JURNAL TEKNIK MESIN
(JOURNAL OF MECHANICAL ENGINEERING)

VOL. 14, NO. 01, February 2025
https://publikasi.mercubuana.ac.id/index.php/jtm/index
DOI :10.22441/jtmv14i1.15307

Exergy Analysis of Power Plants That Utilize Waste Heat from Cement Plants in West Sumatera

Nadry Heroza[1]**, Adjar pratoto** [1]
[1]Mechanical Engineering Study Program, Faculty of Engineering, Andalas University, Padang, 25175, Indonesia.

E-mail: Adjar.pratoto@eng.unand.ac.id

Abstract--*Exergy analysis of power plants that utilize exhaust heat at Cemen plant was carried out to identify the reliability of the generator as a whole system or for each component that could be used as a basis for optimizing the utilization of exhaust heat and optimizing the operation of the generator to make it more efficient with increasing usage life. The exergy flow and efficiency are calculated for each component, and the data is then used to calculate how much exergy is destroyed in each component. Calculations are also carried out on the system at the time of commissioning in order to get how much the exergy efficiency has changed since the system was operational. The components of this plant include an SP boiler, AQC boiler, turbine, condenser, condensate pump, Flasher, boiler feed pump, and economist. AQC boiler is the component with the highest exergy value that is destroyed, which is 4405.34 kW or 32.98% of the total exergy destroyed in the system. The condensate pump is the component that has the smallest destroyed exergy value of 18.94 kW (0.14%). The system efficiency in January 2012 was 62.60% and decreased in December 2019 to 53.04%, where the overall system exergy efficiency decreased by 9.56% within 7 years of operation.*

Article History:
Received: April 10, 2022
Revised: January 28, 2025
Accepted: January 28, 2025
Published: February 04, 2025

Keywords: *Exergy, exergy destruction, exergy efficiency, power plant waste heat*

1. INTRODUCTION

The reliability of power plant performance is critical to the industry in properly utilizing available energy resources. By assessing the performance, it can be determined which areas or components have poor energy conversion and where improvements are required [1]. This greatly helps improve energy efficiency, minimize operating costs, and increase the industry's profitability. Energy analysis is the most common thermodynamic method used in evaluating plant performance [2]. Another method that can also be used is exergy analysis. Exergy analysis provides the difference between energy loss to the environment and internal irreversibility [3]. Conventional energy analysis methods are based on the first law of thermodynamics relating to the principle of energy conservation. The First Law is concerned with the amount of energy of various forms transferred between a system and its environment and the change in energy stored in the system so that the interaction of work and heat is equivalent to energy transfer [4]. However, the first law sometimes gives inaccurate results to the performance of energy conversion equipment, and optimization through the first law has almost reached saturation level [5]. Also, the first law is concerned with the amount of energy and the change from one form to another, which does not consider the quality aspects of energy [6]. The quality aspect of energy is taken into account by the second law of thermodynamics. The second law provides the necessary means to determine the quality and degree of energy degradation during the process.

Exergy is the maximum amount of work that a system or flow of matter or energy can do from a predetermined initial state until it is equal to its environmental state, i.e., the state of death. Exergy measures the potential of a system or flow's potential to cause change due to imperfect equilibrium relative to the environment. Unlike energy, exergy is not eternal during a process; it is always destroyed. The exergy destroyed is proportional to the entropy caused by irreversibility [6], [7].

Some researchers found that by analyzing energy and exergy, a description of the decline in performance and the magnitude of losses due to exergy destruction as a cause of inefficiency in the plant can be obtained [8], [9]. From the exergy analysis, the highest exergy destruction occurs in boiler and condenser components [10], [11], [12]. This is influenced by the temperature difference factor between the working fluid and its ambient temperature. The components' environmental pressure factors and flow rate also greatly affect the exergy efficiency, energy efficiency, and destruction rate [13].

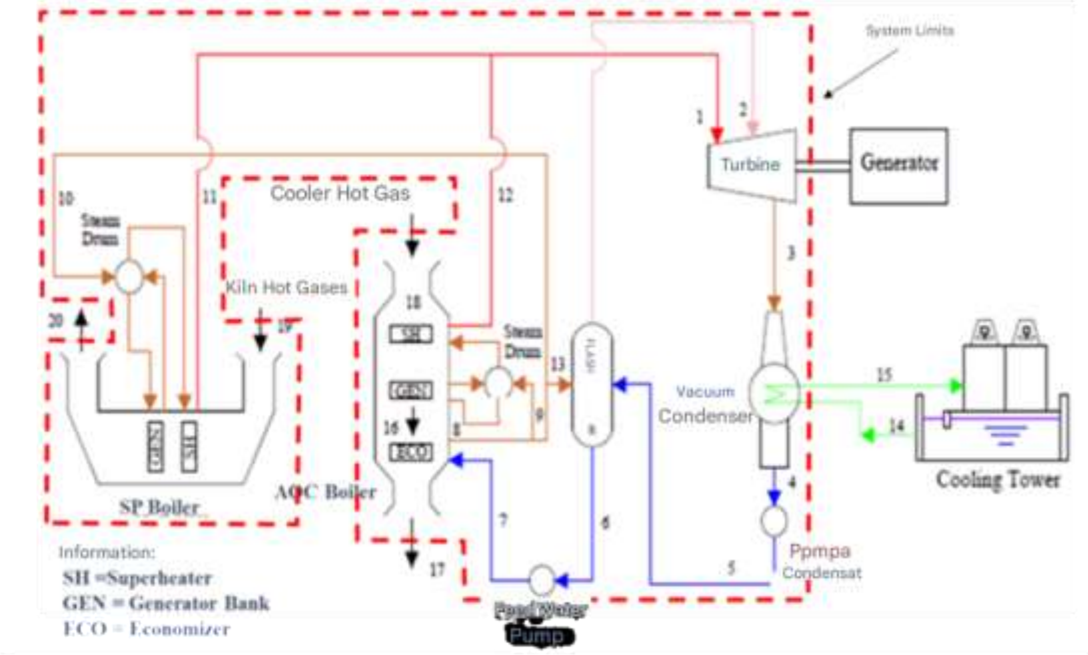


Figure 1. Waste heat power generation system and sytem boundaries for study

In 2009, the Indonesian government, in this case, the Ministry of Industry, and the Japanese government, through the New Energy Technology Development Organization (NEDO), built WHRPG in one of the cement factories in West Sumatra. WHRPG (Waste Heat Recovery Power Generation) is one of the technologies used to produce electrical energy using flue gas from the combustion process or industrial production. This cement plant has a production capacity of 6.3 million tons per year with coal requirements of approximately 760 thousand tons/year, which has the potential to produce considerable CO2 emissions. With the application of WHRPG, CO2 emissions generated can be reduced to increase energy use efficiency, minimize environmental impacts, and slow global warming. In addition, this plant produces around 63.2 GWh of electricity in one year from the heat wasted during the production process [14].

.

2. METHODOLOGY

2.1 System Description

Figure 1 shows the WHRPG system of an 8.5 MW cement plant. The dashed red line is the system boundary used in this study. The system uses two boilers with capacities of 25 tons/hour and 30 tons/hour, respectively. The boiler's heat source comes from the process's waste heat. The first waste heat source is from the suspension preheater, and the second is from the grate cooler. The exhaust gas is used to convert Water into steam, which flows into the turbine to rotate the generator and produce electricity. Boilers that utilize heat from the suspension preheater are referred to as SP boilers (Suspension Preheater boilers), while those that utilize heat from the grate cooler are called SP boilers. grate cooler dinamakan

AQC boiler (Air Quenching Cooler boiler). Other major components of the WHRPG system are the turbine, vacuum condenser, condensate pump, Flasher, boiler feed pump, demineralizer plant and cooling tower. In the process, the feed water in the Flasher is pumped to the Economizer for preheating, then flowed to the Steam drum SP and AQC boiler, and some are returned to the Flasher if the feed water needed in the steam drum SP and AQC boiler are met. The feed water in the steam drum is flowed to the generator bank for the heat transfer process to change the phase from liquid to steam. The steam formed is collected back into the steam drum and flows to the superheater due to the increased pressure in the steam drum. A superheater increases the steam's temperature to become dry steam. Furthermore, the dry steam produced by the SP and AQC boiler flows to the steam turbine to rotate the turbine and generator, producing electricity. The turbine output steam is condensed and cooled by the cooling system and then pumped by the condensate pump to the Flasher. At the Flasher, low-pressure steam production occurs due to the large and sudden pressure change between the economizer output feedwater and the relatively equal flasher pressure. At this level, the paper does not include the demineralized plant and cooling tower (see system boundary in Fig. 1).

2.2 Exergy Analysis

Exergy is a function of enthalpy, temperature, and entropy. Specific exergy can be expressed in the form of the following equation:

$$X = (h - h_0) - T_0\,(s - s_0) \tag{1}$$

X is the specific exergy, h is the enthalpy, h_0 is the dead state enthalpy, T_0 is the dead state temperature, s is the entropy, and s_0 is the dead state entropy. The exergy flow rate can be obtained by multiplying the exergy in Pers. (1) with the mass flow rate as expressed in Eq. where EX is the exergy flow and $\dot{m}$ is the mass flow rate.

For an open and steady-state system, the exergy balance can be written as given by Pers. (3) below:

$$EX = \dot{m}((h - h_0) - T_0\,(s - s_0)) \tag{2}$$

EX is the exergy flow, and $\dot{m}$ is the mass flow rate.

For an open and steady-state system, the exergy balance can be written as given by Pers. (3) below.

$$\sum EX_{in} = \sum EX_{out} + EX_d \tag{3}$$

EX_{in} is the incoming exergy flow, EX_{out} is the outgoing exergy flow, and EX_d is the exergy destroyed. The ratio of annihilated exergy (Y_d) to total annihilated exergy for each component is

$$Y_d = \frac{EX_{d\ komponen}}{EX_{d\ total\ sistem}} \tag{4}$$

However, the exergy efficiency is expressed in the following equation.

$$\eta_{Ex} = \frac{EX_{out}}{EX_{in}} x100 \tag{5}$$

The monthly average data for December 2019 was used to determine the energetic parameters. To evaluate the system's performance over its lifetime, the energetic parameters were compared with the initial conditions, i.e. the conditions at commissioning. The data used was monthly average data in January 2012. The data used includes temperature (°C), pressure (MPa) and mass flow rate (tons/hour). However, enthalpy and entropy are determined using a table of thermodynamic properties and/or an energy balance when temperature data at the point in question is unavailable. The ideal gas approach is used for the evaluation of gas properties.

3. RESULT AND DISCUSSION

Table 1 shows the specific exergy and exergy flow in January 2019, and Table 2 shows the specific exergy and exergy flow in December 2012 at various points in the system.

Table 1. Specific exergy and exergy flow (December 2019)

No	Description	Phase	Temp (oC)	P_{abs} (Bar)	m (kg/s)	Enthalpy (kj/kg)	Entropy (kg/kj.K)	X (kj/kg)	EX (kW)
1	High pressure steam	Vapor	318.0	12.10	10.00	3085.70	7.097	974.24	9742.44
2	Low-pressure steam	Vapour	150.0	2.29	3.64	630.94	1.831	89.64	326.18
3	turbine exit steam	Mixture	45.0	0.09	13.64	2582.49	8.173	150.27	2049.47
4	condensate out condenser	Liquid	52.0	0.91	13.64	217.76	0.730	4.67	63.63
5	Feed Water to the Flasher	Liquid	52.0	7.70	13.19	218.35	0.729	5.55	73.17
6	Feed water goes to the pump	Liquid	73.1	2.28	14.28	306.16	0.993	14.65	209.19

7	Feed Water to the Economizer	Liquid	73.1	31.90	14.28	308.57	0.991	17.65	252.00
8	Economizer output feeds Water	Liquid	188.5	31.90	14.28	801.80	2.219	144.76	2066.83
9	Feed Water to the AQC boiler	Liquid	188.5	31.90	5.81	801.80	2.219	144.76	840.41
10	Feed Water to the SP boiler	Liquid	188.5	31.90	3.75	801.80	2.219	144.76	542.85
11	SH SP boiler output steam	Vapour	345.0	12.20	3.78	3144.20	7.191	1004.72	3795.62
12	SH AQC boiler output steam	Vapour	294.0	12.40	6.22	3032.70	6.995	951.81	5922.38
13	Feed Water back to Flasher	Liquid	188.5	31.90	4.72	801.80	2.219	144.76	683.58
14	Cooling Water to condenser	Liquid	30.3	3.50	694.44	127.31	0.441	0.39	271.94
15	Cooling water output condenser	Liquid	35.1	3.5	694.44	147.37	0.506	1.08	749.72
16	Economizer inlet hot gas	Air	207.0	-	111.11	482.49	2.178	40.58	4509.35
17	Economizer outlet hot gas	Air	99.7	-	111.11	373.40	1.920	8.14	904.46
18	Hot gas enters the AQC boiler.	Air	322.0	-	111.11	601.77	2.400	93.53	10391.76
19	The hot gas in the SP boiler	Air	367.0	-	73.61	649.22	2.477	118.05	8689.35
20	Hot gas out SP boiler	Air	217.0	-	73.61	492.74	2.199	44.53	3277.77

Table 2. Specific exergy and exergy flow at commissioning (January 2012)

No	Description	Phase	Suhu (oC)	Pabs (Bar)	m (kg/s)	Enthalpy (kj/kg)	Entropy (kg/kj.K)	X (kj/kg)	EX (kW)
1	High pressure steam	Vapor	314.0	12.10	8.19	3076.43	7.082	969.58	7945.15
2	Low-pressure steam	Vapour		2.30	3.92	432.69	1.364	30.69	120.20
3	turbine exit steam	Mixture	39.0	0.06	12.11	2572.12	8.347	88.01	1065.93
4	condensate out condenser	Liquid	45.0	0.94	12.78	188.51	0.639	2.54	32.49
5	Feed Water to the Flasher	Liquid	45.0	8.50	12.78	193.35	0.651	3.81	48.62
6	Feed water goes to the pump	Liquid	56.0	2.30	10.94	234.60	0.781	6.30	68.94
7	Feed Water to the Economizer	Liquid	56.0	33.20	10.94	237.23	0.779	9.52	104.17
8	Economizer output feeds Water	Liquid	186.7	33.20	10.94	790.80	2.194	141.21	1545.49
9	Feed Water to the AQC boiler	Liquid	186.7	33.20	3.47	790.80	2.194	141.21	490.32
10	Feed Water to the SP boiler	Liquid	186.7	33.20	5.39	790.80	2.194	141.21	760.98
11	SH SP boiler output steam	Vapour	343.9	12.40	4.61	3138.29	7.174	1004.06	4629.84
12	SH AQC boiler output steam	Vapour	299.3	12.20	3.58	3044.34	7.023	954.98	3422.02
13	Feed Water back to Flasher	Liquid	186.7	33.20	2.08	790.80	2.194	141.21	294.19

14	Cooling Water to condenser	Liquid	26.9	3.50	694.44	113.10	0.394	0.19	129.58
15	Cooling water output condenser	Liquid	31.5	3.50	694.44	132.33	0.457	0.64	443.47
16	Economizer inlet hot gas	Air	200.0	-	111.11	475.32	2.163	37.91	4212.05
17	Economizer outlet hot gas	Air	91.7	-	111.11	365.32	1.898	6.61	734.47
18	Hot gas enters the AQC boiler.	Air	304.2	-	111.11	583.11	2.368	84.34	9371.14
19	The hot gas in the SP boiler	Air	354.7	-	69.44	636.20	2.457	111.15	7718.52
20	Hot gas out SP boiler	Air	221.8	-	69.44	497.67	2.209	46.49	3228.53

Table 3. Exergy destroyed, exergy ratio and exergy efficiency of each component

Peralatan	EX_d **(kW)**		Y_{d} **(%)**		η_{Ex} **(%)**	
	2012	2019	2012	2019	2012	2019
Turbin	2107.02	3167.25	18.40	23.71	73.88	68.54
Kondenser	719.55	1508.07	6.28	11.29	39.81	35.04
Pompa Kondensat	12.67	18.94	0.11	0.14	79.33	79.44
Flasher	153.67	221.38	1.34	1.66	55.17	70.75
Boiler feed pump	94.38	88.19	0.82	0.66	52.47	74.08
Economizer	2036.25	1790.07	17.78	13.40	52.82	62.40
AQC Boiler	5704.96	4405.34	49.83	32.98	42.15	60.78
SP Boiler	621.13	2158.79	5.42	16.16	92.67	76.62

In Fig. 2, it can be seen that the boiler AQC has the largest value of the energy destroyed. Researchers also report the same thing that the largest exergy destroyed is located in the boiler [10], [11]. This occurs due to irreversibility originating from heat transfer in the boiler. In addition, the temperature difference factor between the working fluid and its ambient temperature also affects the value of the energy destroyed. Another factor that affects exergy efficiency, energy efficiency, and

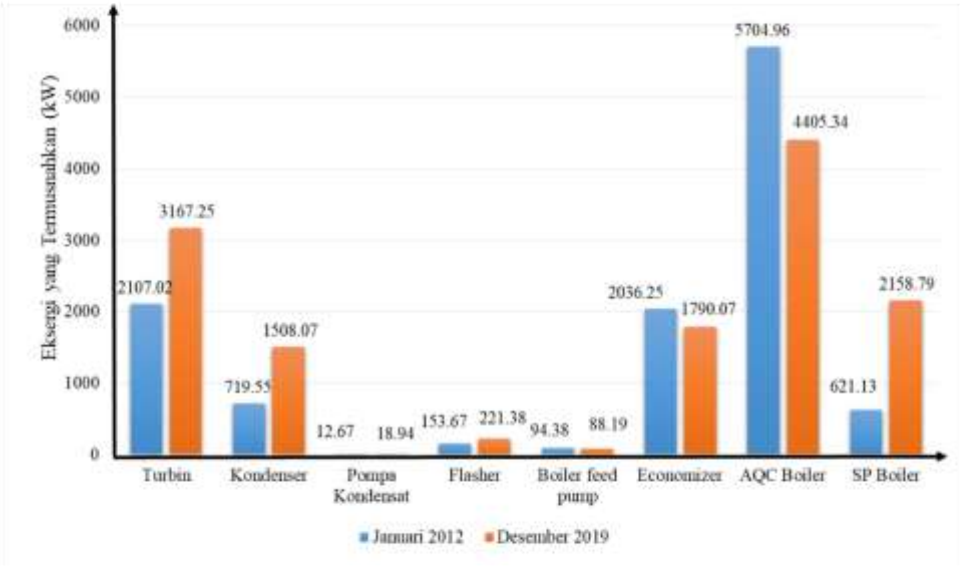


Figure 2. Exergy destroyed in various components of cement plant exhaust heat utilization generation system

destruction rate is the flow rate of the component [13]. In the WHRPG system, the sequence of components with the largest exergy destroyed after the AQC boiler is the turbine, Economizer, SP boiler, condenser, Flasher, boiler feed pump and finally, condensate pump.

When comparing the exergy destroyed in each component between January 2012 and December 2019, it can be seen that there is an increase in the value of exergy destroyed in some equipment such as turbines, condensers, condensate pumps, flashers and SP boilers. In January 2012, the exergy destroyed in the turbine amounted to 2107.02 kW and increased to 3167.25 kW in December 2019. In the condenser, it is also the case where in January 2012, the exergy destroyed was 719.55 kW, and in December 2019, it increased to 1508.07 kW. In January 2012, the exergy destroyed at the condensate pump was 12.67 kW, and in December 2019 increased to 18.97 kW. Likewise, with the Flasher, where in January 2012, the exergy destroyed was 153.67 kW, and in December 2019, it increased to 221.38 kW. For SP boilers, in January 2012, the exergy destroyed was 621.13 kW, and in December 2019, it increased to 2158.79 kW. Unlike the case with the boiler feed pump, Economizer and AQC boiler, where the exergy destroyed in December 2019 is smaller than the exergy destroyed in January 2012, this is due to the influence of the mass flow rate and working temperature entering or leaving the component. In January 2012, the mass flow in and out of the boiler feed pump, Economizer, was 10.94 kg / s, while in December 2019, the mass flow rate of the fluid working on the component was 14.23 kg / s. Likewise, with the mass flow entering and leaving the AQC boiler in January 2012, the feed water entering the boiler was 3.47 kg / s. The steam coming out was 3.58 kg / s, while in December 2019, the feed water entering the boiler was greater than in January 2012, namely 5.81 ks / s and produced 6.22 kg / s of steam. This caused the value of exergy entering, exergy leaving, and exergy destroyed in the boiler AQC in January 2012 to be smaller than in December 2019. In addition, the working temperatures at the boiler feed pump, Economizer and AQC boiler in January 2012 were also smaller than in December 2019.

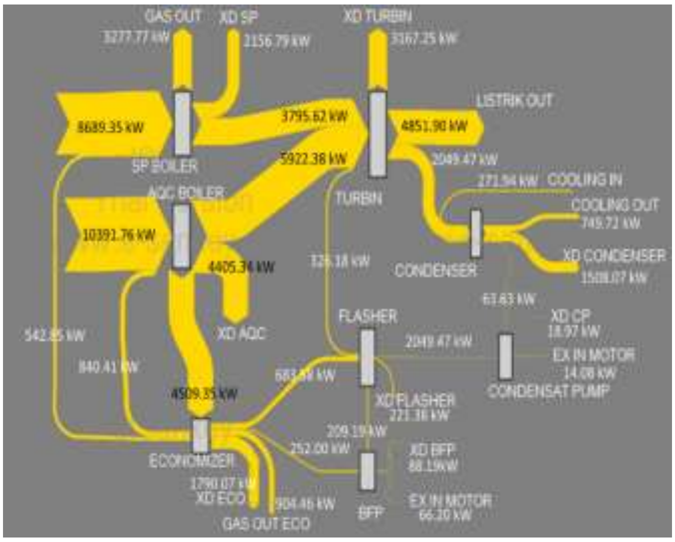
The total exergy destroyed in January 2012 was 11449.63 kW, while in December 2019, it was 13358.02 kW. Comparing the total exergy destroyed in January 2012 and December 2019 revealed an increase of 16.67%, which means that the overall performance of the waste heat utilization generation system is reduced by 16.67%.

In Figure 3, we can see a graph of the ratio of energy destroyed in each component of the waste heat utilization generation system. This ratio of exergy destroyed is the ratio between the exergy destroyed in one component and the total exergy destroyed in the system. Fig. 3 also compares the ratio of exergy destroyed in each component in January 2012 and December 2019. In general, the ratio of exergy destroyed is proportional to the amount of exergy destroyed in each component that has been shown in Fig. 2. When compared to the ratio of exergy destroyed between January 2012 and December 2019, the ratio of exergy destroyed increases with the age of use, namely in the turbine which in January 2012 the ratio of exergy destroyed was 18.40% to 23.71% in December 2019. The same thing also happened to the condenser, condensate pump, Flasher and SP boiler components which sequentially destroyed exergy ratios in January 2012 were 6.28%, 0.11%, 1.34%, 0.82% and 5.42% while the destroyed exergy ratios in December 2019 were 23.71% in the turbine, 11.29% in the condenser, 0.14% in the condensate pump, 1.66% in the Flasher and 16.16% in the SP boiler respectively.

In Fig. 4 can be seen that at the time of commissioning, namely in January 2012, the components of the WHRPG unit with the highest exergy efficiency in order are SP boiler with exergy efficiency of 92.67%, followed by condensate pump 79.33%, turbine 73.88%, Flasher 55.17%, Economizer 52.82%, boiler feed pump 52.47%, AQC boiler 42.15% and condenser 39.81%. Exergy efficiency is influenced by the value of the exergy flow entering and leaving the component and the mass flow rate entering or leaving the component [13]. In December 2019, the exergy efficiency in order the condensate pump with an exergy efficiency of 79.44%, then the SP boiler at 76.62%, the boiler feed pump at 74.08%, the Flasher at 70.75%, the turbine at 68.54%, the Economizer at 62.40%, AQC boiler 60.78% and condenser 35.04%. By comparing the generator output electrical energy to the incoming exergy in the SP boiler and AQC boiler, the WHRPG system efficiency in January 2012 was 62.60% and decreased in December 2019 to 53.04%. Thus, the overall system exergy efficiency decrease is 9.56% within 7 years of operation or on average, there is a decrease in exergy efficiency of 1.06% per year.

The overall WHRPG system exergy efficiency obtained is 53.04%. This value is almost close to the exergy value obtained by previous researchers, where the exergy efficiency value of the power plant system at 75% generator load is 59.64% [7]. Likewise, the value of exergy efficiency in the HRSG (Heat recovery steam generator) system in PLTGU is 60.28% [13].

In Fig. 5, the Sankey diagram explains the distribution of exergy flow and exergy destroyed in each of the main components of the plant. The amount of incoming exergy is 17290.59 kW, sourced from the SP Boiler and AQC boiler. The exergy from the SP boiler of 3795.62 kW flows into the turbine, while the exergy destroyed in the SP boiler is 3167.25 kW. Likewise, in the AQC boiler, the exergy flowed to the turbine amounted to 5922.38 kW, and the exergy destroyed was 4405.34 kW. In the turbine, the incoming exergy of 9718 kW comes out in the form of electrical energy of 4852.90 kW, the exergy destroyed is 3267.25 kW, and the exergy that exits the turbine of 2049.47 kW flows into the condenser. In the condenser, the exergy destroyed is 1508.07 kW



XD = Exergy Destroyed, EX in = Exergy Input

Figure 5. Sankey diagram of cement plant exhaust heat utilization generation system

CONCLUSION

The exergy of each component is directly proportional to the mass flow rate and working temperature. A high working temperature will cause high enthalpy and entropy. In the system studied, the component with the largest exergy destroyed and exergy destroyed ratio is the AQC boiler, which is 4405.34 kW or 32.98% of the total exergy destroyed. The next components with large exergy destroyed are turbine 3167.25 kW (23.71%), SP boiler 2158.79 kW (16.16%), Economizer 1790.07 kW (13.40%), condenser 1508.07 kW (11.29%), Flasher 221.38 kW (1.66%), boiler feed pump 88.19 kW (0.66%) and condensate pump 18.94 kW (0.14%).

The exergy efficiency of the components in order from large to small is the condensate pump with an exergy efficiency of 79.44%, followed by the SP Boiler at 76.62%, boiler feed pump at 74.08%, Flasher at 70.75%, turbine at 68.54%, Economizer 62.40%, AQC boiler 60.78% and condenser 35.04%. At the same time, the overall system exergy efficiency is 53.04%. High exergy efficiency indicates that the component is still in good condition because the exergy destroyed in the component is still small. Within 7 years of operation (2012-2019), there was a decrease in the overall system's exergy efficiency of 9.56%.

REFERENCES

[1] Wu, L., Wang, L., Wang, Y., Hu, X., Dong, C., Yang, Z., et al. 2014. *Component and Process-Based Exergy Evaluation of a 600MW Coal-Fired Power Plant*. Journal of Energy Procedia. Vol. 61, hal. 2097–100.

[2] Saidur, R., Ahamed, JU., Masjuki HH. 2010. *Energy, Exergy and Economic Analysis of Industrial Boilers*. Journal of Energy Policy. Vol. 38 No. 5, hal. 2188-2197.

[3] Aljundi, IH. 2009. *Energy and Exergy Analysis of a Steam Power Plant in Jordan*. Journal of Applied Thermal Engineering. Vol. 29 No. 2–3, hal. 324–328

[4] Kotas, T. 1985. *The Exergy Method of Thermal Plant Analysis.* Florida

[5] Ray, TK., Datta, A., Gupta, A., Ganguly, R.2010. *Exergy-Based Performance Analysis for Proper O&M Decisions in a Steam Power Plant*. Journal of Energy Conversion Management. Vol. 51 No.6, hal. 1333–1344

[6] Cengel, YA., Boles, MA. 2015. *Thermodynamics an Engineering Approach*, 8th ed., Mc Graw-Hill Education, New York

[7] Li, Y., Liu, L. 2012. *Exergy Analysis of 300MW Coal-Fired Power Plant*. Journal of Energy Procedia. Vol. 17, hal. 926–932

[8] Han, T., Wang, C., Zhu, C., Che, D. 2018. *Optimization of Waste Heat Recovery Power Generation System for Cement Plant by Combining Pinch and Exergy Analysis Methods*. Journal of Applied Thermal Engineering. Vol. 140, hal. 334–340

[9] Karyadi, A., Rangkuti, C. 2016. *Analisa Energi Dan Eksergi Pembangkit Listrik Tenaga Uap Banten 3 Lontar*. Seminar NasionalCendekiawan, http://www.trijurnal.lemlit.trisakti.ac.id/index.php/semnas, diakses pada tanggal 10 November 2019

[10] Ahmadi, GR., Toghraie, D. 2016. *Energy and Exergy Analysis of Montazeri Steam Power Plant in Iran*. Journal of Renewable and Sustainable Energy Reviews. Vol. 56, hal. 454–463

[11] Pilankar, KD., Kale R. 2016. *Energy and Exergy Analysis of Steam and Power Generation Plant*. International Journal of Engineering Research and Technology. Vol. 5, hal. 344–350. Available from: www.ijert.org, diakses tanggal 10 November 2019

[12] Ginting, MH., Suryo, MT., Rozi, K. 2013. *Analisa Efisiensi Exergi Boiler di Pltu Unit 3 PT. Indonesia Power Semarang Jawa Tengah*. Jurnal Teknik Mesin UNDIP. Vol. 1 No. 4, hal. 16–25.

[13] Afrianto Y, Utomo M, Kiono B. 2015. *Analisa Efisiensi Exergi pada HRSG (Heat Recovery Steam Generator) di PLTGU*. Jurnal Teknik Mesin UNDIP. Vol. 4 No. 4, hal. 382–388

[14] Anonim. 2012. *JFE Jepang puji operasional WHRPG Semen Padang*, http://www.semenpadang.co.id/en2/?mod=berita&kat=&id=820, diakses tanggal 15 November 2019