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Energy and Exergy Analysis of 6 MW Gas Power Plant at BOB PT. Bumi Siak Pusako - Pertamina Hulu

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ABSTRACT

BOB PT. Bumi Siak Pusako – Pertamina Hulu is Indonesian Operator Company that uses gas power plant for Pekanbaru Coastal Plan (CPP) block. The 4x6 MW energy capacities must follow energy, exergy, economics analysis and environmental impacts due to CO² emission and exhaust gas temperature. From the analysis, the gas power plant thermal efficiency is 42.85%, exegetic efficiency is 33.22% with the largest exergy loss of 18.7 kW in combustion chamber, 7.1 kW in compressor, and 2.69 kW in gas turbine with total cost loss due to exergy destruction of 2,537.52 \$/hour. The cost loss value is 1362.45 \$/hour for compressor, 1,962.28 \$/hour for combustion chamber, and 212.79 \$/hour for gas turbine. The exhaust emission is 0.21 kg/s, forest area required to absorb pollution is 11.63 ha, exhaust heat released is 1913.51 kW. This study indicates that the analytical method carried out can be developed and applied comprehensively to generating facilities in Indonesia.

KEYWORDS: *Energy, Exergy Destruction, Exergy-economic, Exergy-environment.*

NOMENCLATURE

AFR	*Air to fuel ratio*
LHV	*Low Heating Value*
$\bar{c}_p$	*Mole base specific heat* (kJ/ kmol. K)
C_p	*Specific heat at constant pressure* (kJ/ kg. K)
k	*Specific heat ratio*
T_0	*Environmental temperature (K)*
T_1	*Compressor intake air temperature (K)*
T_2	*Compressor outlet air temperature (K)*
T_3	*Temperature (K)*
T_4	*Turbine intake air temperature* (K)
T_5	*The temperature of the fuel entering the chamber burn (K)*
P_0	*Environmental air pressure* (bar)
P_1	*Compressor intake air pressure* (bar)
P_2	*Compressor outlet air pressure* (bar)
P_3	*Pressure during the combustion process* (bar)
P_4	*Exhaust pressure (exhaust process)* (bar)
R	*Gas constant (kJ/kg. K)*
$\dot{m}_{ud}$	*Air mass flow rate* (kg/s)
$\dot{m}_{bb}$	*Mass flow rate of fuel* (kg/s)
$\dot{m}_g$	*Mass flow rate of gas* (kg/s)
W_k	*Compressor work* (MW)
$\dot{Q}_{in}$	*Heat enters, combustion chamber/unit time* (MW)
η_k	*Compressor efficiency* (%)
W_{GT}	*Gas turbine work* (MW)
η_T	*Gas turbine efficiency* (%)
$W_{GT,net}$	*Gas turbine clean work* (MW)
η_{th}	*Energy efficiency (Efficiency thermal)* (%)
$\dot{X}_1$	*Exergy at state 1 (before compression)* (MW)
$\dot{X}_2$	*Exergy at state 2 (after compression)* (MW)
$\dot{X}_3$	*Exergy at state 3 (after combustion)* (MW)
$\dot{X}_4$	*Exergy at state 4 (after expansion)* (MW)
$\dot{X}_5$	*Exergy at state 5 (on fuel intake combustion chamber)* (MW)
$\dot{X}_{fuel}$	*Exergy in* ($\dot{X}_{in}$) (kW)
$\dot{X}_{produk}$	*Exergy out* ($\dot{X}_{out}$)(kW)
$i_{destroyed}$	*Loss of exergy* ($\dot{X}_{destroyed}$) (kW)
η_{II}	*Exergy efficiency* (%)
PEC	*Purchased Equipment Cost* (\$)
C_d	*Debt* (\$)
C_{dn}	*The cost of paying the loan for the n- year*(\$)
U_i	*Fuel price* (\$)
$F\ (c)$	*Fuel cost* (\$)
$\dot{C}_k$	*Annual Levelized Cost* (\$/*tahun*)
$\dot{Z}_k$	*Cost Component Rate* (\$/jam)
$\dot{C}_{D,k}$	*Cost Destruction Component* (\$/*jam*)
C_l	*The price of electricity produced by power plant* (\$/*kWh*)
C_{bb}	*Fuel Prices* (\$/*kWh*)

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$\dot{m}_{exh}$ *Exhaust Gas Mass Flow Rate (kg/s)*
Q_{exh} *Heat Dissipated to the Environment (kW)*

1.0 INTRODUCTION

The requirement of power generation efficiency is very necessary so that the utilization of incoming energy more optimal at low costs. One of the power plants that is widely used is the gas power plant because it is simpler, easy to assemble, small in dimensions and can cope with peak loads and the fuel to power the plant is easy to obtain because Indonesia is rich in natural gas sources.

Power plants in Indonesia are not only used for domestic purposes but also as a source of energy for the industrial sector, including the upstream oil and gas industry, which is the oil and gas mining industry. Several companies operating in Riau contribute as the largest oil producer in Indonesia, which requires electricity from their own power plant to run their operations. One of these companies is BOB PT. Bumi Siak Pusako – Pertamina Hulu as the operator of the Pekanbaru Coastal Plan (CPP) block.

The Indonesian government trusts the management of this CPP block to BOB PT. Bumi Siak Pusako – Pertamina Hulu with a cost-recover cooperation system with a management contract period of every 20 years starting from August 8, 2002 to August 8, 2022 [1]. To run the production operation of this CPP block, a large amount of electrical energy is required. Derived from a gas power plant with a capacity of 4x6 MW, which has been operating for 10 years, where during the operation of this plant, energy analysis carried out using the first law of thermodynamics, namely energy cannot be created and cannot be destroyed, so that the analysis carried out is only a quantitative descriptive of energy utilization. Similar studies have been carried out by several researchers, such as the exergy analysis of the 20 MW gas power plant in Pekanbaru, Riau, with 33.77 % thermal efficiency, 32.25 % exergy efficiency and the largest exergy destruction is in the combustion chamber 71.03% or 21.98 MW and the lowest exergy of 12.33% or 3.15 MW on the compressor [2].

Exergoeconomic analysis for gas turbines in Iran revealed that the combustion chamber is the largest source of exergy destruction and with exergoeconomic analysis obtained 40.75% efficiency and an average production cost of 439 million usd/year [3]. Energy and exergy analysis carried out at power plants Qena Paper Industry Egypt, at the maximum load the largest exergy loss was in the boiler 78.9%, the deaerator 3.6% and the condenser 3.1% [4].

In Malaysian power plants, the results of the analysis obtained are that the largest exergy is in the combustion chamber at 67.5% and energy efficiency in the combustion chamber is 61.8% [5]. A similar analysis combined with environmental analysis was carried out at the power plant in Rivers State Nigeria, where the energy efficiency is 63.62% and the exergy is 58.46 %, the largest exergy is in the combustion chamber of 15% of the total exergy that is destroyed with an energy cost of $ 0.0109 per kWH, environmental analysis shows a specific CO2 emission of 141.2 kg/MWh with the effect of exhaust gas temperature on the environment an average of 60.4 ^{o}C [6].

Energy, exergy, economic and environmental analysis has also been carried out at a power plant in Tehran, Iran, where the energy efficiency is 8.12% with the amount of exergy destruction is 7233 kJ/kWh and the exhaust gas temperature affecting the environment is 2.53% [7]. Analysis of the Aliabad Katoul power plant in northern Iran, exergy efficiency is 45.1% with a cost of 1.91-2.21 US$/s with a CO2 emission level of 0.89 kg/MWh where the pressure ratio on the compressor is 12-16 bar with CO2 emissions of 0.71 kg/MWh with exhaust gas temperatures of 900 K-1400 K [8].

The analysis carried out in accordance with the second law of thermodynamics is the concept of exergy, which is a form of maximal useful work from an environmental condition under certain conditions. The efficiency of the second law of thermodynamics also states that the lost exergy is work lost in the form of heat, pressure and mass caused by an irreversible process [9]. The thermodynamic unit converts economic quantities in the form of operational costs, which can also be called work-economy where with the development of theory thermo-economics can calculate operating costs due to increased operating costs due to reduced useful-exergy during irreversibility of energy transformation [6]. Due to lost exergy and causing inefficiency of a system and to measure its effectiveness, the exergy-economic method should be considered to find the concept of cost optimization [10]-[15]. Investigating and evaluating the place where the largest exergy destruction occurs and calculates the cost of the exergy destruction (loss of exergy).

BOB PT. Bumi Siak Pusako – Pertamina Hulu runs production operations in two main fields, namely Zamrud and Pedada. It is hoped that the points of lost exergy losses and the costs of these losses and their impact on the environment can be known so as to reduce daily operating costs and increase company revenue. For the company's production operations, it costs USD 95,213.12 / day or USD 34,752,788,8 / year so it is necessary to do an energy and exergy analysis that will be very useful as an effort to reduce the electricity cost.

The energy and exergy analysis research carried out based on the identification of problems in gas power plants in several research literature studies that had been carried out elsewhere [16]-[31]. Therefore, this paper aim is to evaluate the lost exergy point in a 6 MW gas power plant at BOB PT. Bumi Siak Pusako - Pertamina Hulu.

2.0 METHODOLOGY

The research was conducted during the period from November 2021 to January 2022 at the BOB CPP power plant facility. The research approach is descriptive quantitative by describing the object or subject according to actual conditions to describe the facts and characteristics of the research object and quantitatively by using mathematical variables. Identify the waste of each sub-process of the research object.

The focus of research on energy and exergy analysis is to get the value of efficiency and energy waste that occurs in equipment in each sub-process. The primary data taken is equipment operation data in the form of operating input and output parameters, exergy flow, and the form of exergy transfer (heat, work and mass).

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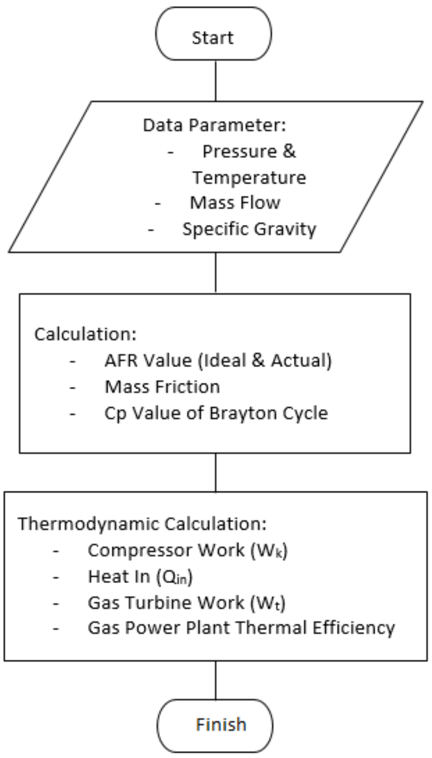

Figure 1: Energy calculation flowchart

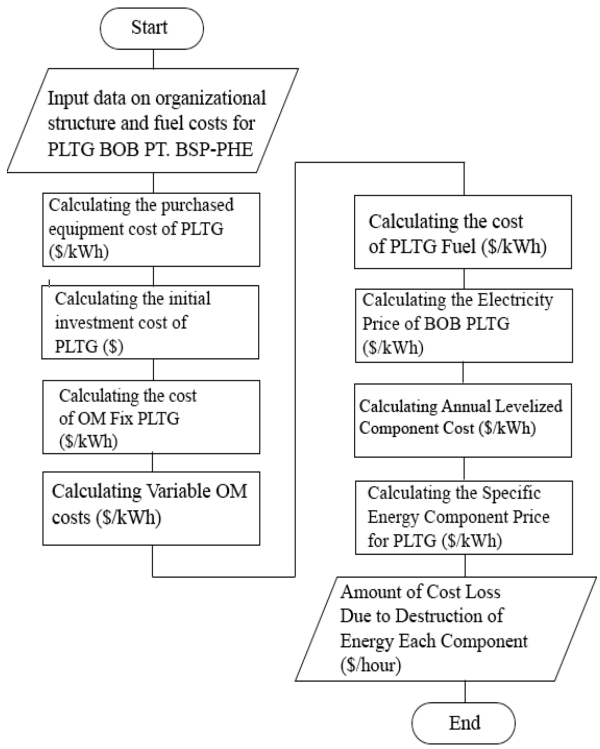

Figure 2: Exergo-economic calculation flowchart

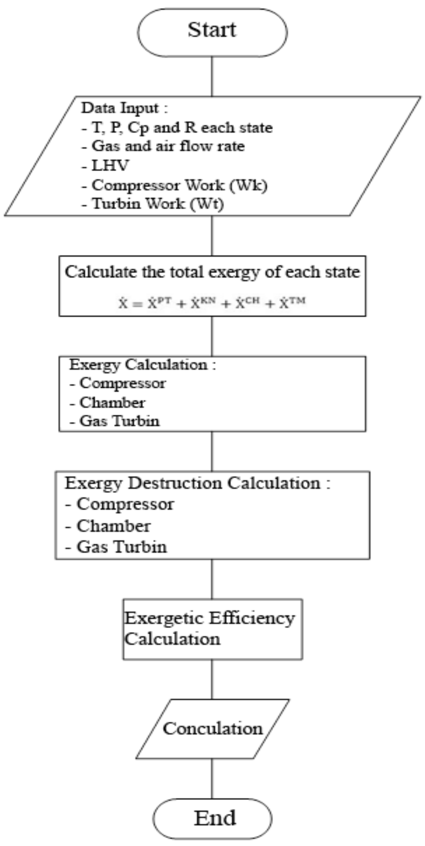

Figure 1: Exergy calculation flowchart

2.1. Data Collecting

Data was collected by direct measurement for each component. Primary data taken is equipment operation data in the form of operating input and output parameters, exergy flow, exergy transfer form (heat, work and mass), economic and environmental.

Secondary data obtained from official data that has been document by the company in the form of working drawings, population data, and technical specifications of equipment as well as literature studies with relevant theories.

2.2. Energy and Exergy Analysis

Exergy analysis carried out based on the second law of thermodynamics [32]. The thermodynamic processes are always not ideal so that there is a decrease in energy quality caused by irreversible processes. Energy changes in a thermal process consist of three forms, namely: potential energy, kinetic energy, and internal energy. The change in internal energy does not depend on the path of change of state but depends on the initial state and the final state where the energy transfer that occurs can be in the form of heat or work.

Energy in an open system consists of three forms, heat, work and mass. In a closed system, energy can be transferred in the form of work (work) in the form of heat (heat transfer), which is as follows [33]:

$$E2 - E1 = Q - W \quad (1)$$

Heat in a closed system transferred by the sum of the changes in the energy of the system (E1 - E2) and the amount of energy transferred in the form of work. The change in the

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energy of the system itself is the sum of the changes in potential, kinetic, and internal energy, namely:

$$\Delta EP - \Delta EK + \Delta U = Q - W \tag{2}$$

Exergy according to the second law of thermodynamics looks at the quality of energy in a thermal system caused by irreversibility processes. Exergy as the maximum work on a thermal process from the initial condition to the dead state. Exergy can be destroyed or called exergy destruction is a function of entropy generation, which is a measure of the randomness of a system. Exergy in a flow of a fluid is the energy carried in the flow through a process that only interacts with the environment.

Physical exergy (thermo mechanical) EPH, kinetic exergy EKN, potential exergy EPT, and chemical exergy ECH [33]:

$$E = EPH + EKN + EPT + ECH \tag{3}$$

The above equation can be expressed on the basis of mass units:

$$e = ePH + eKN + ePT + eCH \tag{4}$$

To calculate the exergy flow rate leaving the compressor, it can be determined by the equation:

$$X2 = \dot{m}ud\ (Cpud\ (T2\text{-}T0)\text{-}T0(s2\text{-}s0)) \tag{5}$$

To calculate exergy in the combustion chamber, namely the sum of physical exergy and chemical exergy:

$$X = \dot{m}bb\ (EPH+eCH)bb \tag{6}$$

$$ePHbb = (h1\text{-}h0)\text{-}\ T0(S5\text{-}S0) \tag{7}$$

For turbines, the exergy rate leaving the turbine unit can be calculated by the equation:

$$X4 = \dot{m}g\ (Cp\ (T1\text{-}T0) - T0\ (S1\text{-}S0)) \tag{8}$$

The overall exergetic efficiency of the gas power plant system is calculated by the equation:

$$\eta_{II} = W_{GT,net} / X \tag{9}$$

3.0 RESULTS AND DISCUSSION

Observational data is the actual data obtained from the company's data record (log sheet) and data based on the results of measurements in the field. In the combustion chamber there is a pressure drop, it assumed that the pressure drop factor in the combustion chamber is 3% [34]. After each temperature value obtained, the specific heat value can be determined using a thermodynamic table. To get the Cp value, the obtained Cp (kJ/kmol.k) divided by the molar mass of each compound (kg/kmol) so that the result is Cp (kJ/Kg.k).

To find out Cp at the conditions of entering the combustion chamber and leaving the combustion chamber (T3 and T4), it can be determined from the combustion reaction in the combustion chamber between air (comes out of state 2),

Table 1: Average data of measurement and observation results at gas power plant

Parameter	Unit	August 2021
LHV Fuel	kJ/Kg	50017,48
Compressor intake air temperature (T_1)	K	301.4
Compressor intake air temperature (T_2)	K	683.7
Turbine outlet air temperature (T_4)	K	738.5
The temperature of the fuel entering the combustion chamber (T_5)	K	584.6
Air pressure entering the compressor (P_1)	Bar	1,01325
Compressor outlet pressure (P_2)	Bar	12.47
The pressure of the fuel entering the combustion chamber (P_5)	Bar	20.3
Environmental air temperature (T_0)	K	301.4
Environmental air pressure (P_0)	Bar	1,01325

and the composition of natural gas (which enters from state 5) which becomes fuel because the fluid in these conditions is no longer air but combustion gases, so to determine Cp under these conditions, a fuel composition is required.

Table 2: Report of analysis gas at *BOB PT. BSP – Pertamina Hulu*

Gas Composition	Units	Result
Methane (CH_4)	% mol	89,5136
Ethane (C_2H_6)	% mol	3,7489
Prophane (C_3H_8)	% mol	1,7866
i-Butane (C_4H_{10})	% mol	0,3361
n-Butane (C_4H_{10})	% mol	0,3721
i-Pentane (C_5H_{12})	% mol	0,1131
n-Pentane (C_5H_{12})	% mol	0,0698
Hexane (C_6H_{14})	% mol	0,0970
Heptanes (C_7H_{16})	% mol	0
Oxtanes (C_8H_{18})	% mol	0
Nonanes (C_9H_{20})	% mol	0
Water (H_2O)	% mol	0,0887
Oxygen (O_2)	% mol	0
Nitrogen (N_2)	% mol	0,4154
Carbon Dioxyde (CO_2)	% mol	3,4585

Source : Gas Power Plant BOB PT. BSP-Pertamina Hulu

Table 3: Requirement of combustion air at stoichiometric conditions

Composition	MR (kg/mol)	Fuel Mole Fraction	Mol O2	Mol N2
Nitrogen (N_2)	28,013	0,004154		
Carbon Dioxyde (CO_2)	44,01	0,034585		
Methane (CH_4)	16,043	0,895136	1,790	6,731
Ethane (C_2H_6)	30,047	0,037489	0,131	0,493
Prophane (C_3H_8)	44,097	0,017866	0,089	0,335
i-Butane (C_4H_{10})	58,124	0,003361	0,021	0,082
n-Butane (C_4H_{10})	58,124	0,003721	0,024	0,091
i-Pentane (C_5H_{12})	72	0,001131	0,009	0,034
n-Pentane (C_5H_{12})	72	0,000698	0,006	0,021
Hexane (C_6H_{14})	86,179	0,00097	0,009	0,034
Total		1	2,08	7,82

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Table 4: Requirement of combustion air at 320% excess air conditions

Composition	MR (kg/mol)	Fuel Mole Fraction	Mol O2	Mol N2
Nitrogen (N_2)	28,013	0,004154		
Carbon Dioxyde (CO_2)	44,01	0,034585		
Methane (CH_4)	16,043	0,895136	6,32	23,749
Ethane (C_2H_6)	30,047	0,037489	0,02	0,076
Prophane (C_3H_8)	44,097	0,017866	0,007	0,025
i-Butane (C_4H_{10})	58,124	0,003361	0,002	0,007
n-Butane (C_4H_{10})	58,124	0,003721	0,0012	0,005
i-Pentane (C_5H_{12})	72	0,001131	0,0005	0,002
n-Pentane (C_5H_{12})	72	0,000698	0,0003	0,0001
Hexane (C_6H_{14})	86,179	0,00097	0,0003	0,0011
Total		1	6,34	23,87

Table 5: Mole conversion to mass conversion of combustion products

Compo - nent	MR	Mole Fraction	Massa	Fraction
CO_2	44,01	0,038	1,65	0,06
H_2O	18,015	0,045	0,82	0,03
O_2	32	0,193	6,17	0,21
N_2	28,013	0,724	20,29	0,70

From the combustion reaction in Table 2, it can be determined the requirement of combustion air based on the mole ratio. From the combustion reaction in Table 3, it can be determined the requirement of combustion air based on the mole ratio, the result is depicted in Table 4. With 320% excess air, the mole fraction and mass fraction of combustion products are obtained as shown in Table 5.

The calculating work and heat on components of *gas power plant of BOB PT.BSP – Pertamina Hulu.* The isentropic efficiency of the compressor and turbine is assumed to be 88% [34].

- Process 1 – 2: The process of isentropic compression on the compressor, to calculate the compressor work can use equation 1.
- Process 2 – 3: The combustion process at constant pressure (isobar) in the combustion chamber (Equation 2)
- Process 3 – 4: The process of isentropic expansion in the turbine, to calculate the work of the gas turbine can use equation 3.
- Gas turbine network, the network on the gas turbine can be calculate by equation 4.
- So, to determine the thermal efficiency, equation 5 can be used.

The results of the Cp value can be seen in Table 6. Based on the results of the calculation of the total efficiency of the generator, where the results obtained are 42.85%, where the reject released is 1272.91 kW, where the results are not much different from the calculation of the heat released from the exhaust.

Table 6: Calculating the overall Cp of fuel

Compo-sition	MR	Mole Fraction BB	Massa	Massa Fraction	Massa Fraction (%)	CP (kJ/kg K)
CO_2	44,01	0,00222	0,097	0,006	0,601	0,006
N_2	28,01	0,00848	0,237	0,014	1,461	0,015
CH_4	16,04	0,98689	15,832	0,974	97,417	3,121
C_2H_6	30,07	0,0018	0,054	0,003	0,333	0,001
C_3H_8	44,09	0,00042	0,018	0,001	0,113	0,003
C_4H_{10}	58,12	0,00009	0,005	0,0003	0,032	0,0009
C_4H_{10}	58,12	0,00006	0,003	0,0002	0,021	0
C_5H_{12}	72	0,00002	0,001	88,6E05	0,008	0,0001
C_5H_{12}	72	0,00001	0,0007	4,43E05	0,004	0,0001
C_6H_{14}	86,17	0,00001	0,0008	5,30E05	0,005	0,0001
Total	**1**	**16,25**				**3,16**

Table 7: Energy Value of Each Component

Parameter	Unit	Value
$W_{compressor}$	kW	27.725,61
$W_{turbine}$	kW	41.955,78
$W_{nett\ gas}$	kW	14.230,17
Q_{in}	kW	55.994,57
System Efficiency	%	27,98

The value of the specific exergy price is the price of electricity(c_L) = 0.15 $/kWh and the price of fuel (c_bb) = 0.76 $/kWh. In Table 7 is depicted the energy value of each component.

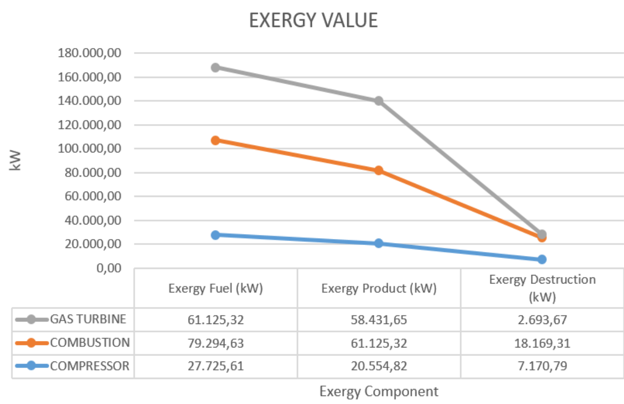

Figure 4. Exergy value of each component

Based on the calculation results from the energy and exergy analysis, there are several suggestions for optimization to the company that can be done in addition to the regular maintenance process. The cause of the combustion chamber experiencing higher exergy annihilation than other components is that the fuel does not burn (unburn fuel), incomplete combustion, and heat loss with the surroundings through the combustion process [35]. The exergy calculation that has been done can also be explained through the Grassman Diagram as is depicted in Figure 5.

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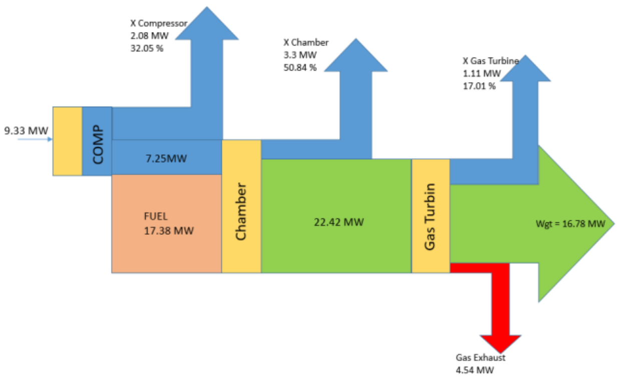

Figure 5. Grassman diagram of a gas power plant

Based on the calculation results that have been obtained, the value of the cost loss from the largest to the smallest on each component of gas power plant *BOB PT. BSP – Petamina Hulu* is a combustion chamber, gas turbine and compressor. In Figure 5 is illustrated the exergy annihilation value for each component of *gas power plant BOB PT. BSP Pertamina Hulu.*

4.0 CONCLUSION

From the results of the calculation analysis, the thermal efficiency of gas power plant is 42.85% and the exergetic efficiency of gas power plant *BOB PT. BSP – PERTAMINA* UPstream 33.22%. Where the thermal efficiency is close to the calculation of the heat released from the exhaust. Exergetic efficiency depend on the performance and setting of the gas turbine, so the company needs to re-plan the maintenance analysis as an effort to optimize the combustion of gas turbines. The largest exergy destruction18.16 kW is in the combustion chamber component, then the compressor is 7.17 kW, and the gas turbine is 2.69 kW. This destroyed exergy is caused by a small portion of the fuel being unburned (unburned fuel) or incomplete combustion occurs, or there is a certain amount of heat released into the environment due to the combustion process.

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