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Performance Investigation of Steam Boiler of PLTU Tello Makassar Using Energy – Exergy and Entropy Balance Approach

Marthen Paloboran, Darmawang, Mohammad Ahsan S. Mandra, Syafiuddin Parenrengi

Abstract – *This work aims to investigate the performance of the boiler of a power plant in Tello Makassar. The boiler has generated an electricity power of 50 MW in order to fulfil the electricity needed by people in Makassar city. Performance investigation of the steam generator is very important due to the operation of the boiler is a long time since 1971. The methodology in this study uses energy and exergy analysis as well as the entropy generation approach. The methodology will be applied in all the boiler components, namely Combustion Chamber, evaporator, superheater IA, superheater IB, superheater II, air heater I, economizer, and air heater II. The result shows a significant decrease in the efficiency of energy and exergy for superheater II of 28.98% and 21.28% respectively. The performance of superheater I and air heater II shows energy efficiency above 90%, while the exergy efficiency is lower than 50% for both components. The economizer has been in the middle performance by placed the efficiency of energy and exergy in 64.48% and 48.35% respectively. In general, boiler components are working very well by the reach an energy efficiency of 90% on average. However, by applications, the exergy analysis of the performances of the components does not reach 50%. The result of the study also shows that the energy and exergy efficiency of the boiler are 41.96% and 29.36% respectively. Meanwhile, the heat inducted to the steam turbine is 35.98 MW and 15.12 MW by energy and exergy analysis when the plant has been working on 10.3 MW of a load.* ***Copyright © 2020 Praise Worthy Prize S.r.l. - All rights reserved.***

***Keywords**: Energy, Exergy, Entropy, Steam Boiler, Power Plant*

Nomenclature

Ex	Exergy [kJ]
h	Specific enthalpy [kJ/kg]
u	Internal energy [kJ/kg]
s	Specific entropy [kJ/kg K]
W	Power [kW]
$\dot{m}_f$	Mass flow rate of fuel [kg/s]
$\dot{m}_a$	Mass flow rate of air [kg/s]
SH	Superheater
AH	Air heater
R	Gas constant [kJ/kg K]
Q	Heat loss [kJ]
chWT	Chemical water treatment
BMC	Boiler mole cooler
FWT	Feed water tank
BFP	Boiler feedwater pump
HPH	High pressure heater
Ex_w	Exergy transfered by work [kW]
I	Irreversibility [MW]
m	Mass [kg]
P	Pressure [bar]
V	Volume [m^3]
T	Absolute temperature [kJ/kg K]
v	Velocity [m/s]
ε	Energy efficiency [%]
η	Exergetic efficiency [%]
g	Gravity [m/s^2]
y_i	Moles fraction [%]
NM	Number of moles [kmol]
MW	Molecular weight [kg/mol]
in	Inlet
out	Outlet
surr	Surrounding
o	Reference
gen	Generation
d=des	Destruction
r	Formation of reactant
p	Formation of product

I. Introduction

Electrical is the most used energy resource in supporting daily activities of people, either household consumption and for other industries and business sectors. The usage of electrical energy will continue to grow with the increase in life quality and human population. Furthermore, many power plants in Indonesia still use fossil fuel, and it will be a problem because it produces carbon emissions by its combustion process.

According to General Directorate of Electricity's data, the number of the power plant in Indonesia in the last of

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2016 is about 60.000. 19.000 of the plant are managed by the private sector while 41.000 are under government controls [1]. However, the number of power plants in Indonesia has not been able to meet all the electricity needs of its people especially the ones in remote areas [1]-[22]. The government should continue to increase the electrification ratio to meet the target of 99% in 2019 [1], [2]. In another situation, electrical consumption is expected to increase from about 1,500 to 4,000 GWh in 2015 up to 2024. Mostly is dominated by household needs and followed by commercial, public, and industry sectors [2]. In fulfilling the target, the government is intensifying the construction of many power plants currently. Most of them utilize renewable energy as fuel, for example geothermal and wind energy. Furthermore, the government has a big task to maintain a continuity of electricity distribution to the consumer. Services disruption is commonly caused by fluctuation of oil price, length of the dry season in a year, mismanagement of the plant include inefficiency of plant operational.

Measuring the inefficiency of thermal plants generally uses energy analysis. It is also called an energy audit that consists of direct and indirect methods. However, the performance investigation of the power plant using energy analysis could not give detailed information [3], because the method only identifies the flow of energy that enters and leaves from the system during the process to describe the ideal conditions of the cycle. It has been inspired by the definition of the first law of thermodynamics that energy is eternal, therefore, it cannot be destroyed. The energy can just change from one form to another one. Actually, in every thermodynamic process, loss of energy will occur, caused by the interaction between thermodynamics system and environment. Therefore, the quality of energy in each one of the processes will be different even though the quantity is equal. The exergy method is a useful analysis to make a distinction between heat and work at a different temperature, indicating the locations of energy degradation and recommends a new design for improved operation of the system [23]. The analysis works based on the second law of thermodynamics that can identify energy forms more clearly. Exergy analysis or availability analysis describing the potential energy that is used in the initial process is larger compared to the energy that is reached at the end of the process. Most of the energy potential is destroyed so that exergy is impermanent [4]. The Exergy analysis can explain the quantity of the potential work that can be utilized in a thermodynamic process in detail. This analysis can also determine the location of losses, the kind of losses as well as the number of waste and its losses. That is the reason why this method is very suitable for designing a thermal system. Moreover, using an exergy analysis saving of energy could be done in the existing power plant system [3]-[5]. All the processes that occur naturally, such as the growth of the human from young to old, are irreversible. Entropy will be produced in the irreversibility when an interaction between a thermodynamics system and surroundings occurs. Thus, if the system is isolated from the environment then the increase of energy is equal to zero. Therefore, in the same state the entropy will continue to increase and ceased when the system is in thermodynamics equilibrium, so the entropy reached maximum value [5].

This article is a comparative study on the performance evaluation of the steam generator of PLTU Tello Makassar using energy, exergy, and entropy balance approach methods.

The next section describes the characteristic of the boiler generally and shown the schematic diagram of the steam boiler of Tello Makassar. Sections III and IV present the basic theories and methods of analysis used to solve the problems in this study. Meanwhile, Section V consists of the results and discussion and it contains some of the explanation of the results of this work.

Finally, in Section VI some suggestions to improve the performance of the boiler of PLTU Makassar or its type are revealed.

II. Characteristic and Flow Diagram of Steam Boiler of PLTU Tello

Many power generations in Indonesia consist of a steam power plant with a boiler as primary equipment.

Most of them use coal as fuel, especially for plants with capacity over 75 MW, while the rest use several types of liquid fuels and gases. The steam power plant of Tello is a state-owned electrical company located in Tello village, sub-district of Panakukang, Makassar city that has been generated a power around 50 MW.

The feedwater of the boiler is taken from Tello River which is right next to the plants. Then, the quality of the feed water is improved by using two closed feedwater heaters and an open one. Meanwhile, the quality of steam is improved by employing three levels of superheated steam, namely superheater IA, superheater IB and superheater II. The maximum pressure and temperature of the plants are 37 atmospheres and 450 °C respectively, while the mass flow rate of the steam is 13.05 kg/s.

Fuel systems of the plants are equipped with two main burners for Marine Fuel Oil (MFO) and High-Speed Diesel (HSD). Burner of HSD is used at the beginning of combustion with maximum capacity 500 kg/h. When the steam of heater has been produced the fuel would switch to the MFO fuel by using a Babcocky burner with 1250 kg/h of capacity. A maximum mass flow rate of 4 burners is 4.5 ton/h, while the research has been conducted when the plants have been at 10.3 MW of operating condition. It is important to consider the use of biofuel fuels, specifically biodiesel or bioethanol as substitutes for MFO and HSD fuels in order to reduce the level of carbon emissions in the atmosphere. The advantages and the disadvantages of bioethanol in varied concentrations for the combustion process have been described fully by Paloboran [6]. Meanwhile, the diagram of the flow of working fluid in the steam generator of Tello is started from the economizer, evaporator, superheater 1A, superheater 1B, and superheater 2. Meanwhile, the components, which are passed by the flue gas flow, start from the combustion chamber or burner, evaporator, superheater 2, superheater 1B, superheater 1B, air heater 2, economizer, and air heater 1. The schematic diagram of the working fluid and flue gas in the steam boiler of Tello Makassar is shown in Figure 1, while the schematic diagram of the steam power plant of PLTU Tello Makassar is shown in Figure 5.

III. Literature Review and Methodology

II.1. The First Law of Thermodynamics

The concept of the energy analysis has been developed based on the interaction of all the things in the thermodynamic system that allow the energy transfer process to occur. However, this concept only addresses the amount of energy transferred while calculating the input and output energy flows in the system and its forms of changes.

This postulate is based on the first law of thermodynamics, which is in a closed system. The energy could be converted into two modes namely work, and heat [7]. In general, energy changes in a closed system are expressed by:

$$\left(Q_{in}+W_{in}\right)-\left(Q_{out}+W_{out}\right)=m\left(u_2-u_1\right) \qquad (1)$$

Therefore, energy balance equation in a closed system is:

$$Q_{in}+W_{in}+mu_1=Q_{out}+W_{out}+mu_2 \qquad (2)$$

where the mass balance equation is m_1=m_2=constant and the changes in potential energy and kinetic energy are negligible. Equations (1) and (2) show that the amount of energy that enters and leaves thermodynamics system are equal.

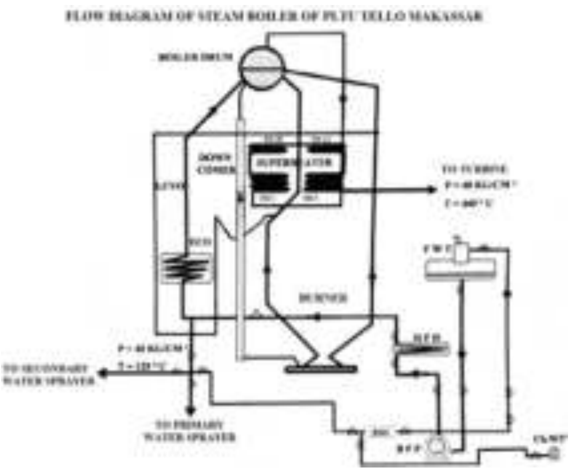

Fig. 1. The schematic diagram of working fluid and flue gas flow in the steam generator of Tello Makassar

This equation also states that there is no loss of energy on the first law of thermodynamic and it cannot be destroyed, but it only changes to other forms. The steady state of the open system, which is mass flow rate, could be across over the control volume, so the energy balance equation is:

$$\dot{Q}_{in}+\dot{W}_{in}+\dot{m}_{in}h_{in}-\dot{Q}_{out}-\dot{W}_{out}-\dot{m}_{out}h_{out}=0 \qquad (3)$$

where the mass balance equation is:

$$dm_{system}/dt=m_{in}-m_{out}=0$$

Meanwhile, on the unsteady state of open system, the energy balance equation is:

$$\frac{dm_{system}}{dt}=\dot{Q}_{in}+\dot{W}_{in}+\dot{m}_{in}h_{in}-\dot{Q}_{out}-\dot{W}_{out}-m_{out}h_{out}$$
$$\frac{d_{system}}{dt}=m_2u_2-m_1u_1 \qquad (4)$$

where the mass balance equation is:

$$m_{in}-m_{out}=\frac{dm_{system}}{dt}=m_2-m_1$$

In practice, there are two methods to audit boiler energy in measure of its performance namely direct and indirect method. One of the most popular versions of this method is based on the standard ASME ptc4.1. In the direct method, the efficiency of the steam boiler is calculated directly by evaluating input and output energy substance. Meanwhile, in the indirect method, every use and loss of energy are calculated separately in order to accumulate the steam boiler efficiency [8].

II.2. The Second Law of Thermodynamics

The second law of thermodynamics defines energy as the maximum works that could be obtained from the system by consideration of its surrounding environment.

Therefore, the result of the exergy analysis depends on the system and environment condition. In the energy analysis, the law of energy conservation becomes the main consideration, while the exergy analysis explains the actual works obtained from unbalanced conditions between a system and its surrounding, so the method expresses the quality of the energy. Based on the definition, the exergy transfer through the works is equivalent to the actual works, or:

$$Ex_W=W \qquad (5)$$

Therefore, the exergy transfer on the boundary condition is:

$$Ex_W=W-W_{surr}=P_o\left(V_2-V_1\right) \qquad (6)$$

The greater contribution of the environment in the energy transfer is the smaller useful work that will be generated during the process in a thermodynamics cycle.

It is caused by the irreversibility of the system, so the heat or energy released to the environment cannot be returned into the system without a special treatment. This condition is signed by an increased entropy generation of the system. Thus, the exergy destruction of the system is equal to the irreversibility of the system, and it is expressed by the equation below:

$$Ex_d = I = T_o S_{gen}$$

Furthermore, the exergy analysis also describes the actual transfer of energy that happens in nature, so this method is appropriate in order to identify sources of energy losses on the components of the thermal plant.

These analyses have involved not only the heat but also a gradient of pressure and temperature on ambient conditions [7], [9]. All the properties of the system on the environment are considered as a reference and it is called dead state. It is signed by the subscript zero wherein on that condition the exergy is equal to zero. According to the statements above, exergy changes in the closed system are:

$$Ex = \left(u - u_o\right) + P_o\left(V - V_o\right) - T_o\left(s - s_o\right) + \frac{v^2}{2} + gz \quad (7)$$

Therefore, the changes of exergy from initial to final condition during the process are described in the formula:

$$\begin{aligned} Ex &= \left(u_2 - u_1\right) + P_o\left(V_2 - V_1\right) - T_o\left(s_1 - s_2\right) \\ &+ \frac{v_2^{\,2} - v_1^2}{2} + g\left(z_2 - z_1\right) \end{aligned} \quad (8)$$

In the stationery closed system, the change of energy of kinetic and potential is equal to zero, while the exergy change from the initial to the final condition in an open system is defined by the equation:

$$Ex = \left(h_2 - h_1\right) - T_o\left(s_2 - s_1\right) \quad (9)$$

The changes in potential and kinetic energy in equation (8) are negligible. Meanwhile, the exergy flow rate in heat transfer from the heat sources of the system with T temperature into the environment can be calculated by the equation:

$$Ex_Q = Q\left[1 - \left(\frac{T_o}{T}\right)\right] \quad (10)$$

where T_o is the temperature of the surround on the dead state. Furthermore, the exergy and the entropy balance both in the close and open system are below:

a) The exergy and entropy balance in the close system:

$$Q_{in}\left[1 - \left(\frac{T_0}{T_s}\right)\right] + m_1 Ex_1 = W_{out} + m_2 Ex_2 + Ex_d \quad (11\text{-a})$$

$$\frac{Q_{in}}{T_s} + S_{gen} + m_1 s_1 = m_2 s_2 \quad (11\text{-b})$$

b) The exergy and entropy balance in the open system:

$$\begin{aligned} &\dot{Q}_{in}\left[1 - \left(\frac{T_0}{T_s}\right)\right] + \dot{m}_{in}\dot{E}x_{in} = \\ &= \dot{W}_{out} + \dot{m}_{out}\dot{E}x_{out} + \dot{E}x_d \end{aligned} \quad (12\text{-a})$$

$$\dot{S}_{gen} + \dot{m}_{in} S_{in} = \dot{m}_{out} S_{out} + \frac{\dot{Q}_{out}}{T_{surr}} \quad (12\text{-b})$$

Most researchers in the power plant field have applied the concept of exergy in order to evaluate the performance of the thermal equipment. The method is a complement of the energy analysis as an ideal analysis of the thermodynamics cycle. Analysis energy and exergy are applied by Leveni [10] in order to investigate a geothermal power plant in Torre Alfina, Italy. The result shows an energy utilization factor of 46.2% and an exergy efficiency of 27.7%. Economizer is the most wasteful plant component according to the exergy analysis that is around 8.6%. Wang Xi et al [11] have evaluated the performance of turbocharging of spark ignition engine with hydrogen-fueled using energy and exergy analysis. The engine efficiency is 59% by energy analysis, while only 35.1% is exergy efficiency. In biodiesel production, the concept of exergy has been applied by Darvishmanesh et al [12] in order to investigate the loss of energy and exergy in that process.

The result shows that the biggest loss of energy occurs in refining biodiesel, while the chemical reaction process is considered the biggest loss of exergy during its process. The study has also showed that exergy analysis will produce the high quality and environmental friendly of the biodiesel. The impact of sunlight concentration ratio on performance of solar cell conversion to electrical power in the PV-TE hybrids system has done by Dianhong Li et al [13]. The work shows that the biggest exergy destruction occurs when solar power is converted into electrical power and thermal energy. The study also shows that the exergy destruction could decrease by replacing the module of the hybrid system. This results as a proof that exergy analysis could detect a source of exergy destruction in the component of the system.

Performance analysis of V groove solar cell collector with varying solar radiation in range 300-1200 W/m^2 using energy and exergy method has been conducted by Fudholi [14]. In this research, a mathematical model is used to describe the balance of energy and exergy as a theoretical basis then it has been compared to the experimental study.

The result shows that the average PVT energy efficiency is 65.52% and 66.73% for theoretical and experimental studies, respectively. Meanwhile, the average PVT Exergy efficiency is 12.91% and 12.66% for theoretical and experimental studies, respectively.

Another result has showed that the mass flow rate and solar radiation have the lowest efficiency of energy and exergy.

However, the mass flow rate has a high performance based on the energy analysis.

In the internal combustion engine, the concept of exergy has been applied by Sohret [15] in order to analyze the influence of ignition timing and compression ratio on the performance of the engine using hydrogen-fueled.

The result shows that exergy destruction has increased and engine performance has decreased when the ignition timing is more advanced. Furthermore, indicative and effective thermal efficiency obtained from the experiment is equal to the result of thermodynamics analysis both on energy and exergy analysis. In the gasification process, the exergy method has been applied by Chen et al [16] in order to compare the cold gas efficiency and the exergy efficiency that is gained from supercritical water coal gasification (SCWG) technology and O_2-H_2O gasification technology. Both technologies are applied to produce high hydrogen syngas of coal. As a result, in higher coal water slurry, the gasification process has produced more carbon than the combustion one so cold gas efficiency and exergy efficiency for both technologies have increased. In general, the performance of SCWG technology is higher than O_2-H_2O technology in both CGE efficiency and exergy efficiency.

Martinez et al [17] have studied three-stage of process i.e. torrefaction, pyrolysis, and pyrolysis with catalyst and compared it using energy and exergy analysis. The result shows that independent pyrolysis obtains higher exergy efficiency than other processes, while pyrolysis with the catalyst is the lowest one. The result of the researchers above shows that exergy analysis would give a wider perspective about energy utilization in the thermodynamics system than energy analysis. The energy analysis that is based on the first law of thermodynamics just explains the initial and the final condition of the energy transfer process. The exergy analysis of the second law of thermodynamics can investigate the causes and sources of energy loss, and make an analysis and new design that can improve the efficiency of component and an energy system. The exergy analysis is also most oriented to the environment so the balance of the system and the environment can be maintained.

Similar to the research above, in this work a comparative study on the boiler performance of PLTU Tello Makassar will be conducted using energy, exergy, and entropy analysis. The standard data, as an operational data of the plant, is presented in Table I.

IV. Energy, Exergy and Entropy Balance of The Boiler

IV.1. Energy Balance in the Combustion Chamber

The process of energy conversion in the combustion chamber is a thermochemical reaction where the potential energy of the fuel is converted into heat through the combustion process.

The amount of potential energy of fuel that is converted into the heat influenced by the air-fuel ratio. AFR is obtained from the chemical reaction balance equation. Meanwhile, the combustion chamber of the boiler is fueled by Marine Fuel Oil (MFO) that has 41.012 kJ/kg of HHV wherein 1 kg of fuel in percent weight contained are 84.91 of carbon, 10.89 of hydrogen, 3.32 of sulphur, 0.246 of nitrogen, 0.464 of oxygen and 0.1 of water.

TABLE I
OPERATIONAL CONDITION OF THE PLANT AT LOAD OF 10.3 MW

No.	Components	Fluids	$m\left[\frac{kg}{s}\right]$	P_{in} [bar]	P_{out} [bar]	T_{in} [K]	T_{out} [K]
1	Furnace /Comb. Chamber	Fuel	1.25	15.0038		363	
		Air	18.49*	0.03727		573	
		Gases	19.74*		1.01315		2140
2	Evaporator	Water	14.72	56.88		455	
		Steam	13.06	38.25	38.25		520.66
		Gases	19.74	1.01315	1.01296	2140	1273
3	Superheater II	Steam	13.06	38.25	38.25	636	713
		Gases	19.74	1.01296	1.01276	1273	945
4	Superheater IB	Steam	13.06	38.25	38.25	568	668
		Gases	19.74	1.01276	1.01247	945	802
5	Superheater IA	Steam	13.06	38.25	38.25	556	593
		Gases	19.74	1.01247	1.01158	802	738
6	Air Heater II	Air	18.49	0.04119	0.03727	398	573
		Gases	19.74	1.01158	1.0108	738	585
7	Economizer	Water	14.72	56.88	56.88	435	455
		Gases	19.74	1.0108	1.00962	585	493
8	Air Heater I	Air	18.49	0.04511	0.04119	308	398
		Gases	19.74	1.00962	1.00835	493	413

*) Parameters are calculated

The percentage of oxygen in the flue gas is 1.7% thus, it will be considered in the calculation of the chemical reaction that is written in the equation below:

$$\overbrace{\frac{0.8491}{12}C+\frac{0.1089}{2}H_2+\frac{0.0332}{32}S+\frac{0.00246}{28}N_2+\frac{0.00464}{32}O_2}^{FUEL}+\overbrace{a\left(O_2+3.76N_2\right)}^{AIR}\rightarrow\overbrace{bCO_2+dSO_2+eO_2+fN_2+gH_2O}^{PRODUCT}\qquad(13)$$

Then the reaction coefficient found by equating each of elements on the left and right of the reaction equation as well as considering the percentage of O_2 in the flue gas of 1.7%, so the final reaction equation is:

$$\overbrace{0.07076C+0.0545H_2+0.00104S+0.0000879N_2+0.000145O_2}^{FUEL}+\overbrace{0.1072\left(O_2+3.76N_2\right)}^{AIR}\rightarrow\qquad(14)$$

$$\rightarrow\overbrace{0.07076CO_2+0.0545H_2O+0.00104SO_2+0.403072N_2+0.00832O_2}^{PRODUCT}$$

Based on Equation (14), moles fraction and molecular weight of each of the elements in the fuel, air and combustion gas are given in Table II. The energy balance in the combustion chamber (furnace) will be obtained from the formula as follows:

$$\overbrace{\sum\left(N_r\bar{h}_{f^o}-N_p\bar{h}_{f^o}\right)}^{a}+\overbrace{\sum N_r\left(\bar{h}-\bar{h}^o\right)}^{b}=\overbrace{\sum N_p\left(\bar{h}-\bar{h}^o\right)}^{c}+Q_{loss}\qquad(15)$$

where $\overbrace{\sum\left(N_r\bar{h}_{f^o}-N_p\bar{h}_{f^o}\right)}^{a}$ is the energy of fuel or LHV of fuel, $\overbrace{\sum N_r\left(\bar{h}-\bar{h}^o\right)}^{b}$ is the energy of reactant, $\overbrace{\sum N_p\left(\bar{h}-\bar{h}^o\right)}^{c}$ is the energy of combustion product, $\bar{h}$ is the enthalpy of elements, $\bar{h}_f$ is the enthalpy formation of substance, N is the moles of elements The values of enthalpy formation and absolute enthalpy of the elements are taken from thermochemical properties of the selected substances as shown in Table III. By equation (15), the energy of fuel is:

$$h_A=\left[\sum\left(N_r\bar{h}_{f^o}-N_p\bar{h}_{f^o}\right)\right]x\dot{m}_f$$

$$h_A=0-\begin{bmatrix}0.0707583\dfrac{\text{kmol}}{\text{kg}}\left(-393520\dfrac{\text{kJ}}{\text{kmol}}\right)_{CO_2}\\+0.05445\dfrac{\text{kmol}}{\text{kg}}\left(-241820\dfrac{\text{kJ}}{\text{kmol}}\right)_{H_2O}\end{bmatrix}1.25\frac{\text{kg}}{\text{s}}$$

$$h_A=51264.88\text{ kW}$$

Then, the energy of air is:

$$h_B=\left[\sum N_r\bar{h}=\left(N\bar{h}\right)_{N_2}+\left(N\bar{h}\right)_{O_2}\right]x\dot{m}_f$$

$$=10727.262\text{ kW}$$

The energy of combustion product is:

$$h_c=\sum N_P\bar{h}=\begin{bmatrix}\left(N\bar{h}\right)_{CO_2}+\left(N\bar{h}\right)_{H_2O}\\+\left(N\bar{h}\right)_{SO_2}+\left(N\bar{h}\right)_{N_2}+\left(N\bar{h}\right)_{O_2}\end{bmatrix}\dot{m}_f$$

$$=51748.934\text{ kW}$$

The loss of energy in the Combustion Chamber is:

$$Q_{out}=\left(h_A+h_B\right)-h_C=10243.209\text{ kW}$$

Fig. 2. Fluid flow in the Combustion Chamber

TABLE II
NUMBER OF MOLES (NM), MOLES FRACTION (yi) AND MOLECULAR WEIGHT (WM) OF THE ELEMENTS

Subs	Fuel			Air			Subs	Gas		
	NM [kmol]	y_i [%]	*MW* [kg/kmol]	*NM* [kmol]	y_i [%]	*MW* [kg/kmol]		*NM* [kmol]	y_i [%]	*MW* [kg/kmol]
C	0.07076	55.945	6.7134				CO_2	0.07076	13.16	5.79
H_2	0.0545	43.051	0.8610				H_2O	0.0545	10.13	1.82
N_2	0.0000879	0.070	0.0195	0.403072	79	22.12	N_2	0.403072	74.97	20.99
S	0.00104	0.820	0.2625				SO_2	0.00104	0.19	0.12
O_2	0.000145	0.115	0.0367	0.10720	21	6.72	O_2	0.00832	1.55	0.50
Tot	0.126479	100	7.8930	0.5103	100	28.84	Tot	0.53773	100	29.224

TABLE III
ENTHALPY FORMATION, ABSOLUTE ENTHALPY AND ENTROPY OF SUBSTANCE

Fluids	Elements	$\bar{h}_f$ (kJ/kmol)	$\bar{h}$ (kJ/kmol)	$\bar{h}_o$ (kJ/kmol)	$S(T,P_o)$ kJ/kmol K	S_o kJ/kmol K
Fuel	C	0	0	0	0	5.75
	H_2	0	10349.15	8468	136.28	130.574
	S	0	0	0	0	0
	N_2	0	10558.6	8669	197.24	191.502
	O_2	0	10600.41	8682	210.85	205.033
Air	N_2	0	16752	8669	210.684	191.502
	O_2	0	17066.7	8682	224.879	205.033
Gases	CO_2	-393520	109291.2	9364	313.303	213.685
	H_2O	-241820	89811	9904	268.057	188.720
	SO_2	-	-	-	0	0
	N_2	-	69864.2	8669	254.408	191.502
	O_2	-	73192	8682	271.220	205.033

IV.2. Entropy Balance in the Combustion Chamber

Entropy balance in the Combustion Chamber will be calculated by Equation (12-b) or written detailed in the formula below:

$$\begin{aligned} S_{gen} &= \left(S_{prod} + {}^{Q}\!/_{T_b} \right) - S_{react} \\ &= \left(\sum N_p \bar{S}_p + {}^{Q}\!/_{T_b} \right) + \sum N_r \bar{S}_r \end{aligned} \tag{16}$$

where $\sum N_r \bar{S}_r$ contains entropy of fuel and air, each one calculated as follows. The entropy of fuel in the Combustion Chamber is:

$$\begin{aligned} S_A &= \left[\sum N_i \left(\bar{S}\{T,P_o\} - \{S_o - R\ln y_i P_m\} \right) \right] \times \dot{m}_f \\ S_A &= (N_i)_C \left[\bar{S}(T,P_o) - (S_o - R\ln y_i P_m) \right]_C \\ &+ (N_i)_{H_2} \left[\bar{S}(T,P_o) - (S_o - R\ln y_i P_m) \right]_{H_2} \\ &+ (N_i)_S \left[\bar{S}(T,P_o) - (S_o - R\ln y_i P_m) \right]_S \\ &+ (N_i)_{N_2} \left[\bar{S}(T,P_o) - (S_o - R\ln y_i P_m) \right]_{N_2} \\ &+ (N_i)_{O_2} \left[\bar{S}(T,P_o) - (S_o - R\ln y_i P_m) \right]_{O_2} \times \\ &\times \dot{m}_f \\ S_A &= 2.4523 \ \frac{\text{kW}}{\text{K}} \end{aligned} \tag{17}$$

$P_m = P_{abs}/P_{atm}$= partial pressure of fuel, R=8.314 kJ/kmol=constant of universal gases, y_i=fraction of substances. Then, the entropy of the air is calculated by the formula below:

$$\begin{aligned} S_B &= \left[\sum N_i \left\{ \bar{S}(T,P_o) - S_o \right\} \right] \times \dot{m}_f \\ S_B &= \begin{bmatrix} (N_i)_{N_2} \left\{ \bar{S}(T,P_o) - S_o \right\}_{N_2} \\ +(N_i)_{O_2} \left\{ \bar{S}(T,P_o) - S_o \right\}_{O_2} \end{bmatrix} \times \\ \times \dot{m}_f &= 12.3240 \ \frac{\text{kW}}{\text{K}} \end{aligned} \tag{18}$$

Then, the entropy of the combustion product or gases is:

$$\begin{aligned} S_C &= \left[\sum N_i \left\{ \bar{S}(T,P_o) - (S_{298} - R\ln y_i P_m) \right\} \right] \times \dot{m}_f \\ S_C &= (N_i)_{CO_2} \left[\bar{S}(T,P_o) - (S_o - R\ln y_i P_m) \right]_{CO_2} + \\ &+ (N_i)_{H_2O} \left[\bar{S}(T,P_o) - (S_o - R\ln y_i P_m) \right]_{H_2O} + \\ &+ (N_i)_{SO_2} \left[\bar{S}(T,P_o) - (S_o - R\ln y_i P_m) \right]_{SO_2} + \\ &+ (N_i)_{N_2} \left[\bar{S}(T,P_o) - (S_o - R\ln y_i P_m) \right]_{N_2} + \\ &+ (N_i)_{O_2} \left[\bar{S}(T,P_o) - (S_o - R\ln y_i P_m) \right]_{O_2} \times \dot{m}_f \\ S_C &= 42.2457 \ \frac{\text{kW}}{\text{K}} \end{aligned} \tag{19}$$

Meanwhile, the entropy production in the energy loss is calculated by the equation:

$$\frac{Q_{out}}{T_b} = \frac{10243.209 \ \text{kW}}{298 \ \text{K}} = 34.3732 \ \frac{\text{kW}}{\text{K}} \tag{20}$$

where T_b is the wall temperature that is assumed equivalent to the temperature of surround (T_s). The entropy generation in the Combustion Chamber will be taken from Equation (12-b) and simplified by the formula below:

$$\begin{aligned} S_{gen} &= \sum S_{out} - \sum S_{in} = \\ &= \left(S_C + \frac{Q_{out}}{T_b} \right) - (S_A + S_B) \\ &= 61.8426 \ \frac{\text{kW}}{\text{K}} \end{aligned} \tag{21}$$

Therefore, the irreversibility in the Combustion Chamber is:

$$\begin{aligned} I &= T_o S_{gen} = 298 \ \text{K} \times 61.8426 \ \frac{\text{kW}}{\text{K}} = \\ &= 18429.083 \ \text{kW} \end{aligned} \tag{22}$$

IV.3. Exergy Balance in the Combustion Chamber

The exergy analysis in the Combustion Chamber is developed from equation (12-a), so the exergy of fuel is calculated by the formula below:

$$\begin{aligned} \psi_A &= \begin{bmatrix} (h - h_o) - 298(S - S_o) \\ = \left(h_A - \sum N h_o \right) - 298 S_A \end{bmatrix} \dot{m}_f \\ \psi_A &= 49955.221 \ \text{kW} \end{aligned} \tag{23}$$

where:

$$\begin{aligned} \sum N h_o &= \left[N_i (h_o) \right]_C + \left[N_i (h_o) \right]_{H_2} + \\ &+ \left[N_i (h_o) \right]_S + \left[N_i (h_o) \right]_{N_2} + \left[N_i (h_o) \right]_{O_2} \end{aligned} \tag{24}$$

Then, the exergy of the air is calculated by the following formula:

$$\psi_B = \begin{bmatrix} (h-h_o)-298(S-S_o) \\ =\left(h_B-\sum Nh_o\right)-298\,S_B \end{bmatrix}\dot{m}_f \qquad (25)$$

$$\psi_B = 1523.535\ kW$$

The exergy of the combustion product is:

$$\psi_C = \left[\left(h_C-\sum Nh_o\right)-298\,S_C\right]\dot{m}_f \qquad (26)$$

$$\psi_C = 33198.346\ \text{kW}$$

The Values of $\sum N_i h_o$ in Equations (25) and (26) are obtained in the same way of Equation (24) and then, the exergy in energy losses is:

$$Q_{out}\left(1-\frac{T_o}{T_b}\right)=0 \qquad (27)$$

where $T_b=T_o$, so the exergy destruction in the Combustion Chamber is obtained from the exergy balance (Eq. (12-a)) that is:

$$\begin{aligned} X_{Des} &= X_{in}-X_{out}= \\ &=(\psi_A+\psi_B)-\left[\psi_C+Q_{out}\left(1-\frac{T_o}{T_b}\right)\right] \qquad (28) \\ X_{Des} &= 18280.421\ \text{kW} \end{aligned}$$

The result in equations (22) and (28) show that irreversibility in a thermal system is identical to the exergy destruction. The result also reveals that the entropy generation in the actual process is proportional to the irreversibility of the system during the process [8].

IV.4. Energy, Exergy and Entropy Analysis in Heat Exchanger

The economizer, the evaporator, the superheater and the air heater are considered as a heat exchanger, so the energy balance of the components is:

$$h_{in}=h_{out}+Q_{out} \qquad (29)$$

The exergy balance in each one of the heat exchangers of the boiler is obtained by the formula:

$$\begin{aligned} X_{Des} &= X_{in}-X_{out}-\left(1-\frac{T_o}{T_b}\right)Q_{out} \\ X_{Des} &= \left[(h_{in}-h_o)-T_o(S-S_o)\right]_{in}- \\ &\quad \left[(h_{out}-h_o)-T_o(S-S_o)\right]_{out}- \qquad (30) \\ &\quad \left(1-\frac{T_o}{T_b}\right)Q_{out} \end{aligned}$$

The entropy balance is expressed by the equation:

$$S_{gen}=\left[\sum S_e-\sum S_i\right] \qquad (31)$$

Therefore, the irreversibility in the heat exchanger of the boiler is calculated by equation (22). The energy efficiency of the boiler will be calculated by the equation as follows:

$$\varepsilon=\frac{\text{Temp.change of fluid stream}}{\text{maxpossible temp.change of stream}} \qquad (32)$$

Meanwhile, the exergetic efficiency is:

$$\eta=\frac{\text{Exergy released}}{\text{Exergy absorbed}} \qquad (33)$$

V. Result and Discussion

The complete analysis of energy, exergy, and entropy in all the components of the boiler of PLTU Tello Makassar is shown in Table IV. Generally, these results show that the exergy efficiency is lower than energy efficiency on all the components. It is because exergy analysis expresses an actual condition of the process, while energy analysis is only the identification of a process on initial and final condition. Exergy analyses are an actual process in which the environment is involved in the heat transfer process. In the actual process, irreversibility will happen in each one of the components of the boiler. The irreversibility in a thermodynamic cycle will generate entropy so the performance of the system decreases. Therefore, the exergy analysis is more accurate to detect the sources of dissipation and loss of energy. The highest energy efficiency on the components of the boiler is obtained on air heater I (AH-I) which is about 98.57% Table IV).

This component is designed to increase the combustion air temperature in the first level by using the flow rate of combustion gas before out coming from the stack as flue gas. It is described that almost all the gases that come from the economizer are utilized and absorbed by the combustion air.

However, the exergy analysis has found different results where the useful energy of the AH-I is only a part of its energy efficiency that is around 43.96%. It is an indication that there is 56.04% or 0.325 MW of the energy of the combustion gases unable to be absorbed by the air in AH-I. It goes out to the environment and becomes the exergy destruction. The irreversibility in air heater I (AH-I) could be reduced by extending the pipeline of the air or, so, the heat of the gas can be absorbed by the air maximally. Meanwhile, the component of the boiler that consistently shows the best performance either in energy and exergy analysis is superheater IB (SH-IB) those are 97.09% and 72.48% respectively. This result indicates that both the construction and the placement of the SH-IB in the boiler have been right.

TABLE IV
FLOW RATE BALANCE OF ENERGY, EXERGY AND ENTROPY IN THE BOILER OF PLTU TELLO MAKASSAR

Components	Working Fluid	Energy				Exergy				Entropy (kW)				
		h_{in}	h_{out}	Q_{out}	ε	X_{in}	X_{out}	X_{des}	η	S_{in}	S_{out}	$\frac{Q_{out}}{T_b}$	S_{gen}	I
			MW		%		MW		%		kW/K			MW
CC / Fur	Fuel	51.265			83,48	49.955			64.49	2.45				
	Air	10.727				1.524				12.32				
	Gases		51.749	10.243			33.198	18.280			42.25	34.37	61.84	18.249
EVA	Water	11.367			97.80	1.963			51.95	31.78				
	Steam		34.030				11.860				74.60			
	Gases	51.749	28.575	0.511		33.198	14.149	9.152		42.25	28.40	1.71	30.69	9.145
SH-II	Steam	40.840	43.209		28.98	15.037	16.307		21.28	86.79	90.48			
	Gases	28.575	20.398	5.808		14.149	8.183	4.697		28.40	20.99	19.49	15.76	4.697
SH-IB	Steam	38.536	41.839		97.09	13.915	15.538		72.48	82.82	88.46			
	Gases	20.398	16.997	0.0990		8.183	5.944	0.616		20.99	17.09	0.33	2.07	0.616
SH-IA	Steam	38.070	39.409		90.15	13.891	14.265		41.16	81.34	84.58			
	Gases	16.997	15.512	0.146		5.944	5.035	0.535		17.09	15.15	0.49	1.79	0.535
AH-II	Air	7.396	10.727		96.62	0.258	1.524		67.07	5.39	12.32			
	Gases	15.512	12.065	0.117		5.035	3.149	0.621		15.15	9.92	0.39	2.09	0.621
ECO	Water	10.074	11.367		64.48	1.532	1.963		48.35	28.89	31.78			
	Gases	12.065	10.060	0.712		3.149	2.257	0.461		9.92	6.18	2.39	1.55	0.461
AH-I	Air	5.714	7.396		98.57	0.0034	0.258		43.96	0.60	5.39			
	Gases	10.060	8.353	0.0245		2.257	1.677	0.325		6.18	2.40	0.08	1.09	0.325

Therefore, the thermal heat transfer process could be going on in maximal to change the working fluid from the saturated liquid into the saturated vapor at constant pressure. Based on the two conditions explained above, the components of the boiler that require repairs and redesign to improve their performances are superheater II (SH-II). It is because these components have the lowest energy and exergy efficiency among the other equipment. Moreover, the loss of exergy on the tools could be overcome by reducing the temperature of combustion [18]. Therefore, many burners are in the design of the boiler as one of the alternative preferences to reduce the temperature of gases. As mentioned previously, Table III also shows that the efficiency of the Second Law of Thermodynamics (SLT) is lower than the efficiency of the First Law of Thermodynamics (FLT) on all of the boiler components. According to the FLT, the energy absorbed by the system would not be lost but it only changes in another energy form. Meanwhile, the SLT has stated that the heat flows spontaneously on the material from the high to low temperature in one certain direction; it does not flow in the opposite one. Related to the heat engines, it is impossible that a heat engine that works in a cycle would absorb heat from a reservoir and convert it entirely into work or other forms of energy.

Those statements prove that the thermal heat transfer process, which occurs spontaneously, would be followed by the irreversible, which is signed by the increase of entropy generation. Therefore, not all of the heat is absorbed by the engine will be changed to work, but a part of it would be wasted into the environment. Exergy losses not only occur caused by the temperature difference between cold and hot fluids is too far [18], [22], even if it is in the close interval will cause the same thing. The case is shown in air heater 1 and economizer where both are at a small temperature difference, namely 185 °C and 150 °C respectively. The two cases mentioned previously prove that the exergy analysis is the actual condition of a thermal process in a system where the thermal equilibrium between the system and its environment will determine the flow of exergy losses.

The loss and absorb of energy and exergy in boiler components of PLTU Tello Makassar are illustrated in Sankey and Grassman diagram as described in Figure 3 and Figure 4. Finally, the balance, the rate, and the overall efficiency of energy and exergy in components of the steam generator of PLTU Tello Makassar on South Sulawesi, Indonesia are shown in Table V and Table VI.

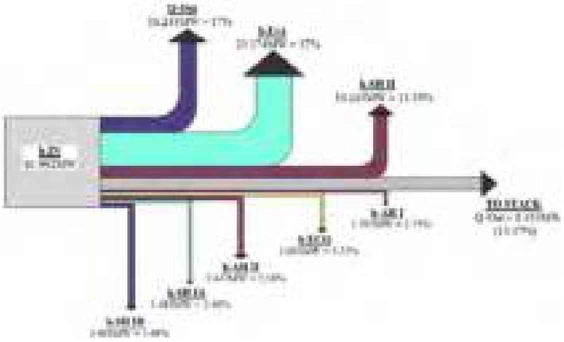

Fig. 3. Sankey diagram of absorption and loss of energy in the components of Boiler of PLTU Tello Makassar

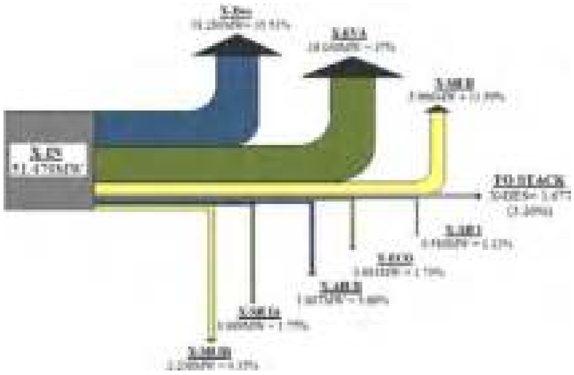

Fig. 4. Grassman diagram of absorption and loss of exergy in the components of Boiler of PLTU Tello Makassar

TABLE V
BALANCE AND RATE OF ENERGY IN COMPONENTS OF STEAM GENERATOR

Components	Energy balance (MW)			Rate of energy (%)
	Input	Loss	Output	
Fuel	61.992	0	-	100
CC/Furnace	-	10.243	-	16.52
Evaporator		0.511	-	0.987
Superheater II		5.808	-	0.113
Superheater IB		0.099	-	0.160
Superheater IA		0.146	-	0.236
Air Heater II		0.117	-	0.189
Economizer		0.712	-	1.149
Air Heater I		0.0245	-	0.040
To Stack		8.353	-	13.474
Total		26.014	-	41.963
To Turbine	-	-	35.978	58.037

TABLE VI
BALANCE AND RATE OF EXERGY IN COMPONENTS OF STEAM GENERATOR

Components	Exergy balance (MW)			Rate of exergy (%)
	Input	Loss	Output	
Fuel	51.479	0	-	100
CC/Furnace	-	18.280	-	35.510
Evaporator		9.152	-	17.778
Superheater II		4.697	-	9.124
Superheater IB		0.616	-	1.197
Superheater IA		0.535	-	1.039
Air Heater II		0.621	-	1.206
Economiser		0.461	-	0.896
Air Heater I		0.325	-	0.631
To Stack		1.677	-	3.528
Sub-Total		36.364	-	70.639
To Turbine	-	-	15.115	29.361
Total	51.479	36.364	15.115	100.000

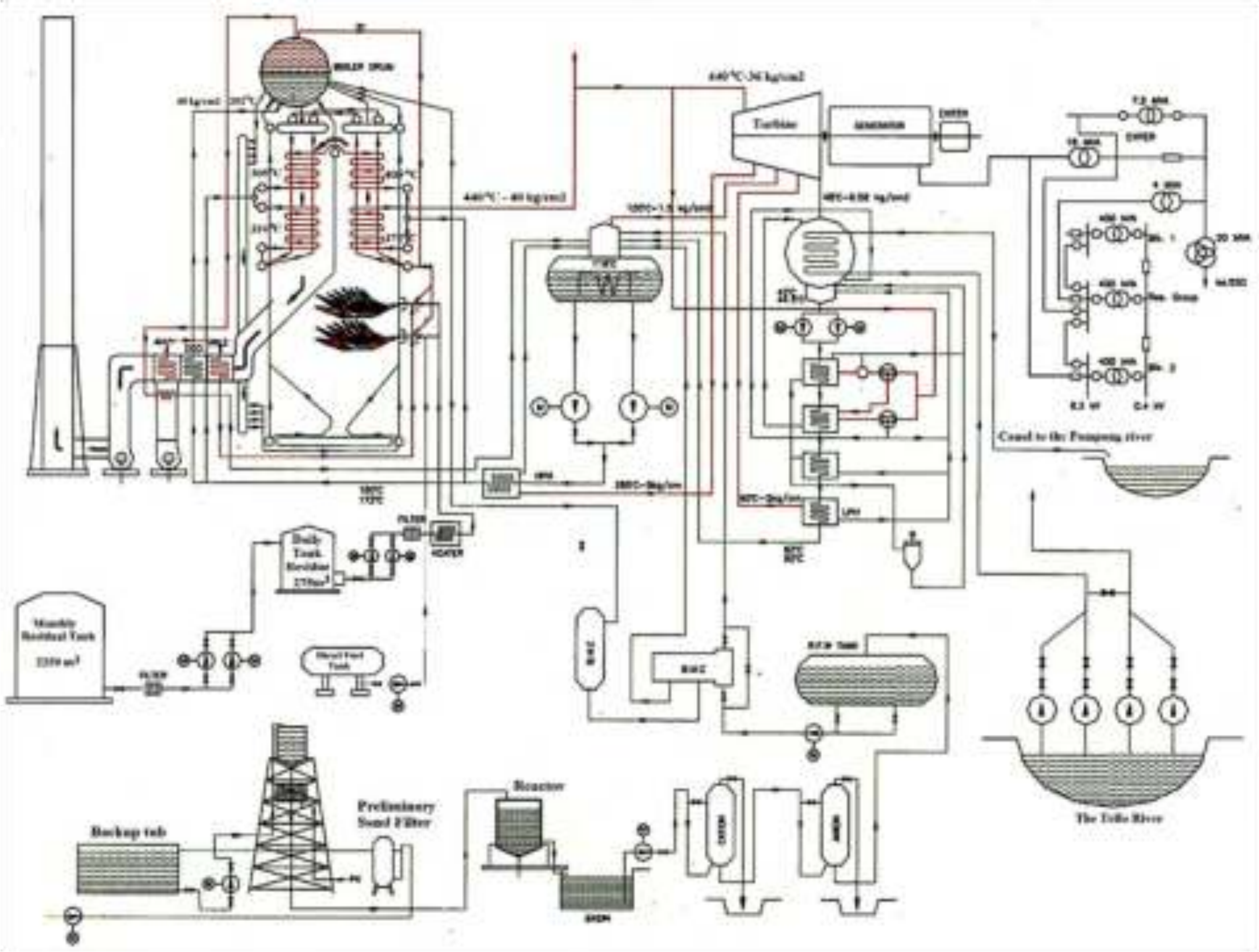

Fig. 5. Schematic diagram of the steam power plant of PLTU Tello Makassar, South Sulawesi-Indonesia

VI. Conclusion

It is proven that empirically, the exergy destruction rate in each component of the power generation system is equal to the irreversibility of the component. It has been evidenced in this work, whose results are shown in columns 9 and 15 of Table IV. Irreversibility would increase when the entropy production increased or the quantity of the irreversible is equivalent to the entropy generation in a dead state. The entropy generation in the thermal power plant system is caused by a chemical reaction in the combustion process, friction, and temperature change during fluid flow and heat transfer process in the tools [19]-[21]. In this study, it has been proven that the highest exergy loss is in the Combustion Chamber. This study has also found out that the highest inefficiency of boiler components both in energy and exergy analysis is SH-II. Approximately 70% up to 80% of heat from the evaporator is wasted to the surrounding so that increasing entropy of the environments. The other components that generate exergy efficiency below 50% are SH-IA, AH-I, and economizer. It means that the equipment should be repaired in both redesign and relocation. The surface extends of heat transfer tools and placed it in the right position are an important consideration. The method will increase the heat transfer process and reduce friction so the heat absorption will be maximized. This study results prove that the energy analysis based on the first law to thermodynamics or energy audit method shows an ideal cycle of a thermodynamic process. The second law of the thermodynamics shows an actual cycle of a thermodynamic process. Thus by applying the exergy analysis, the deviation of the ideal cycle from its actual cycle could be clarified. Moreover, by the exergy method, the sources of energy degradation can be found so it will give the recommendation to redesign, repair, and rearrange even replacing the components of the steam generator, which is in low performance.

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