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Investigation of Biomass Combustion and Conceptual Design of a Fluidized-Bed

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ABSTRACT

This study investigates the combustion process of empty fruit bunches (EFB) and palm kernel shells (PKS) in a bubbly fluidized-bed combustion chamber. The biomass combustion simulation process uses a kinetic model consisting of chemical kinetic and hydrodynamic flow. This modelling is based on the two-phase theory in the fluidized bed. Where both phases in the bed are assumed that there are a mass and energy transfer between them. These phases include the emulsion phase and the bubble phase which contains solid particles. The constant temperatures throughout the reactor are assumed in this modelling. This study also investigates the parametric and effects of various parameters carried out. The experimental research shows that there is a change in bed diameter and has a negligible effect on combustion performance. The results of biomass combustion experiments with a fluidized-bed design have promising and satisfying results compared to several experimental studies in the literature. In addition, the increase in reactor temperature and a bed height of combustion efficiency also increased. However, the moisture of the biomass and the speed of the fuel entering can affect various for combustion efficiencies. Suitable operating conditions can produce maximum overall efficiency.

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1. Introduction

Indonesia is one of the countries that have abundant renewable energy sources in the Southeast Asian region. However, the utilization and available resources are still very minimal so that the available energy sources cannot be utilized optimally [1,2]. Existing energy sources can be utilized for decades to come if they can be utilized properly and can even replace dependence on fossil energy [3].

Current researchers have paid more special attention to computational methods compared to before. This is because the costs are cheaper and the results obtained are relatively acceptable with this method than the experimental methods in Mechanical Engineering with various aspects. The problems of oil recovery continue to increase [4–6]. In addition, chemical reactions, molecular dynamics, fine particle hydrodynamics [7–10] have also been discussed. Vibration analysis and application [11,12], spray and atomization technology [13], droplet dynamics [14,15] and Nano-fluid applications [16–18] have been investigated. However, some of these works are numerical studies in Mechanical Engineering for various aspects. Renewable energy is one of the most important aspects of Mechanical Engineering and certainly needs to be investigated and studied in more detail. One of the most important renewable energy systems in the future is biomass energy because hydrogen from biomass can be produced on a large scale that can contribute to the development of renewable energy that is environmentally friendly [19–21]. However, the high energy consumption of technology in producing hydrogen sourced from biomass has hampered its development so that technology is only limited to the laboratory scale [22–24]. The availability of biomass for energy production processes has two general categories such as biological and thermochemical processes. The various methods used in hydrogen production through biological procedures have been reviewed [25].

The discovery of these procedures took place a century ago, but at the time they were discovered they were not included or became practical. In the thermochemical process, there are four categories namely; combustion, liquefaction, gasification and pyrolysis. The sustainable development, combustion, is not very suitable for hydrogen production. While biomass has disadvantages such as operating conditions are very difficult to achieve and low hydrogen production. Therefore, producing hydrogen from thawing is not very profitable [26–28]. Pyrolysis can be grouped into fast and slow pyrolysis because its main product is produced from charcoal. The pyrolysis with the slow category cannot be produced into hydrogen. While fast pyrolysis has a high temperature in the process, where biomass heating can be done without air with a fast system. This is done so that steam can be formed and condensed into a dark brown liquid bio-liquid. Most of the pyrolysis can be produced into biofuels and hydrogen production can be done directly with fast pyrolysis if it gets high temperatures and sufficient volatile phase periods are allowed. Moreover, hydrogen can be produced and enhanced by reforming steam from the reaction during the shifting gas hydrocarbon water obtained from water vapor and CO. The various types of suitable catalysts, heating rate, residence time and temperature are control parameters for the pyrolysis process. Hydrogen production, high heating rate, reactor phase residence time and high temperature can support the gas product needed [29–31]. The selection of these parameters can be regulated by various reactors and heat transfer modes such as heat transfer in solid conductive and solid-gas convection heat. Investigation of various reactor features and different heat transfer has been carried out [32–34]. From various investigations, it can be concluded that the high heating level shown by the fluidized bed reactor makes it very promising to produce hydrogen sourced from biomass pyrolysis.

The purpose of the gasification process is to produce gas products compared to charcoal and bio-liquid. Therefore, the gasification process is more profitable in hydrogen production than pyrolysis.

In addition, the solid biomass process is gasified in the presence of O_2. However, the process of oxygen with biomass gasification has two associated disadvantages. Low hydrogen content is one of the weaknesses with the dilution of N_2 which is sourced from the air, high CO_2 emissions during the gasification process is also a related constraint [35]. The use of steam as a biomass gasification agent can be done so that losses can be reduced. In addition, other advantages can also be found in steam gasification. Higher-level heating can maximize the product gas produced. Moreover, the benefits of residence time characteristics, char efficiency and tar reduction due to steam reform. However, the endothermic nature of the steam gasification reaction as a whole can operate the reactor more precisely so that important activation energy is provided. The method required for heat input must use steam and air mixtures as gasification agents which can lead to losses from air gasification [36–38].

In 1952, Johnson and Toomey proposed a two-phase fluidization theory in which the main hypothesis was divided the two phases in reactors such as emulsions and bubbles. Emulsion and gas phases are solid materials with a limited amount of gas present in the bubble phase [39]. The bubbling and assemblage bubble models found in the two-phase modes presented in 1969 have the most references in their fields [40]. Emulsion and bubble phases have written the conservative equation of the mass of the gas species. The controlled entry and exit rates of mass conservation and inconsistent diffusion effects for gas species at each phase need to be considered [41,42]. The assumption of this model is for the empty bubble phase of solid particles distributed to uniform species. This equation can also be considered by assuming for simplification so as to obtain a differential equation [43]. The conservative equations modelled on this type are considered under established conditions [44].

In this work, the process of burning empty fruit bunches (EFB) and palm kernel shells (PKS) in the bubbling fluidized-bed combustion chamber is investigated. The kinetic method with two phases was developed to simulate the combustion process with hydrodynamic parameters derived from the reactor flow, transport species equations and chemical reactions. There are two-phase modes for biomass combustion and division of the reactor into two parts solid particles are not present on a freeboard. The diffusion effect in this model namely; freeboard and bed. The combustion chamber can contain gas and solid particles, while is neglected, but it is assumed that there are some small solids present in the bubble phase.

2. Process Modelling

Kinetic models for the combustion process can provide information about the final results of experiments. In addition, information about the product distribution at the reactor consists of hydrodynamics sourced from inside the reactor. Features are very important criteria for measuring, designing, and optimizing parameters during the operations in a reactor [25,34–36]. This study aims to investigate the burning of bubbly biomass in certain operational conditions. This investigation was carried out using a two-phase model of the results of the development made. In addition, the effect on domain parameters on combustion performance was also investigated. Finally, the design of combustion at a certain input can be done with the algorithm of the development results. To model combustion kinetic, pyrolysis, chemical kinetic reaction, hydrodynamic flow behavior and mass conservation are considered in this study.

2.1 Hydrodynamic Flow

The research and investigation of biomass combustion performance will use the following assumptions:

a. The minimum fluidization conditions can maximize the emulsion phase. Therefore, the overlay fraction and velocity are always equal to the minimum fluidization conditions.
b. The process of pyrolysis is only for a moment when the biomass enters the combustion chamber. Furthermore, it becomes charcoal, gas and tar. In other words, the presentation of pyrolysis production with this model as a limited condition because it can only be determined by experimental results.
c. Pure carbon can be assumed as char, and solid particles do not disappear from the bed.
d. Experiments for burning biomass in a fluidized bed reactor are rational [45,46].
e. The Freeboard reactor has no solid particles and gas velocity. This plug flow model used can simulate various biomass combustion processes.
f. The volume in the bubble phase that is formed can increase with the height found in the bed.
g. Gas species in this investigation such as CO_2, CO, H_2, H_2O, CH_4, N_2, O_2, and trainers. This is done because there are nine gases in the reactor. In addition, due to low temperatures by ignoring the nitrogen reaction.
h. Meanwhile, the gas species are considered perfect.

To produce the speed of channel fluid entering the combustion, the situation of the bed fluidization depends on the number of maximum and minimum limitations. The minimum fluidization speed U_{mf} and the terminal speed Ut must be lower than the speed of the incoming channel. To calculate the parameters of hydrodynamics, it can use the equation below [47–49].

Minimum fluidization velocity $u_{mf} = \frac{\mu_g\left(\sqrt{27.2^2+0.0408Ar-27.2}\right)}{d_p\rho_g}$ (1)

Terminal velocity $u_t = d_p\left[\frac{4(\rho_p-\rho_g)^2 g^2}{225\rho_g\mu_g}\right]^{\frac{1}{3}}$ (2)

Diameter of bubble after distributor $d_{bm} = 0.652\left(\frac{\pi}{4}\, d_t^2\,(u_o - u_{mf})\right)^{0.4}$ (3)

Diameter of bubble maximum $d_{bo} = 0.00376(u_o - u_{mf})^{0.4}$ (4)

Diameter of bubble in reactor $d_b = d_{bm} + (d_{bo} - d_{bm})e^{-\frac{0.3z}{d_t}}$ (5)

Volume of bubble fraction $\delta_b = \frac{u_o - u_{mf}}{u_b - u_{mf}}$ (6)

Velocity of bubble $u_{br} = 0.711(g.d_b)^{0.5}\ \frac{d_b}{d_t} < 0.125$ (7)

Emulsion considering $u_{br} = [0.711(g.d_b)^{0.5}]\ 1.2\ exp\left(-\frac{1.49d_b}{d_t}\right) 0.125\frac{d_b}{d_t} < 0.6$ (8)

Velocity of bubble in bed $u_b = (u_o - u_{mf}) + u_{br}$ (9)

Factor of transfer between bubble and emulsion $K_{be} = \frac{0.11}{d_b}$ (10)

This study uses biomass fuels such as oil palm midribs (OPM), palm empty fruit bunches (EFB) and palm kernel shells (PKS). This biomass fuel is tested on a specially designed fluidized bed as shown in Figure 1. This fluidized-bed design can also be used for burning biomass from composite palm oil and others.

2.2 Mass Conservative Equations for Species

The kinetic model used in the reactor can produce a wide variety of species with the conservation of species mass. Thus, the settlement of solid and gas species from a conservative mass equation can be solved at the bottom and when on a freeboard.

a. Two-phase model bed fluidizing

This process is assumed to be a steady state, while its diffusion effect is ignored. Figure 2 can be assumed in the equation for the conservative mass of the emulsion and bubble as below.

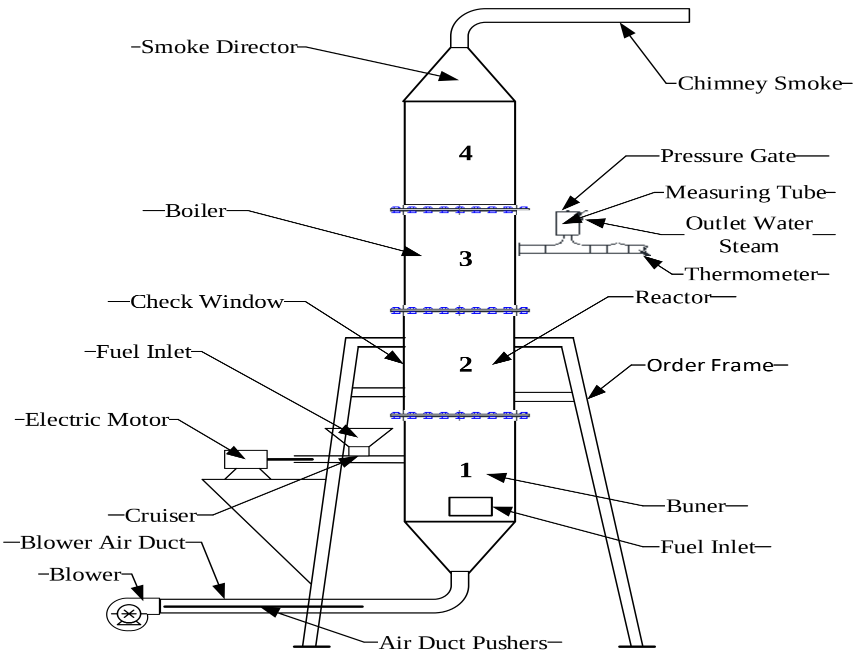

Fig. 1. Design Fluidized-bed for biomass combustion

The term from the equation above is the rate of change of mass represented by the right-hand side for each phase with adjusted convection? The first of these terms starts from the left side so that it can represent the rate of change in mass in each phase of the emulsion and bubble and at the end that is where it remains in the equation. Therefore, the resulting chemical reaction can represent the rate of change in mass in phase. For the equation of the conservative char, mass is shown in Eq. (13). Changes in the concentration of carbon are functions for the conservation of mass and non-homogeneous reactions to charcoal in completing the emulsion phase.

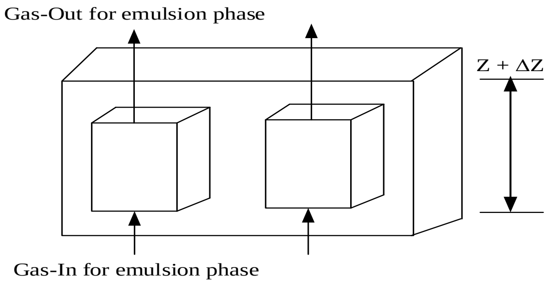

Fig. 2. Two-phase model bed fluidizing

$$\frac{\partial(\delta_b u_b C_{i,b})}{\partial_z} = -K_{be}\,\delta_b\left(C_{b,i} - C_{i,e}\right) + \delta_b \sum\nolimits_{g-g} v_{ji} r_i \tag{11}$$

$$\frac{\partial(\delta_b u_b C_{i,b})}{\partial_z} = -K_{be}\,\delta_b\left(C_{b,i} - C_{i,e}\right) + (1-\delta_b) \sum\nolimits_{g-g} v_{ji} r_i + \frac{(1-\delta_b)(1-\varepsilon_{mf})}{\varepsilon_{mf}} \sum\nolimits_{s-g} v_{ji} r_i \tag{12}$$

$$\frac{\partial C_C}{\partial_z} = \frac{1}{u_c} \sum\nolimits_{s-g} v_{ji} r_i \tag{13}$$

b. Freeboard

Solid particles with low concentration and low gas velocity in the freeboard section in this simulation can adjust the flow process in the modelling. In this case, mass diffusion for gas species as in the mass conservation Eq. (14). It is assumed that ug is the speed of gas in a freeboard.

$$\frac{\partial(u_g C_i)}{\partial_z} = \sum\nolimits_{g-g} v_{ji} r_i \tag{14}$$

c. Solving method

For solving the presented system of equations, a computational code was developed. The flowchart of the generated model can be seen in Figure 3. The silica is considered to be sand particles to the bed reactor and biomass composite as a feed. Silica sand and biomass composites are shown in Table 1.

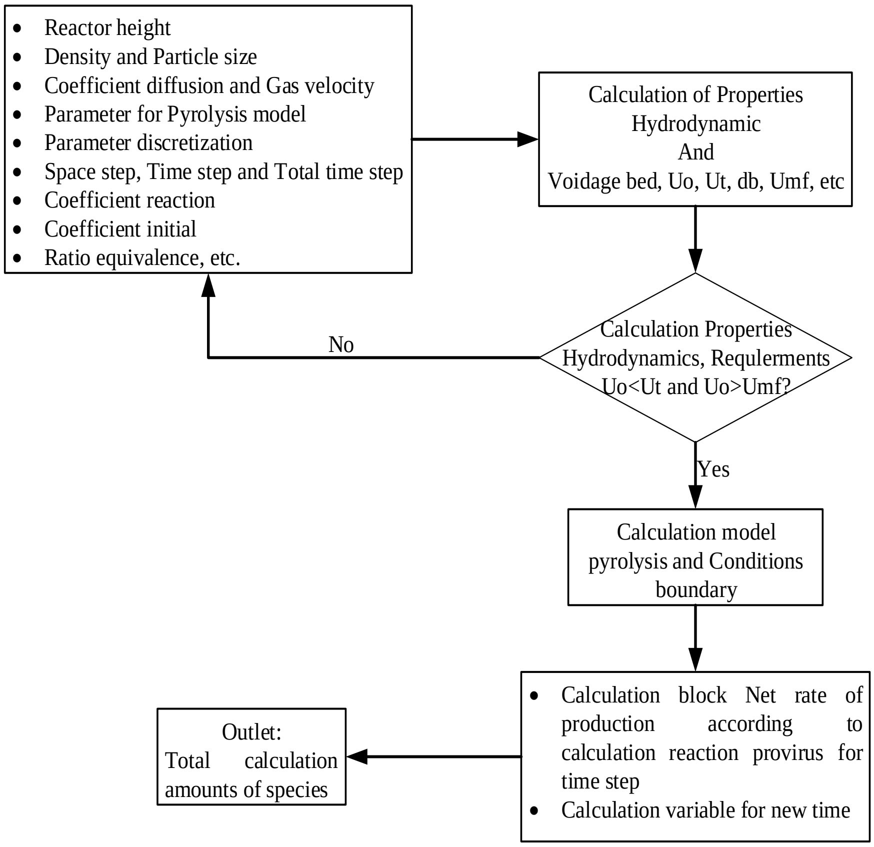

Fig. 3. Flowchart of calculation procedure

Table 1
The characteristics of silica sand particles and rice husk [50–52]

Silica sand particle's		Diameter (mm)	Density (kg/m^3)
	Silica sand particles	150-450	2650
Rice husk	humidity	Approximate analysis (mass percentage)	12.10
	volatile matter percentage (dry)		70.36
	carbon percentage (dry)		15.07
	ash percentage (dry)		14.57
	C	Element analysis (mass percentage based on dry)	39.78
	H		4.97
	O		40.02
	N		0.46
	S		0.2

3. Results

The biomass combustion reactor has a standard operating temperature. This setting presents a minimum operating temperature of 600°C. Because pyrolysis is assumed to have a velocity with inlet fuel. Moreover, the maximum temperature operated at the reactor is 900°C. This is made higher than the number of particles in the bed to accelerate the melt and heavier particles are formed quickly which stick together so that the hydrodynamic properties of the bed can be changed. The heating value of the gas with respect to the equality constellation which is different from the temperature and the combustion agent is shown in Figure 4. Based on Figure 4, the temperature increases with increasing heating value. However, the heating value is negatively affected by the equality ratio. A

30% increase in heating value when burning using oxygen as a burning agent. These results show as expected.

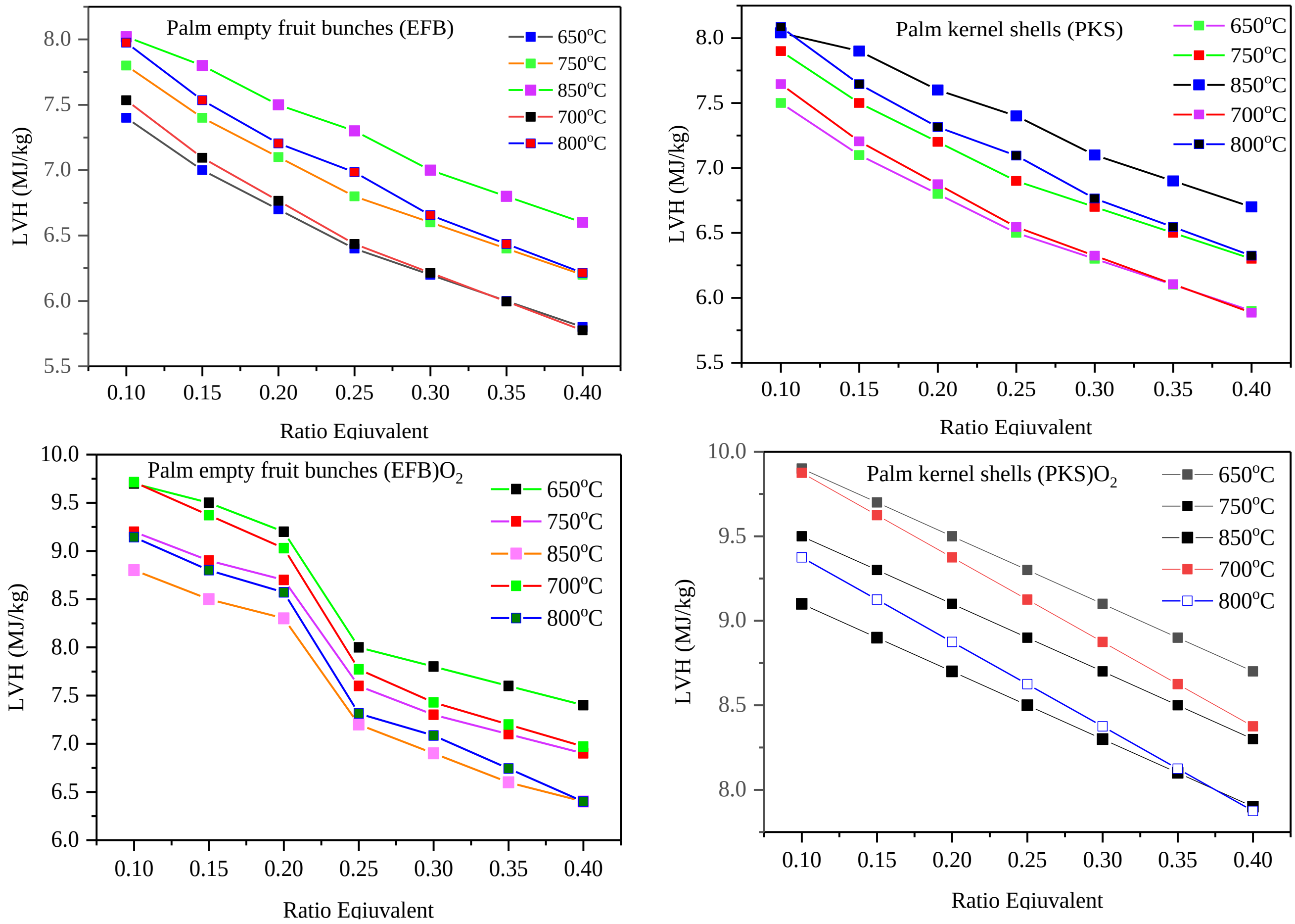

Fig. 4. LHV for different temperature using air and O_2 as combustion agents

Combustion efficiency to different equality ratios, temperatures and combustion agents is illustrated in Figure 5. The amount of temperature increases indicates that efficiency can be directly affected. However, increasing the equality ratio can increase efficiency initially and subsequently decrease. This can be explained by looking at and paying attention to the definition of efficiency. This is the heating value and function of the output gas flow rate. This multiplied parameter has caused an increase in the initial period; however, in its continuation, the decreasing effect predominates in the heating value. The maximum efficiency for combustion EFB with an equality ratio level of 0.31 and its quantity to be 0.73 is recorded at 900°C. Combustion using oxygen on the other hand maximum efficiency with an equivalent ratio of 0.33 and a quantity of 0.83 is also recorded at 900°C.

The heating value of the gas against various equal ratios of combustion agents and increasing humidity is shown in Figure 6. Increased biomass humidity has reduced the heating value, this is due to the increased amount of water vapour in the produced gas and the reduced molar fractions such as H_2, CH_4, and CO. Combustion of EFB biomass, in this case, uses oxygen, where humidity has increased by 14% from 2% and the heating value of 11% and 16% can decrease, respectively. The combustion efficiency of various equality ratios, combustion agents and humidity values is illustrated in Figure 7. Where these results indicate that the percentage of increased biomass humidity can cause the efficiency of cold gas in the reactor to decrease. The reduced EFB biomass and oxygen are 0.18 and 0.21, respectively.

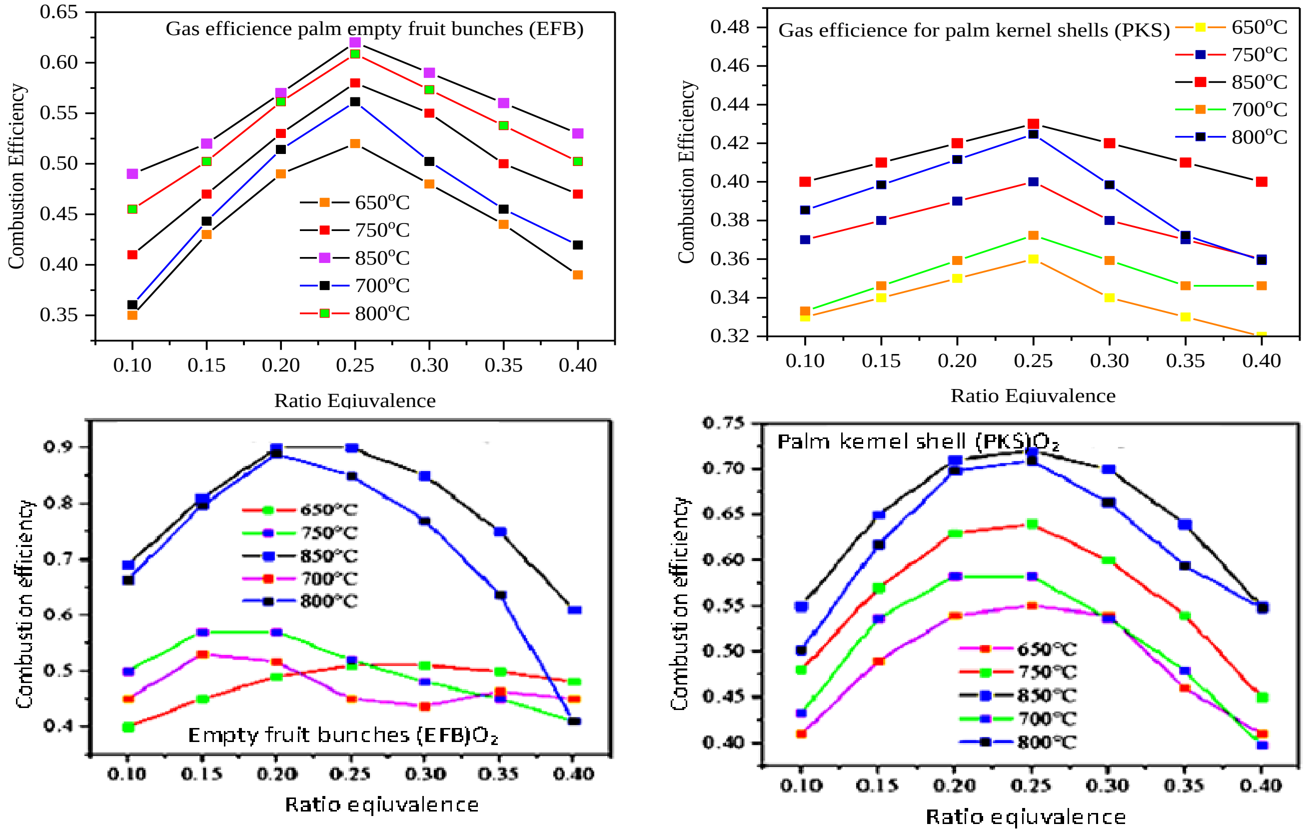

Fig. 5. Combustion efficiency for RE using air and O_2 as combustion agents

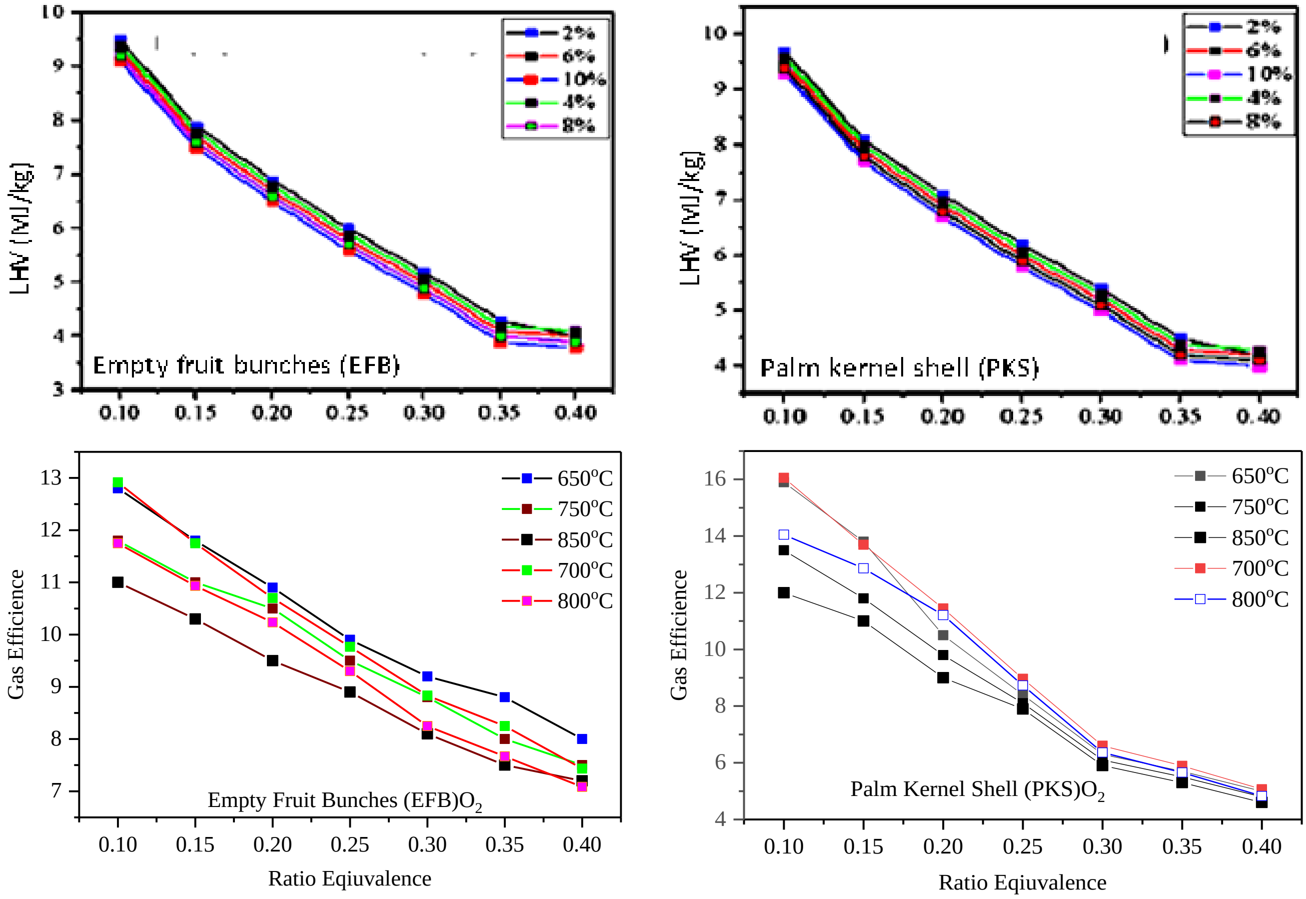

Fig. 6. LHV for different RE using air and O_2 as combustion agents

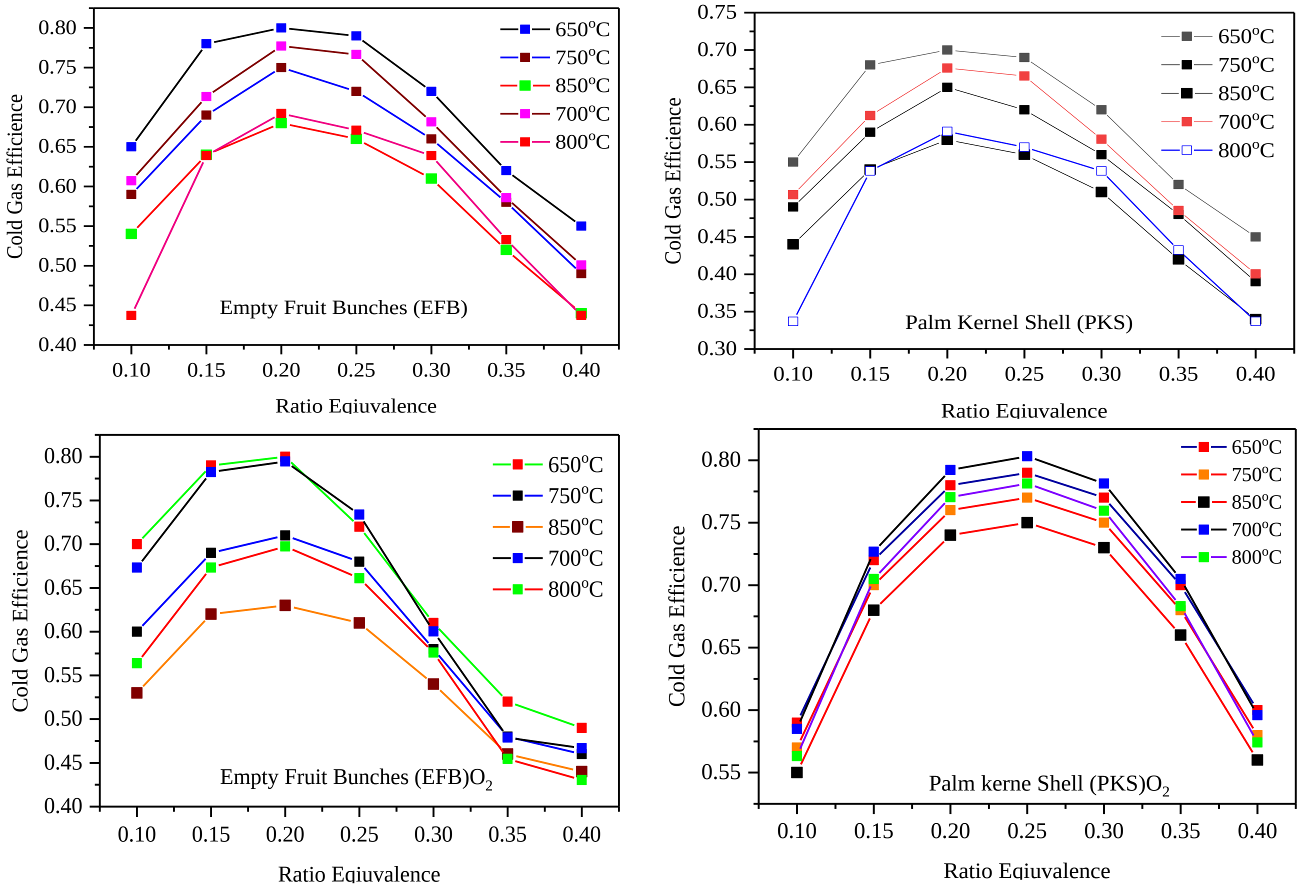

Fig. 7. Different RE outputs use air and O_2 as combustion agents

Species interactions can also be affected by the hydrodynamic flow and heat between the base material and the fuel that moves. Hydrodynamic flow can affect the volume in the bubble phase and the level of the emulsion and bubble phase and their subsequent growth. The value of the heated gas produced and the efficiency of the combustion agent against the inlet speed for different combustion agents are shown in Figure 8. The increased speed of the combustion agent can reduce the value of heating efficiency. It can be stated that as speed increases, fuel operating time in bed is not enough. In other words, the time available has decreased. Therefore, the reactor efficiency and the existing heating value can be reduced.

Comparison of the efficiency and heating value of the bed is illustrated in Figure 9. The height that increases directly has an effect on the heating efficiency value. However, the changes that occur are not too significant. Increased altitude, carbon conversion and increased residence time were recorded so that the amount of gas obtained then increased. The value of the heating efficiency shows the effect on the diameter of the bed as shown in Figure 10. The results can be concluded that the diameter of the bed becomes a very dominant parameter in combustion. Combustion using oxygen and an increased layer of diameter can cause a small increase in the efficiency and heating value. This can be due to the increasing diameter so that the process of bubbles and coagulation that rarely joins can be delayed. Thus, the contraction between the particles and the fuel used can be affected.

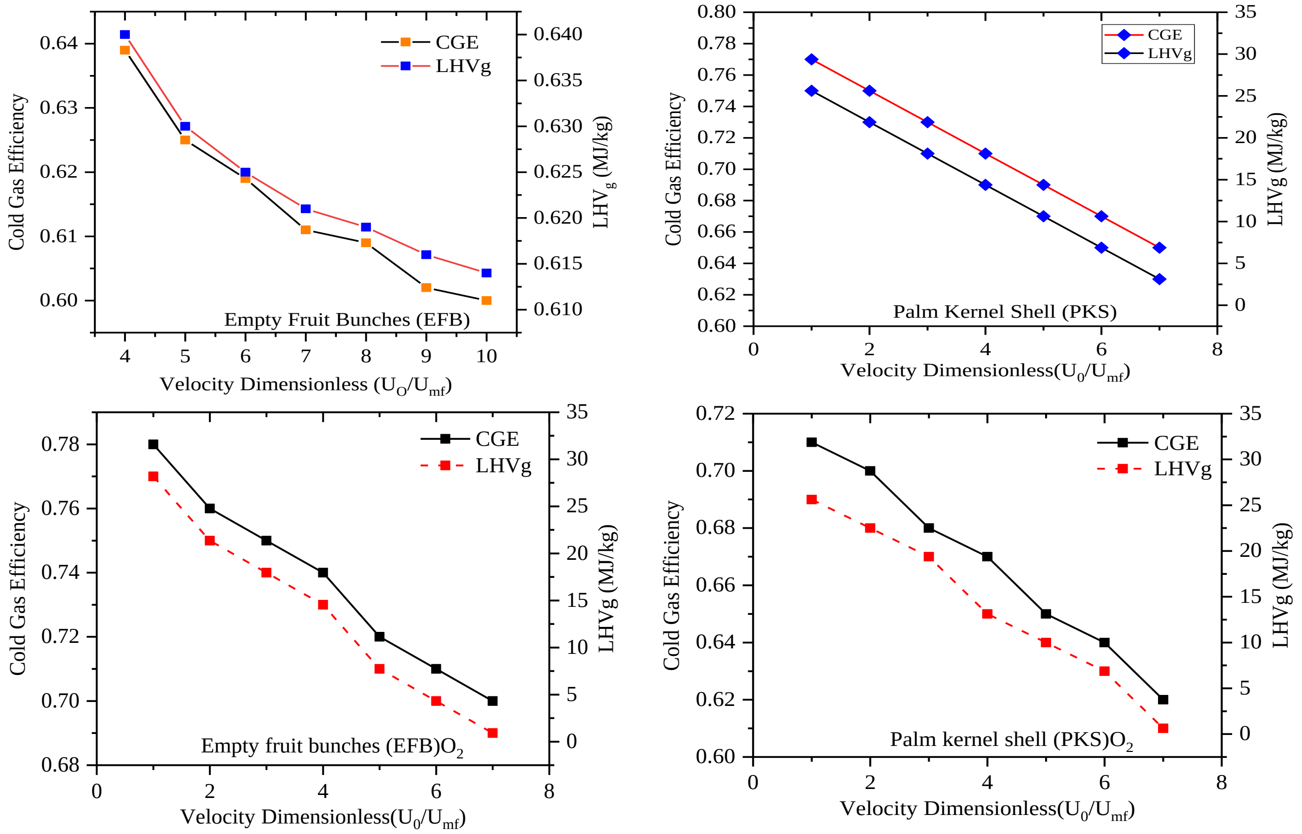

Fig. 8. LHV efficiency for gas outlets and gasifiers by using air and O_2 as combustion agents

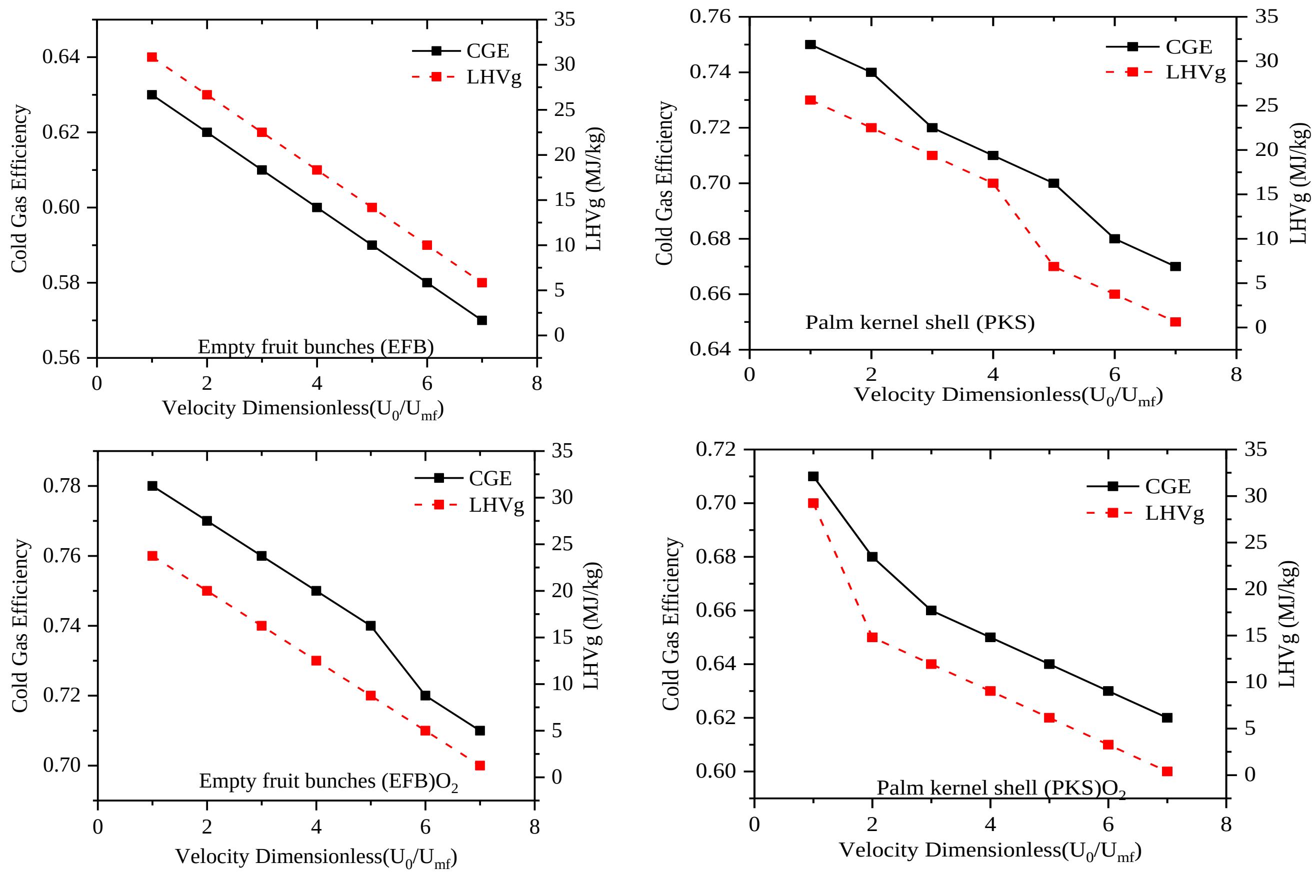

Fig. 9. LHV for specific bed heights for outlet gas and gasifier output using air and O_2 as combustion agents

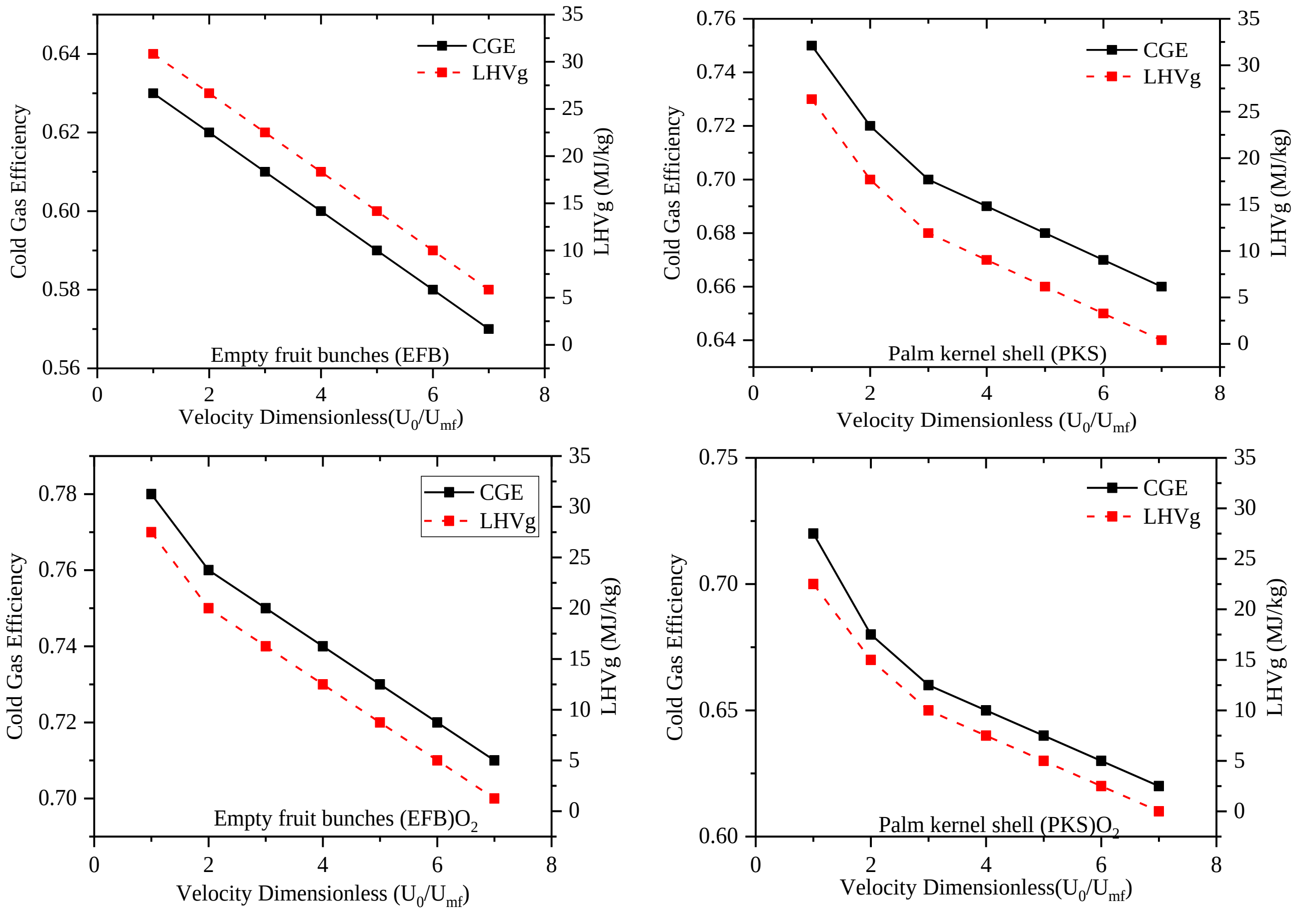

Fig. 10. The result combustion for gasifiers by using air and O_2 as combustion agents

The value of the heating efficiency shows the effect on the diameter of the bed as shown in Figure 10. The results can be concluded that the diameter of the bed becomes a very dominant parameter in combustion. Combustion using oxygen and an increased layer of diameter can cause a small increase in the efficiency and heating value. This can be due to the increasing diameter so that the process of bubbles and coagulation that rarely joins can be delayed. Thus, the contraction between the particles and the fuel used can be affected. The efficiency and heating value of the different bed particle diameters are shown in Figure 11. By changing the diameter of the bed particles in these four cases the efficiency and heating values initially increase, however, then continue to decrease. These results indicate that the diameter of 150 to 200µm hydrodynamic conditions are given optimal and have the best interaction between the bed particles and fuel in the reactor.

The gas molar fraction of the difference inequality constellations is shown in Figure 12. The increase in nitrogen and oxygen due to the ratio of air to fuel is also increasing. It is assumed that oxygen is consumed during the process and all that is left is nitrogen at the end and H_2, CH_4, and CO which decrease with increasing equality ratios. However, the air used remains constant for CO_2 to increase when combustion uses oxygen. In addition, an increase also occurred in H_2O for both cases. The ratio of equality increases as the number of oxygen increases. Therefore, the oxygen used can take place more quickly and produce more CO_2 and H_2O. While the reaction on oxygen consumption to consume H_2, CH_4, CO and molar fraction has decreased. Combustion using EFB biomass can reduce the molar fraction of CH_4, while the heating value such as CH_4, H_2, CO and the heating value of the resulting gas becomes reduced. The results of this study are a continuation of the analysis of the utilization of biomass for power plants that have been done previously [53]. The results of research on biomass burning have also been done before [53–55]. The pre-treatment and hydrolysis process for the production of POME-based biogas with evaluation through the application of hydrolytic enzymes, cellulose and lipases has also been carried out [56]. Where the results reported that about 66.67% more free fatty acids (FFA) than treatment without using POME.

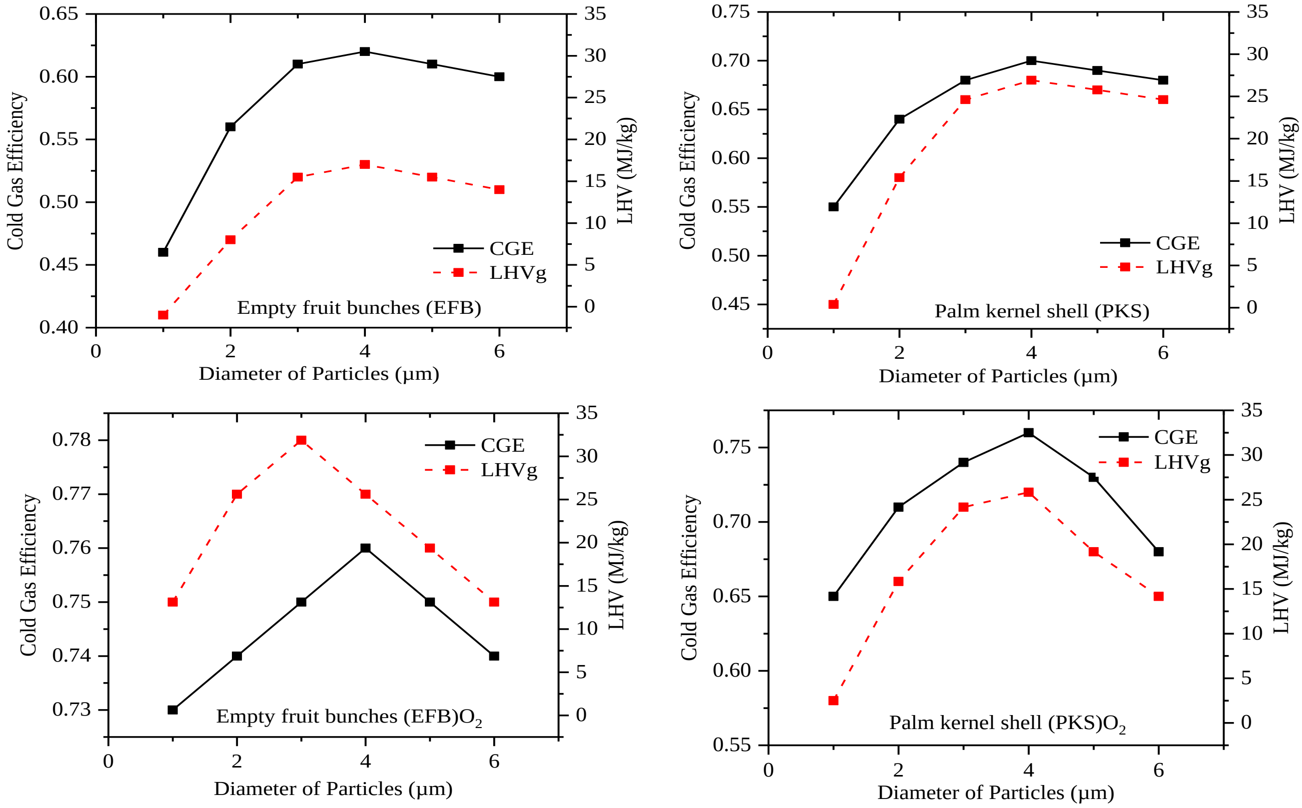

Fig. 11. Efficiency of gas combustion using air and O_2 as combustion agents

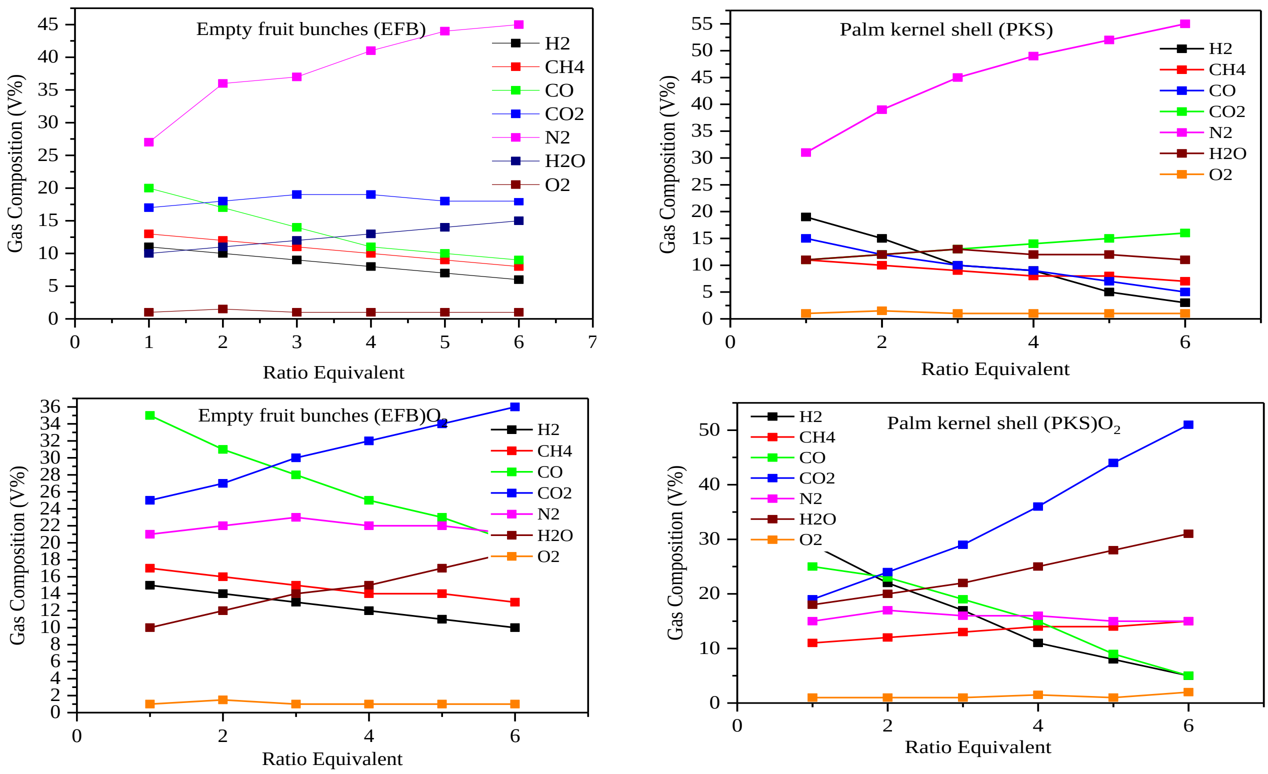

Fig. 12. The result combustion for RE by using air and O_2 as combustion agents

4. Conclusions

This experimental study of the process of burning palm empty fruit bunches (EFB) and palm kernel shells (PKS) is bubbling fluidized beds. The use of kinetic models aims at the simulation process. From the results of this experimental study, several conclusions can be drawn as follows:

i. Oxygen used as a combustion agent can increase combustion efficiency and heating value.
ii. Reactor temperature which increases directly can affect combustion efficiency and heating value.
iii. The equality ratio is increased initially, increased efficiency, and then reduced. However, the equivalence ratio shown is poor to the heating value of the gas output.
iv. The increased humidity can reduce heating efficiency and value. Therefore, using a dryer is considered more appropriate.
v. The diameter of the reactor is ignored because it has an effect on combustion performance. However, the height of the reactor that increases can cause efficiency, carbon conversion and heating value to increase.

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