Int. J. Adv. Eng. Pure Sci. 2019, 4: 286-294
DOI: 10.7240/jeps.492429

RESEARCH ARTICLE / ARAŞTIRMA MAKALESİ

Thermoeconomic Performance Analysis of Steam Boilers of a Power Plant Operating with Various Fuels

Çeşitli Yakıtlarla Çalışan Bir Santralin Buhar Kazanlarının Termoekonomik Performans Analizi

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Abstract

Energy consumption is one of the most concerned topics of the industry, and the cost of energy represents a large proportion of operating expenditure for energy-intensive sectors. In the analysis and design of industrial processes, mainly thermodynamics is often used with economic principles to obtain the optimum design for energy-efficient systems. The performance of the system can be analyzed via applying the conservation principles of energy that is defined by the first law of thermodynamics. However, only regarding the conservation of energy is not sufficient to determine the real performance of the system. At this point, an exergy analysis is done to predict the useful part of the energy, also to provide the magnitudes and places of the irreversibilities and losses within the system. Moreover, the thermoeconomic analysis is done for providing useful information to design and operate a cost-effective system. In this study, thermoeconomic analysis of the steam boilers in a power plant was performed. The simulations of the steam boilers were done by using the Aspen HYSYS simulation software. The mass, energy and cost balance equations were obtained for the boilers to determine the effect of various fuels on the process economics.

Keywords: Energy, Exergy, Thermoeconomic Analysis, Steam Boiler, Simulation.

Öz

Enerji tüketimi, endüstrinin en önemli konularından biridir ve enerji maliyeti, enerji yoğun sektörler için işletme giderlerinin büyük bir bölümünü oluşturur. Endüstriyel proseslerin analizinde ve tasarımında, enerji verimli bir sistem için en uygun tasarımı elde etmek üzere temel olarak termodinamik ve ekonomik prensipler birlikte kullanılır. Sistemin performansı, termodinamiğin birinci yasası tarafından tanımlanan enerji korunumu prensipleri uygulanarak analiz edilebilir. Ancak, sadece enerji korunumu prensibi sistemin gerçek performansını belirlemek için yeterli değildir. Bu noktada, enerjinin yararlı kısmının belirlenmesi için ekserji analizi yapılır, ayrıca sistem içindeki tersinmezliklerin ve kayıpların büyüklüklerini ve yerleri de belirlenir. Buna ilaveten, maliyet-etkin bir sistem tasarlamak ve işletmek üzere faydalı bilgi sağlamak için termoekonomik analiz yapılır. Bu çalışmada, bir santralin buhar kazanlarının termoekonomik analizi gerçekleştirilmiştir. Buhar kazanlarının simülasyonları Aspen HYSYS simülasyon yazılımı kullanılarak yapılmıştır. Kazanlar için kütle, enerji ve maliyet dengesi denklemleri çeşitli yakıtların proses ekonomisi üzerindeki etkisini belirlemek üzere elde edilmiştir.

Anahtar Kelimeler: Enerji, Ekserji, Termoekonomik Analiz, Buhar Kazanı, Simülasyon.

1. INTRODUCTION

The basis of conservation of energy called as the first law of thermodynamics, defines that energy cannot be created or eliminated in a system; it can only transform its form [1]. Moreover, the second law of thermodynamics introduces the difference in quality between various forms of energy, and also states that all irreversible processes progress to maximize entropy; that is, to become more randomized and to transform energy into a less useful form [2].

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Gönderilme/Submitted: 11.12.2018, **Düzenleme/Revised:** 26.09.2019, **Kabul/Accepted:** 16.10.2019

Unlike energy, exergy or the available part of energy is not conserved in actual processes. Exergy is explained as the maximum amount of work that can be obtained by a system or a flow of matter or energy as it approaches into balance with a reference environment, and it is always expended or eliminated throughout a real process in proportion to the entropy generation because of the irreversibilities related with that process [3]. Exergy analysis is a practical method for system performance assessment and improvement since it enables accurate magnitudes of the losses to be identified.

In literature, many studies related to energy conversion and storage systems were reported by researchers for various applications. Sari and Kaygusuz [4] studied energy and exergy evaluations of energy storage systems. Ozturk performed an exergy analysis of biological energy conversion [5]. Mert et al. investigated a chemical heat pump system to progress the low level thermal energy to upper levels [6]. Tsatsaronis and Cziesla summarized the definitions and fundamentals of thermoeconomics [7]. A brief summary of exergy based economic-analysis approaches for analyzing thermal processes were done by Dincer and Rosen [8]. A systematic methodology for describing and calculating exergetic efficiencies and exergy related costs in thermal processes is offered by Lazzaretto and Tsatsaronis [9]. Atmaca carried out exergy analysis of a cogeneration system including steam and gas turbines [10]. Gümüş and Atmaca investigated the exergy analyses of a compression ignition engine using diesel and compressed natural gas as fuels [11]. Thermoeconomic evaluation of a geothermal power plant was studied by Yildirim and Ozgener [12]. Kwak et al. have done the exergoeconomic analysis for a 500 MW combined cycle plant [13]. Sahoo performed the exergoeconomic analysis and optimization of a cogeneration system using evolutionary programming [14]. El-Emam and Dincer performed the thermodynamic and economic analyses of a geothermal regenerative organic Rankine cycle based energy and exergy concepts [15]. Pellegrini et al. have done a comparative thermoeconomic study of supercritical steam cycles and biomass integrated gasification combined cycles for sugarcane mills [16]. The exergetic and economic evaluations of an iron and steel factory were done by Mert et al. [17]. A detailed thermoeconomic cost analyzes of a 600 MW oxy-combustion coal-fired power plant were studied by Xiong et al [18]. Exergoeconomic comparison of absorption refrigeration systems have done by Farshi et al. [19]. Gungor et al. performed exergoeconomic analysis of a gas engine driven heat pump drier and food drying process [20]. Ozgeners presented exergy efficiencies and exergoeconomic parameters of geothermal district heating systems [21]. The optimization of integrated heat, mass and pressure exchange network using exergoeconomic method was studied by Dong et al. [22].

In this work, thermoeconomic analysis of steam boilers with steam production capacities of 80 ton/h and 100 ton/h in a power plant in Turkey was studied. The mass, energy, exergy and cost balance equations were obtained for steam boilers, and their simulation was done by using the Aspen HYSYS Simulation Software to investigate the effect of fuel types on the process economics. Thus, the examinations of the steam boilers, which have relatively large capacity, were carried out by using exergy and thermoeconomics methods in order to determine the place of thermodynamic irreversibilities and the feasible improvements.

II. EXERGY ANALYSIS

Exergy analysis is a functional tool for constructing, assessing and improving energy conversion systems. Exergy of a system in a given state can be described as the maximum work that can be obtained through interaction of the system with the reference environment as it reaches chemical, mechanical and thermal equilibrium [23]. Here, the reference environment is considered to be so large, that its parameters are not influenced by interaction with the system under consideration [24].

The total exergy of a system has been composed of four components when the other energy effects were neglected [7,8]:

$$\dot{\Xi} = \dot{\Xi}^{ph} + \dot{\Xi}^{ch} + \dot{\Xi}^{pt} + \dot{\Xi}^{kn} \tag{1}$$

$\dot{\Xi}^{ph}$, $\dot{\Xi}^{ch}$, $\dot{\Xi}^{pt}$ and $\dot{\Xi}^{kn}$ denotes the physical, chemical, potential and kinetic exergy components, respectively. Kinetic and potential exergies are neglected in the exergy analysis of this study. The reason for this is the variations of velocity and elevations are insignificant and do not result in a substantial change in exergy [25].

Physical exergy of a system or a stream is the available part of the energy of that system when the system delivered to initial to environmental states via taking only a physical process.

$$\dot{\Xi}^{ph} = \dot{m}\left[(h - h_0) - T_0(s - s_0)\right] \tag{2}$$

The chemical exergy of a stream can be explained as the maximum work that can be achieved by taking the stream to compositional equilibrium with the environment:

$$\dot{\Xi}^{ch} = \dot{m}\left(\sum y_i \bar{e}^{ch} + RT_0 \sum y_i \ln y_i\right) \tag{3}$$

The place, amount and cause of the thermodynamic inefficiencies in a thermal system could be determined by an exergy analysis [7]. The general exergy balance equation can be written for the kth component of a system, as follows:

$$\dot{\Xi}_{F,k} = \dot{\Xi}_{P,k} + \dot{\Xi}_{L,k} + \dot{\Xi}_{D,k} \tag{4}$$

Here the F, P, L, and D denote the fuel, product, loss and destruction, respectively. The exergy of fuel is the exergy entering the system, and the exergy of product is the exergy of exiting stream or work. Exergy loss is the thermodynamic loss due to the exergy transfer to the surroundings. Exergy destruction is the loss caused by the irreversibilities within the system limits, and when the limits are assumed as the reference temperature T_0, the exergy loss is zero, and the thermodynamic inefficiencies composed of solely of exergy destruction.

Exergy loss and exergy destruction can be written as follows, respectively:

$$\dot{\Xi}_{L,k} = \dot{Q}_k.(1 - T_o / T) \tag{5}$$

$$\dot{\Xi}_{D,k} = T_0 \dot{S}_{gen,k} \tag{6}$$

The exergetic efficiency (ε) of a system can be formulated as:

$$\varepsilon_k = \dot{\Xi}_{P,k} / \dot{\Xi}_{F,k} = 1 - (\dot{\Xi}_{D,k} / \dot{\Xi}_{F,k}) \tag{7}$$

III. THERMOECONOMIC ANALYSIS

Thermoeconomic analysis relates thermodynamic assessments relies on an exergy analysis with economic principles, in order to allow the designer or operator of a system that is beneficial to the design and operate of a cost-effective system, but not acquirable by classical economic and exergy analysis. Thermoeconomics stands to the concept that exergy is the exclusively acceptable base for determining pecuniary costs to the interactions that a system experiences with its surroundings and to the causes of thermodynamic inefficiencies within it [7, 26, 27].

The cost balance for a system operating at the steady state can be written as;

$$\dot{C}_{P,tot} = \dot{Z}_k + \dot{C}_{F,tot} \tag{8}$$

Here, $\dot{C}_{P,tot}$ signifies the total cost rate of the products, $\dot{C}_{F,tot}$ is the total cost rate of the fuels and $\dot{Z}_k$ is the sum of the cost rates related with the capital investment ($\dot{Z}^{CI}_{tot}$) and operating & maintenance costs ($\dot{Z}^{OM}_{tot}$) [7, 26]:

$$\dot{Z}_k = \dot{Z}^{CI}_{tot} + \dot{Z}^{OM}_{tot} \tag{9}$$

In exergy costing, a cost is correlated with each exergy stream. So, Equations (10-11) are written for the entering (i) and exiting (o) streams of matter with corresponding exergy transfer rates. Equations (12-13) are written for the exergy transfer rate associated with heat and power [7, 26]:

$$\dot{C}_i = c_i \dot{\Xi}_i = c_i (\dot{m}_i . e_i) \tag{10}$$

$$\dot{C}_o = c_o \dot{\Xi}_o = c_o (\dot{m}_o . e_o) \tag{11}$$

$$\dot{C}_q = c_q \dot{\Xi}_q = c_q \dot{Q}_q (1 - T_o / T) \tag{12}$$

$$\dot{C}_w = c_w \dot{\Xi}_w = c_w \dot{W} \tag{13}$$

Here, c_i, c_o, c_w and c_q indicates the average costs per unit of exergy transfer rate ($/GJ) so the units of $\dot{C}_i$, $\dot{C}_o$, $\dot{C}_w$ and $\dot{C}_q$ are dollars per hour ($/h).

Exergy costing includes cost balances commonly defined for each component individually. The cost equation for a component that gets heat and generates power is [7, 26];

$$\sum_o \dot{C}_{o\,k} + \dot{C}_{w\,k} = \sum_i \dot{C}_{i\,k} + \dot{C}_{q\,k} + \dot{Z}_k \tag{14}$$

Equation (14) defines that the total cost of exiting exergy streams equals the total outgoings to achieve them. By applying above cost equations (Equations (10-14)), the Equation (15) can be written [7, 26];

$$\sum_o (c_o \dot{\Xi}_o)_k + (c_w \dot{\Xi}_w)_k = \sum_i (c_i \dot{\Xi}_i)_k + (c_q \dot{\Xi}_q)_k + \dot{Z}_k \tag{15}$$

IV. STEAM BOILERS

In this work, the energy, exergy and thermoeconomic analyses of two individual steam boilers (SB-1 and SB-2), with steam production capacities of 80 ton/h and 100 ton/h were done. The simulation screen view of the steam boiler-1 is presented in Figure 1 while steam boiler-2 has identical view with its own stream numbers.

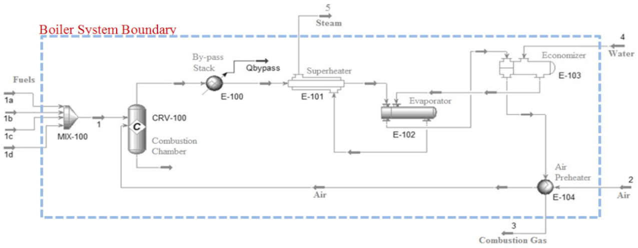

Figure 1. Steam boiler SB-1 and SB-2

The considered steam boilers were individually composed of an air preheater, an economizer, an evaporator, a superheater and a combustion chamber, and have the ability of combusting different types of liquid and gaseous fuels. Here, SB-1 was firing blast furnace gas (BFG), coke gas (CG), steelworks off-gas (SOG) and coal tar (CT) while SB-2 was firing blast furnace gas (BFG), coke gas (CG), steelworks off-gas (SOG) and natural gas (NG). The stream properties of steam boilers were given in Table 1 and the compositions of air and fuels were given in Figure 2.

Table 1. Flow stream properties of the boilers

Steam Boiler-1 (SB-1)				Steam Boiler-2 (SB-2)			
Stream	$\dot{m}$ (kg/s)	P (bar)	T (K)	Stream	$\dot{m}$ (kg/s)	P (bar)	T (K)
1a (BFG)	0.3	1	298	6a (BFG)	11.5	1	298
1b (CG)	0.1	1	298	6b (CG)	0.5	1	298
1c (SOG)	8.4	1	298	6c (SOG)	8.0	1	298
1d (CT)	0.8	8	353	6d (NG)	0.1	16	353
2 (Air)	28.1	1	298	7 (Air)	43.1	1	298
3 (CMB)	37.8	1	419	8 (CMB)	62.4	1	424
4 (WT)	16.1	55	383	9 (WT)	23.6	55	383
5 (ST)	16.1	45	716.2	10 (ST)	23.6	45	716.2

V. RESULTS AND DISCUSSION

The thermoeconomic analysis of the steam boilers has been carried out with the following assumptions:

- •The boilers were operated at the steady-state during the analysis.
- •Kinetic and potential energy effects were insignificant.
- •Combustion reaction was occurred completely.
- •Fuel/air ratio was kept constant.
- •The reference state that used in calculations was 298.15 K and 1.013 bar.

The equations required for thermoeconomic analysis of steam boilers were given in Table 2.

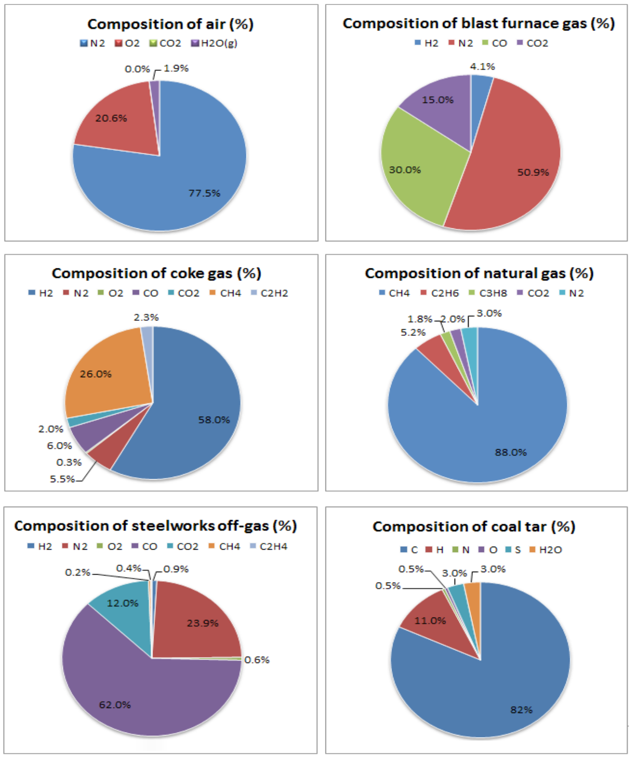

Figure 2. The compositions of air and fuels

Table 2. The mass, energy and exergy balances, exergy destruction, exergy efficiency, energy efficiency, improvement potential and cost equations for the boilers

Steam Boiler-1	Steam Boiler-2
$\dot{m}_{1a}+\dot{m}_{1b}+\dot{m}_{1c}+\dot{m}_{1d}+\dot{m}_2=\dot{m}_3$, $\dot{m}_4=\dot{m}_5$	$\dot{m}_{6a}+\dot{m}_{6b}+\dot{m}_{6c}+\dot{m}_{6d}+\dot{m}_7=\dot{m}_8$, $\dot{m}_9=\dot{m}_{10}$
$\dot{E}_{1a}+\dot{E}_{1b}+\dot{E}_{1c}+\dot{E}_{1d}+\dot{E}_2+\dot{E}_4=\dot{E}_3+\dot{E}_5$	$\dot{E}_{6a}+\dot{E}_{6b}+\dot{E}_{6c}+\dot{E}_{6d}+\dot{E}_7+\dot{E}_9=\dot{E}_8+\dot{E}_{10}$
$\dot{\Xi}_{1a}+\dot{\Xi}_{1b}+\dot{\Xi}_{1c}+\dot{\Xi}_{1d}+\dot{\Xi}_2$ $+\dot{\Xi}_4=\dot{\Xi}_3+\dot{\Xi}_5+\dot{\Xi}_L+\dot{\Xi}_D$	$\dot{\Xi}_{6a}+\dot{\Xi}_{6b}+\dot{\Xi}_{6c}+\dot{\Xi}_{6d}+\dot{\Xi}_7$ $+\dot{\Xi}_9=\dot{\Xi}_8+\dot{\Xi}_{10}+\dot{\Xi}_L+\dot{\Xi}_D$
$\dot{\Xi}_D=\dot{\Xi}_{1a}+\dot{\Xi}_{1b}+\dot{\Xi}_{1c}+\dot{\Xi}_{1d}+\dot{\Xi}_2+\dot{\Xi}_4-\dot{\Xi}_3-\dot{\Xi}_5$	$\dot{\Xi}_D=\dot{\Xi}_{6a}+\dot{\Xi}_{6b}+\dot{\Xi}_{6c}+\dot{\Xi}_{6d}+\dot{\Xi}_7+\dot{\Xi}_9-\dot{\Xi}_8-\dot{\Xi}_{10}$
$\varepsilon=(\Xi_5-\Xi_4)/(\Xi_{1a}+\Xi_{1b}+\Xi_{1c}+\Xi_{1d}+\Xi_2)$	$\varepsilon=(\dot{\Xi}_{10}-\dot{\Xi}_9)/(\dot{\Xi}_{6a}+\dot{\Xi}_{6b}+\dot{\Xi}_{6c}+\dot{\Xi}_{6d}+\dot{\Xi}_7)$
$\eta=\dot{E}_5/(\dot{E}_{1a}+\dot{E}_{1b}+\dot{E}_{1c}+\dot{E}_{1d}+\dot{E}_2+\dot{E}_4)$	$\eta=\dot{E}_{10}/(\dot{E}_{6a}+\dot{E}_{6b}+\dot{E}_{6c}+\dot{E}_{6d}+\dot{E}_7+\dot{E}_9)$
$\dot{I}_{pot}=\dot{\Xi}_D(1-\varepsilon)+\dot{\Xi}_3$	$\dot{I}_{pot}=\dot{\Xi}_D(1-\varepsilon)+\dot{\Xi}_8$
Cost balance $\dot{C}_{1a}+\dot{C}_{1b}+\dot{C}_{1c}+\dot{C}_{1d}+\dot{C}_2+\dot{C}_4$ $+\dot{Z}_{SB-1}=\dot{C}_3+\dot{C}_5$	Cost balance $\dot{C}_{6a}+\dot{C}_{6b}+\dot{C}_{6c}+\dot{C}_{6d}+\dot{C}_7+\dot{C}_9$ $+\dot{Z}_{SB-2}=\dot{C}_8+\dot{C}_{10}$
$c_{1a}.\dot{\Xi}_{1a}+c_{1b}.\dot{\Xi}_{1b}+c_{1c}.\dot{\Xi}_{1c}+c_{1d}.\dot{\Xi}_{1d}$ $+c_2.\dot{\Xi}_2+c_4.\dot{\Xi}_4+\dot{Z}_{SB-1}=c_3.\dot{\Xi}_3+c_5.\dot{\Xi}_5$	$c_{6a}.\dot{\Xi}_{6a}+c_{6b}.\dot{\Xi}_{6b}+c_{6c}.\dot{\Xi}_{6c}+c_{6d}.\dot{\Xi}_{6d}$ $+c_7.\dot{\Xi}_7+c_9\cdot\dot{\Xi}_9+\dot{Z}_{SB-2}=c_8.\dot{\Xi}_8+c_{10}.\dot{\Xi}_{10}$
Variable calculated from cost balance $c_5=\left[\begin{array}{l}c_{1a}.\dot{\Xi}_{1a}+c_{1b}.\dot{\Xi}_{1b}+c_{1c}.\dot{\Xi}_{1c}\\ \quad +c_{1d}.\dot{\Xi}_{1d}+c_4\cdot\dot{\Xi}_4+\dot{Z}_{SB-1}\end{array}\right]/(\dot{\Xi}_5)$	Variable calculated from cost balance $c_{10}=\left[\begin{array}{l}c_{6a}.\dot{\Xi}_{6a}+c_{6b}.\dot{\Xi}_{6b}+c_{6c}.\dot{\Xi}_{6c}\\ \quad +c_{6d}.\dot{\Xi}_{6d}+c_9\cdot\dot{\Xi}_9+\dot{Z}_{SB-2}\end{array}\right]/(\dot{\Xi}_{10})$

According to the data obtained from the power plant, the unit exergetic cost of BFG, CG, SOG, CT and NG were taken as 4.05 \$/GJ, 3.08 \$/GJ, 4.42 \$/GJ, 4.25 \$/GJ, 8.49 \$/GJ, respectively. On the other hand, the sum of the cost rates related with equipment were taken as 222.08 \$/h and 256 \$/h for SB-1 and SB-2. Furthermore, since there is no additional cost to intake the air required for combustion in steam boilers, the costs of air sucked from the environment were taken as zero. Likewise, there is no additional cost to exhaust the formed combustion gases.

The calculated values for the exergy of fuels (MW), exergy of products (MW), exergy destruction (MW), energy and exergy efficiencies (%) and improvement potential (MW) of the steam boilers were given in Figure 3. The results of thermoeconomic analysis were presented in Figure 4 for SB-1 and SB-2.

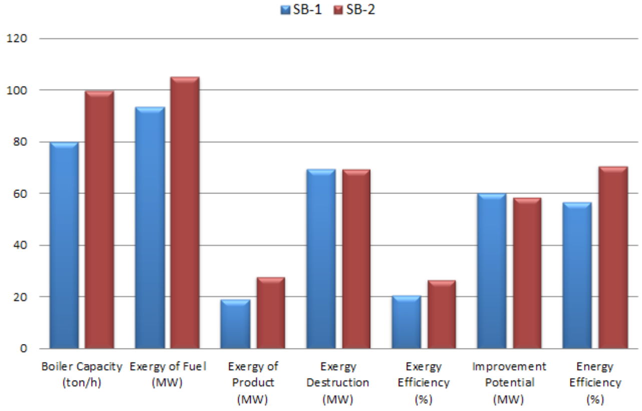

Figure 3. Results of the exergy analysis

According to the Figure 3, the exergy destruction rates were almost the same for the boilers. While the improvement potential of SB-1 was slightly higher than the improvement potential of SB-2 based on the losses and the exergetic efficiencies of the boilers. It was obvious from the Figure 3 that steam boiler-2 operates more efficiently based on its higher steam generation capacity. Figure 4 shows the cost distribution of generated steam from the boilers. It was understood from the figure that the exergetic cost of steam produced from SB-2 was higher than that of SB-1 based on the different feed compositions of the fuels. Since the analyzed boilers were a part of power cycle, which was operating in a closed cycle, the addition or consumption of water in the boilers and their costs were negligible as mentioned in the assumptions.

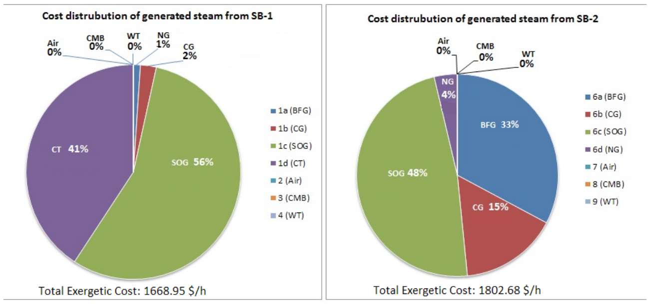

Figure 4. Results obtained from the thermoeconomic analysis

In the second part of this work, determination of the impact of fuel types on the process economics were carried out by using software called Aspen HYSYS [28]. The steam boiler-2 (SB-2) was chosen to investigate the effect of various fuels. Once the real operating condition of SB-2 was simulated as Base Case, which was firing mixture of BFG, CG, SOG and NG, then the effect of individual types of fuel namely, BFG, CG, SOG and NG were simulated respectively among Case1 to Case 4. Assumptions were made as steady-state operation, the constant fuel/air ratio, the constant O_2 moles % at flue gas, and complete combustion.

According to the simulation results, comparison of the percentages of fuel composition of the cases, comparison of fuel / CO_2 mass flow rate and comparison of the unit exergetic cost / CO_2 mass flow rates of the cases were obtained as in Figure 5, Figure 6 and Figure 7, respectively. The simulations demonstrated that the lowest fuel flows observed in case 2 and case 4 due the fuels higher energy content. As a result, CO_2 flow rates in these case considerably low

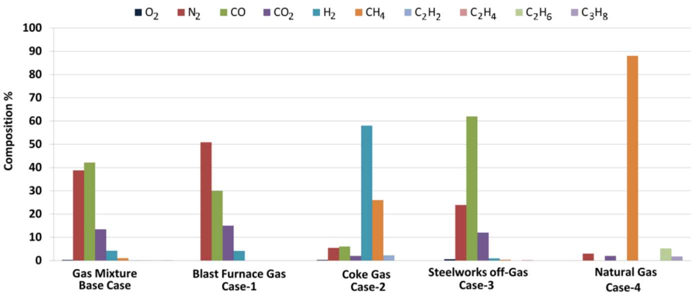

Figure 5. Comparison of the percentages of fuel composition of the cases

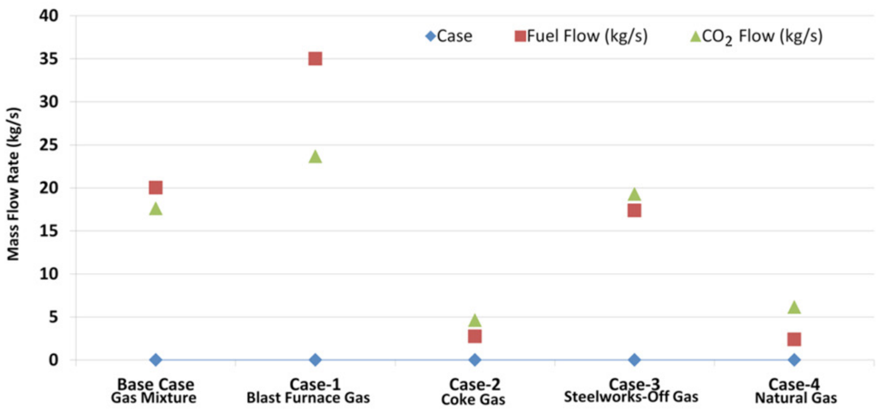

Figure 6. Comparison of fuel and CO_2 mass flow rate of the cases

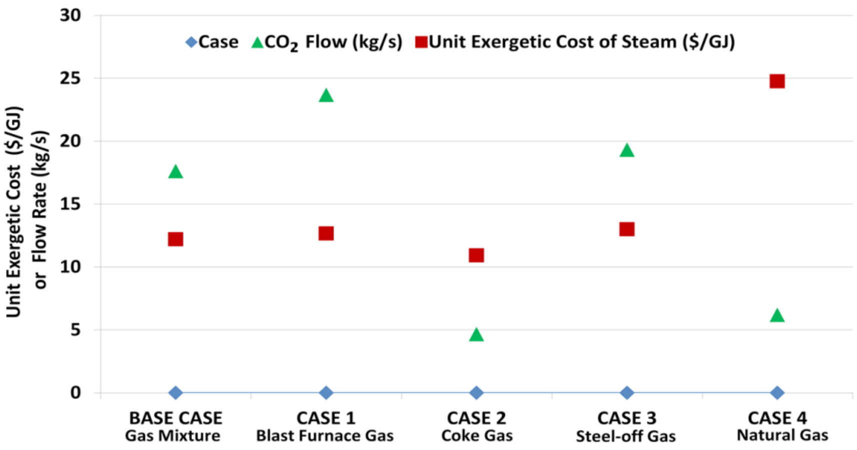

Figure 7. Comparison of the unit exergetic cost and CO_2 mass flow rate

compared to the other cases. While the unit exergetic cost of natural gas was the highest (Figure 7).

The mole compositions of combustion gases (%), depending on the fixed oxygen content (%) in the flue gas during boiler operation were given in Table 4. Accordingly, CO_2 mass flow rate in the combustions gas was highest in Case 3 based on the higher CO and CO_2 content of SOG. The mass flow rates of the fuels and the amount of CO_2, which were obtained by using Aspen HYSYS simulation, were compared in Table 5. Based on the simulations and calculations, the results of exergy and exergoeconomic analyses were shown in Table 6 and Table 7, respectively.

Table 6 illustrates the results obtained from the boiler exergy analysis based on the constant amount of steam production scenarios during operation. It was understood from the table that the highest exergy destruction was occurred in Case 2 while the lowest energy and exergy efficiencies realized in this case. Conversely, the most efficient scenario was Case 3 while it has the lowest exergy destruction rates. Moreover, the exergetic costs of the generated steam in Case 2 was the lowest (1613.70 $/h) and Case 4 was the highest (3662.45 $/h) due to the unit exergetic costs of the fuels. The mass flow rates, the exergy amounts and the cost of each stream in the cases were summarized in Table 7. The results were demonstrated that the cost of generated steam which were higher than the Base Case (1802.68 $/h) except the Case 2, were following the order of Case 4 > Case 3 > Case 1 > Case 2.

Table 4. Mole compositions of combustion gases (%), depending on the fixed oxygen content (%) in the flue gas during boiler operation

Composition (%)	**O_2**	**N_2**	**CO_2**	**H_2O**
Base Case	5.000	69.965	19.590	5.445
Case 1 (BFG)	5.000	71.560	20.400	3.041
Case 2 (CG)	5.000	70.694	5.796	18.510

Case 3 (SOG)	5.000	68.694	24.960	2.146
Case 4 (NG)	5.000	72.285	7.305	15.410

Table 5. Simulation results: Fuel type, fuel and CO_2 mass flow rate

SB-2	Base Case	Case1	Case2	Case3	Case4
Fuel Type	Gas Mix.	BFG	CG	SOG	NG
Fuel Flow (kg/s)	20.0	35.0	2.8	17.4	2.4
CO_2 Flow (kg/s)	17.6	23.7	4.6	19.3	6.2

Table 6. The results obtained from the boiler exergy analysis based on the constant amount of steam production scenarios during operation

SB-2	$\dot{\Xi}_F$ (MW)	$\dot{\Xi}_P$ (MW)	$\dot{\Xi}_D$ (MW)	ε (%)	I_{pot} (MW)	η (%)
BASE CASE	105.16	28.00	69.56	26.62	58.57	70.76
CASE 1	111.05	28.00	71.75	25.21	64.88	65.47
CASE 2	122.61	28.00	89.44	22.84	74.11	63.70
CASE 3	104.90	28.00	68.71	26.69	58.48	70.78
CASE 4	111.56	28.04	78.33	25.10	63.83	64.61

Table 7. Results obtained from exergoeconomic analysis

Stream	$\dot{m}$ (kg/s)	$\dot{\Xi}$ (MW)	c ($/GJ)	$\dot{C}$ ($/h)
		CASE 1		
$6a^{CS-1}$ (BFG)	35.0	110.93	4.045	1615.36
7^{CS-1} (Air)	47.3	0.12	0.000	0.00
8^{CS-1} (CMB)	82.3	11.25	0.000	0.00
9^{CS-1} (WT)	23.6	13.04	0.000	0.00
10^{CS-1} (ST)	23.6	41.09	12.650	1871.24
		CASE 2		
$6b^{CS-2}$ (CG)	2.8	122.49	3.079	1357.73
7^{CS-2} (Air)	47.1	0.12	0.000	0.00
8^{CS-2} (CMB)	49.9	5.13	0.000	0.00
9^{CS-2} (WT)	23.6	13.04	0.000	0.00
10^{CS-2} (ST)	23.6	41.09	10.909	1613.70
		CASE 3		
$6c^{CS-3}$(SOG)	17.4	104.80	4.419	1667.20
7^{CS-3} (Air)	38.9	0.10	0.000	0.00
8^{CS-3} (CMB)	56.3	8.15	0.000	0.00
9^{CS-3} (WT)	23.6	13.04	0.000	0.00
10^{CS-3} (ST)	23.6	41.09	13.001	1923.16
		CASE 4		
$6d^{CS-4}$ NG)	2.4	111.44	8.491	3406.45
7^{CS-4} (Air)	51.2	0.13	0.000	0.00
8^{CS-4} (CMB)	53.6	5.19	0.000	0.00
9^{CS-4} (WT)	23.6	13.04	0.000	0.00
10^{CS-4} (ST)	23.6	41.09	24.759	3662.45

Exergy flows and improvement potential of the cases were demonstrated in Figure 8. Thus, the magnitudes of exergy flows of the cases were compared. Based on the constant amount of steam production scenarios, it can be said that the highest amount of exergy was supplied in Case 2 and this resulted a highest exergetic destruction rate. Furthermore, the performance analyses of the cases were shown in Figure 9. It was found that the exergetic efficiencies slightly differ in the cases however, these differences are greater in energy efficiencies.

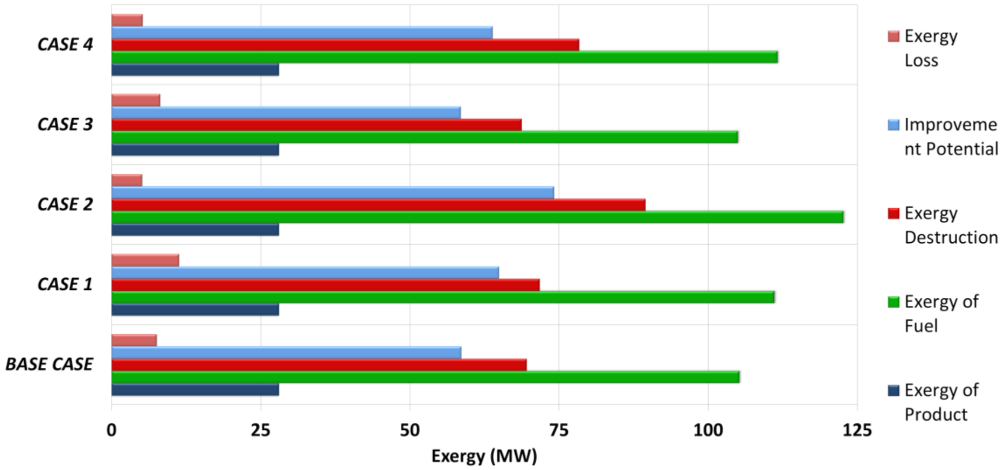

Figure 8. Exergy flows and improvement potential of the cases

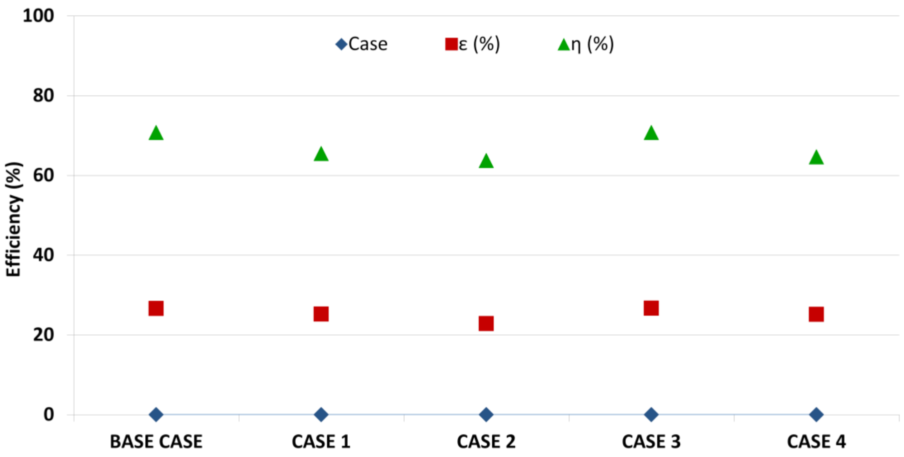

Figure 9. The demonstration of energy and exergy efficiencies

VI. CONCLUSIONS

The steam boilers of a power plant were analyzed, and the following results were achieved. Due to the exergy analysis, the energy efficiencies were found to be 56.79% and 70.76%, and exergetic efficiencies were found to be 20.47% and 26.62% for SB-1 and SB-2, respectively. Furthermore, the amounts of exergy destructions were 69.40 MW and 69.56 MW; the improvement potentials were 60.16 MW and 58.57 MW, and the exergy destruction rates were 74.22% and 66.15% for SB-1 and SB-2 respectively. Due to the thermoeconomic evaluation, it was found that the costs of fuel of SB-1 and SB-2 were 1446.90 $/h and 1546.62 $/h. The costs of steam generated by SB-1 and SB-2 were 1668.95 $/h and 1802.68 $/h or as 28.76 $/ton and 21.21 $/ton, respectively.

On the other hand, in order to investigate the effect of the type of fuel further simulations were done for SB-2 by using Aspen HYSYS simulation software. According to the simulation case studies, the following results were obtained. The energy efficiencies were found to be 65.47%, 63.70%, 70.78% and 64.61%, and exergetic efficiencies were found to be 25.25%, 22.87%, 26.73% and 25.14%, for the fuel BFG, CG, SOG and NG, respectively. Based on the thermoeconomic assessment, the costs of fuels were calculated (Table 7). It was found that CG has the lowest and NG has the highest exergetic costs as 1357.73 $/h and 3406.45 $/h, respectively. In general, the results indicate that the cost of fuels were following the order of CG < BFG < SOG < NG. In other words, the costs of steam were 18.98 $/ton and 43.09 $/h while the CO_2 mass flow rate was 4.6 kg/s and 6.2 kg/s for CG and NG, respectively.

Consequently, thermoeconomic analysis that identifies place amount and causes of thermodynamic inefficiencies in a system with an economic viewpoint is a very helpful tool to reduce environmental impacts, improve the energy conversion systems and increase benefits. This study illustrates the picture of system's exergetic costs and can be used as guiding study for the resembling systems.

NOMENCLATURE

BFG	Blast Furnace Gas
c	Cost per Exergy Unit, $/GJ
$\dot{C}$	Cost Rate, $/h
CI	Capital Investment
CG	Coke Gas
COMB	Combustion Gas
CT	Coal Tar
e	Specific Exergy, kJ/kg
h	Specific Enthalpy, kJ/kg
$\dot{m}$	Mass Flow, kg/s
NG	Natural Gas
OM	Operating And Maintenance Cost
SB	Steam Boiler
SOG	Steelworks Off-Gas
P	Pressure, Bar
s	Specific Entropy, kJ/kgK
ST	Steam
T	Temperature, K
WT	Water
X	Mole Composition, %
$\dot{Z}$	Capital Investment and Operating & Maintenance Cost
Greek Letters	
$\dot{\Xi}$	Exergy Flow Rate, MW
ε	Exergy Efficiency
$\dot{I}_{pot}$	Improvement Potential, MW

η	Energy Efficiency
Subscripts	
ch	chemical
CS	case
i	in
kn	kinetic
o	out
ph	physical
pt	potential

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