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Analysis of Combustion Characteristics on Boiler Using Comparison of Coal Fuel Mixtures and Bark Biomass To Determine Optimal Combustion Conditions in a Steam Power Plant

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Abstract

Currently, several material production industries have used self-sustaining power generation systems. Where the most common steam power plant system is found as an option to be used as a source of electricity. The use of biomass as an additional material for fuel in power plant has been widely carried out. This method is more commonly known as cofiring. Analysis of the cofiring combustion system of biomass in the boiler needs to be carried out in order to determine the characteristics of the combustion system that occurs. By varying the composition of the fuel, an analysis of the energy produced from the combustion reaction will be calculated. In this study, the comparison of the use of coal and wood bark was varied at conditions 80:20, 70:30, 60:40, 50:50, 40:60, 30:70, 20:80. Assuming that the steam rate and temperature conditions to be achieved from the combustion products are constant. From the results of the analysis it was found that an increase in the amount of cofiring bark resulted in a decrease in the heating value of the combustion reaction and an increase in fuel capacity. Thus, it can be concluded that the use of bark cofiring in boilers with a coal design is less effective because it will require additional energy to increase the fuel consumption rate and reduce combustion efficiency due to not achieving optimal combustion energy because the initial design combustion chamber capacity is fixed.

Keywords: Biomass, Cofiring, Energy, Combustion.

1. Introduction

Currently, several material production industries have used self-sustaining power generation systems. Where the most common steam power plant system is found as an option to be used as a source of electricity. Where the electricity will be used to operate the raw material production system for various materials. However, to achieve the energy obtained from a generator is strongly influenced by various factors such as fuel, combustion systems, automation systems and so on. To achieve optimal energy conversion in a thermodynamic system, such as in Thermal Power Plants (TPPs), is a complex task because it involves several factors [1]. One effective way to determine the quantity & quality of the energy system is through combustion energy analysis. Process-based exergy analysis aims to determine the degree of imperfection of the main process, which will break the limitations of single-component performance optimization (sensitivity analysis) and enlighten process-level optimization with innovative flow design and consideration of interactions between components [2]. Therefore it is very important to study the various possible factors so that a power plant system can operate optimally and is far more friendly to the environment.

Power plant system generally use coal as fuel. The use of coal fuel needs to be analyzed first in order to determine its quality. In general, coal analysis produces proximate and ultimate data [3]. With the data from this analysis, combustion engineering can then be carried out to optimize the combustion that occurs in the combustion chamber. When the combustion reaction that occurs is optimal, the energy produced will reach optimal conditions so that the efficiency obtained is achieved.

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Biomass is an alternative energy source that can be used as a substitute or mixture of fuels because it contains a calorific value that is high enough to be used. Several studies have provided an analysis of the potential of biomass as a fuel source. Such as the use of candlenut shells which were analyzed to reach 80% efficiency or torrefacted palm shells can increase biomass equivalent to coal [4], [5]. To improve the quality of this biomass fuel, torrefaction can also be carried out or by reducing the potassium content contained in the biomass [6], [7], [8]. With reduced potassium, there will be less potential for soot growth in the combustion process.

The use of biomass as an additional material for fuel in power plant has been carried out a lot. This method is more commonly known as cofiring. The use of this method is for the reason of reducing coal fuel consumption and increasing cost optimization in fuel use. However, it is necessary to analyze the heating value contained in the composition of the biomass used. The calorific value of fuel is calculated using the Dulong and Petit formulas, then the calorific value of the calculation results is compared with the calorific value of oil and the calorific value of coal from the literature [9]. This is done in an effort to develop new and renewable energy potential. In several studies with the addition of 5% biomass, it has been proven that biomass can be used as cofiring fuel in power plant [10], [11]. The percentage of biomass composition and the right combustion setting will be able to produce optimal boiler efficiency [12]. In addition, ash from the combustion of biomass is classified as a detrital mineral [13].

Cofiring of coal with various biomasses has received a lot of attention due to environmental factors and is considered a low cost option. Although cofiring coal with biomass seems feasible, it has the potential to generate ash, which causes problems in the boiler, such as fouling and slagging [14]. Preliminary selection is needed to determine the feasibility and safety of using blended fuels for co-firing. One way that can be done is to predict the potential for slagging and fouling [15]. One of the factors that can reduce these costs is the rate of fuel and the energy value obtained from the combustion system. The magnitude of this fuel rate needs to be taken into account because it has a great deal to do with the combustion reactions that will occur in the combustion chamber. Because of the need to calculate the rate of fuel and air fuel so that the combustion system that occurs obtains the optimal combustion energy as desired. The magnitude of the potential that can be generated from the combustion system can be seen from the calculation of the comparison of the combustion reaction coefficients.

The largest source of carbon dioxide (CO_2) emissions is believed to come from power plants that use fossil fuels [16]. Therefore, the effect of fuel in a power plant is very important to be analyzed as an effort so that an energy generation system is converted optimally. Where in this case a study was carried out by analyzing the power system with variations in the mixture of coal and biomass fuels. The idea of using mixed materials is one of the factors that affect the environment and also reduces costs [17]. Therefore various things are done to achieve optimal conditions in order to be achieved by an energy generation system. Therefore the need for an analysis of the boiler combustion system in a steam power plant with a mixture of coal and biomass fuel which in this study is wood bark.

Several previous studies described the results of analyzing the effect of co-firing sawdust biomass at 5% resulting in a temperature reduction of 4.2 ^{0}C compared to using 100% coal fuel [11], while others also examined the circuit fluidzed bed (CFB) boiler model on the effect of biomass. Palm shells have the effect of reducing boiler efficiency by 2.94% by changing 100% of the fuel from coal to palm shells [18].

Analysis of the cofiring biomass combustion system in the boiler needs to be carried out in order to know the characteristics of the combustion system that occurs. By varying the composition of the fuel, an analysis of the energy produced from the combustion reaction will be calculated. Therefore the aim of this research is to find out the amount of fuel flow, the calorific value resulting in variations in the percentage ratio of the fuel mixture in order to obtain the optimal value which can then be used as a reference in implementing the cofiring method. Where in this study using a mixture of coal with bark with a certain ratio. The following are several previous research journals as a comparison for this research.

2. Research Methodology

This research was conducted using sample data in a factory that has a power plant with a mixture of coal and wood bark fuel The calorific value contained in fuel can be analyzed theoretically. The research flow can be seen from the following flow diagram in Figure 1.

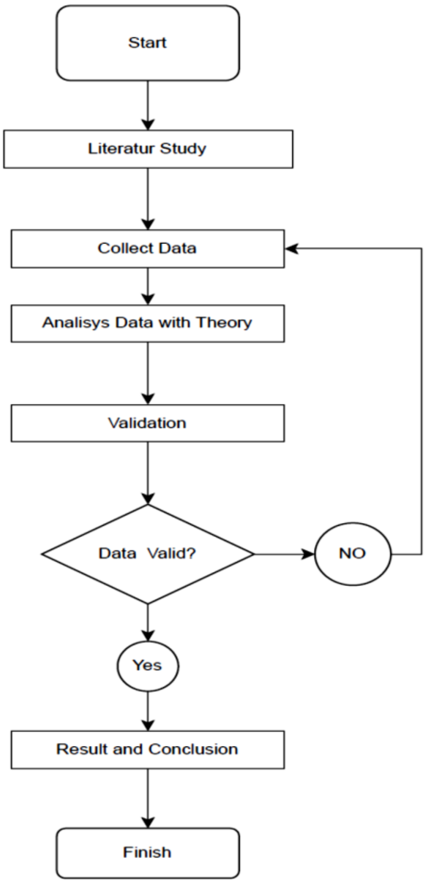

Figure 1. Research Flow Diagram

2.1 Heating Value

The calorific value contained in the fuel really needs to be analyzed as the main factor in determining the amount of energy produced in combustion. The amount of the calorific value contained in the fuel can be calculated using the Dulong and Petit equation [19].

$$High\ heating\ Value\ (HHV) = 33950 + 144200\left(H - \frac{O_2}{8}\right) + 9.400\ S \quad kcal/kg \tag{2.1}$$

$$Low\ heating\ Value\ (LHV) = HHV - 2.400(H_2O + 9H_2) \quad kcal/kg \tag{2.2}$$

By using the above equation, it can be known that the ultimate value is actually contained in the fuel element. The fixed carbon value contained in the fuel can be calculated using the following equation [20].

$$Fixed\ Carbon = 100\% - \%Moisture - \%Volatile\ Matter - \%Ash$$

Meanwhile, to calculate the molecular bonding reactions that occur between the constituent elements, the following stoichiometric equation can be used.

$$Molality\ X = Mass\ X : Relative\ Molecule\ \left(\frac{Mr}{Ar}\right) \tag{2.3}$$

To calculate the combustion reaction of 1 kg of solid fuel [21].

$$C^i + H^i + N^i + O^i + S^i + M^i + W_t^i = 100\%\ or\ 1\ kg\ solid\ fuel \tag{2.4}$$

Calculation of the amount of energy needed in the boiler can use the formula [22]:

$$Q = G(h\ output\ steam - h\ feed\ water/\eta)$$

where Q: Boiler heat requirements (kJ/hours), G: Steam mass flow rate (kg/hours), $h_{output\ steam}$: Enthalpy vapor exits (kJ/kg), $h_{feed\ water}$: Enthalpy feedwater (kJ/kg), η: Boiler efficiency

In a power plant the amount of fuel needed to produce steam under certain conditions can be calculated. The equation used to calculate the mass flow rate of the fuel needed during the combustion process to obtain the desired steam heat is:

$$m = \frac{Q}{LHV} \quad \text{or} \quad m = \frac{Q}{HHV} \tag{2.5}$$

where m : The mass flow rate of the fuel (kg/hours), Q: Boiler heat requirement (kJ/hours), LHV: Low heating value/calorific value (kJ/kg). As for calculating boiler efficiency with the direct method is to use the following equation [23]:

$$\eta fuel = \frac{Qsteam}{Qfuel} \times 100\% \tag{2.6}$$

$$\eta fuel = \frac{Q \times (hg - hf)}{q \times GCV} \times 100\% \tag{2.7}$$

where η_{fuel} : Boiler fuel efficiency (%), Q_{steam} : The total heat energy absorbed by the water vapor (calori; Joule), Q : Discharge of water vapor out of the boiler (kg/hour), h_g : Steam enthalpy leaving the boiler (kcal/kg), Q_{fuel} : Heat energy generated from burning fuel (calori; Joule), q : fuel demand debit (kg/hour), GCV : Gross calorific value or the specific calorific value of the fuel (kcal/kg).

The above equation will be used to calculate the effect of fuel cofiring on changes in boiler efficiency in a power plant. The data were analyzed by varying the percentage of the mixture of coal and bark in order to determine the potential for CO_2 gas from the combustion reaction. Assuming that the combustion reaction is perfect and constant at all times. The magnitude of the reduction in efficiency of each fuel ratio reaction can be predicted by the direct method.

In this study, the comparison of the use of coal and wood bark was varied at conditions 80:20, 70:30, 60:40, 50:50, 40:60, 30:70, 20:80. Assuming that the steam rate and temperature conditions to be achieved from the combustion products are constant. So that it can be obtained the influence of variations in fuel comparisons on the amount of fuel and also the amount of CO_2 and residual substances produced.

Analysis of the fuel content can be done by looking at the compounds contained in the fuel. Table 1 and Table 2 below show data on the elemental content of coal and bark based on the results of laboratory testing of power plant in an industry. The equation obtained from the fuel empirical formula will then be used to analyze the combustion reaction in each fuel ratio condition. Where in the calculation of the empirical formula of the compound contained in the molecule can use formula 2.3 above. The results of laboratory testing obtained coal fuel data as follows in Table 1.

Table 1. Data on Coal Fuel Content [24]

Item		Number	Unit
Proximate Analysis	Moisture	27.76	%weight
	Ash	18.38	% dry weight
	Volatile matter	32.70	% dry weight
	Fixed Carbon	21.16	% dry weight
Ultimate Analysis	Carbon	32.70	% dry weight
	Hidrogen	9.40	% dry weight
	Nitrogen	1.03	% dry weight
	Sulfur	0.95	% dry weight
	Oksigen	51.40	% dry weight
	Calor Value	5,514	Kcal/kg

From the relative molecular data and molality using equation 2.3, it can be obtained that the empirical formula of coal fuel tested in this study is $CH_{3,449}O_{0,589}N_{0,024}S_{0,025}$. Meanwhile, to find out the empirical formula of wood bark fuel, molality analysis can be used. The data obtained from the results of laboratory tests are as shown in Table 2 below. The results of laboratory tests obtained data on wood bark fuel as follows.

Table 2. Data of Bark Fuel Content [25]

	Item	Number	Unit
Proximate Analysis	Moisture	47.72	%weight
	Ash	1.42	% dry weight
	Volatile matter	35.41	% dry weight
	Fixed Carbon	15.45	% dry weight
Ultimate Analysis	Carbon	49.74	% dry weight
	Hidrogen	5.26	% dry weight
	Nitrogen	1.85	% dry weight
	Sulfur	0.04	% dry weight
	Oksigen	43.11	% dry weight
	Calory Value	4,329	Kcal/kg

From the relative molecular data and molality using equation 2.3, it can be obtained that the empirical formula of the Bark fuel tested in this study is $CH_{1.268}N_{0.028}O_{0.325}$.

From the equation of the empirical formula of the two fuels above, then an analysis of various combustion reactions is carried out by varying the coal with bark at the composition 80:20, 70:30, 60:40, 50:50, 40:60, 30:70, and 20:80. The combustion reaction of each fuel composition ratio can be seen in the following discussion.

3. Result and Discussion

Table 1 and Table 2 show the composition contained in coal and wood bark fuel. By using equation 2.3 and 2.4, the empirical formulas of compounds from the elements of coal and bark are $CH_{3,449O0,589}N_{0,024}S_{0,025}$ and $CH_{1.268}N_{0.028O0.325}$. By using the assumption that the air content is 21% O_2, 79% N_2, the equation for the condition of the combustion air is O_2 + 3.6 N_2 and it is assumed that the combustion process that occurs is perfect and by using equation 2.1 the calorific value data from the calculation of the combustion reaction is in Table 3 as follows:

Table 3. Combustion Reaction of Coal and Bark

No	Number of Coal $CH_{3,449}O_{0,589}N_{0,024}S_{0,025}$	Number of Wood bark $CH_{1.268}N_{0.028}O_{0.325}$	Number of Air	Product of Reaction				
			O_2+3,6 N_2	CO_2	N_2	O_2	H_2O	SO_2
1	0.8	0.2	3.7847	1	13.63730	1.52640	3.0128	0.0200
2	0.7	0.3	3.5748	1	12.88190	1.41485	2.7947	0.0175
3	0.6	0.4	3.3649	1	12.12640	1.30330	2.5766	0.0150
4	0.5	0.5	3.1550	1	11.37100	1.19175	2.3585	0.0125
5	0.4	0.6	2.9451	1	10.61560	1.08020	2.1404	0.0100
6	0.3	0.7	2.7352	1	9.86012	0.96865	1.9223	0.0075
7	0.2	0.8	2.5253	1	9.10468	0.85710	1.7042	0.0050

In this study it is assumed that the operational conditions in the power cycle schematic at a steam power plant in a factory with constant steam produced by the boiler are 413 T/H, 530 . The data can be seen from Figure 2 below.

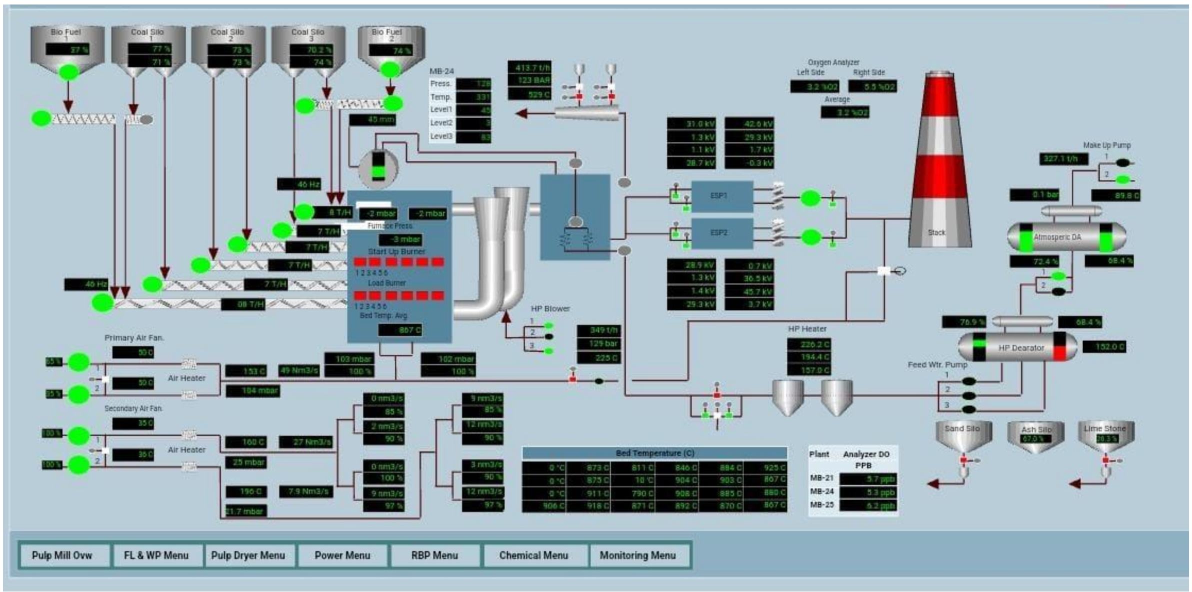

Figure 2. Generating Cycle Schematic at Steam Power Plant System [25]

From the data in the schematic image above, it can be calculated the amount of heat vapor produced by the boiler by using the equation $\dot{Q}_{steam}$ = steam rate x steam enthalpy, then it can be obtained:

$\dot{Q}_{steam}$ = steam rate x steam enthalpy
$\dot{Q}_{steam}$ = $\dot{m}_{steam}$ x H_{steam}
Where, H_{steam}= h_{steam}-$h_{feedwater}$

From the table of Properties, water saturation conditions at 89.8 ^{0}C, hair is 376.151 kJ/kg, and water vapor conditions at 530 ^{0}C, steam is 3426.34 kJ/kg. By looking at the operational data of a generator shown in Figure 2 above which has an efficiency of 0.85, the following is obtained by the heat rate of steam.

$$Q = G(h_{steam} - h_{feedwater}/\eta$$

$$\dot{Q}_{steam} = \{413\ x 1000\ kg/hour\ x\ (3426{,}34 - 376{,}151)\ kJ/kg\}/0{,}85 = 1482{,}04\ x\ 106\ kJ/hour$$

Assuming that the calorific value of the steam produced is constant, namely 1,482.04 x10^6 kJ/hour, it can be calculated the amount of fuel needed for each combustion reaction in Table 3 above using equation 2.4 as follows.

- Coal 80% and Wood Bark 20%

$$0.8CH_{3.449}O_{0.589}N_{0.024}S_{0.025} + 0.2CH_{1.268}N_{0.028}O_{0.325} + 1.288(O_2 + 3.6N_2) \rightarrow CO_2 + 2.6008N_2 + 3.0128H_2O + 0.02SO_2$$

$$HHV = 459{,}004.0227\,\frac{kcal}{kg}\ or\ 1{,}920{,}427.381\,\frac{kJ}{kg}$$

$$\dot{m}_{fuel} = \frac{\dot{Q}_{steam}}{HHV} = \frac{1{,}482.04\ x 10^6\ \frac{kJ}{hour}}{1{,}920{,}472.831\ \frac{kJ}{kg}} = 771{,}89\,\frac{kg}{hour},$$

$$in\ terms\ of\ 617.512\ kg\ of\ coal\ and\ 154.378\ kg\ of\ bark\ per\ hour$$

- Coal 70% and Wood Bark 30%

$$0.7CH_{3.449}O_{0.589}N_{0.024}S_{0.025} + 0.3CH_{1.268}N_{0.028}O_{0.325} + 1.2045(O_2 + 3.6N_2) \rightarrow CO_2 + 2.4342N_2 + 2.7947H_2O + 0.0175SO_2$$

$$HHV = 428{,}014.4835\,\frac{kcal}{kg}\ or\ 1{,}790{,}812.599\,\frac{kJ}{kg}$$

$$\dot{m}_{fuel} = \frac{\dot{Q}_{steam}}{HHV} = \frac{1{,}482.04\,x10^6\,\frac{kJ}{hour}}{1{,}790{,}812.599\,\frac{kJ}{kg}} = 827.955\,\frac{kg}{hour},$$

$$in\ terms\ of\ 579.568\ kg\ of\ coal\ and\ 248.386\ kg\ of\ bark\ per\ hour$$

- Coal 60% and Wood Bark 40%

$$0.6CH_{3.449}O_{0.589}N_{0.024}S_{0.025} + 0.4CH_{1.268}N_{0.028}O_{0.325} + 1.221(O_2 + 3.6N_2) \rightarrow CO_2 + 2.5766N_2 + 2.5766H_2O + 0.0175SO_2$$

$$HHV = 397{,}024.9442\,\frac{kcal}{kg}\,or\ 1{,}661{,}152.367\,\frac{kJ}{kg}$$

$$\dot{m}_{fuel} = \frac{\dot{Q}_{steam}}{HHV} = \frac{1{,}482.04\,x10^6\,\frac{kJ}{hour}}{1{,}661{,}152.367\,\frac{kJ}{kg}} = 892.257\,\frac{kg}{hour},$$

$$in\ terms\ of\ 535.354\ kg\ of\ coal\ and\ 356.902\ kg\ of\ bark\ per\ hour$$

- Coal 50% and Wood Bark 50%

$$0.5CH_{3.449}O_{0.589}N_{0.024}S_{0.025} + 0.5CH_{1.268}N_{0.028}O_{0.325} + 1.0735(O_2 + 3.6N_2) \rightarrow CO_2 + 2.101N_2 + 2.3585H_2O + 0.0125SO_2$$

$$HHV = 366{,}035.4050\,\frac{kcal}{kg}\,or\ 1{,}531{,}492.134\,\frac{kJ}{kg}$$

$$\dot{m}_{fuel} = \frac{\dot{Q}_{steam}}{HHV} = \frac{1{,}482.04\,x10^6\,\frac{kJ}{hour}}{1{,}531{,}492.134\,\frac{kJ}{kg}} = 968.02\,\frac{kg}{hour},$$

$$in\ terms\ of\ 484.01\ kg\ of\ coal\ and\ 484.01\ kg\ of\ bark\ per\ hour$$

- Coal 40% and Wood Bark 60%

$$0.4CH_{3.449}O_{0.589}N_{0.024}S_{0.025} + 0.6CH_{1.268}N_{0.028}O_{0.325} + 0.954(O_2 + 3.6N_2) \rightarrow CO_2 + 1.9344N_2 + 2.1404H_2O + 0.01SO_2$$

$$HHV = 335{,}045.8657\,\frac{kcal}{kg}\,or\ 1{,}401{,}831.902\,\frac{kJ}{kg}$$

$$\dot{m}_{fuel} = \frac{\dot{Q}_{steam}}{HHV} = \frac{1{,}482.04\,x10^6\,\frac{kJ}{hour}}{1{,}401{,}831.902\,\frac{kJ}{kg}} = 1{,}057.24\,\frac{kg}{hour},$$

$$in\ terms\ of\ 422.896\ kg\ of\ coal\ and\ 634.344\ kg\ of\ bark\ per\ hour$$

- Coal 30% and Wood Bark 70%

$$0.3CH_{3.449}O_{0.589}N_{0.024}S_{0.025} + 0.7CH_{1.268}N_{0.028}O_{0.325} + 0.8705(O_2 + 3.6N_2) \rightarrow CO_2 + 1.7678N_2 + 1.9223H_2O + 0.02SO_2$$

$$HHV = 304{,}056.3264\,\frac{kcal}{kg}\,or\ 1{,}272{,}171.67\,\frac{kJ}{kg}$$

$$\dot{m}_{fuel} = \frac{\dot{Q}_{steam}}{HHV} = \frac{1{,}482.04\,x10^6\,\frac{kJ}{hour}}{1{,}272{,}171.67\,\frac{kJ}{kg}} = 1{,}165.034\,\frac{kg}{hour},$$

$$in\ terms\ of\ 349.51\ kg\ of\ coal\ and\ 815.52\ kg\ of\ bark\ per\ hour$$

- Coal 20% and Wood Bark 80%

$$0.2CH_{3.449}O_{0.589}N_{0.024}S_{0.025} + 0.8CH_{1.268}N_{0.028}O_{0.325} + 0.787(O_2 + 3.6N_2) \rightarrow CO_2 + 1.6012N_2 + 1.7042H_2O + 0.005SO_2$$

$$HHV = 273{,}066.7872\,\frac{kcal}{kg}\,or\ 1{,}142{,}511{,}438\,\frac{kJ}{kg}$$

$$\dot{m}_{fuel} = \frac{\dot{Q}_{steam}}{HHV} = \frac{1{,}482.04\,x10^6\,\frac{kJ}{hour}}{1{,}142{,}511{,}438\,\frac{kJ}{kg}} = 1.297.19\,\frac{kg}{hour},$$

$$in\ terms\ of\ 259.43\ kg\ of\ coal\ and\ 1{,}037.75\ kg\ of\ bark\ per\ hour$$

The results of the above calculation analysis can be seen that there is a change in the calorific value of each combustion reaction condition. This also indicates a potential change in the efficiency of the combustion system. The phenomenon of change itself is a very important factor to be calculated as the missing value from the condition it should be.

The amount of change in calorific value and rate of fuel consumption from each combustion reaction which is affected by the composition of the fuel using the direct method can be seen from Table 4 below.

Table 4. Changes in Calorific value and Fuel Consumption using the direct method

Comparison of fuel composition	Fuel amount (kg/hour)	HHV fuel kJ/kg
80 : 20	771.890	1,920,472.831
70 : 30	827.955	1,790,812.599
60 : 40	892.257	1,661,152.367
50 : 50	968.020	1,531,492.134
40 : 60	1,057.240	1,401,831.902
30 : 70	1,165.034	1,272,171.670
20 : 80	1,297.190	1,142,511.438

From Figure 3 combustion efficiency graph above, it can be seen the magnitude of the influence of the composition of the fuel mixture on changes in the efficiency of the combustion system. Where it can be seen that the fuel composition of 80% coal and 20% bark has the highest efficiency, while the fuel composition of 20% coal and 80% bark has the lowest efficiency of the combustion system. Therefore, it is very important to reconsider the composition of the fuel mixture to achieve better efficiency values. Because decreasing combustion efficiency will affect the energy produced and the costs incurred

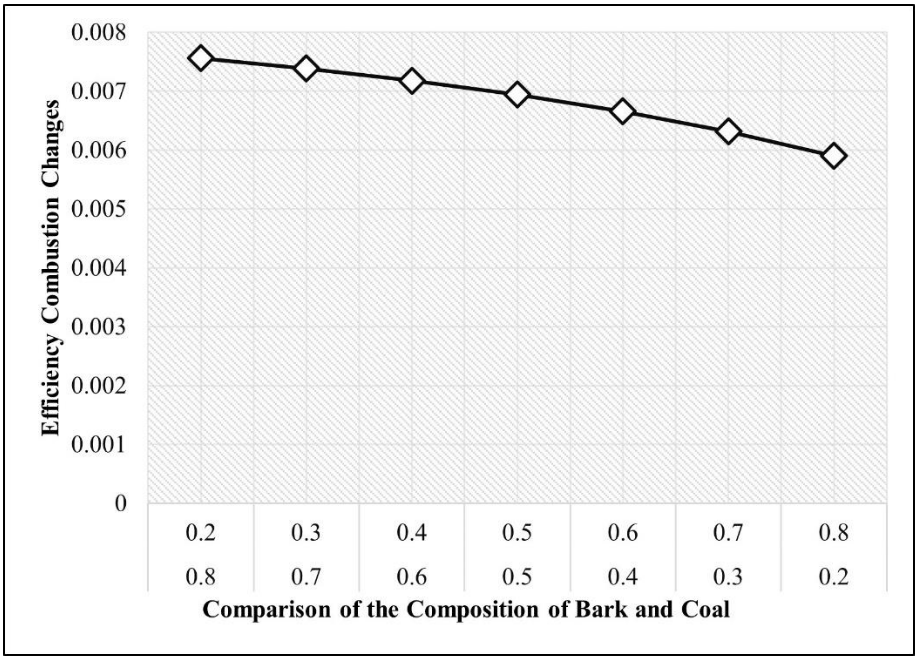

Figure 3 Combustion Efficiency Graph

4. Conclusion

From the results of the analysis it was found that an increase in the amount of cofiring of bark resulted in a decrease in the calorific value of the combustion reaction and an increase in fuel capacity. This shows that to obtain the same calorific value as the use of coal, you must increase the capacity of the combustion chamber and the rate of fuel. If we use the design capacity of the combustion chamber for coal-fired power plants by applying the cofiring method, this will affect the heating value obtained from the combustion reaction. It can be seen from the combustion reaction that to obtain the same combustion calorific value, a larger mass rate of bark is required. The use of cofiring bark with the highest HHV value was in the composition of 80:20 which was 1.92 x10^6 kJ/kg with a mass rate of

771.89 kg/hour. Meanwhile, by increasing the composition of the bark at a ratio of 20:80, you only get an HHV of 1.14x10^6 kJ/kg with a significant increase in the mass rate of 1,297.19 kg/hour. This shows that the energy produced by adding bark cannot be compared to using coal. If you want to use the cofiring method of wood bark biomass, a larger combustion chamber capacity is needed to obtain the same energy as using coal fuel. This will also increase the need for auxiliary equipment in order to achieve the same calorific value. This of course will later increase procurement and operational costs of the power plant if the cofiring method is applied. Thus, it can be concluded that the use of bark cofiring in boilers with a coal design is less effective because it will require additional energy to increase the fuel consumption rate and reduce combustion efficiency due to not achieving optimal combustion energy because the initial design combustion chamber capacity is fixed. Therefore, the development of boiler design using the cofiring method should be studied from the start without combining the boiler design system with coal.

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