 kg/s

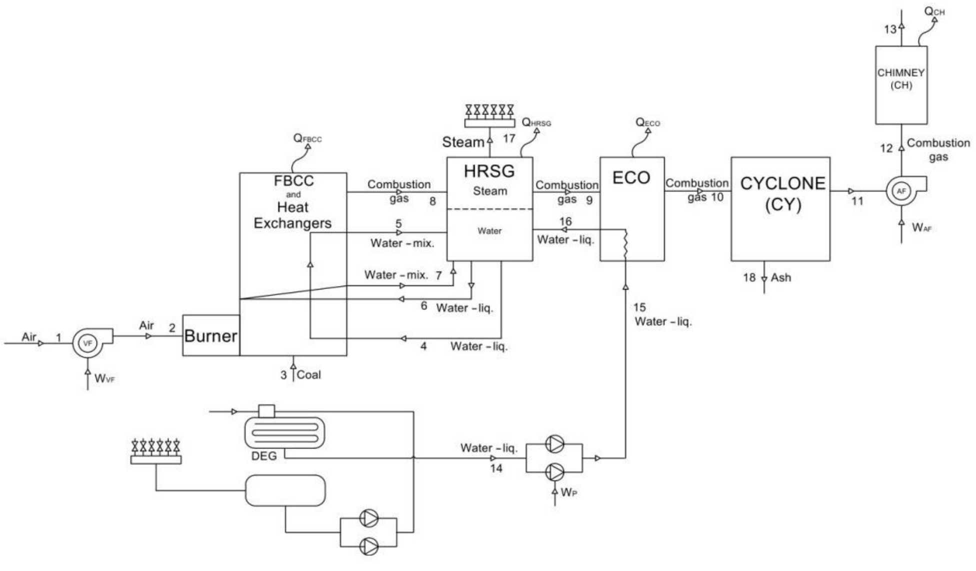

Fig.1. Figural representation of the power plant [14]

3. Analysis

The purpose of this work is to implement an intensive thermoeconomic analysis to figure out and demonstrate the relationship between exergetic and economic factors. To be understood of the cost based performance of the FBCC steam plants, real operational data are employed.

The thermodynamic tables are used to find out the thermodynamic properties of steam, water and combustion gases. Moreover, T_0 = 25 ^oC, P_0 = 101.3 kPa are accepted as the temperature and pressure values of reference environment. The content of the combustion gases and the reference environment are shown in Tab. 3 and 4, respectively.

Tab. 3
Content of the combustion gas [14]

Combustion Gas	Mole ratio [%]
CO	11,16
H_2	0,42
O_2	6,82
SO_2	81,60
λ	48

Tab. 4
Content of the reference ambient [14]

Reference Component	Mole ratio [%]
CO	0,70E-03
H_2	0,05E-03
O_2	20,35
SO_2	0,20E-03

3.1. Thermodynamic Analysis

Energy can not be produced or destroyed that the first law of thermodynamics refers to this idea. In terms of thermodynamics, the balance equations for the mass and energy are given below.

$$\text{Mass Input} = \text{Mass Output}\ (\Sigma\,\dot{m}_{in} = \Sigma\,\dot{m}_{out}) \quad (1)$$

$$\text{Energy Input} - \text{Energy Output} = \text{Net Energy}\ (\dot{Q} + \dot{W} = \Sigma\,\dot{m}_{out}\,h_{out} - \Sigma\,\dot{m}_{in}\,h_{in}) \quad (2)$$

Exergy can not be maintained as energy, namely it can be destructed during the process. In the other words, exergy can be defined as the maximum work potential in terms of thermodynamics. In terms of thermodynamics, the balance equation for exergy is given as Eq. (3):

$$\text{Exergy Input - Exergy Output - Exergy Destruction = Net Exergy} \quad (3)$$

Tab. 5

The balance equations for second law analysis

Components	Balance Equations
VF	$Ex_1 + \dot{W}_{vf} = Ex_2 + Ex_Q^{VF} + Ex_D$
FBCC	$Ex_2 + Ex_3 + Ex_4 + Ex_6 = Ex_5 + Ex_7 + Ex_8 + Ex_Q^{FBCC} + Ex_D$
HRSG	$Ex_5 + Ex_7 + Ex_8 + Ex_{16} = Ex_4 + Ex_6 + Ex_9 + Ex_{17} + Ex_Q^{HRSG} + Ex_D$
ECO	$Ex_9 + Ex_{15} = Ex_{10} + Ex_{16} + Ex_Q^{ECO} + Ex_D$

CY	$Ex_{10} = Ex_{11} + Ex_{18} + Ex_D$
AF	$Ex_{11} + W_{AF} = Ex_{12} + Ex_Q^{AF} + Ex_D$
CH	$Ex_{12} = Ex_{13} + Ex_Q^{CH} + Ex_D$
P	$Ex_{14} + W_P = Ex_{15} + Ex_Q^{P} + Ex_D$

3.2. Exergoeconomic Analysis

The exergoeconomic method is the composition of exergy analysis and economic analysis to ensure the information, which is not attainable with general thermodynamic analysis. In a traditional economic performance methodology, a balance equation for cost is occurred as below for every component *i*:

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

$$\dot{C}_i = c_i Ex_i \quad (5)$$

$$\dot{C}_i^W = c_i W_i \quad (6)$$

$$\dot{C}_i^Q = c_i Ex_i^Q \quad (7)$$

$$\dot{Z}_i^T = \dot{Z}_i^{CI} + \dot{Z}_i^{OM} \quad (8)$$

where $\dot{C}_i$, $\dot{C}_i^W$, $\dot{C}_i^Q$ are the costs of exergy of the flows, work and heat; c is the unit costs of exergy of the flows, work and heating; Ex_i, W_i and Ex_i^Q are the exergy rate of flow, work and heating in the control volume; $\dot{Z}_i^{CI}$, $\dot{Z}_i^{OM}$ and $\dot{Z}_i^T$ are the hourly levelized costs of the capital investment cost, operating and maintenance costs and the total cost of component.

The capital recovery factor:

$$CRF = (i(i+1)^n)/((i+1)^n - 1) \quad (9)$$

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

$$\dot{Z}_i^{CI} = (CRF/\tau) PEC_i \quad (10)$$

The cost rate of the auxiliary components CR_i:

$$CR_i = PEC_i / \sum PEC_{FBCCSP} \quad (11)$$

where, n, τ, i and PEC are the life time of the steam plant, annual number of hours for the full time operation, the interest rate and the purchased equipment cost, respectively. In the FBCC steam plant i, n and τ are obtained as 0.1, 10 year and 8400, respectively.

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

while the maintenance and operating costs are calculated, φ is accepted as 0.85 for this system.

The total investment cost of this plant is 325000 US$ and the other equipment's price are found with the help of the cost rates, given by the officer of the steam plant, as represented in Tab. 9. c_3^{coal} is the unit cost of exergy of the coal,

$$c_3^{coal} = \mathrm{Pr}^{coal}/(\mathrm{ER\ LHV}\ 10^{-6})\ [\mathrm{GjkJ^{-1}}] \tag{13}$$

where Pr^{coal}, ER and LHV can be referred as the coal selling cost, the exchange rate [$\mathrm{TLUS\$^{-1}}$] and the LHV of the coal, respectively. $c_{19}^{\dot{W}} = c_{20}^{W} = c_{21}^{W}$ is the unit cost of exergy of the electricity,

$$c^{W} = \mathrm{Pr}^{W}/(\mathrm{ER}\ 3600\ 10^{-6})\ [\mathrm{sh^{-1}}]\ [\mathrm{GjkJ^{-1}}] \tag{14}$$

where Pr^{W} is called as the electricity selling cost in the Turkish Lira [TL].

The exergoeconomic analysis intends the better and detailed comprehension for the formation of cost duration and estimations of the cost rate for all output produced by steam plant. The cost balance equations and supporting equations for all of the components are shown in Tab. 6. The exergoeconomic factor ensures detailed information about the compound of exergy loss, destruction and costs which are irrelevant with exergy. The exergetic fuel is described as the depleted input to produce an output.

$$f_i = Z_i\mathrm{T}\ /\ (\dot{Z}_i^{T} + (c_{f,i}\ (\mathrm{Ex}_{D,i} + \mathrm{Ex}_{L,i}))) \tag{15}$$

Tab. 6

The exergoeconomic balance equations for the components

Components	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	$C_{14} + C_{20}^W + Z_P^T = C_{15}$

4. Results and Discussions

The thermoeconomic analysis is implemented with the help of first and second laws of thermodynamic and economic factors to provide the relation among the thermodynamic and economic assessment of equipments in the system. Using the given and measured parameters in Tab. 1 and 2, exergy rates for the system components 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.

According the results, shown in Tab. 8, the first law efficiencies of CH, CY, HRSG, ECO and FBCC are listed descending order as 97.36%, 93.79%, 90.85%, 88.61% and 63.78%, respectively. In the same way, the second law efficiencies of CH, CY, HRSG, ECO and FBCC are sorted from big to small order as 100%, 99.70%, 99.38%, 48.90% and 20.53%, respectively. The energy and exergy efficiencies of the fluidized bed coal combustor plant are found as 55.60% and 15.53%, respectively. The significant amount of exergy destruction, taking place in the FBCC , is 4894.19 kW. The exergy destruction of the whole FBCCSP is found as 5181.95 kW.

Tab. 7

The rate of exergy and thermodynamicproperties of flow (for stream numbers indicates to Fig. 1 for the FBCC) (ambient condition is 101.32 kPa and 298 K)

Stream no	Fluid Type	Mass flow rate [kg/s]	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	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

Tab. 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
FBCCSP	5181,95	55,60	15,53

The operating and maintenance cost, the hourly levelized capital investment cost, purchased equipment cost and the total costs of the system and auxiliary components are illustrated in Tab. 9. The cost rates, the purchased equipment costs and the total investment costs of the auxiliary equipments are exhibited in Fig. 2-3-4, respectively. The maximum amount of the rate of cost, the cost of total investment and the purchased equipment are occurred in FBCCSP component. With the combination of the values given in Tab. 9, the cost balance equations are demonstrated in Tab. 6. Moreover, the exergy rate values are shown in Tab. 7. Furthermore, cost of unit exergy and cost of exergy of the components on FBCCSP are reckoned as shown in Tab. 10 in connection with stream numbers. Based on the results, shown in Tab. 10, the cost of unit exergy and cost of exergy of the coal, that is used in the FBCCSP, are found as 3.33 US$/GJ and 112.44 US$/h, respectively. The cost of unit exergy and cost of exergy of the steam, which is generated by HRSG, are calculated as 16.59 US$/GJ and 91.87 US$/h, respectively. The costs of operating and maintenance, cost of capital investment, and total cost of fluidized bed coal combustor plant are found to be 5.35, 6.30 and 11.65 US$/h, respectively.

Tab. 9

The dispersion of the cost rate, the cost of purchased equipment, the levelized capital investment, the costs of operating and maintenance and total costs of the equipment

Components	CR_i	PEC [US$]	Z_i^{CI}[US$/h]	Z_i^{OM}[US$/h]	Z_i^{T}[US$/h]
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

Tab. 10

The dispersion of the rate of exergy, cost of unit exergy and cost of exergy at different locations of the FBCCSP (for stream numbers refers to Fig.1)

Stream	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

The exergy destruction cost rates of the equipments are represented in Fig. 5. The highest cost rate value occurs in FBCC. Moreover, FBCC is the major component in terms of exergoeconomic point. The exergoeconomic factors of the equipments are illustrated in Fig. 6. FBCC has the quite low rate of exergoeconomic factor due to the excess amount of destruction of exergy. To diminish the exergy destruction rate in the 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 economizer and pump means a decrement in the investment costs of these components.

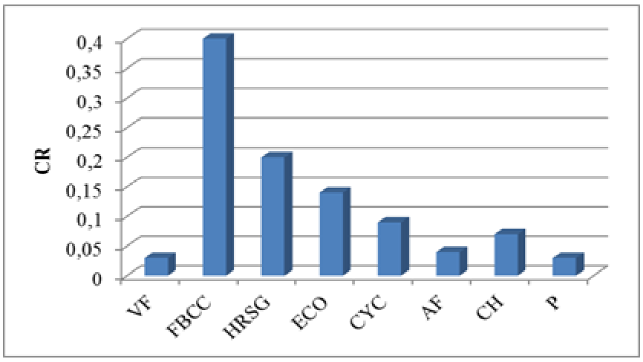

Fig.2. The cost rates of equipments

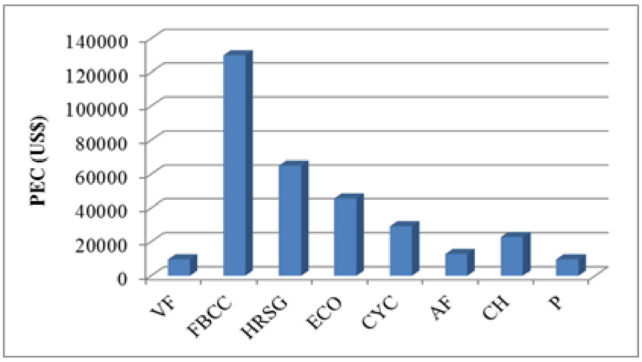

Fig.3. The equipment purchasing costs rates

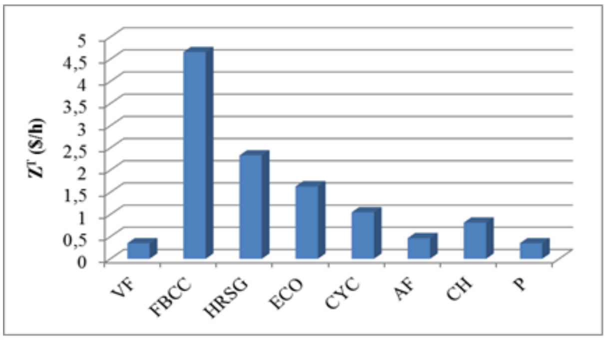

Fig.4. The total investment costs of the equipments

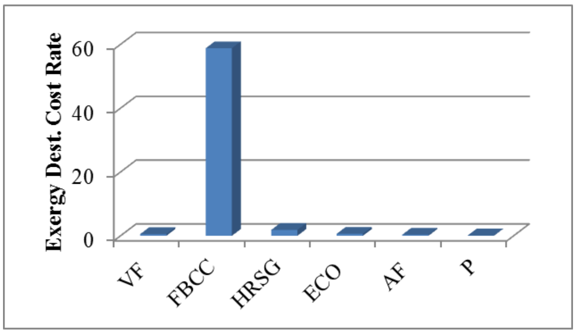

Fig.5. The rate of the exergy destruction cost of the equipments

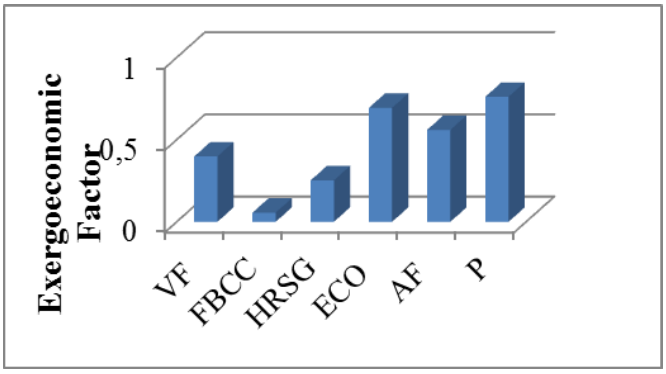

Fig.6. The exergoeconomic factors of the equipments

5. Conclusions

This scientific study introduces an elaborate exergoeconomic examination for a FBCCSP. The second law efficiencies and exergy destruction are calculated to show the effectiveness of the FBCC steam plant in exergetic point of view. Cost of exergy and cost of unit exergy terms are found to point out the evaluation of the thermoeconomic methodology. Some results obtained from this investigation can be listed as follows:

- The energy and exergy efficiencies of the FBCCSP are found as 55.60% and 15.53%, respectively. The rate of exergy destruction of the FBCCSP is 5181.95 kW. The major exergy destruction happens in the FBCC component with approximately 4894.19 kW due to poor combustion efficiency and significant amount of excess air. The usage of preheating before FBCC can cause the decrement of the destruction of exergy. The efficiencies of the energy and exergy of the FBCC are reckoned as 63.78% and 20.53%, respectively.

- The costs of operating and maintenance, cost of capital investment, and total cost of FBCC plant are obtained to be 5.35, 6.30 and 11.65 US$/h, respectively. The cost of unit exergy and cost of exergy of the coal are calculated as 3.33 US$/GJ and 112.44 US$/h, respectively. The cost of unit exergy and cost of exergy of the steam, which is generated in HRSG, are calculated as 16.59 US$/GJ and 91.87 US$/h, respectively. The lowest exergoeconomic factor rate is observed in FBCC owing to the occurrence of high rate of exergy destruction. The excess rate of exergoeconomic factor in economizer and pump means a decrement in the investment costs of these components.

Nomenclature		*Subscripts*	
c	cost of unit exergy [US$/GJ]	AF	air fan
C	cost of exergy [US$/h]	CH	chimney
CR	cost rate	CI	capital investment
CRF	capital recovery factor	comb.	combustion gas
ex	specific exergy [kJ/kg]	CY	cyclone
$\dot{E}x_D$	exergy Destruction [Kw]	destr.	destruction
f	exergoeconomic factor	ECO	economizer
h	specific enthalpy [kJ/kg]	FBCC	fluidized bed coal combustor
LHV	lower heating value of coal [kJ/kg]	HRSG	heat recovery steam generator
$\dot{m}$	mass flow rate [kg/s]	OM	operating and maintenance
P	pressure [Pa]	P	Pump
$\dot{Q}$	rate of heat transfer [W]	VF	ventilation fan
s	specific entropy [kJ/kg K]	0	reference state
T	temperature [K]	*Greek symbols*	
$\dot{W}$	rate of work [W]	η_I	first law efficiency
$\dot{Z}$	hourly levelized cost of investment [US$/h]	η_{II}	second law efficiency

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