SVU-International Journal of Engineering Sciences and Applications (2022) 3(2): 1-10
Print ISSN 2785-9967 | Online ISSN 2735-4571
DOI 10.21608/svusrc.2022.138251.1051

Exergoeconomic Improvement of Power Boiler in Paper Industry at Different Operating Modes

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Abstract in the paper, the exergoeconomic improvement of power boiler at hybrid operating mode (with recovery boiler) and singular operating mode (without recovery boiler) in paper industry is performed. The natural gas and black liquor are the main fuels utilized in the power boiler and the recovery boiler, respectively. The chemical black liquor recovery system that has essential benefits to avoid the environmental pollution by burning the organic waste and recycling the soda is comprehensively studied. A soda mass inflow rate of 9.16 kg/s that is required for cooking process is recovered in the chemical pulp plant. The exergy analysis for power boiler is studied through one year with different environment ambient temperatures i.e., 17, 22, 32, 37, and 47 ^{0}C. The outcomes confirmed that the exergy destruction rate of the power boiler is increasing with increasing of environment temperature at hybrid and singular operating modes. With adjustment the combustion process it found that the exergy destruction for power boiler is reduced within 2 and 4.71% at hybrid and singular modes, respectively. For hybrid mode, the exergy destruction cost rate of power boiler is decreased from 1304.41 to 1278.28 $/h at environment temperature 17 ^{0}C. In addition, the exergoeconomic factor is improved from 16.09 to 16.37%. For singular mode the destruction cost rate of power boiler is reduced from 1470.19 to 1400.95 $/h at environment temperatures of 17 ^{0}C while, the exergoeconomic factor is improved from 15.32 to 15.96 %.

Keywords: Exergy analysis, Exergoeconomic, Power boiler, Recovery boiler and Paper industry.

1 Introduction

Energy, exergy and exergoeconomic analysis is considered a major challenge due to the limited sources of fuel and the harmful emissions to the environment. Therefore, this analytical study helps to determine the losses in the system components to improve it, which reduces fuel consumption and accordingly reduces harmful emissions to the environment. The chemical recovery system has essential benefits to avoid the environmental pollution by burning the organic waste (black liquor) and recycling soda. Recovery boiler (RB) contributes with generated steam as a by-product required for production the electrical and thermal energy required for industrial processes through a cogeneration system [1][2][3][4]. A lot of works are now available where the analyses have been applied based on second-law of thermodynamics to increase the performance of electricity generation systems using coal as main fuel [5][6], fluidized bed [7] such as gas turbine [8], internal combustion engine [9] combined cycle technology [10] and cogeneration system [11].

Exergoeconomic is a method combines the second law of thermodynamics from combine exergy with economics and economic techniques [12]. The exergoeconomic analysis is a powerful tool to provide the system designer or operator with information not available through conventional energy analysis and economic analysis [13]. The approach gives a way to assess the cost of inefficiencies or the costs of each process streams, which include intermediate and last products. A whole exergoeconomic analyses normally includes an exergy analysis, an economic evaluation and an exergy costing approach with the assist of auxiliary equations [14]. For this reason, the exergy and exergoeconomic evaluation drawn greater interest by scientists and system designers with inside the previous few years. Many researchers have achieved considerable amount of work to study this analysis. The present overview will throw light on the state of knowhow on the exergy and exergoeconomic analysis.

Received: 13 May 2022/ Accepted: 8 June 2022

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Ameri et al [15] performed exergy and exergoeconomic analysis of steam power plant suing natural gas (NG) as a fuel. In this study energy and exergy destruction of each component of the power plant were estimated. The percentage of exergy destructions in the boiler was about 86% compared with the total exergy destruction of the power plant. Ahmadi and Toghraie [16] investigated an energy and exergy analysis of steam power plant of Isfahan with individual unit capacity of 200 MW using natural gas as a main fuel. From the results noticed that, the exergy analysis showed that the boiler contributed with 85.66% of the whole exergy destruction.

Guoqiang et al. [17] carried out an energy and exergy analysis for 300 MW thermal power plant. The results confirmed that the major percent ratio of the exergy destruction to the total exergy destruction is found in the boiler within 67.78 %. Saidur et al. [18] applied the energy and exergy approaches to analyze the industrial boiler using natural gas as main fuel. The energy and exergy efficiencies of the boiler were calculated and the results showed that the combustion phenomenon contributes the biggest amount of exergy destruction by 65% compared with the total exergy destruction. The authors provided numerous energies saving measures such as using of variable speed drive fan in boilers and recovery of heat from flue gas to growth the general efficiencies of the system. Ameri et al. [19] fulfilled an energy, exergy and exergoeconomic evaluation for the Hamedan power plant in Iran using NG as the main fuel. the major exergy percentage of destruction was found in the boiler by 81%.

Cortés and Rivera [20] performed an exergetic and exergoeconomic optimization of a cogeneration CHP and PM plant including the use of a heat transformer. The higher exergy destruction was in evaporators and the exergy efficiency of RB was 11.96%. Ramos et al. [21] studied an exergy analysis of real kraft biomass boiler installed in Minas Gerais, Brazil. The exergy analysis results showed that the furnace and the water walls have the higher exergy destruction, accounting for 47% and 30% of the total exergy destruction, respectively. Rosen and Dincer [22] achieved an exergoeconomic analysis of power plants operating on various fuels.

The thermodynamic losses to the capital cost for steam generators, turbines, and condenser were 3.41, 26.25, and 1.16 W/$, respectively. Sotomonte et al. [23] studied an exergoeconomic investigation of a cogeneration plant in pulp plant. The results showed that the unit exergy costs of turbogenerator, chiller, and pump were 39.06, 39.06, and 185.57$/MWh, respectively. Bolatturk et al. [24] performed thermodynamic and exergoeconomic examination of Cayirhan warm force plant in Turkey. Additionally, the factors of exergoeconomic are checked, the main consideration is found in turbine followed by the condenser. Soltanian et al. [25] performed an exergoeconomic evaluation of cogeneration from sugarcane residues by a biorefinery approach. The study includes exergy destruction cost rate, the cost rate of components, the whole cost rate and the parameters of the exergoeconomic. From the results it shown that the main total cost of steam generation unit was 3715.86$/h. Caliskan et al. [26] The study showed discusses the exergy and the economic analysis of energy storage for example latent, sensible and thermochemical alternatives combined with various units for building warming applications under varying reference temperatures of 8 C^0, 9 C^0 and 10 C^0, respectively. It is seen that the variety reference temperature affects the thermoeconomic parameters. The cost of exergy gets higher at the higher reference conditions, as directly proportional to the corresponding to the fluctuating dead state condition. It additionally gets least at 8 C^0 reference temperature as 196.96 $/h while it is greatest at 10 C^0 dead-state temperature with 357.60 $/h. However, the major capital cost is found 4.612 $/h. There are studies that have worked on exergoeconomic analysis [27][28][29]. From the literature reviews, it is clear that the study of exergy and exergoeconomic analysis has drawn more attention by scientists and designers. In the current study the power boiler is proposed and investigated in detail from viewpoint of exergoeconomic at operation load and varying of environment temperature in paper industry. The current study will throw light on exergy destruction and exergy destruction improvement for power boiler (PB) at different environment temperatures. Also, light will be shed on the exergy destruction cost rate, exergoeconomic factor, exergy destruction cost rate improvement and exergoeconomic factor improvement for PB at changing environment temperatures. In addition, this study mainly helps operators and designers in making maintenance and replacement decisions.

NOMENCLATURE

Latin letters

$\dot{Q}$	Heat transfer (kJ/s)
$\dot{X}$	Total exergy rate (MW)
$\dot{X}_F$	Exergy destruction rate of fuel (MW)
$\dot{m}$	Mass flow rate (kg/s)
$\dot{W}$	Work done rate by the system (KW)
c	The bulk velocity of the working fluid (m/s)
g	The specific gravitational force (m/s^2)
s	Specific entropy (kJ/kg K)
T	Temperature (K)
Z	The altitude of the stream above the sea level (m)
$\dot{Z}_{PB}^{OM}$	Operating and maintenance cost ($/h)
$\dot{Z}_{PB}^{T}$	Total Capital investment cost ($/h)
$\dot{Z}_{PB}^{CI}$	Investment cost ($/h)
c_F	Average cost per unit fuel exergy ($/MWh)
$\dot{C}$	Total exergy cost ($/h)
f	Exergoeconomic factor (%)
i	Interest rate (%)
n	Lifetime of the system (year)
t	Time (h)

Greek Letters

μ	Salvage value percentage (%)
$\O$	Maintenance factor
τ	Operation hour in a year (h/year)
Σ	Summation
Ψ	Specific exergy rate (kJ/kg)

Acronyms

AC	Annual capital Cost (M$/year)
BL	Black Liquor
$Ca(OH)_2$	Calcium Hydroxide
$CaCO_3$	Calcium Carbonate
CaO	Calcium Oxide
CAU	Caustizing
CH_4	Methane
CHP	Chemical Pulp
CO_2	Carbon Dioxide
CRF	Capital Recovery Factor
DP	Depreciation Percentage (%)
DT	Dissolving Tank
FGH	Flue Gas Heater
GL	Green Liquor
H_2SO_4	Sulfuric acid
HFO	Heavy Fuel Oil
NaOH	Sodium Hydroxide
NG	Natural Gas
PB	Power Boiler
PEC	Purchased Equipment Cost (M$)
PM	Paper Machine
PW	Present Worth (M$)
PWF	Present Worth Factor
RB	Recovery Boiler
SO_2	Sulfur Dioxide
SV	Salvage Value (M$)
TCI	Total Capital of Investment (M$)
TUR	Turbine
TV	Throttling Valve
WL	White liquor

Subscripts

d	Destruction
in	Inlet
k	Number of components
K	sources
out	Outlet
PB	Power boiler
w	Power output

2 System Description

There are two cases for operation of power boiler. The first case is hybrid operating mode (the power boiler with the recovery boiler). The second case is at singular operating mode (the power boiler without the recovery boiler). The schematic of PB at hybrid operating mode is shown in Fig. 1. The operating thermodynamic properties for various points at hybrid mode are listed in Table. 1. When the dry solids content of black liquor is about 63%, it can be combusted in the recovery boiler, in which the inorganic cooking chemicals is recovered to produce steam supplied to generate electricity as well as to provide the steam required for various processes. After the organic material from the black liquor is combusted in the recovery boiler, an inorganic smelt remains. Then the smelt passes through a smelt spout out from the recovery boiler to a smelt dissolving tank (DT), where it is dissolved into water, at this point the smelt is named a green liquor (GL). The next step is the causticizing process, when the green liquor (GL) is blended with calcium oxide, CaO, it slakes with water and forms a calcium hydroxide, $Ca(OH)_2$. This chemical reacts continuously with a sodium carbonate, Na_2CO_3, in the green liquor to produce sodium hydroxide, NaOH, and calcium carbonate, $CaCO_3$.When the sodium carbonate is converted to a sodium hydroxide the liquor is called white liquor (WL).

For singular mode, the schematic of PB at hybrid mode is shown in Fig. 2. The operating thermodynamic properties for various points at singular mode are presented in Table. 2. In this case, the dependence of the steam production is on the power boiler only, without the chemical recovery boiler. In addition, all stages of chemical recovery processes are in service for a certain period. Also in this case, the fuel used is natural gas (NG) only because the recovery boiler is out of service. The production of black liquid is placed in a storage tank until the recovery boiler is operated. There is also a storage tank for the white liquid that was produced before, and the shortage of white liquids is compensated by adding caustic soda at a concentration of 50%, after diluting it to 10%.

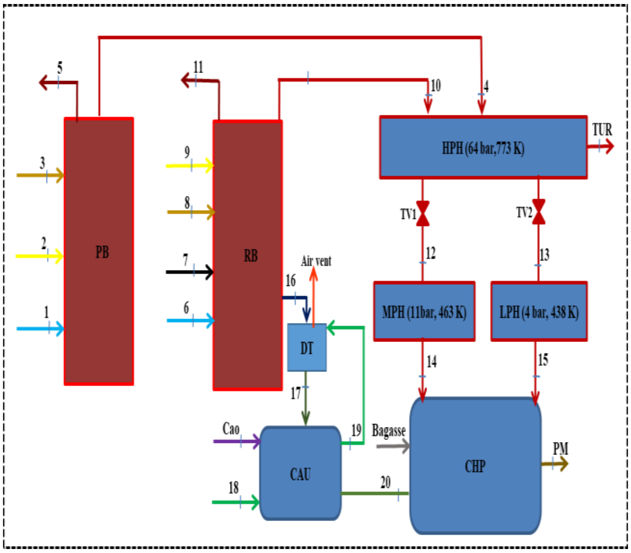

Fig. 1 Hybrid operating mode (PB combined with RB)

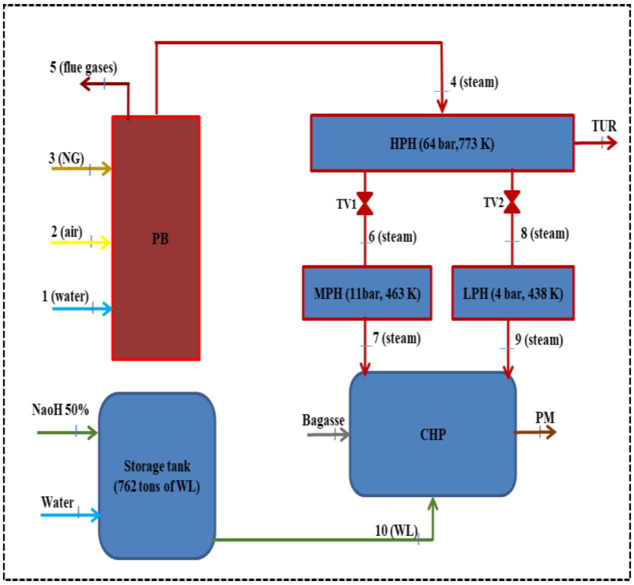

Fig. 2 Singular operating mode (PB only)

Table. 1 The operating conditions for different points at hybrid operating mode.

Point	Substance	*T* (K)	*P* (bar)	ṁ (kg/s)	*h* (kJ/kg)	*s* (kJ/kg.K)
1	Water	451	76	45.642	757.8	2.111
2	Air	523	1	48.444	527.2	7.434
3	NG	293	7	2.713		
4	Steam	773	65	44.285	3414	6.821
5	FG	443	1	50.000	155.35	7.628
6	Water	453	77	11.510	766.6	2.13
7	BL (62%)	390	1.4	7.315	1162.59	
8	HFO	363	8	0.08		
9	Air	503	1	15.000	506.6	7.393
10	Steam	773	65	11	3414	6.821
11	FG	438	1	19.000	109.03	6.8788
12	Steam	463	11	3.170	2797	6.587
13	Steam	438	4	3.828	2789	7.007
14	Steam	457	10.5	8.5	2785	6.581
15	Steam	434	3.9	1.950	2778	7
16	Smelt	1373	1	1.5	1837	
17	GL	363	1	9.3	1332.21	
18	Condensate	353	1	7.9	334.8	1.075
19	Water	343	1	7.8	293	0.9548
20	WL	348	1	9.166	1224.96	

Table. 2 The operating conditions for the different points at singular operating mode.

Point	Substance	*T* (K)	*P* (bar)	ṁ (kg/s)	*h* (kJ/kg)	*s* (kJ/kg.K)
1	Water	451	76	54.25	757.8	2.111
2	Air	523	1	52.777		
3	NG	293	7	3.076		
4	Steam	773	65	52.777	3414	6.821
5	FG	443	1	56	152.2	7.4701
6	Steam	463	11	3.62	2797	6.587
7	Steam	438	4	4.92	2786	7.007
8	Steam	457	10.5	8.5	2785	6.581
9	Steam	434	3.9	1.950	2778	7
10	WL	348	1	9.166	1224.96	

3 Thermodynamic Evaluation

The basic concepts of thermodynamic derived for steady-state/steady-flow process is in brief introduced. The following assumptions are proposed to derive a set of thermodynamics relations:

- The changing of kinetic and potential energies is neglected.
- The atmospheric pressure denoting the reference dead state is constant at 1.013 bar.
- The surroundings environment temperature is marginally changed within ±0.5 K during the data collections.

The first law of thermodynamics for energy balance of the steady flow process of any open system is given by [30].

$$\sum \dot{Q}_k + \sum \dot{m}_{in}\left(h_{in} + \frac{c_{in}^2}{2} + gZ_{in}\right) = \sum \dot{m}_{out}\left(h_{out} + \frac{c_{out}^2}{2} + gZ_{out}\right) + \dot{W} \qquad (1)$$

Exergy balance for any control volume at steady state with neglecting the potential and kinetic energy changes can be expressed by the following equation:

$$\sum_{in}\dot{X} + \sum_{in}\left(1-\frac{T}{T_k}\right)\dot{Q}_k = \sum_{out}\dot{X} + \dot{W} + \dot{X}_{des} \qquad (2)$$

Where the total exergy rate associated with a working fluid becomes:

$$\dot{X} = \dot{m}\Psi \qquad (3)$$

Hence, the specific exergy is given by:

$$\Psi = (h - h_0) - T_0\,(s - s_0) \qquad (4)$$

4 Exergoeconomic Evaluation

In the present study, the exergoeconomic analysis is carried out according to the actual available data during one year. The equation of cost balance for the system can be written as following [31] [32];

$$\sum_{in}\dot{C}_k + \dot{Z}_k^T = \sum_{out}\dot{C}_k + \dot{C}_w \qquad (5)$$

$$\dot{Z}_k^T = \dot{Z}_k^{CI} + \dot{Z}_k^{OM} \qquad (6)$$

When performing the exergoeconomic analysis for PB, it was agreed with the shareholders upon establishing and the operating was in 2000, to take the following values;

- Purchased equipment cost (PEC) =10.371 M$

- Salvage value (SV) = 12% of purchased equipment cost (PEC).
- Interest rate (i) = 10%.
- Lifetime of cogeneration (n) = 25 years.
- Maintenance factor (Ø) = 1.06
- Depreciation percentages (DP) = 6 %.
- Operation hour (τ) of PB and RB during year are 8158 and 6930 h, respectively.

In order to calculate the investment cost of PB ($\dot{Z}^{CI}_{PB}$) the subsequent steps have be done. These are given as follows.

The present worth of the investigated system ($\mathrm{PW_{PB}}$) [33][26] :

$$PW_{PB} = total\ \ investment\ cost\ (TCI) - [SV]PWF\ (i,n) \qquad (7)$$

The present value factor (PWF) can be estimated by:

$$PWF = \frac{1}{(1+i)^n} \qquad (8)$$

$$[SV] = [AC]_{\mu} \qquad (9)$$

Annual capital cost (AC) [34]:

$$AC_{PB} = PW_{PB}CRF\ (i,n) \qquad (10)$$

Capital recovery factor (CRF) [35]:

$$CRF = \frac{i(i+1)^n}{(i+1)^n - 1} \qquad (11)$$

Annualized equipment cost of cogeneration system $\dot{Z}^{T}_{cog}$:

$$\dot{Z}^{T}_{cog} = \frac{\emptyset AC_{cog}}{3600\ (sh^{-1})\tau(h\ year^{-1})} \qquad (12)$$

Where $\emptyset$ is the factor of operating and maintenance cost and was taken as 1.06 [36][37] and AC_{cog} was 26.323 M$/year.

Hourly levelized capital investment cost of PB:

$$\dot{Z}^{CI}_{PB} = \dot{Z}^{T}_{cog} \frac{PEC_{PB}}{\sum_{cog} PEC} \qquad (13)$$

Operating and maintenance cost of PB is:

$$\dot{Z}^{OM}_{PB} = Z^{OM}_{cog} \frac{PEC_{PB}}{\tau \sum_{cog} PEC} \qquad (14)$$

Where $\dot{Z}^{T}_{cog}$ and Z^{OM}_{cog} were 5853, 2433 and 6226 and 2806 $/h at hybrid and singular modes, respectively.

The cost flow rate related to the exergy destruction ($\dot{C}_{d,k}$) can be calculated by [38]:

$$\dot{C}_{d,k} = c_{F,k}\dot{X}_{d,k} \qquad (15)$$

The exergoeconomic factor (f_k) is a parameter is represented by [39][40]:

$$f_k = \frac{\dot{Z}^{T}_{k}}{\dot{Z}^{T}_{k} + \dot{C}_{d,k}} \qquad (16)$$

5 Results and Discussions

The exergy destruction of flue gas with stack gases is decreased with decreasing the temperature of flue gas. The flue gas temperature is leaving the boiler at range from 150 to 250 C0. Recovering part of the heat from the flue gas can help to improve the exergy destruction of the boiler. Heat can be recovered from the flue gas by passing it through flue gas heater (FGH) to pre-heat the required air for combustion in furnace, and hence, this will save the energy use consequently it reduces the fuel consumption [41]. The objective in improvement of the cogeneration system is to reduce the product cost. This cost is proportional to the costs associated with exergy destruction, environmental impact and capital investment as well as operating and maintenance [31]. The exergy destruction is the main part of cost rate in power boiler not because of the capital and operating costs. The high heating value of NG and BL is taken as 50 and 15 MJ/kg[1][3] [42], respectively.

The consumption of WL, NG and NaOH (50%cocentrarion) at hybrid and singular modes are illustrated in Fig.3. The amount of consumption of white liquid at hybrid mode was 221760 tons per year, While at single mode, the amount of consumption of the white liquid increases by about 2% due to the addition of caustic soda with a concentration of 50%. In addition, the consumption of natural gas in the power boiler was less by 36.5% at hybrid mode, because the black liquid used as fuel in the recovery boiler produces the amount of steam generated as a by- product, which reduces the amount of steam generated from the power boiler, which leads to a reduction in the amount of NG consumption.

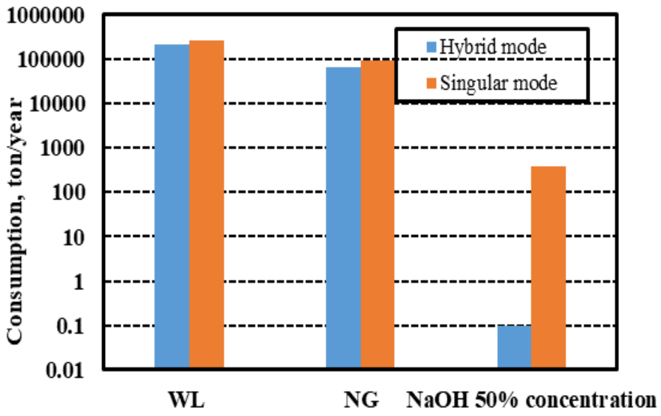

Fig. 3 Consumption of WL, NG and NaOH (50%cocentrarion) at hybrid and singular modes

Figure 4 shows the cost of NG in hybrid mode, cost of NG and NaOH in singular mode and NaOH saving in hybrid mode. In the case of correlation, we find that the cost of natural gas is 18.896 million dollars annually. On the other hand, this system saves 19 million dollars annually, as a result of the process of chemical conversion of inorganic materials into soda used in the production of pulp.

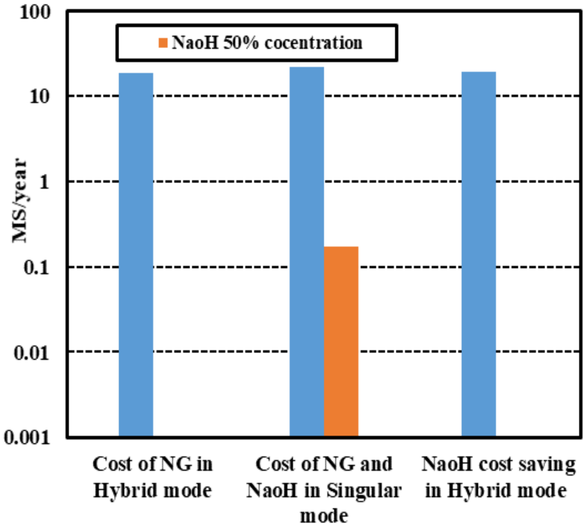

Fig.4 Cost of NG in hybrid mode, cost of NG and NaOH in singular mode and NaOH saving in hybrid mode

Figure 5 shows the PB exergy destruction versus the environment temperature before and after the improvements due controlling of flue gas temperature and using soot blowers at hybrid and singular operating modes. For hybrid mode, it is found that the PB exergy destruction is decreased by 2, 1.86, 1.6, 1.51 and 1.29% at the environment temperature of 290, 295, 305, 310, and 320 K, respectively while, at singular mode the outcomes show that the exergy destruction of PB is reduced by 4.71, 4.53, 4.2, 4.07 and 3.79 % at environment temperatures of 290, 295, 305, 310, and 320 K, respectively.

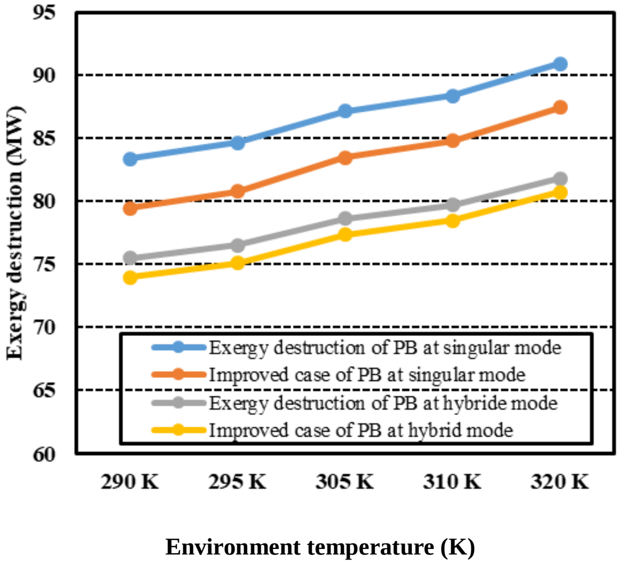

Fig. 5 Exergy destruction and improved cases of PB at singular and hybrid modes

Figure 6 illustrates the exergy destruction cost rate, exergoeconomic factor and improved cases at hybrid mode. It notices that the cost rate of exergy destruction for PB is decreased with 26.13, 24.71, 22.01, 20.98 and 18.54 $/h at environment temperatures of 290, 295, 305, 310 and 320 K, respectively. On other hand, the increase of the exergoeconomic factor means that the reduction of the exergy destruction cost rate. From the figure is found that the exergoeconomic factor is improved by 1.74, 1.61, 1.41, 1.27 and 1.08 % at environment temperatures of 290, 295, 305, 310, and 320 K, respectively.

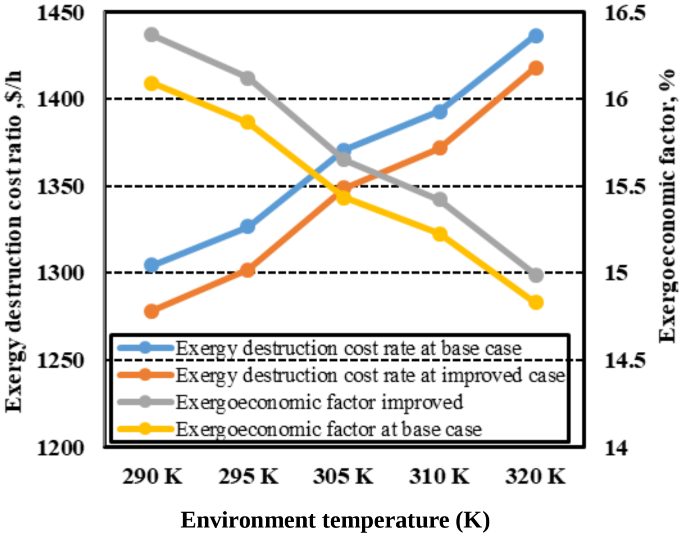

Fig. 6 Exergy destruction cost rate, exergoeconomic factor and improvements f PB at hybrid operating mode

Figure 7 shows the exergy destruction cost rate, exergoeconomic factor and their improvement at singular operating mode. As seen that the PB exergy destruction cost rate is reduced by 69.24, 67.53, 64.86, 63.87 and 61.44 \$/h at environment temperatures of 290, 295, 305, 310 and 320 K, respectively. From the figure is found that the exergoeconomic factor is improved by 4.14, 3.97, 3.71, 3.57 and 3.36 % at environment temperatures of 290, 295, 305, 310, and 320 K, respectively.

Figure 8 shows the improvement of exergy destruction cost rate for hybrid and singular operating modes. It seen that at hybrid operating mode the exergy destruction cost rate decreases by 62.26, 63.41, 66.07, 67.14 and 69.82% with increasing environment temperature from 290 to 320 K, respectively. While, it noticed that the exergoeconomic factor at hybrid operating mod is reduced by 55.93, 57.53, 60.21, 62.54 and 66.07% with increasing environment temperature from 290 to 320 K, respectively.

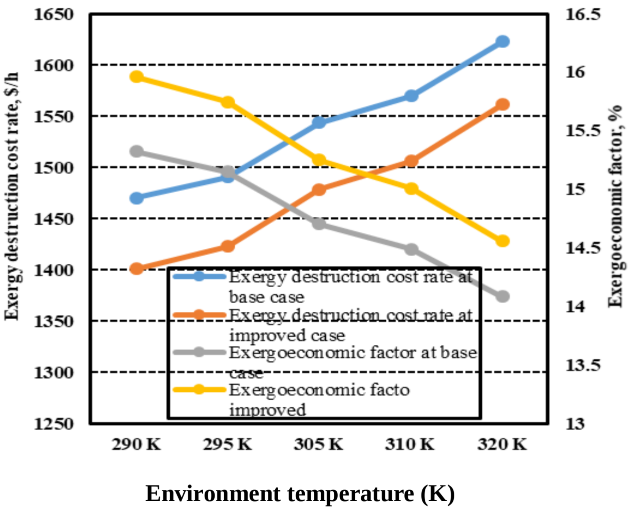

Fig. 7 Exergy destruction cost rate, exergoeconomic factor and improvements of PB at singular operating mode

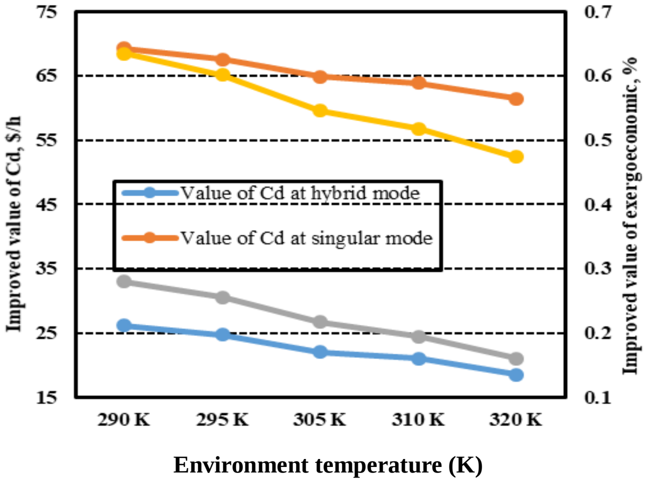

Fig. 8 The value of improvement of exergy destruction cost and exergoeconomic factor for hybrid versus singular operating mode

6 Conclusions

In this study, exergy destruction and exergoeconomic improvement for power boiler at various operating modes were studied based on the data obtained from the real operation conditions with taking the consideration of the change in the ambient temperature during the operating load. For hybrid operating mode, it is found that the improvement of exergy destruction for PB was improved by from 2, to 1.29 % with increasing of environment temperature from 290 to 320 K, respectively. for exergoeconomic improvement, it notices that the value of exergy destruction cost rates and exergoeconomic factor of the power boiler were improved by 26.13\$/h and 1.74 % at environment temperatures of 290 K, respectively. On other hand, for singular operating mode, the exergy destruction improvement of PB was improved within from 4.71 to 3.79 % with increasing of environment temperatures from 290 to 320 K, respectively. While, the exergoeconomic improvement it found that the value of exergy destruction cost rate and exergoeconomic factor of the power boiler were improved by 69.24\$/h and 4.14% at environment temperatures of 290 K, respectively.

applications and extensions.

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