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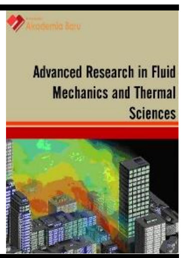

Experimental Studies on Combustion Characteristics of Oil-Palm Biomass in Fluidized-Bed: A Heat Energy Alternative

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ARTICLE INFO	ABSTRACT

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One of the technologies that can be used to meet energy needs is biomass combustion. In this study, the oil palm biomass fuels used were empty fruit bunches, oil palm fibers, oil palm midribs, and palm kernel shells. This research was carried out by a direct combustion method using a fluidized-bed combustor. The purpose of this experiment was to investigate the reaction of kinetics and the mechanism of combustion of oil-palm biomass in fluidized-bed combustor. The characteristics observed in this test were the combustion temperature profile, flue-gas composition, and the composition of the ash-deposit chemical compound. The results of the experiments conducted showed that the best biomass combustion temperature profile was recorded at 2 kg biomass with an air flow rate of 0.9375 m^3/s at 90.1%. The maximum temperature of biomass combustion recorded at biomass 3 kg with an air flow rate of 1.25 m^3/s are 950°C (95%). The higher conversion combustion of biomass was found at biomass condition of 3 kg with an air flow rate of 0.9375 m^3/s. The value of O_2 emissions from biomass combustion shows that it was very small 0.2%. While the highest CO_2 value was recorded at 19.9%. The highest combustion efficiency on FBC found 1 kg of biomass fuel with an air flow rate of 0.0654 m^3/s recorded 94.9%.

Keywords:
Oil-palm biomass; Combustion characteristics; Fluidized bed; Flue gas; Ash deposit

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1. Introduction

Environmental and energy problems in the next few years which continue to experience depletion have attracted the attention of researchers to investigate various alternative fuels instead of fossils. At present, researchers pay much attention to studying combustion from oil palm biomass, because it is more efficient and economical [1–4]. Fluidized-bed technology has proven to be the most effective in transforming various types of palm oil biomass into a renewable and sustainable energy [5–10]. Biomass fuels from various oil-palm composites are more efficient and economical than coal biomass. Besides, the storage is easy, convenient to use for transportation, and environment friendly. Biomass can also be used as raw material, power plants, etc. [4,11–15]. Combustion efficient is one of the important factors to determine the effectiveness of the performance of a device that is being run. The level of ability of a tool depends on efficiency in carrying out the work provided [16,17].

Oil palm biomass composites (OPBC) can be obtained easily from the mill and flow very well during fluidization. The flow of particles and biomass fuel characteristics have been investigated by several previous researchers [18–21]. However, investigations that are often carried out are based solely on biomass particles with regular and relatively smaller forms, such as straw, sawdust, rice husks, etc. Thus, the characteristics of the fluidization of OPBC in this study are very important to be investigated. Investigations into the combustion mechanism using biomass fuel have been widely studied [22-24]. Investigations on the mechanism of the reaction using four distinct types of biomass have been studied by [25–27]. Testing of biomass combustion is carried out through three phases, such as the process of evaporation of water, combustion in volatile components, and fixed carbon combustion. Other findings regarding the characteristics of biomass combustion show a higher biomass combustion rate compared to coal combustion [28–30]. Investigations on NO emissions from the combustion of biomass fuel have also been carried out by [31–33]. The results of the experiments conducted show that NO emissions decrease with more air and the temperature of the bed increases. In addition, NO emissions are more dominant in the presence of sources of reactants than volatile-N and char-N. The performance and emissions from combustion with biomass are quite good as the results of research conducted by [34–36]. This combustion is achieved when the palm kernel shell is burned using a particle size of 5 mm by giving air around 40-50%. While the results of research conducted by [37–39] show that the main source of agglomeration problems is the high percentage of chlorine, alkali (potassium) and ash content. The in-bed stoichiometric oxygen ratios can increase CO emissions; however, excessive oxygen ratios can reduce CO emissions [40,41].

Biomass Raw Materials have a relatively broad physical and chemical characterization [21]. This biomass composite can be obtained very easily from a palm oil mill in Aceh Province as shown in Figure 3. The main focus of this research is to investigate the temperature, efficiency and combustion emissions of oil palm biomass in a fluidized-bed boiler. The OPBC used in this research experiment consisted mainly of Empty Fruit Bunches (EFB), Palm Kernel Shells (PKS), Oil Palm Midrib (OPM) and Oil Palm Fiber (OPF). This research specifically explored the use of various materials from palm oil as a renewable, sustainable alternative fuel additive and evaluated its utilization.

2. Experimental Setup and Methodology

2.1 Experiment Setup

The characteristics of mixing oil palm biomass fuel are studied at stabilized room temperature. The schematic diagram for fuel mixing is shown in Figure 1. This device consists of a set that is used as an air supply at the sensor pressure and fluidized bed. The height of the fluidizing reactor is about

1.5 m which is made of Plexiglas with a cross-section length of 110 mm ∗ 30 mm. This is intended as a tool to study oil palm biomass flow in a vertical and horizontal position. A schematic diagram for the steps from the beginning to the end of the fluidized-bed is shown in Figure 1. The mixture that enters the fluidized bed is divided into nine parts and then all oil palm biomass fuel content is measured. The content of flow meters, wind chambers, and air blowers are obtained from the air supply. The flowmeter can control the air blower provided by the gas. Signal pressure is monitored using a 200 mm height sensor produced from an air distributor. This experiment frequency is measured at 100 Hz so that it can produce more data.

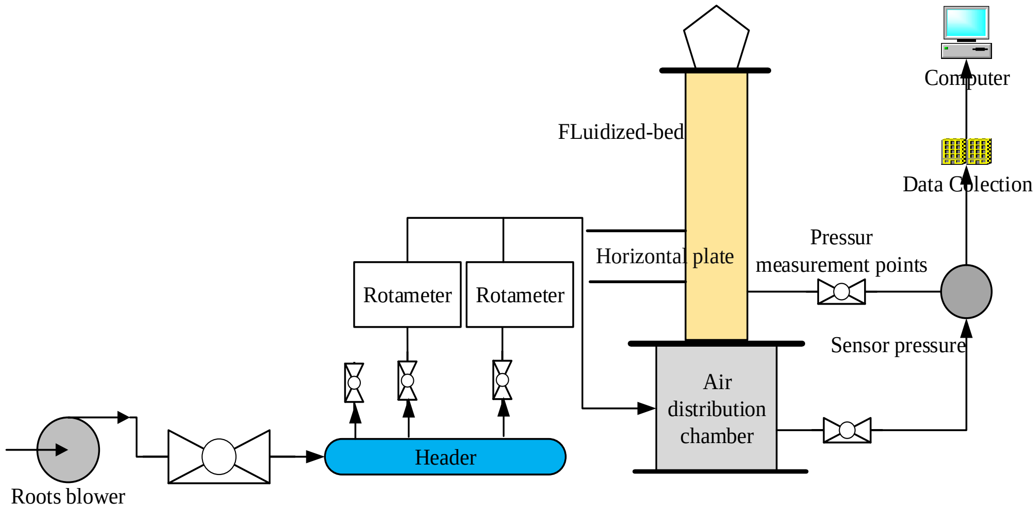

Fig. 1. Schematic diagram of the fluidized bed

The experiments in this study were carried out on combustion equipment as illustrated in the schematic diagram of Figure 2. This combustion system consists of several fluidized bed reactors, gas supplies, heaters, induction fans, and dust collectors. The fluidized bed reactor is made of stainless steel with a diameter of 50 mm and a height of 3 m. So that the combustion time in a fluidized bed can be maintained longer when the fluidization speed is 2 m/s. The combustion chamber can provide additional heat by sending a high gas temperature which is the result of direct combustion on the outer jacket of the fluidized bed, the heating of the initial fluidized air as well as the heat exchanger. The possibility of rod deformation in spiral feeding has a higher temperature increase, so as a precaution the water cooler is also designed. The operating temperature in the combustion chamber can reach 250-1200°C. The air at the bottom of the fluidization can directly enter the reactor through a tube that is about 10 mm in diameter and can also pass through 0.1 mm pores on a cone-shaped surface as a distributor. The fluidized top layer which is located in the middle of the tool with a height of about 1.5 m serve for secondary air use. Temperature measurements are distributed along the fluid bed using K-type thermocouple devices.

This measurement aims to investigate the ability of fluidized beds for burning palm oil biomass by observing variations in bed temperature. In addition, the burning of oil palm biomass is likely to cause the formation of slagging and fouling. Therefore, fly ash is analyzed with X-ray fluorescence to examine the problem. This experiment was carried out using oil palm biomass such as EFB, PKS, OPM and OPF. While the air flow rate used is 1.25, 0.9375 and 0.625 m^3/s. This experiment uses biomass composite materials 1 kg, 2 kg and 3 kg respectively. The first test is done using 1 kg of biomass with a time of 14-16 minutes. Furthermore, the second test with a time of 16 minutes and last for 22 minutes. Then the temperature is adjusted to the feed speed on the screw rod, the temperature is maintained at a certain range (740-780°C). When fluidized conditions are stable, such as changes at relatively small temperatures, the combustion temperature profile along the bed is recorded and analyzed. The exhaust gas from the combustion of oil palm biomass is disposed of through chimneys with separated cyclones and filters with a cloth. Finally, fly ash is collected to be used and analyzed.

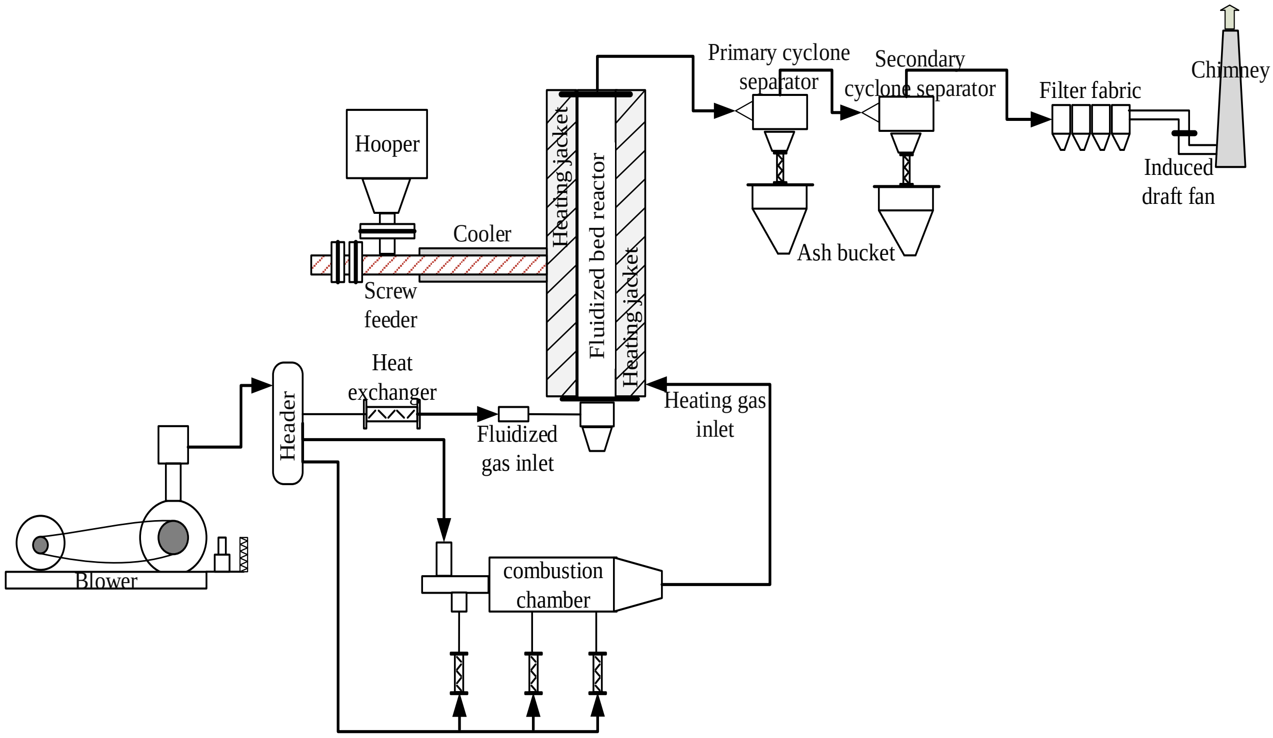

Fig. 2. Schematic diagram of the combustion experimental set-up

2.2 Properties of OPBC

The material used in this study is oil palm biomass which can be obtained easily from oil palm mills. While the material used in this study is shown in Figure 3 While the chemical composition of oil palm biomass is shown in Table 1. Dried oil-palm empty bunches contain heating value around 9.619 MJ/kg, shells 17-21 MJ/kg, and fibers from 4.6 to 5 MJ/kg. The composition and dry weight of oil palm fiber consists of N, P, K, Mg, and Ca 0.29-1.4%, 0.07-0.08%, 0.47-1.18%, 0,02%, and 0.11%, respectively. In addition, oil palm fiber contains biochemical components in the form of cellulose, hemicellulose, and lignin with 34.5%, 31.8%, and 25.7%, respectively. The biochemical composition of oil palm shells with dry weight consisting of cellulose, hemicellulose, and lignin is 20.8%, 22.7%, and 50.7%, respectively. The composition of the main elements of shell formation is N 0.3-0.6%, P 0.3-0.6% and K 0.01%, 0.15% and C 46.75%, H 5.92% and O 37.97. While the dry weight of oil palm empty fruit bunches contains organic matter consisting of N 0.8%, P 0.1-0.7%, K 2.4-2.8% and Mg 0.2-0.8. The chemical composition of oil palm biomass fuels has also been described in [42–45].

Oil Palm Midrib
Empty Fruit Bunches
Palm Kernel Shells
Oil Palm Fiber

Fig. 3. Material for oil-palm biomass

Table 1
The properties of oil-palm biomass [46-49]

Variable biomass	Measurement Proximate and Ultimate (%)								
	Water content	Volatile Matter	Ash	Fixed Carbon	C	H	N	S	O
OPM	8,75	79,67	3,02	8,65	48,79	7,33	3,02	0,68	40,18
PKS	5,73	73,74	2,21	18,37	53,78	7,2	2,21	0,51	36,3
EFB	9,89	53	6	41	42,55	5,48	2,18	0,11	50,32
OPF	6,56	75,99	5,33	12,39	50,27	7,07	0,42	0,63	38,28

Note: C=Carbon; H=Hydrogen; N=Nitrogen; S=Sulfur; O=Oxygen

The characteristics of palm oil biomass fuel is a very important one and also affects the combustion performance. The low calorific value can cause a decrease in maximum combustion temperature and increase combustion time [34,50,51]. The process of burning fuel generally consists of three processes, namely:

$$C + O_2 \qquad CO_2 + Heat \tag{1}$$

$$H_2 + ½\,O_2 \qquad H_2O + Heat \tag{2}$$

$$S + O_2 \qquad SO_2 + Heat \tag{3}$$

2.3 Experimental Procedure

Bait or fuel consisting of a mixture of EFB, PKS, OPM and OPF is weighed of 1 kg, 2 kg, and 3 kg for a single test with one loading without inter-fuel feeding. Combustion temperature measurements are carried out every 1-s interval on the wall and combustor at each point and 3 in the freeboard (bottom, middle and top) as shown in Figure 4. The analysis of the composition of the flue gas is carried out using a DWYER 1207A device with sensors placed at the top of FBC. The ash deposit data is taken in the combustor section and then analyzed for the composition of the chemical compound with using technic pyrolysis.

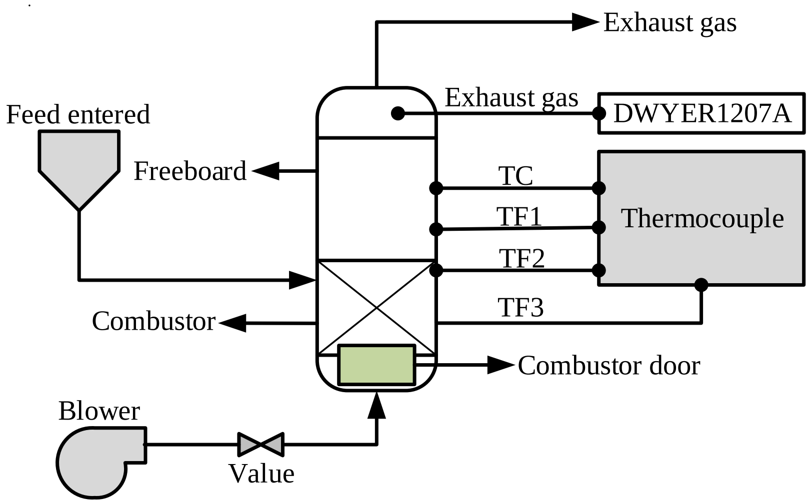

Fig. 4. Scheme of Fluidized Bed

2.4 Theory Differential TG (DTG) and TG

The data are taken from the Differential TG (DTG) curve and TG aims to determine kinetic parameters. These parameters are adjusted to the Freeman-Carroll integral method. The use of this method is carried out on the biomass kinetics by decomposition and combustion. The kinetic equation can be expressed as:

$$da/dt = Ae^{-E|RT}f(a) \tag{4}$$

Assuming, f(a)=(1−a)n and n=1, is first-order reaction. To bring it into Eq. (4):

$$da/dt = Ae^{-E|RT}(1-a) \tag{5}$$

Under the condition of linear heating, the heating rate ofw=dT/dt is brought into Eq. (5):

$$da/dt = \frac{A}{W}e^{-E|RT}(1-a) \tag{6}$$

Eq. (6) can be transformed by the integration as follow:

$$\text{In}\left[\frac{-In\,(1-\alpha}{T^2}\right] = In\left[\frac{AR}{wE}\left(1-\frac{2RT}{E}\right)\right] - \frac{E}{RT} \tag{7}$$

The definition of the conversion coefficient is a = (m_0 - m) / (m_0 - m_F), where m_0 represents the initial mass of the sample. While *m* represents sample mass during the experimental process. Whereas, *mF* represents the mass of residue in combustion; *t* represents the reaction time and w represents the rate of heating during the combustion process. *A* is a pre-exponential factor; E is the obvious energy for activation; R is the gas constant (8,314 J/(mol-K) and *T* represents the reaction temperature.

For most reactions, 2RT/E is much less than 1, and *a* = In $\left[\frac{-In\,(1-\alpha)}{T^2}\right]$ can be regarded as constant.

Then if y = In $\left[\frac{-In\,(1-\alpha)}{T^2}\right]$, a = In $\left[\frac{AR}{eW}\right]$, b = $\frac{E}{R}$, X = $\frac{1}{T}$

Simplification can also be done in Eq. (7) as y = a + bx. This simplification takes a bit of a series of points contained in the TG curve. Furthermore, the *y* value, *x* is adjusted and calculated by a straight line made in the linear regression method. Where slope, *b*, and intercept, *a*, can be produced. Finally the energy activation E and the frequency factor A can also be measured.

3. Results and Discussion

3.1 Analysis of Temperature Combustion for Mass Biomass

The testing experiment in this study was to analyze the combustion temperature of oil palm biomass mass using Fluidized Bed Combustor (FBC). The combustion temperature of biomass in the combustion chamber is observed with four different parameters. Details of the four sections were analyzed such as (combustion temperature (CT), freeboard temperature one (FT1), freeboard temperature two (FT2) and freeboard temperature three (FT3). The measurement of combustion temperature was carried out using Thermocouple which was placed on the part of each measured part.

The results of the combustion temperature analysis on Fluidized Bed Combustor (FBC) using oil palm biomass with a composition of EFB 35%, OPM 30%, OPF 20% and OPS 15% with a mass weight of one kg (1 kg) and each variation in air flow rate 1.25, 0.9375 and 0.625 m^3/s are shown in Figure 4. Combustion temperatures with an air flow rate of 1.25 m^3/sec showed better results compared to air flow rates of 0.625 and 0.9375. This maximum result can be obtained when the new combustion lasts for three OPF. This maximum speed can be obtained quickly because it is caused by the moisture content and pollutants that evaporate in the biomass at the start of combustion [52].

Combustion temperatures with air flow rates of 0.9375 and 0.625 m^3/s are lower than air flow rates at 1.25 m^3/s for all experiments conducted. The maximum temperature level can be achieved when the combustion lasted four and five minute. The difference in temperature at the beginning of combustion was caused by the preparation of the fuel used such as the conditions of the air flow rate of 1.25, 0.9375 and 0.625 m^3/s in the combustor. The volatility of each biomass used showed a difference such as EFB 79.67%, OPM 53%, OPS 73.74% and OPF 75.99%. With the volatility of different biomass and the preparation of fuel in the combustion chamber, it greatly affected the increase or decrease in temperature at the beginning of combustion. A higher rate of stable and heat combustion indicated that the temperature from burning oil palm biomass can be categorized as good. From the three air flow rates used for 1 kg of biomass tested and analyzed, a good combustion temperature and the highest combustion rate were obtained at an air flow rate of 1.25 m^3/s compared to the others.

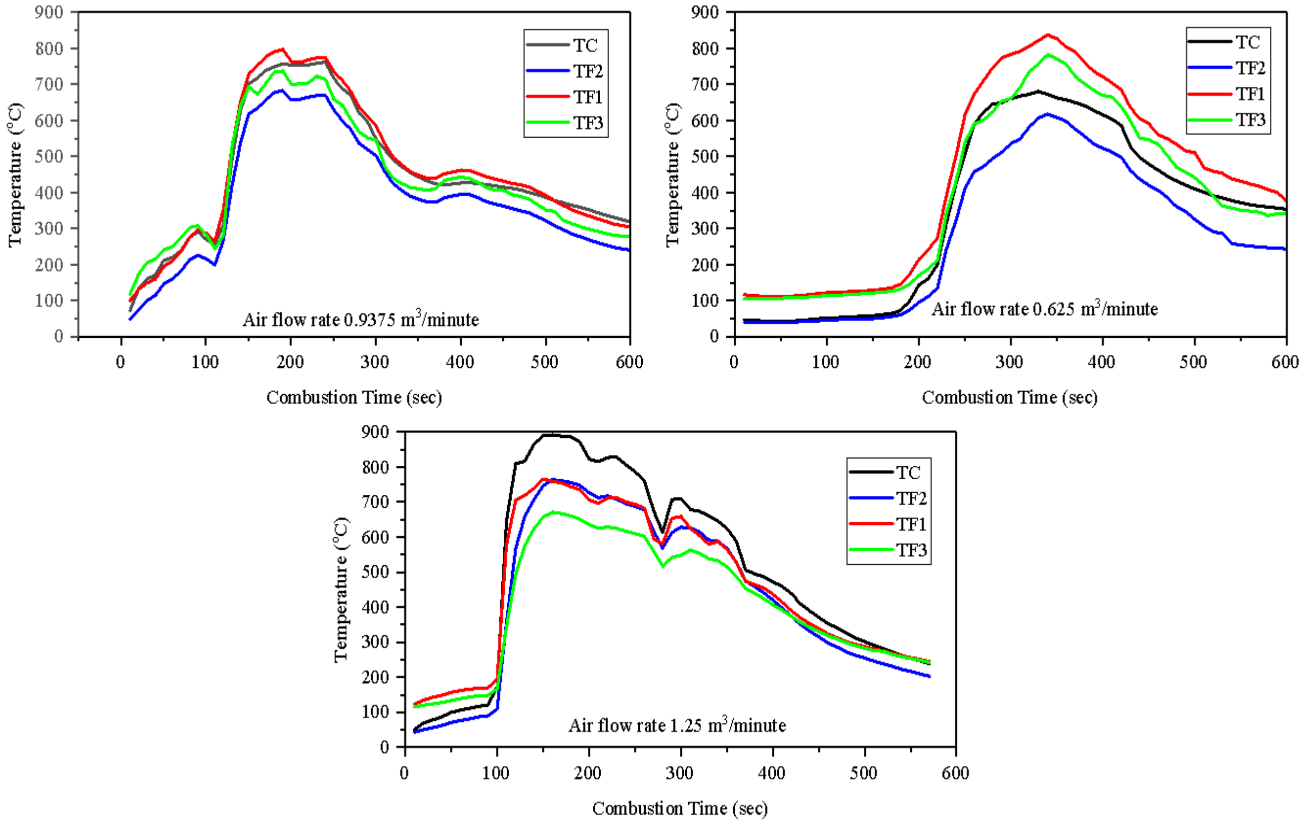

Fig. 4. Temperature combustion for biomass 1 kg on fluidized bed with air flow rate 1.25, 0.9375 and 0.625 m^3/s

Furthermore, at a mass of two biomass (2 kg), the maximum combustion rate was recorded at the air flow rate of 1.25 and 0.625 m^3/s as shown in Figure 5. This maximum level is obtained by burning time for 4 and 7 minutes shown in Figure 5. Meanwhile, the fastest maximum temperature was recorded at two (2 minute) at the beginning of combustion. At an air flow rate of 0.9375 m^3/s, combustion produces slightly slower than air flow rates of 1.25 and 0.625 m^3/s. The higher water content and volatility can cause a reduction in the combustion process in the boiler. The maximum speed of combustion temperature in a Fluidized Bed Combustor (FBC) was strongly influenced by the water contained in biomass fuels. Investigations regarding the combustion of biomass in boilers have also been studied by [52–54]. However, this study only tested 1 kg, 2 kg and 3 kg of biomass.

The experiments carried out with a mass of 3 kg to analyze the combustion temperature in Fluidized Bed Combustor (FBC) are shown in Figure 6. This test was carried out with four different compositions, i.e. EFB 35%, OPM 30%, OPF 20% and OPS 15% with three air variations on the air flow rate (1.25, 09375 and 0.625 m^3/s). From the composition tested, it can be noted that air flow 1.25 and 0.625 indicated delays at the beginning of combustion. The maximum temperature was reached when the combustion ran for eight until sixteen (8-16) minute. While the maximum speed of the test with biomass of three (3 kg) at five minute maximum the temperature was achieved. As for the air flow rate of 0.9375 m^3/s, it showed almost the same results in the process with the mass of biomass (1 kg and 2 kg). The temperature of TF3 combustion slightly increased compared to TF2 and TF1. However, at the beginning of burning TF1 and TF3 were slower than TC and TF2. Whereas at an air flow rate of 0.625, the difference with air flow rate was at 1.25 and 0.9375 m^3/s. The maximum combustion with an air flow rate of 0.9375 m^3/s is higher than the air flow rate of 1.25 and 0.625 m^3/s when testing for TF1.

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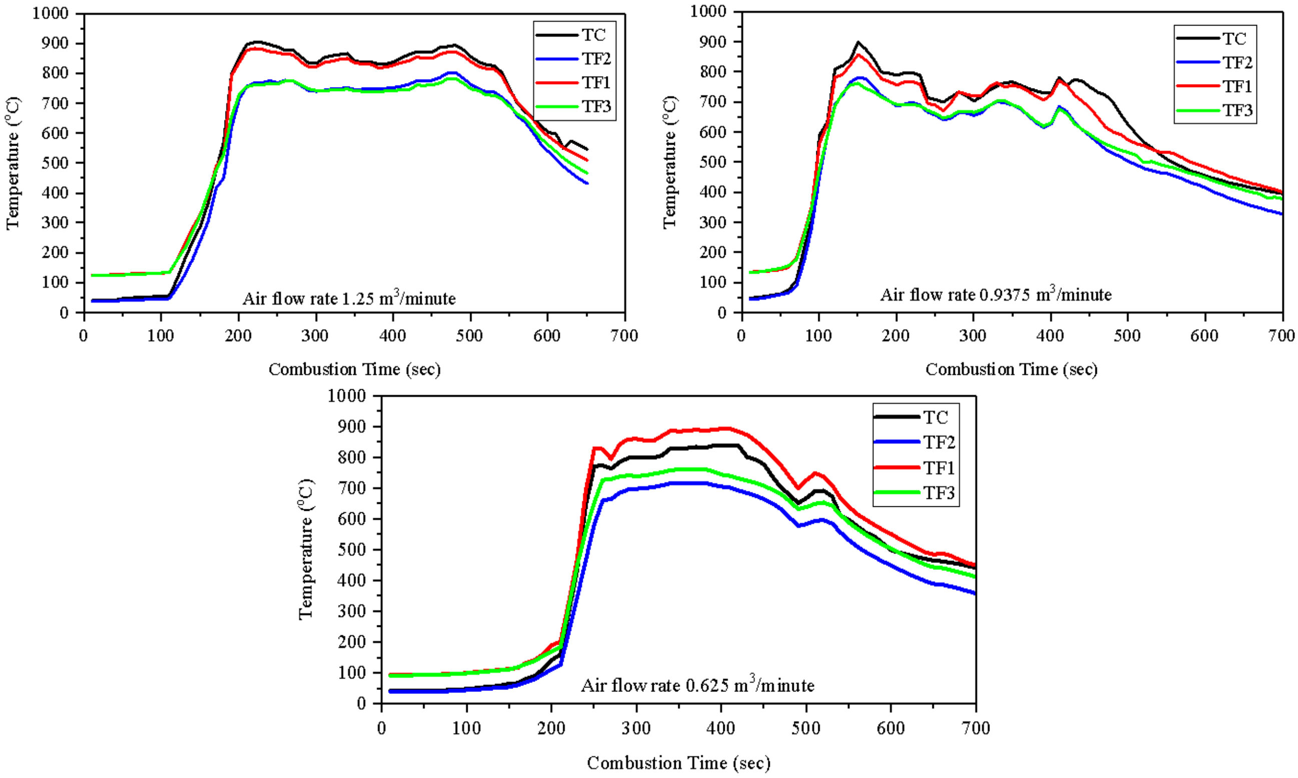

Fig. 5. Temperature combustion for biomass 2 kg on fluidized bed with air flow rate 1.25, 0.9375 and 0.625 m^3/s

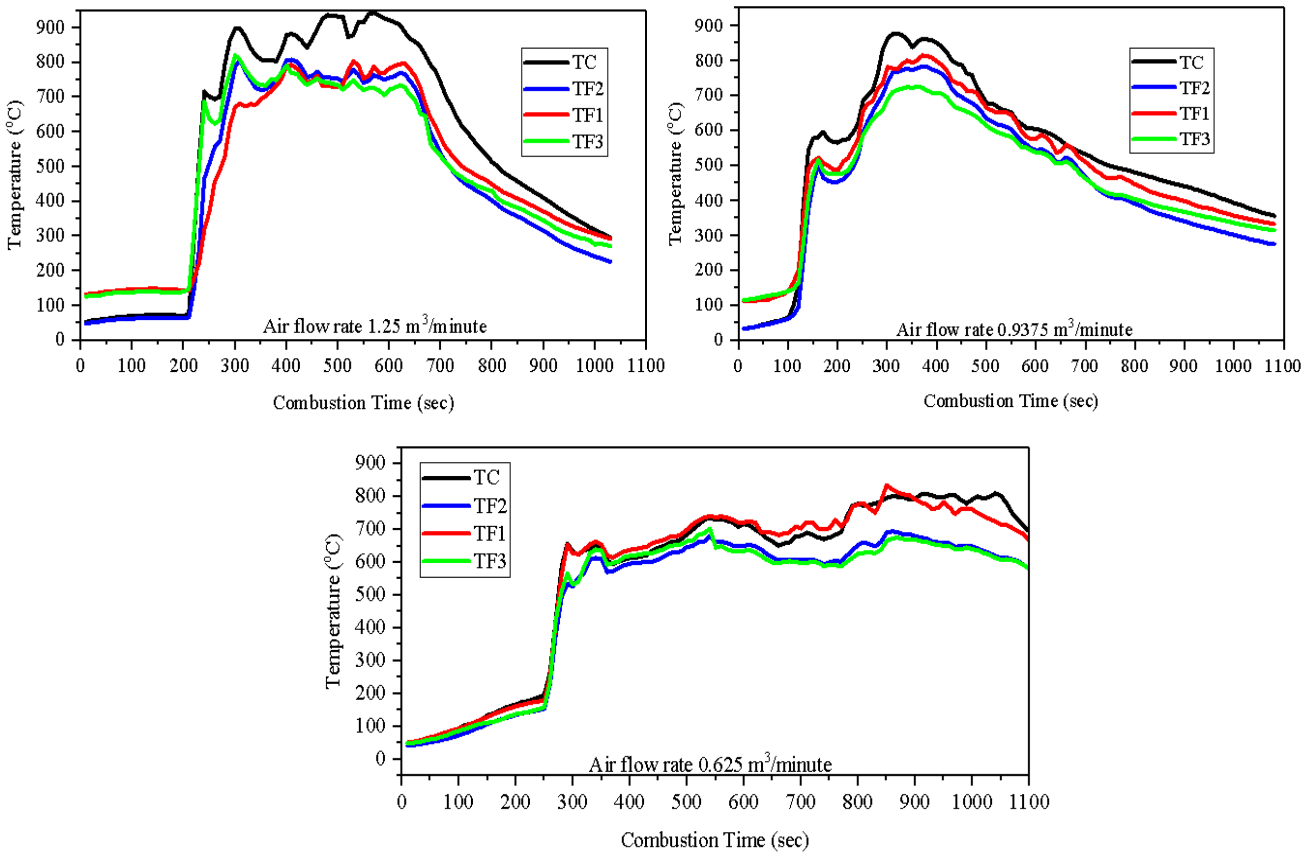

Fig. 6. Temperature combustion for biomass 3 kg on fluidized bed with air flow rate 1.25, 0.9375 and 0.625 m^3/s

The arrangement of different fuels in the combustor (chamber) greatly affects the condition of the air flow rate. The low air content found in the mixture of biomass fuel can accelerate the maximum temperature in the combustion chamber. If more water content is found in the fuel, the maximum temperature is obtained longer. From the three masses used in the test, it was reported that the air flow rate of 1.25 m^3/s showed the maximum temperature that was more perfect than the air flow rate of 0.9375 and 0.625 m^3/s. This was greatly influenced by the low water available on biomass fuel. The most stable combustion temperature of the three masses used was found in two biomass (2 kg) compared to mass (1 kg and 3 kg). However, the results were obtained at air flow rates of 0.9375 m^3/s compared to the others. Measurements regarding the combustion temperature using biomass fuels have also been analyzed by [55,56]. This is similar to the results of research conducted by [23,57,58].

3.2 Emission Analysis on FBC

Analysis of O_2 and CO_2 emissions in this experiment was carried out using the independent variables of water, biomass mass, flue gas composition and combustion efficiency related to the variables. Combustion in a boiler also requires sufficient air. With sufficient air supply in the combustion chamber, the results obtained can approximate the perfect combustion. The air flow rates used in the experiment include 1.25, 0.625 and 0.9375 m^3/s. The air flow rate supply is a parameter for analyzing combustion, emissions and reactions of chemical properties contained in oil palm biomass [59–61]. The combustion process in the machine requires excess water, however, the excess of water used must have certain limitations. This is because if the supply of excess water exceeds or decreases, it can affect the gas flue product produced. The analysis of flue gas in this study merely measured O_2 and CO_2.

The analytical tool for measurement is placed at the top of the FBC. This combustion analysis consists of 1 kg, 2 kg and 3 kg biomass. O_2 emissions from the combustion of 1 kg biomass show an almost similar trend as shown in Figure 7. During the combustion process in the middle of time, all the tested air flow rates decreased. However, at the end of the process of burning O_2 emissions again, it showed an increase. The decrease in O_2 can be caused by the rate of air flow supplied not yet operating properly. So that the gas flue analyzer still read a lot of O_2 emissions at the place where the gas was released. However, when the air supplied has worked properly, O_2 emissions were decreased. The combustion reactions can be produced well, as O_2 emissions are reduced. The minimum O_2 emission value was recorded at an air flow rate of 0.9375 m^3/s with a time of 4 minute of 3.9%. These results indicate or achieve the appropriate composition between air and biomass for 1 kg.

The results of CO_2 emissions show different results with O_2, where the value of CO_2 emissions from the incineration process was inversely proportional to the one obtained by O_2. When the combustion process was in the middle time, CO_2 increased and then decreased at the end of the combustion process being tested. The maximum emission of CO_2 from the combustion of 1 kg of biomass was produced at an air flow rate of 0.9375 m^3/s in the 4th s of 16.3%. From the results of the analysis carried out with 1 kg of biomass excess, water greatly affected O_2 and CO_2 emissions. Because the quantity of flue emissions of carbon dioxide gas depends on the oxidation reaction that occurs. Carbon dioxide can be reduced by a larger supply of O_2. The carbon dioxide gas formed indicates that the chemical element of carbon in oil palm biomass can be oxidized properly [57,60]. The maximum CO_2 emissions analyzed occurred when the composition compatibility between air and biomass at the air flow rate was 0.9375 m^3/s for 1 kg of biomass.

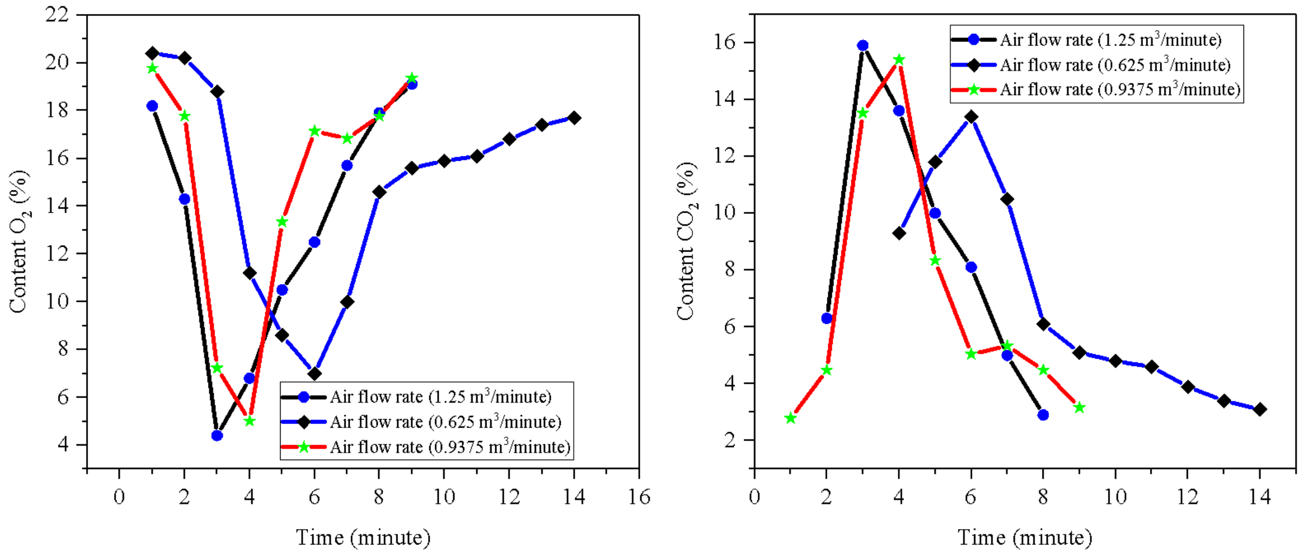

Fig. 7.a Fig. 7.b

Fig. 7. Emission O_2 and CO_2 for biomass 1 kg with air flow rate 1.25, 0.9375 and 0.625 m^3/s

Furthermore, an analysis of O_2 and CO_2 emissions was carried out on 2 kg of biomass fuel. The results of the analysis of O_2 and CO_2 emissions as a whole process were the same as the combustion process on 1 kg biomass as shown in Figure 8. O_2 emissions for the air flow rate of 1.25 m^3/s show differences. Where in the initial and mid processes, the burner showed a better trend than the air flow rate of 0.9375 and 0.625 m^3/s. However, at the end of the process, a significant increase in air flow rates was 0.9375 and 0.625 m^3/minute compared to the air flow rate of 1.25 m^3/s. As for the minimum O2 emissions from the beginning to the middle of the combustion process found for air flow rates of 0.625. However, when the combustion process will end the maximum O_2 emissions are recorded at an air flow rate of 0.9375 m^3/s.

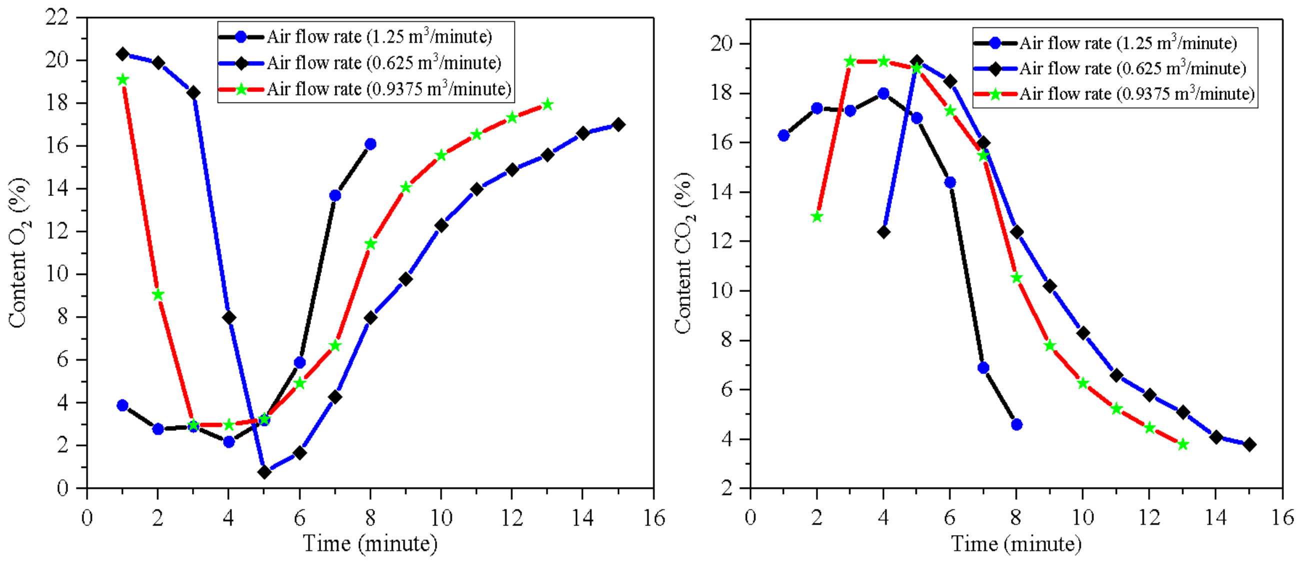

Fig. 8.a Fig. 8.b

Fig. 8. Emission O_2 and CO_2 for biomass 2 kg with air flow rate 1.25, 0.9375 and 0.625 m^3/s

CO_2 emissions from the combustion process of 2 kg biomass show a slight difference with 1 kg of biomass. This difference was recorded at the beginning to the end of the combustion process on the FBC. The increase in CO_2 emissions in the process was not too far at the beginning of the process compared to the process in 1 kg of biomass. The air flow rate of 1.25 m^3/s indicates earlier on fire than the other air flow rates. Because the air flow rate supplied in the combustion chamber is suitable for the combustion of biomass used in this experiment. However, the combustion process also ends faster because it was influenced by the low water contained at the air flow rate of 1.25 m^3/s. So that the longer the burning process starts, the longer the burning process ends. The combustion process of 1.25 m^3/s air flow lane for 2 kg biomass only took 8 ss. Meanwhile, for air flow rates of 0.9375 and 0.625 m^3/s, each took 13.5 to 14.5 minute for the biomass of 2 kg as shown in Figure 8. The maximum amount of CO_2 emissions was recorded at the air flow rate of 0.9375 m^3/s with a time of 3 to 4 minute of 19.2%. Therefore, the biomass burning process in FBC in experiments shows that CO_2 emissions are very high.

The final stage of the analysis of O_2 and CO_2 emissions in this study was carried out in the process of combustion of three kg of biomass (3 kg) as shown in Figure 9, where the process tested at this stage the parts were equal to biomass 1 kg and 2 kg. O_2 emissions at the end of the process showed a maximum yield of 19.2% at the 3rd and 4th inclines with an air flow rate of 0.9375 m3/min. Combustion of 3 kg biomass at the time of process intervals showed a slightly longer trend than 1 kg and 2 kg. The process needed to complete combustion from the beginning to the end took 22 ss. This much time can be due to the water content that was too large compared to biomass 1 kg and 2 kg. The minimum amount of O_2 emissions recorded at the second s of 0.2% for the air flow rate of 1.25 m^3/s is shown in Figure 9. Meanwhile, the air flow rate of 0.625 showed a trend that was slightly slower than the others. However, the very fast increasing trend was recorded at the air flow rate of 0.9375 m^3/s. CO_2 emissions experienced a very significant increase in the mid-combustion process of 19.9% for air flow rates of 1.25 m^3/s. Whereas the minimum value of CO_2 was also recorded at an air flow rate of 1.25 m^3/s at 2.5%. The air flow rate of 0.9375 m^3/s showed a slight decrease compared to the other two. The longest burning time was recorded at an air flow rate of 0.9375 m^3/s which reached up to 22 minute.

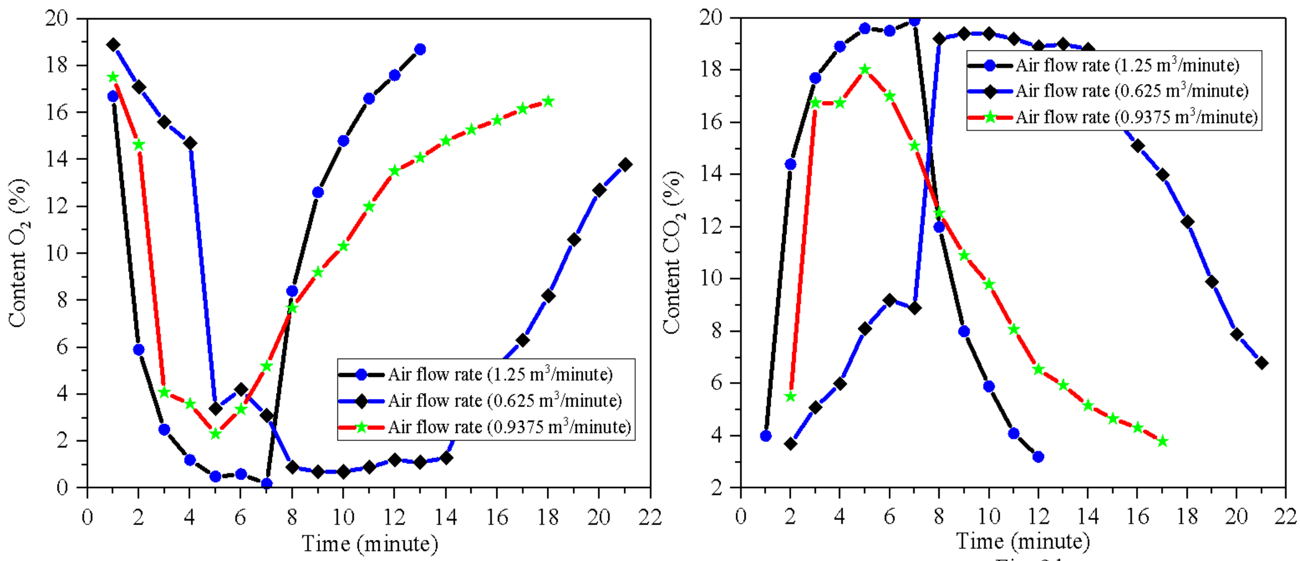

Fig. 9.a
Fig. 9.b

Fig. 9. Emission O_2 and CO_2 for biomass 3 kg with air flow rate 1.25, 0.9375 and 0.625 m^3/s

The combustion process of the three variations used in this study showed a different time, where 1 kg biomass took 14 minute for CO_2 and 16 minute for O_2, while 2 kg biomass needed burning time for 16 minute to produce O_2 and CO_2 emissions. In addition, 3 kg of biomass needed 22 ss. Increased CO_2 emissions indicate that the reaction process of carbon (C) in the combustion chamber can react perfectly. The experiment results using three variations of biomass fuel and three air flow rates on FBC show that the best value of O_2 and CO_2 emissions obtained at air flow was 1.25 m^3/s by 0.2% and 19.9%. The reaction between the biomass and air supplied took place very well. This can be said to be perfect because the value of O_2 contained in the gas flue increased and CO_2 decreased at the end of each process as shown in Figure 7, Figure 8 and Figure 9. Investigations on CO_2 emissions and the efficiency of combustion performance with air-fuel mixtures have also been carried out by [63–65].

3.3 Effect of Air Excess on Combustion Efficiency in FBC

The combustion efficiency of biomass using a FBC with different variations and air flow rates is also explained. One indicator used to determine whether combustion is good or not is combustion efficient. The combustion efficiency referred to in this analysis includes converted thermal efficiency, carbon efficiency, or hydrogen efficiency [66,67]. However, in this study, the combustion efficiency was evaluated only for combustion when an experiment was carried out with FBC. Measurement of thermal efficiency was taken from the results of a comparison between the amounts of heat in the combustion gases to the amount of heat of fuel. The results of the combustion efficiency analysis obtained from each of the variables used during the combustion process are shown in Figure 10. Previous research on combustion efficiency has also been carried out by [21]. However, in this study the combustion efficiency was only carried out for 1 kg, 2 kg and 3 kg biomass as a parameter for fuel.

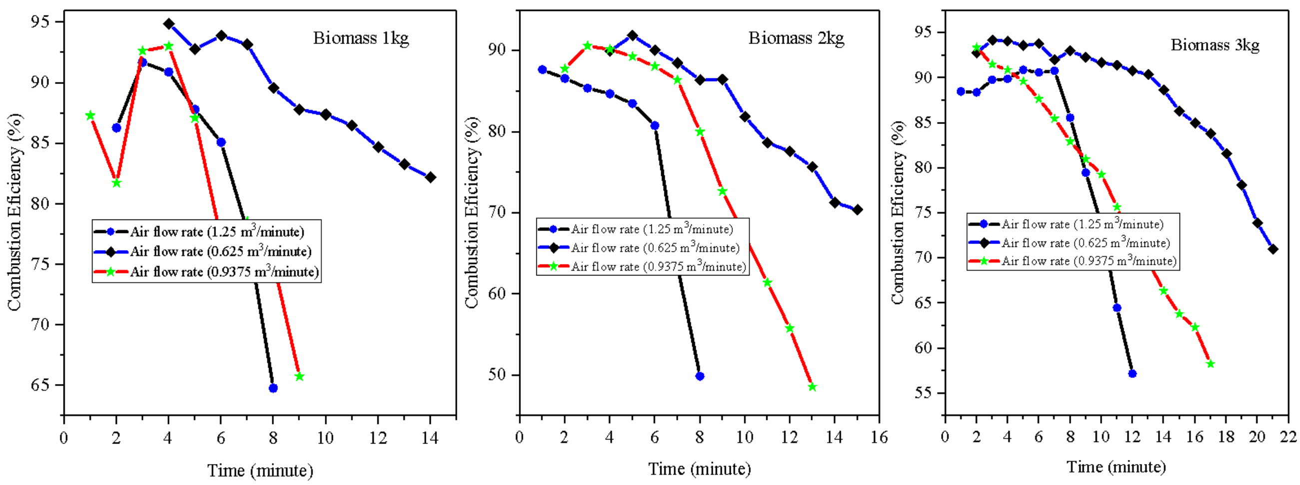

Fig. 10. Combustion efficiency at FBC for biomass 1 kg, 2 kg, and 3 kg with air flow rate 1.25, 0.9375 and 0.625 m^3/s

The maximum efficiency value of the three variations and air flow rates tested on the Fluidized Bed Combustor were obtained from 1 kg of biomass with an air flow rate of 0.625 m^3/s in the 4th s at 94.9%. Meanwhile, the minimum efficiency value recorded on 3 kg biomass fuel with an air flow rate of 0.9375 m^3/s was produced in the 17th s of 47.7%. Based on the results of combustion efficiency analysis using biomass, supplying more excess water can reduce the efficiency of the tool. However, too much water supply can reduce combustion efficiency. This is in line with the results of research conducted by [59,68–71].

3.4 Analysis of Chemical Compounds in Ash Deposits

Ash deposit is the residual ash from combustion from oil palm biomass. I The composition of the oil palm biomass mixture used in this experiment was EFB 35%, OPM 30%, OPF 20% and OPS 15%. The ash deposit analysis of the remaining ash taken in the combustor after completion of combustion was carried out. Such palm oil biomass can be obtained at a very low cost and can even be obtained for free. So far, the POFA is only considered an environmental destroyer because it is the result of the disposal of an oil palm mill which is deliberately placed in an empty area [70]. This Ash deposit was analysed to examine the chemistry of the compounds contained in it using Proximate Analysis. Furthermore, it is compared with the chemical compounds of the remaining ash which are original from the combustion results. The results of the analyzed of chemical compounds from ash deposits from biomass combustion in this study are shown in Table 2.

Table 2
The chemical composition of the compound from the remaining combustion ash [72–74]

Chemical Compounds	Total (%) OPBC	POFA	Coal
SiO_2	30,860	66,91	48,06
CaO	10,55	5,56	25,06
MgO	2,54	3,13	14,53
K_2O	1,910	NA	28,56
Al_2SO_3	4,710	NA	34,76
Fe	0,63	NA	NA
Na	0,11	NA	NA
Al_2O_3	NA	6,44	NA
Fe_2O_3	NA	5,72	3,91
Na_2O	NA	0,19	0,75
SO_3	NA	0,33	NA
P_2O_2	NA	3,73	NA
Air	NA	NA	0,65
Cd	< 0,0004*	NA	NA
Cu	151,5964*	NA	NA
Ni	15,1967*	NA	NA
LOI	NA	23	NA

Note: *Unit in mg/kg

The composition of the chemical compounds contained in the ash deposit based on laboratory analysis is shown in Table 2 [21,75–80]. Chemical compounds from burning palm oil biomass can be found easily. This is very possible to be used for various purposes, for example, fertilizer which is an alternative and has a very cheap price. Because the remaining ash from biomass combustion contains a lot of nutrients for plant needs, such as K, Ca and Mg [81,82]. In addition, the composition of ash deposits from oil palm biomass is very similar to the chemical compounds from the remaining ash from coal combustion. This content is usually used as a mixture of making concrete which is often referred to as SiO_2 content [83]. The remaining ash from palm oil biomass burning contained SiO_2 in coal by 30%. The content of SiO_2 from the ash residue of oil palm biomass in the experiment reached 30.86%. Therefore, the remaining ash of palm oil biomass can also be used as a mixture for making concrete. This is similar to what is explained about the content of SiO_2 for a mixture of concrete making [84]. In addition, the remaining ash from burning palm oil biomass can also be used as an air filter for motorized vehicles.

4. Conclusions

This study presents the oil palm biomass combustion applied to FBC. Burning biomass can produce heat power to be used as a power plant. From the results of the experiments in this study, several conclusions can be noted as follows:

i. The best temperature profile was found in 2 kg biomass with an air velocity of 0.9375 m^3/s at 90.1%. Meanwhile, combustion efficiency is obtained from 3 kg of biomass with an air flow rate of 1.25 m^3/s are 950ºC (95%).
ii. The composition of the flue gas in this study only focused on O_2 and CO_2. Minimum O_2 and maximum CO_2 levels were recorded in the combustion of 3 kg biomass with air velocity 1.25 m^3/s being obtained 0.2% and 19.9%, respectively. The results of O_2 and CO_2 indicate that the biomass combustion process worked very well.
iii. The combustion efficiency in a FBC was very much dependent on the amount of heat in the gas produced during the process. The maximum combustion efficiency was obtained from 1 kg biomass at an airspeed was 0.625 m^3/s at 94.9%.
iv. Giving more air during the process the biomass combustion can produce better combustion. However, it does not guarantee an effective combustion process by giving a lot of water excess.
v. The best excess water was obtained when the process of burning biomass was 3 kg with an air flow rate of 1.25 m^3/s.

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