IDENTIFYING THE IMPROVEMENT POSSIBILITIES OF A FLUIDIZED BED BOILER WITH EXERGY ANALYSIS

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Keywords	Abstract
Fluidized Bed, Boiler, Exergy Efficiency, Exergy Destruction.	In this study, a circulation-type fluidized bed boiler's exergy performance in a power generation plant was investigated. The boiler was examined not as a whole but by dividing it into its sub-systems. In the analysis, the sub-systems' exergy performance was evaluated in terms of criteria such as exergy efficiency, exergy destruction, fuel depletion ratio, relative exergy destruction ratio, exergetic improvement potential, and productivity lack ratio. In addition, the effect of different dead state temperatures on these exergy performance criteria is compared and discussed. As a result of the analysis, the highest exergy efficiency was achieved in the furnace with 80.2% at 6℃, while the highest exergy destruction occurred in the furnace as 18,118.9 kW at 27℃. The highest exergetic improvement potential was realized in Economizer-II with 11,593.82 kW at 6℃, and the lowest in Economizer-I at 27℃ with 631,9 kW. The effect of the increase in the dead state temperature on the exergy performance criteria applied to boiler sub-systems was variable. It showed its effect as an increase in some sub-systems and a decrease in others.

EKSERJİ ANALİZİ İLE BİR AKIŞKAN YATAKLI KAZANIN İYİLEŞTİRME OLANAKLARININ TESPİT EDİLMESİ

Anahtar Kelimeler	Öz
Akışkan Yatak, Kazan, Ekserji Verimi, Ekserji Yıkımı.	Bu çalışmada, bir güç üretim tesisinde kullanılan dolaşım tipli akışkan yataklı kazanın ekserji performansı araştırılmıştır. Kazan bir bütün olarak değil, alt sistemlerine ayrılarak incelemeye tabi tutulmuştur. Analizde alt sistemlerin ekserji performansı, ekserji verimliliği, ekserji yıkımı, nispi ekserji yıkımı oranı, yakıt tüketme oranı, ekserjetik gelişim potansiyeli ve üretkenlik eksikliği oranı gibi kriterler bakımından değerlendirilmiştir. Ayrıca, farklı ölü hal sıcaklıklarının bu ekserji performans kriterleri üzerindeki etkisi kıyaslanmış ve tartışılmıştır. Yapılan analizler sonucunda en yüksek ekserji verimi %80,2 ile 6℃'de yanma odasında, en yüksek ekserji yıkımı ise yine yanma odasında 27℃'de 18.118,9 kW olarak gerçekleşmiştir. En yüksek ekserjetik gelişim potansiyeli 11.593,82 kW ile 6℃'de eko-II'de, en düşük ise 631,9 kW ile 27℃'de eko-I'de gerçekleşmiştir. Ölü hal sıcaklığındaki artışın kazan alt sistemlerine uygulanan ekserji performans kriterleri üzerindeki etkisi değişken olmuştur. Kimi alt sistemde artış kimi alt sistemde ise düşüş olarak etkisini göstermiştir.

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1. Introduction

No matter what energy source is used, power generation facilities are high-cost investments in terms of installation and operation. More investments are required to meet the increasing energy consumption in parallel with the growing population and industrialization. Beyond building new energy generation facilities, maximizing energy savings and more efficient use of energy-producing and consuming machines will constitute the strongest part of a sustainable energy policy.

In industrial plants that produce electricity or steam and both, boilers play a key role. In these facilities, the main goal is to generate more power with the same amount of fuel. For this, it is necessary to follow the annual efficiency changes of the boilers. At the same time, situations that lead to inefficiency should also be prevented. At first, the energy analysis method based on thermodynamics' first law was one of the most used tools. Although only the first law analysis is a useful tool at determining the amount of energy use, it remains helpless, especially in detecting inefficiencies and how much more existing efficiency can be improved. At this point, exergy analysis based on the second law of thermodynamics provides essential convenience. Many researchers have benefited from exergy analysis of different systems (Kolip and Savas, 2010; Akkurt and Kahraman, 2017; İpek et al., 2017; Topal et al., 2017)

In recent years, exergy analysis, which has been sought after by researchers, has become a useful diagnostic method for detecting inefficiencies in plants. With the exergy analysis, the components with high exergy destruction in the examined plants can be determined, and thus, prevention can be taken. Thermal power plants can be examined by dividing them into sub-systems, and only one component in the facility can be examined by exergy analysis. In many parts of the World, researchers have tried to demonstrate the performance of thermal power plants in operation by applying exergy analysis. Some of these are as follows; ten different power plants in Turkey (Erdem et al., 2009), 50 MW Neyveli thermal power plant (Ganapathy et al., 2009), 62.5 MW thermal power plant burning pulverized coal (Suresh et al., 2011). Li and Liu (2012) and Wu et al. (2014) applied exergy analysis in the fuel product concept to the 300 MW thermal power plant and in component and process concept to 600 MW thermal power plant, respectively. Wang et al. (2014) applied exergy analysis to a 600 MW supercritical coal-burning thermal power plant. Gürtürk and Oztop (2016), applied exergy analysis to a cogeneration power plant. In their study, they took the reference temperature to be 20°C (293 K). Pattanayak and Sahu (2015) calculated and the exergy efficiency and exergy destructions of a pulverized coal fired thermal power plant in the design (500 MW) and operating conditions (460 MW). Si et al. (2017) examined the exergy efficiency, exergy loss coefficient, exergy loss ratio, and exergy distribution of a 100 MW double re-heating ultra-supercritical thermal power plant. Also, they investigated the effect of load, feedwater temperature, main steam and reheat steam temperature and pressures on exergy efficiency. Xiong et al. (2011) compared the exergy destruction values of conventional and oxy-fired pulverized thermal power plant subcomponents. Zhou et al. (2019) conducted a comprehensive energy and exergy analysis for conventional steam power plants (TSPP) and supercritical carbon dioxide (S-CO2) power plants.

Previous studies have shown that the greatest exergy destructions in power generation facilities occurred in the boiler section. Thus, many researchers focused solely on the boiler part rather than examining the entire facility. Hepbasli (2009) created an exergetic analysis model for fluidized bed boilers and made calculations for 65 t/h steam capacity oil-shale fired boiler based on actual data. Callak et al. (2015) performed conventional and advanced exergy analysis using actual data from a fluidized bed boiler and heat recovery unit. Behbahaninia et al. (2017) proposed a new method for exergy diagnosis of steam boilers by adapting the ASME ptc 4.1 methods to exergy analysis. Thus, they estimated the exergy efficiency and exergy losses. Zhang et al. (2018) created an exergy analysis model to improve coal-fired industrial boilers' operating performance.

In addition to proving itself in detecting inefficiencies, exergy analysis is also preferred in decision-making processes and optimization processes. Several authors have made studies to question how the boilers will show their effectiveness under actual operating conditions. Sengupta et al. (2007) applied exergy analysis to a 210 MW thermal power plant based on actual data obtained under different conditions, load, and condenser pressure as well as with and without regenerative heaters and in different turbine management settings and examined the performance change. Kopac and Hilalci (2007) applied exergy analysis to investigate ambient temperature's effect on efficiency errors and thermal power plant sub-systems' rational efficiency. Aljundi (2009) investigated the exergy efficiency and exergy destruction change of all 396 MW thermal power plant sub-systems at different ambient temperatures. Eskin et al. (2009) applied exergy analysis to the fluidized bed boiler and sub-systems of the 7.7 MW thermal power plant. In addition, the effect of ambient temperature and excess air amount on exergy efficiency has been investigated. Regulagadda et al. (2010) conducted analyses at different operating pressures, flow rates, and temperatures to determine the parameters that maximize a 32 MW coal-fired power plant's performance. Sharma and Singh (2016) investigated the exergy losses and efficiencies of the boiler sub-systems

such as superheater, evaporator, and economizer in a combined cycle power plant at different dead-state conditions. Ozdil et al. (2016) investigated the effect of change in ambient temperature on the first and second law efficiency of a 6.5 MW power plant. Elhelw et al. (2019) investigated the effect of lowering condenser and IPT inlet pressure, increase in S/H steam temperature entering HPT, and increase in S/H steam temperature entering both HPT and IPT on exergy destruction, second law efficiency, and power savings. The calculations have been made for the operating conditions of the facility under full and half load conditions. Eskin and Kılıç (1996) aimed to determine the effect of cooling tubes placed at different heights of the boiler on the fluidized bed boiler's efficiency in real-time conditions and inefficiencies with exergy analysis.

Previous studies have shown that the place where exergy destruction occurs most in the electricity generation process is the boiler section, where the heat is generated. As a result, it is necessary to separate the boiler into sub-systems and apply exergy analysis to each of them separately to determine in which parts and in what amount the exergy destructions occur in the boiler. Also, it will be useful to determine how much the exergy performance will be affected by the changes in actual operating conditions of the system under examination. However, previous studies have been limited. In this study, exergy analysis has been applied to a fluidized bed boiler with its sub-systems. The effect of change in environmental temperature on exergy performance criteria such as exergy efficiency, exergy destruction, fuel depletion rate, relative exergy destruction, exergetic improvement potential, and productivity lack was examined. Thus, it is aimed to identify inefficient points in the boiler and to facilitate the decision-making process for improvement studies.

3. Material and Method

3.1. System Description

The system examined in this study is a circulation-type fluidized bed boiler located in a power generation facility in Kütahya, Turkey. The main use of the boiler is to provide steam for the production process. In addition, the electrical energy requirement of the machine park in the process is met by converting the steam generated in the boiler into electricity in a turbine-generator group. In this study, the boiler and its sub-systems are examined as given in Figure-1. Thus, the turbine-generator group, condenser, pumps, and other auxiliary components were not examined. Steam is produced in the boiler at a temperature of 448°C with a capacity of 65 tons/h. In this study, the boiler is divided into sub-systems as furnace, superheater-I, superheater-II, economizer-I, economizer-II, and air heater to detect inefficient points in the boiler.
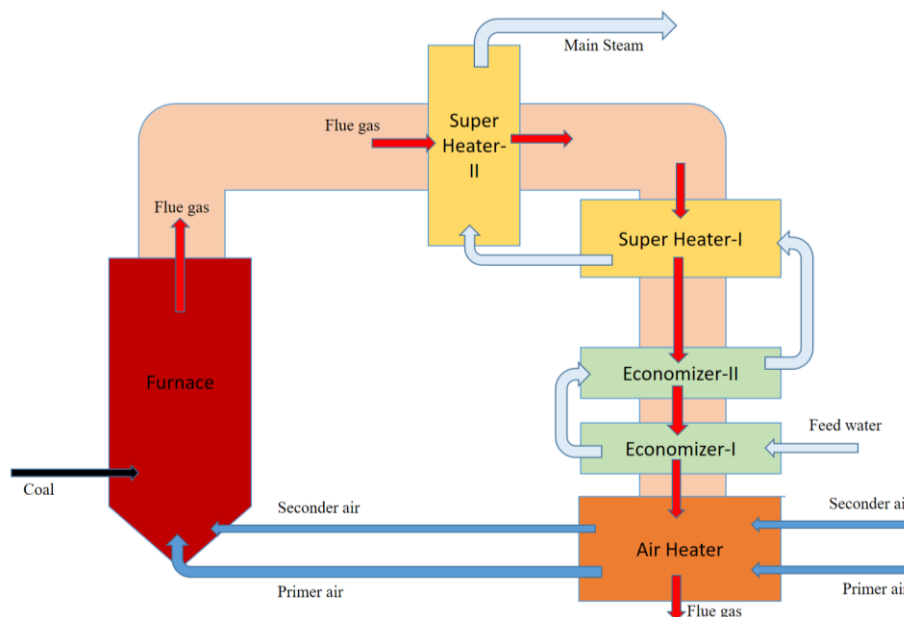
Figure 1. Simple Line Flow Chart of The Analyzed Circulation-Type Fluidized Bed Boiler

3.2. Exergy Analysis

In this part of the study, an exergy analysis model has been created to determine the inefficiencies in the boiler and sub-systems mentioned above. Based on the second law of thermodynamics, the concept of exergy is generally expressed as the usable part of energy. Çengel and Boles (2008) described this concept as the maximum useful work that can be obtained from the system in a certain state.

The exergy analysis of the system examined in this study was carried out under steady-state conditions. The boiler was analyzed not as a whole but divided into its sub-systems. Each of the boiler sub-systems is considered as a control volume. Pressure and exergy losses in piping systems are not taken into account. The dead state conditions are taken as the temperature 25°C and the pressure as 101.325 kPa. However, to observe the change in the boiler's exergy performance according to the actual environmental conditions, the dead state temperature value was based on the seasonal temperature averages of Kütahya. According to this, the dead state temperature values were accepted as 6°C, 16°C, 19°C and 27°C for the winter, autumn, spring and summer seasons, respectively.

Exergy balances should be established in order to determine the exergy efficiency and exergy destruction values of the boiler sub-systems. First of all, the incoming and outgoing flows were determined for each of these sub-systems, and nodal points were formed. The total specific exergy value for each node is calculated using Equation 1.

$$ex_t = ex_p + ex_{ch} + ex_{kn} + ex_{pt} \tag{1}$$

where ex_t is total specific exergy, ex_p is physical exergy, ex_{ch} is chemical exergy, ex_{kn} is kinetic exergy, and ex_{pt} is potential exergy. The kinetic and potential exergy values at the nodes of the sub-systems determined in the boiler have been neglected since they remain low enough not to change the result. The overall flow exergy was calculated using the following equation,

$$ex_p = (h - h_0) - T_0 (s - s_0) \tag{2}$$

In this study, Equation 3 is used to calculate the physical exergy value of air, which is considered as the ideal gas,

$$ex_{p,air} = \left[c_p \left(T - T_0 - T_0 \ln \frac{T}{T_0} \right) + RT_0 \ln \frac{P}{P_0} \right] \tag{3}$$

where R is the ideal gas constant of air, c_p is the specific heat of air, T is temperature, and P is pressure. The index 0 expresses the value in the dead state for temperature and pressure. Chemical exergy calculation of flue gas on a molar basis,

$$\overline{ex}_{ch} = \sum x_k \overline{e}_k^{ch} + \overline{R} T_0 \sum x_k \ln x_k \tag{4}$$

In the equation given above, x_k is the molar fraction, $\overline{e}_k^{ch}$ standard molar chemical exergy of the flue gas components, and $\overline{R}$ is the universal gas constant. The physical exergy of burning the solid coal fuel in the boiler has been neglected because it is very low compared to its chemical exergy. Szargut's chemical exergy equation of coal was used to calculate coal's chemical exergy (Szargut, 2005).

$$ex_{ch} = \varphi (LHV) \tag{5}$$

$$\varphi = 1.0437 + 0.1896 \left(\frac{h}{c} \right) + 0.2499 \left(\frac{o}{c} \right) + 0.0428 \left(\frac{n}{c} \right) \tag{6}$$

LHV represents the lower calorific value of the fuel, h, c, o, and n denotes the fuel elements' ratio, and φ represents the chemical exergy factor. General exergy balance and exergy efficiency expressions are derived for the boiler sub-systems. The equations created are given in Table 1. With these equations' help, each sub-system of the boiler's exergy efficiency and exergy destructions are determined. In addition to these exergy performance evaluation criteria, fuel depletion rate, relative exergy destruction rate, and productivity lack rate criteria were also investigated (Xiang et al., 2004; Balli et al., 2008; Şöhret et al., 2015).

$$\delta_k = \frac{\dot{Ex}_{D,k}}{\dot{Ex}_{fuel,total}} \tag{7}$$

$$\chi_k = \frac{\dot{E}x_{D,k}}{\dot{E}x_{D,Total}} \tag{8}$$

$$\zeta_k = \frac{\dot{E}x_{D,k}}{\dot{E}x_{product,total}} \tag{9}$$

Van Gool (1992) proposed the exergetic improvement potential method to demonstrate how the system's performance can be further improved. Dincer and Rosen (2007) applied the exergy improvement potential method for coal fired power plants.

$$I\dot{P}_k = \left(1 - \eta_{ex,k}\right)\left(\dot{E}x_{in} - \dot{E}x_{out}\right) \tag{10}$$

Table 1. General Exergy Balance and Exergy Efficiency Equations of Boiler Sub-Systems

Sub-systems	Description	Equations	
Furnace	Exergy Balance	$\dot{E}x_{coal} + \dot{E}x_{p.air} + \dot{E}x_{s.air} - \dot{E}x_{fluegas} = \dot{E}x_{dest}$	(11)
	Exergy Efficiency	$\eta_{II-furnace} = \dot{E}x_{fluegas} \Big/ \left(\dot{E}x_{coal} + \dot{E}x_{p.air} + \dot{E}x_{s.air}\right)$	(12)
Superheater-I	Exergy Balance	$\left(\dot{E}x_{fluegas,in} - \dot{E}x_{fluegas,out}\right) + \left(\dot{E}x_{steam,out} - \dot{E}x_{steam,in}\right) = \dot{E}x_{dest.}$	(13)
	Exergy Efficiency	$\eta_{II-s.heater-I} = \left(\dot{E}x_{steam,out} - \dot{E}x_{steam,in}\right) \Big/ \left(\dot{E}x_{fluegas,in} - \dot{E}x_{fluegas,out}\right)$	(14)
Superheater-II	Exergy Balance	$\left(\dot{E}x_{fluegas,in} - \dot{E}x_{fluegas,out}\right) + \left(\dot{E}x_{steam,out} - \dot{E}x_{steam,in}\right) = \dot{E}x_{dest.}$	(15)
	Exergy Efficiency	$\eta_{II-s.heater-II} = \left(\dot{E}x_{steam,out} - \dot{E}x_{steam,in}\right) \Big/ \left(\dot{E}x_{fluegas,in} - \dot{E}x_{fluegas,out}\right)$	(16)
Economizer-I	Exergy Balance	$\left(\dot{E}x_{fluegas,in} - \dot{E}x_{fluegas,out}\right) + \left(\dot{E}x_{steam,out} - \dot{E}x_{steam,in}\right) = \dot{E}x_{dest.}$	(17)
	Exergy Efficiency	$\eta_{II-eco-I} = \left(\dot{E}x_{steam,out} - \dot{E}x_{steam,in}\right) \Big/ \left(\dot{E}x_{fluegas,in} - \dot{E}x_{fluegas,out}\right)$	(18)
Economizer-II	Exergy Balance	$\left(\dot{E}x_{fluegas,in} - \dot{E}x_{fluegas,out}\right) + \left(\dot{E}x_{steam,out} - \dot{E}x_{steam,in}\right) = \dot{E}x_{dest.}$	(19)
	Exergy Efficiency	$\eta_{II-eco-II} = \left(\dot{E}x_{steam,out} - \dot{E}x_{steam,in}\right) \Big/ \left(\dot{E}x_{fluegas,in} - \dot{E}x_{fluegas,out}\right)$	(20)
Air Heater	Exergy Balance	$\left(\dot{E}x_{fluegas,in} - \dot{E}x_{fluegas,out}\right) + \left(\dot{E}x_{p.air,out} - \dot{E}x_{p.air,in}\right)$ $+ \left(\dot{E}x_{s.air,out} - \dot{E}x_{s.air,in}\right) = \dot{E}x_{dest.}$	(21)
	Exergy Efficiency	$\eta_{II-airheater} = \dfrac{\left(\dot{E}x_{p.air,out} - \dot{E}x_{p.air,in}\right) + \left(\dot{E}x_{s.air,out} - \dot{E}x_{s.air,in}\right)}{\left(\dot{E}x_{fluegas,in} - \dot{E}x_{fluegas,out}\right)}$	(22)

4. Results and Discussions

In this section, the calculation results made by applying real data to the exergy analysis model created for the sub-systems of the fluidized bed boiler are given and discussed. Actual data used in the calculations are taken from the boiler control-automation system. Some of the values obtained are as given in Table 2. Coal burned in the boiler is produced in Kütahya Tunçbilek, Turkey. Coal is fed into the combustion chamber at a flow rate of 3.1 kg/s and burned. Elemental analysis values of coal are as given in Table 3 (Yazıcı and Köse, 2019). According to this, the lower calorific value of the fired coal is 5169 kcal/kg. Coal contains 11.8% moisture, 1.04% sulfur and 55.2% carbon. By placing the data given in Table 3 into Equation 5 and Equation 6, the exergy of coal was calculated as 72,568.055 kW. Besides, the primary combustion air at 205°C and the secondary combustion air at 193°C heated in the air heater enter the combustion chamber from different levels. The steam entering the economizer-I at 115°C circulates through the economizer-II, superheater-I, and finally exits the superheater-II as steam at 448°C at 18.06 kg/s.

Table 2. Some Thermodynamic Values of System Components

Items	Value	Items	Value
Furnace			
The mass flow rate of coal	3,1 kg/s	The temperature of seconder air	193℃
Mass flow rate of primer air	13,9 kg/s	Mass flow rate of flue gas	18,6 kg/s
The temperature of primer air	205℃	The outlet temperature of flue gas	840℃
The mass flow rate of seconder air	6,3 kg/s		
Air Heater			
The mass flow rate of primer air	13,9 kg/s	The outlet temperature of seconder air	193℃
The inlet temperature of primer air	35℃	The mass flow rate of flue gas	18,6 kg/s
The outlet temperature of primer air	205℃	The inlet temperature of flue gas	280℃
The mass flow rate of seconder air	6,3 kg/s	The outlet temperature of flue gas	195℃
The inlet temperature of seconder air	30℃		
Super heater-I			
Mass flow rate of flue gas	18,6 kg/s	Mass flow rate of steam	18,06 kg/s
The inlet temperature of flue gas	690℃	The inlet temperature of the steam	226℃
The outlet temperature of flue gas	600℃	The outlet temperature of the steam	352℃
Super heater-II			
Mass flow rate of flue gas	18,6 kg/s	Mass flow rate of steam	18,06 kg/s
The inlet temperature of flue gas	760℃	The inlet temperature of the steam	336℃
The outlet temperature of flue gas	690℃	The outlet temperature of the steam	448℃
Economizer-I			
Mass flow rate of flue gas	18,6 kg/s	Mass flow rate of steam	18,06 kg/s
The inlet temperature of flue gas	380℃	The inlet temperature of the steam	115℃
The outlet temperature of flue gas	280℃	The outlet temperature of the steam	158℃
Economizer-II			
Mass flow rate of flue gas	18,6 kg/s	Mass flow rate of steam	18,06 kg/s
The inlet temperature of flue gas	600℃	The inlet temperature of the steam	158℃
The outlet temperature of flue gas	380℃	The outlet temperature of the steam	230℃

Table 3. Coal's Analysis Values

Items	Unit	Value
C	(%)	55,2
H_2	(%)	3,94
O_2	(%)	6,36
N_2	(%)	2,08
S_2	(%)	1,04
Moisture	(%)	11,81
Lower Heating Value	(kcal/kg)	5149
Higher Heating Value	(kcal/kg)	5408

Flue gas measurements were made with a flue gas analyzer before the electrostatic filter (ESP). Measurement values are given in Table 4. SO_2 at a rate of 0.18%, CO at a rate of 0.02%, and O_2 at a rate of 3.9% were detected in the flue gas. In addition to these, there is 15.2% CO_2 and 80.7% N_2. Mass flow rate, molar flow rate, and molar fractions were calculated for each of the components that make up the flue gas using the percentage ratios.

Table 4. Measurement Values of Flue Gas

Combustion Gaseous	Mass Fraction	Mass flow rates (kg/s)	Molar mass (kg/kmol)	Molar flow rates (kmol/s)	Molar fractions	Standard chemical exergy (Szargut et al., 1988)
O_2	0,039	0,7137	31,99	0,0223	0,036365	3970
CO_2	0,152	2,7816	44,01	0,0632	0,103049	21140
CO	0,0002	0,00366	28,011	0,0001	0,000213	275430
SO_2	0,0018	0,03294	64,063	0,0005	0,000838	303500
N_2	0,807	14,7681	28,013	0,5272	0,859535	720
Total	**1**	**18,3**		**0,6133**	**1**	

Exergy efficiency values of the boiler sub-systems were calculated according to the seasonal temperature averages of Kütahya. As shown in Table 5, the ambient temperature change caused significant changes in some sub-systems' exergy efficiency, while minimal change occurred in others. The highest exergy efficiency was obtained in the combustion chamber at 6℃ ambient conditions. While the superheater-I's exergy efficiency increased in parallel with the increase in the ambient temperature, there was a decrease in the superheater-II's exergy efficiency. There was a 0.3% increase in the efficiency of superheater-I and a 1% decrease in superheater-II. The exergy efficiency

of the furnace decreased from 80.2% at 6°C to 75.4% at 27°C. The decrease occurring here is due to the effect of the post-combustion gases from the increase in ambient temperature. The exergy of fuel burned remains constant at all temperature values. Unlike other sub-systems, there was an increase in exergy efficiency in economizer-I and economizer-II I parallel with the rise in ambient temperature.

Table 5. Exergy Efficiencies Values of Boiler Sub-Systems at Different Ambient Temperature Conditions

Sub-systems	6°C	16°C	19°C	25°C	27°C
Furnace	80,2	77,8	77,2	75,8	75,4
S-Heater-II	41,4	40,9	40,8	40,5	40,4
S-Heater-I	43,6	43,7	43,8	43,9	43,9
Economizer-II	20,1	21,2	21,5	22,1	22,3
Economizer-I	60,1	63,7	64,8	67,1	67,9
Air Heater	21,5	20,4	20,1	19,3	18,9

In order to increase efficiency by making improvements in the examined systems, it is necessary to determine the parts where exergy destruction occurs. In this study, the amount of exergy destruction occurring in the boiler sub-systems at different dead state temperature values was calculated. Calculated values are given in Table 6. At the ambient temperature increasing from 6°C to 27°C, exergy destruction values increased at the combustion rate, while the superheater-I, superheater-II, economizer-I, economizer-II, and air heater decreased. The total exergy destruction in the boiler increased with the increase in the dead state temperature. The highest exergy destruction value occurred at 27°C in the furnace. While the highest exergy destruction at 25°C was 17,796.6 kW in the furnace, the second-highest destruction happened in the economizer-II with 13,530.8 kW. The lowest exergy destruction was in economizer-I with 2031.1 kW.

Table 6. Exergy Destructions Values of Boiler Sub-Systems at Different Environment Temperature Conditions

Sub-systems	6°C	16°C	19°C	25°C	27°C
Furnace	14619,4	16308,5	16807,9	17796,6	18118,9
S-Heater-II	4078,2	4045,5	4035,8	4016,5	4010,1
S-Heater-I	4807,04	4709	4679,7	4621,3	4601,8
Economizer-II	14512,2	13984,71	13839,9	13530,8	13428
Economizer-I	2630,7	2314,5	2219,9	2031,1	1968,4
Air Heater	3499,5	3386,2	3352,5	3285,1	3267,1
Total	**44.147,04**	**44.748,41**	**44.935,7**	**45.281,4**	**45.394,3**

The fuel depletion rate, relative exergy destruction rate, exergetic improvement potential value, and productivity lack were calculated and compared for each fluidized bed boiler sub-system. The results of these calculated exergy performance evaluation criteria are given in Table 7, Table 8, Table 9 Table 10 and Table 11 for 6°C, 16°C, 19°C, 25°C and 27°C, respectively. When these given tables are examined, the best value in terms of relative exergy destruction rate, fuel depletion rate, and productivity lack rate criteria was determined in economizer-I, and the best value for exergetic development potential was determined in economizer-II. In terms of relative exergy destruction rate, fuel depletion rate, and productivity lack rate, the worst value was determined in the furnace and economizer-II, and the worst value was determined in economizer-I for exergetic improvement potential. Within the framework of these results, in case of improvement work for boiler sub-systems, priority should be given to the economizer-II and then to the combustion chamber. In particular, 10,537.8 kW (77.9%) of the exergy destruction of 13,530.8 kW in economizer-II at 25°C can be improved.

Table 7. Exergy Performance Values of Boiler Sub-Systems At 6°C Ambient Temperature Condition

| Sub-systems	δ (%)	χ (%)	IP_k (kW)	ζ (%)
Furnace	12,3	33,1	2897,75	19,6
S-Heater-II	3,4	9,2	2390,58	5,5
S-Heater-I	4,06	10,9	2712,79	6,5
Economizer-II	12,2	32,8	11593,8	19,5
Economizer-I	2,2	5,9	1049,7	3,5
Air Heater	2,9	7,9	2746,45	4,71

Table 8. Exergy Performance Values of Boiler Sub-Systems at 16°C Ambient Temperature Condition

Sub-systems	δ (%)	χ (%)	IP_k (kW)	ζ (%)
Furnace	13,9	36,4	3610,9	22,5
S-Heater-II	3,4	9,04	2389,7	5,6
S-Heater-I	4,01	10,5	2649,6	6,5
Economizer-II	11,9	31,2	11019,4	19,3
Economizer-I	1,9	5,2	840,7	3,2
Air Heater	2,9	7,5	2695,3	4,7

Table 9. Exergy Performance Values of Boiler Sub-Systems at 19°C Ambient Temperature Condition

Sub-systems	δ (%)	χ (%)	IP$_k$ (kW)	ζ (%)
Furnace	14,4	37,4	3836,9	23,3
S-Heater-II	3,45	8,9	2389,5	5,6
S-Heater-I	4	10,4	2630,7	6,5
Economizer-II	11,8	30,8	10868,9	19,2
Economizer-I	1,8	4,9	781,5	3,1
Air Heater	2,86	7,4	2680,4	4,65

Table 10. Exergy Performance Values of Boiler Sub-Systems at 25°C Ambient Temperature Condition

Sub-systems	δ (%)	χ (%)	IP$_k$ (kW)	ζ (%)
Furnace	15,3	39,3	4304,8	25,1
S-Heater-II	3,4	8,9	2389,5	5,6
S-Heater-I	3,9	10,2	2593,2	6,5
Economizer-II	11,6	29,9	10537,8	19,1
Economizer-I	1,7	4,5	668,1	2,8
Air Heater	2,8	7,2	2650,9	4,6

Table 11. Exergy Performance Values of Boiler Sub-Systems at 27°C Ambient Temperature Condition

Sub-systems	δ (%)	χ (%)	IP$_k$ (kW)	ζ (%)
Furnace	15,6	40	4463,5	25,7
S-Heater-II	3,4	8,8	2389,5	5,7
S-Heater-I	3,9	10,1	2580,7	6,5
Economizer-II	11,6	29,6	10427,9	19
Economizer-I	1,7	4,3	631,9	2,8
Air Heater	2,8	7,2	2648,4	4,6

After calculating the exergy destruction values in the boiler sub-systems according to different ambient temperatures, the specific exergy destruction rates were compared. As given in Figure 2, the furnace and economizer-II have the highest relative exergy destruction rate. The increase in the dead state temperature only increased the relative exergy destruction rate of the furnace. It was found that there was a decrease in other parts. While 33.1% of the exergy destruction occurring in the entire boiler at 6°C occurs in the furnace when the ambient temperature rises to 27°C, the ratio increases to 39.9%. In economizer-II, it decreased from 32.8% to 29.6% in the same temperature range. In other parts, minimal amounts of change were experienced.
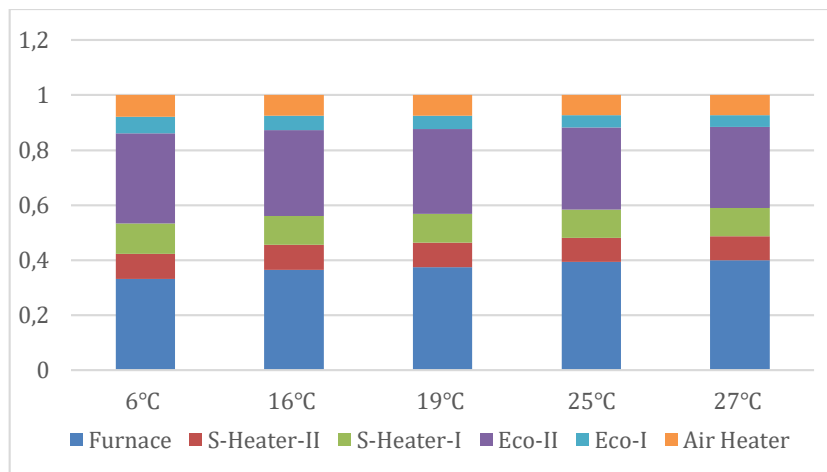
Figure 2. Relative Exergy Destruction of Boiler Sub-Systems at Different Ambient Temperatures

The variation of exergetic improvement potentials of boiler sub-systems at different ambient temperatures is given in Figure 3. The highest exergetic development potential was realized as 11,593.8 kW at 6°C in economizer-II. The lowest value was 631.9 kW in economizer-I at 27°C. As with the specific exergy destruction rate in the boiler sub-systems, the ambient temperature increase had a similar effect on all sub-systems' exergetic development potential value. Although the highest potential was in economizer-II, the highest rate of change occurred in the combustion chamber. This value, which was 2897.7 kW at 6°C, rose to 4463.5 kW with an increase of 54% when it came to 27°C.

Figure 4 and Figure 5 show the productivity lack and fuel depletion rates of the boiler sub-systems at different temperatures, respectively. Depending on the increase in the ambient temperature, the productivity lack ate, and the fuel consumption rate for the furnace and superheater-II of the boiler sub-systems increased, while only the

productivity lack rate increased in the superheater-I. In other parts, on the contrary, there was a decrease. For both criteria, the furnace was mainly affected by the change in the ambient temperature. Thus, the productivity lack rate increased from 19.7% at 6℃ to 25.7% at 27℃. Likewise, the fuel depletion ratio increased from 12.3% at 6℃ to 15.6% at 27℃. Except for the combustion chamber, there was a reduction of 1/5 in productivity lack and ¼ in fuel consumption ratio in the same temperature range in economizer-I. In other parts, the change occurred at very low rates.
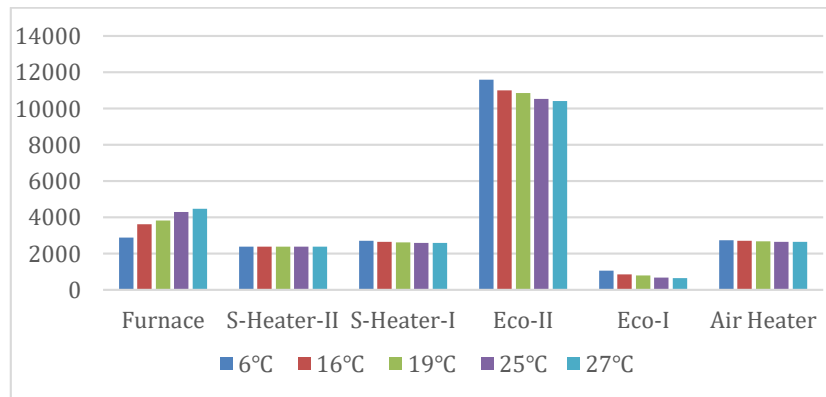
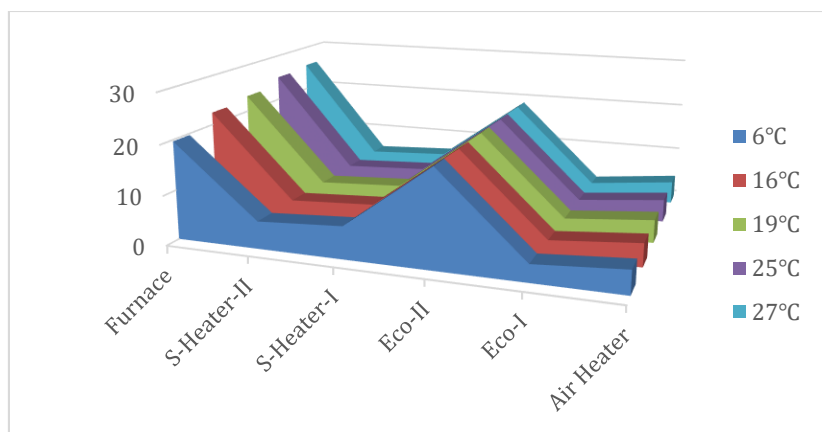**Figure 3.** Exergetic Improvement Potential of Boiler Sub-Systems at Different Ambient Temperatures

Figure 4. Productivity Lack of Boiler Sub-Systems at Different Ambient Temperatures
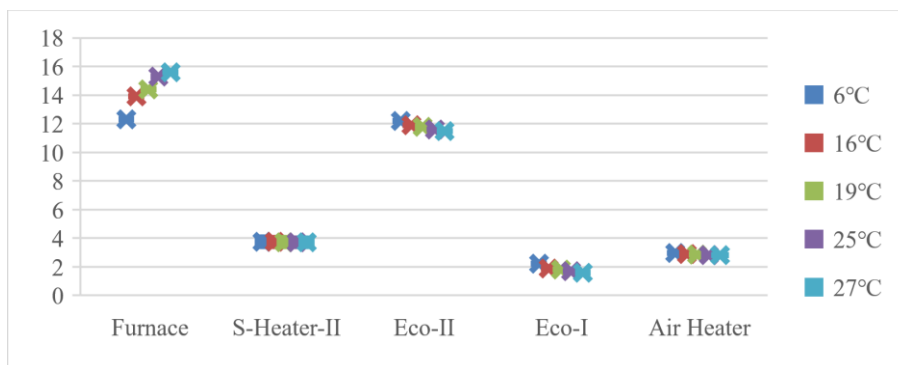

Figure 5. The Fuel Depletion Rate of Boiler Sub-Systems at Different Ambient Temperatures

Figure 6 simply shows the exergy flow in boiler sub-systems at 25℃. Accordingly, the 72,568.055 kW exergy obtained from the coal burned in the combustion chamber is utilized in the boiler's other sub-systems and is destroyed and eventually leaves the 5139.8 kW exergy boiler as flue gas from the air heater.
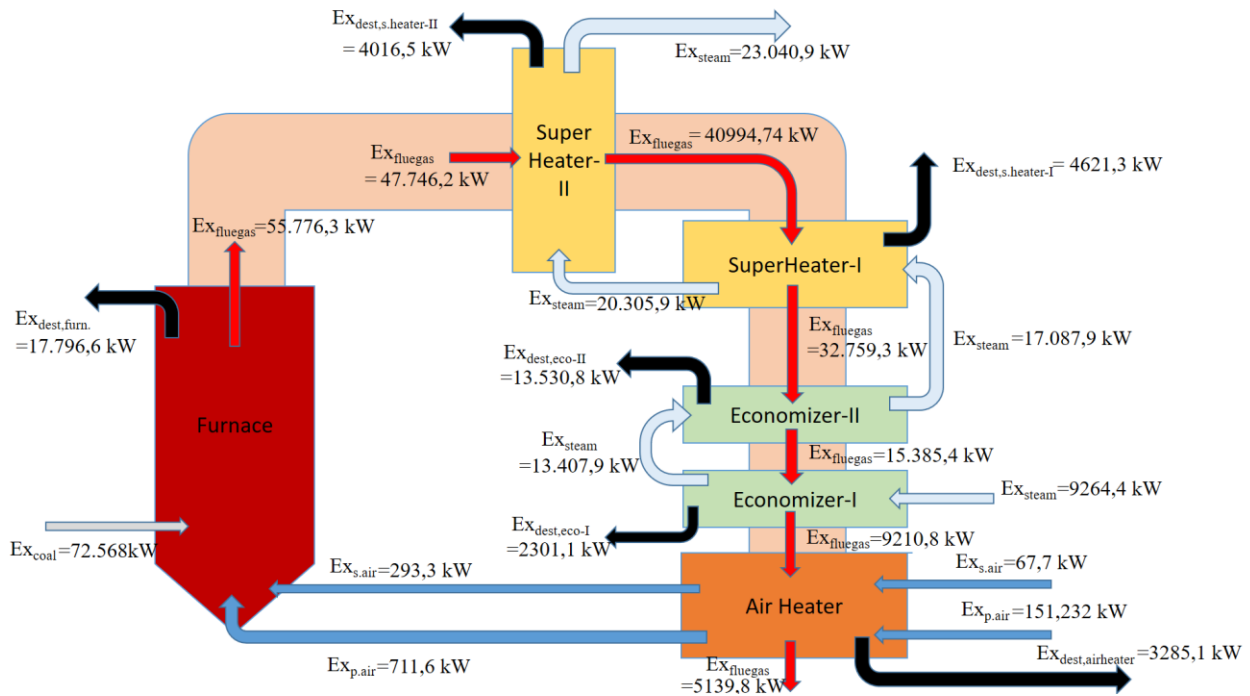
Figure 6. Simple Exergy Flow Diagram For 25°C Dead State Temperature of Boiler Sub-Systems

5. Conclusions

In this study, a circulation-type fluidized bed boiler's exergy performance in a power generation plant was investigated. The boiler was examined not as a whole but by dividing it into its sub-systems. In the analysis, the sub-systems' exergy performance was evaluated in terms of criteria such as exergy efficiency, exergy destruction, fuel depletion rate, relative exergy destruction, exergetic improvement potential, and productivity lack rate. Also, the effect of different dead state temperatures on these exergy performance criteria was compared and discussed. The results obtained are listed below.

• The highest exergy efficiency was realized in the furnace at 6°C with 80.2%. The lowest exergy efficiency was realized in the air heater at 27°C with 18.9%. While the exergy efficiency of superheater-I, economizer-I, and economizer-II increased with the increase in the dead state temperatures, it decreased in the furnace, air heater, and superheater-II.

• The highest exergy destruction occurred in the furnace with 18,118.9 kW at 27°C, the lowest in the economizer-I with 1968.4 kW at the same temperature. With the increase in the dead state temperature, only the exergy destruction that occurred in the furnace increased, while the other parts decreased.

• The highest exergetic improvement potential was realized in the economizer-II with 11,593.82 Kw at 6°C. The lowest value, on the other hand, was 131.9 kW at 27°C in economizer-I.

• The productivity lack was highest in the furnace at 27°C with 25.7%. The other highest productivity lack occurs in economizer-II, while other parts are lower than these two components.

• In the fuel depletion rate criterion, the highest value was at 15.6% in the furnace at 27°C, and the lowest was in the economizer-I at the same temperature.

• Depending on the increase in the ambient temperature, relative exergy destruction and exergetic improvement potential only increased in the furnace, while other parts decreased. There was an increase in the furnace and superheater-II for the fuel depletion ratio and a decrease in the other parts. For the productivity lack, the increase in ambient temperature showed its effect as an increase in the furnace, superheater-I, and superheater-II, and a decrease in the other parts.

• As a result, although the highest efficiency happened in the furnace, the highest exergy destruction happened in this part. In addition, the highest exergetic development potential was realized in economizer-II. If improvement work is to be done to increase efficiency in the boiler, priority can be given to the economizer-II part.

Conflict of Interest

No conflict of interest was declared by the authors.

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