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Investigation of experimental study of biomass performance of wood pellets, palm shells, and rice husk in vacuum pressure gasification system

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Abstract

Biomass-based renewable energy research has gained extra momentum due to the energy crisis from fossil fuels and global warming. Vacuum suction gasification can create combustible power plant synthesis gas. In vacuum gasification, palm shell biomass and wood pellets have better performance than rice husks. Palm kernel shells and wood pellets can produce stable synthetic gas for 6.5 hours, and the indicator is a flare for 6.5 hours. Another indicator is that palm shells and wood pellets can maintain a sustainable high temperature in the reactor. Rice husk is not suitable for this type of gasification. It does not maintain the high temperature necessary for the gasification process to work properly. The mass of rice husk, which is lighter than other biomass, causes the risk husk to be unable to push it down to the bottom of the reactor so that it becomes empty. This massive event will cause the biomass and temperature in the reactor to drop suddenly. The value of heat loss in the reactor wall is quite large, more than 2000 watts, which may be a factor causing the performance of vacuum gasification to not be optimal. In this experiment, the addition of water to the reactor was tested to determine the performance behavior of the system. Palm shells respond well to this treatment. This results in a sustainably better syngas output. Wood pellets do not respond well because they are easily damaged by water. The rice husks failed to respond. The syngas produced by the reactor is burned and used to boil water. In this gasification system, palm shells and wood pellets have a heating value of 5.62 kW and 5.41 kW, respectively. The efficiencies of palm shell and wood pellets were 29.20 percent and 29.96 percent, respectively.

INTRODUCTION

Indonesia, an agricultural nation, has a huge potential for biomass made from waste forestry and agricultural products. There are 32.6 gigawatts of biomass potential, yet only 1.81 gigawatts, or 5.55%, of that is used (Primadita et al., 2020). Biomass is an alternative energy source that will be used to replace fossil fuels because they will run out in 70 years (Gioietta Kuo, 2019). Biomass energy is a clean, renewable energy source that can help reduce greenhouse gas emissions and the effects of global warming (Kuang, 2021).

Gasification is one way to turn biomass into energy to replace fossil fuels (De et al., 2018). Through a thermochemical process, biomass gasification converts solid materials from living beings into combustible gases (Jarvik et al., 2020). To substitute gasoline, biomass can be thermochemically transformed into flammable synthesis gas that contains carbon monoxide (CO) and hydrogen (H_2) (Motta et al., 2018). According to Motta et al., the thermochemical process goes through four stages: drying, pyrolysis, oxidation, and reduction. The drying process is the evaporation of the water content in the biomass. The pyrolysis

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process is a process of decomposing biomass into volatile evaporation products such as CO, CO2, light hydrocarbons, and tar through chemical reactions (Motta et al., 2018):

$$CH_xO_y \text{ (biomass)} + O_2 \rightarrow CO + CO_2 + H_2O + H_2 + CH_4 + \text{hydrocarbons} + \text{tar} + \text{char} + \text{ashes} \quad (1)$$

Oxidation, also known as combustion, is the only exothermic step of gasification. Consequently, oxidation can provide heat energy for other endothermic processes. The exothermic nature of the oxidation reaction contributes to an increase in temperature in the gasifier to about 800-1100 °C. Oxidation requires the presence of oxygen under stoichiometric conditions to oxidize only part of the fuel. Finally, in the reduction process, the pyrolysis and oxidation products, e.g., gas and char, react in the presence of a gasifying agent to produce the final syngas composition. The general reduction reaction is shown in equations (2–3):

$$C + CO_2 \rightarrow 2CO \quad (2)$$

$$C + H_2O \rightarrow CO + H_2 \quad (3)$$

Vacuum pressure gasification generates flammable synthesis gas, according to experiments by Novandri and Muhtar. A 457-watt generator engine can be run for 30 minutes on synthetic gas (Setioputro et al., 2021). Despite the limited and transient nature of the power produced, it nonetheless marks a substantial advancement in the safety and simplicity of biomass gasification. The reactor cannot maintain a temperature of 800–1000 °C as a result of the insulation being only on the outside. The value of the heat coming out of the reactor is not more than 2000 watts (Tri Setioputro et al., n.d.). The gasification process reached temperatures between 600 and 800°C during the 30-minute experiment, according to research by Susastriawan et al., (Susastriawan et al., 2019)

In this study, a vacuum pressure gasification experiment was carried out for six hours to find that the process was continuous with three biomass. In this study, the vacuum pressure gasification process was carried out for six hours to obtain an overview of the sustainable process with rice husk biomass, palm shells, and wood pellets. The chosen time is six hours because the experiment with full biomass conditions until it runs out in the reactor takes 1.5 hours, so the experiments after six hours are considered sustainable. The ultimate goal of this experiment is to calculate the performance of the thermal system in terms of its efficiency. If the efficiency of the system has a higher value than the standard efficiency, then the system has good performance. The efficiency parameter is determined from the calculation of the system energy input-output ratio. Standard steam-based biomass gasification systems usually have efficiency levels below 19–23% (Prins et al., 2007) and gas engines/turbines between 38–50 percent (Sikarwar et al., 2016).

MATERIALS AND METHODS

Vacuum Gasification

Since the pressure inside the reactor is lower than the atmospheric pressure, vacuum pressure biomass gasification involves introducing air into the system to burn biomass (vacuum pressure). The suction pump at the system's mouth end creates vacuum pressure as it operates. The vacuum pressure system will make it simpler for the system to open (there will be no need to close it), allowing for simple feeding of the biomass feed into the reactor.

The biomass is burned within the reactor to create heat that is needed in the gasification process. By providing oxygen from the air that was drawn in by the system, the combustion reaction is fueled. Due to a lower risk of explosion, vacuum-pressure gasification is a safer process than high-pressure gasification. The system won't ever build up pressure, even if the lines are shut and the flow is stopped. For the gasification reaction to be more effective, water is sprayed into the reactor. It is hoped that there will be a balance between the generation of synthesis gas and the incoming biomass in the reactor (Samiran et al., 2016).

Properties Biomass

Rice husks, palm shells, and wood pellets were the three types of biomass used in this investigation (Figure 1). The industrial waste from rice mills in Subang Regency, West Java Province, is provided with rice husk. The palm oil processing industry in Lebak Regency, Banten Province, provides palm shells. The trash produced by woodworkers in the Subang Regency, West Java Province, is compressed into wood pellets. To determine the biomass's lowest water content, the three different varieties were dried out in the sun.

Figure 1. Three types of biomass used in the experiment: palm cell, rice husks, wood pellets.

Proximate analysis and heating value of biomass raw materials are shown in table 1.

Table 1. The properties of palm cells (Uemura et al., 2011), rice husks (*Rice Husks*, n.d.), and wood pellets (Miranda et al., 2010).

Value Property	**Unit**	**Value** Palm cells	 Rice husks	 Wood pellets	**Method**
		Proximate analysis			
Most content	wt%	13.00	7	9.00	Measured
Ash content	wt%	3,77	16.74	3,73	Measured
		Ultimate analysis (macro elements)			
Carbon	wt%	39.91	33.48	49.12	Measured
Hydrogen	wt%	5.49	4.84	7.12	Measured
Oxygen	wt%	37.47	35.34	35.28	Calculated
Nitrogen	wt%	0.35	0.28	0.51	Measured
sulfur	wt%	0.02	0.04	0.02	Measured
Net calorific value (LHV)	Mj/kg	14.88	13.48	15.63	Measured

Experimental Facilities

Experimental research and testing are done in the Manufacturing Laboratory of the Department of Mechanical Engineering, Faculty of Engineering, University of Subang. A schematic representation of the vacuum pressure biomass gasification system employed in this investigation is shown in Fig. 2. The temperature of the reactor, the consumption of biomass, the amount of water evaporating from the boiler, and the hue of the flame is the main measurement points. The reactor used refractories with a 1.01 W/m.K thermal conductivity value for its 5cm thick inner insulation. Steel plates with a thickness of 3mm and a thermal conductivity value of 60.5 W/m.K are used in the reactor's primary frame. Ceramic fiber insulation measuring 5cm thick and 0.19 W/m.K in thermal conductivity is used to insulate the reactor's exterior (Theodore, 2020).

The temperature of reactors T_1, T_2, and T_3 is measured by three K-type thermocouple temperature sensors (Fig. 3). The T1 position in the reactor is used to gauge the temperature of the gasification process. T2 gauges the temperature inside the ceramic fiber insulation (the middle position of the reactor wall thickness). T3 gauges the reactor outside temperature. Every five minutes, the temperature of the reactor was recorded using a Digital Thermometer Krisbow KW06-283 50-1300°C. An electric motor with a rotational power/speed of 0.25 Hp/1400 rpm drives the air suction pump (blower). A 125-Watt water pump powers this water cooler.

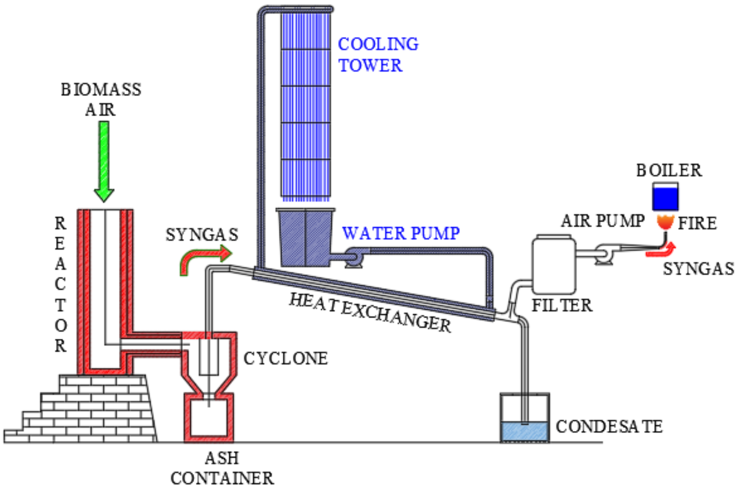

Figure 2. Biomass gasification experiment facility.

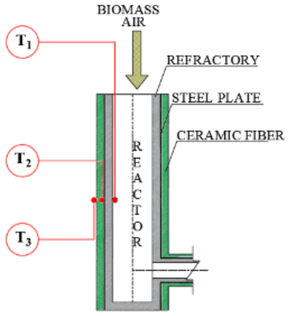

Figure 3. Temperature sensor placement scheme

Experimental Procedure

The experimental steps are as follows: first put the charcoal into the reactor until it is full and burn it as preheating. Next, the cooling system and suction pump run. Biomass feed is carried out after preheating until 800°C is reached. In the final stage, burn the syngas on the flare with a lighter to see if the gasification process has taken place. Apart from that, burning the flare removes CO gas, because CO is toxic. As soon as the reactor has reached the gasification temperature and the biomass has been fed into it; the data logger begins to record information on temperature, biomass mass, water in the boiler, and water sprayed. Once the fire has been burning steadily for a period of time, the lighter is turned off to signify that the gasification process is complete. The test, which lasted six hours, was conducted to see if the gasification process could be run constantly.

Table 2. Experimental combinations

No	Biomass	Flame Test	Boiler test
1	Palm shells	6 hours	30 minutes
2	Wood pellets	6 hours	30 minutes
3	Rice husks	6 hours	30 minutes

During the preheating activity, 33.1 kg of charcoal was burned as preheating which would burn out in 1.5 hours and be replaced by biomass charcoal. Furthermore, it is hoped that the biomass gasification process can take place continuously for six hours. Sure, that the gasification process was produced from the feed biomass, the experiment was run for six hours. The boiler water cooking test was conducted for 30 minutes as the final step. This study conducted 6 combination experiments (Table 2).

Calculation of System Performance

The value of efficiency is typically calculated as part of the system performance calculation. Eq. (4) is used to calculate the system's thermal efficiency η_{sys} (Barmina et al., 2013):

$$\eta_{sys} = \frac{Q_{use}}{Q_{in}} \tag{4}$$

Eq. (5) is used to determine the heat rate that boiler Q_{use} when burning synthetic gas produced through gasification (Foust, 2022) :

$$\dot{Q}_{use} = \dot{m}_w(h_g - h_f), \tag{5}$$

Where $\dot{m}_w$ is the mass rate of water (kg/s), h_g = enthalpy of vapor at 100 °C and 1 atm is 2676.1 kJ/kg, h_f = enthalpy of liquid water at 100 °C and 1 atm is 519.04 kJ/kg (Moran et al., 2014).

Based on the amount of biomass use up until the end of our investigation, Eq. (6) can be used to determine the rate at which heat rate enters the $\dot{Q}_{in}$ system (UCHMAN et al., 2016):

$$\dot{Q}_{in} = \dot{m}_b LHV \ , \tag{6}$$

Where $\dot{m}_b$ is biomass rate (kg/s), LHV = biomass calorific value (MJ/kg).

This experiment also determines the reactor wall rate of heat transmission. Fig. 4 depicts the heat transfer in the reactor wall (Fig. 4). The rate of heat transmission in the reactor wall is calculated using Eq. (7) (Kreith & Manglik, 2016):

$$\dot{Q}_{cond} = 2\pi Lk \frac{(T_2 - T_3)}{\ln(r_2/r_1)} \tag{7}$$

Where: $\dot{Q}_{cond}$ = heat transfer in the reactor wall (Watts), L = cylinder lenght (m), k = thermal conductivity of the material (W/m.K), T_2 = inner temperature (°C), T_3 = outer temperature (°C), and r = cylinder radius (m)

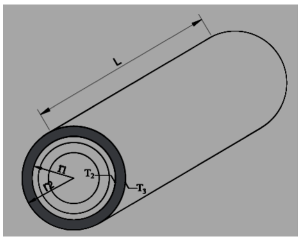

Figure 4. Heat conduction in a cylindrical body

RESULTS AND DISCUSSION

Vacuum Gasification

The temperature sensor T_1 is broken, making it impossible to gauge the temperature within the reactor. The temperature in the reactor is higher than the sensor's temperature resistance, which is above 1000°C, this is causing damage to the temperature sensor T_1. A specialized temperature sensor with a high-temperature tolerance of 1300°C is required to measure the temperature within the reactor [35].

Due to its proximity to the heat source, the temperature measured near the center of the T2 wall thickness is higher than that outside the reactor wall (Fig. 6a and 6b). The ceramic fiber insulation can withstand temperatures up to T2, where they begin to rapidly decline to T3. The maximum temperature difference that ceramic fiber insulation can withstand is 380°C (Fig. 6c). If the heat transfer rate is less than 2000 watts, it is an excellent gasification reactor [20]. The heat loss figure was calculated using Eq. (7), and the result was a number more than 2000 watts (Fig. 6d). This shows that the insulation in this reactor is still subpar and must be repaired.

The maximum temperature was found in rice husks, next in palm shells and wood pellets (fig. 5). Compared to palm shells and wood pellets, rice husks are lighter and more flammable. This is because rice husk is combustible, it heats up more quickly than palm husks or wood pellets. In experiments conducted at intervals of 195 minutes to 305 minutes, the temperature of rice husks decreased significantly from 536°C to 303°C. After that, the temperature rises slowly to 364 °C. Due to its lightweight and ease of ashing when compared to wood pellets and palm shells, rice husk temperature drops as a result. In addition, rice husks are smaller in size than wood pellets and palm shells. The airflow cavity gaps in the reactor become smaller due to the small size of the biomass.

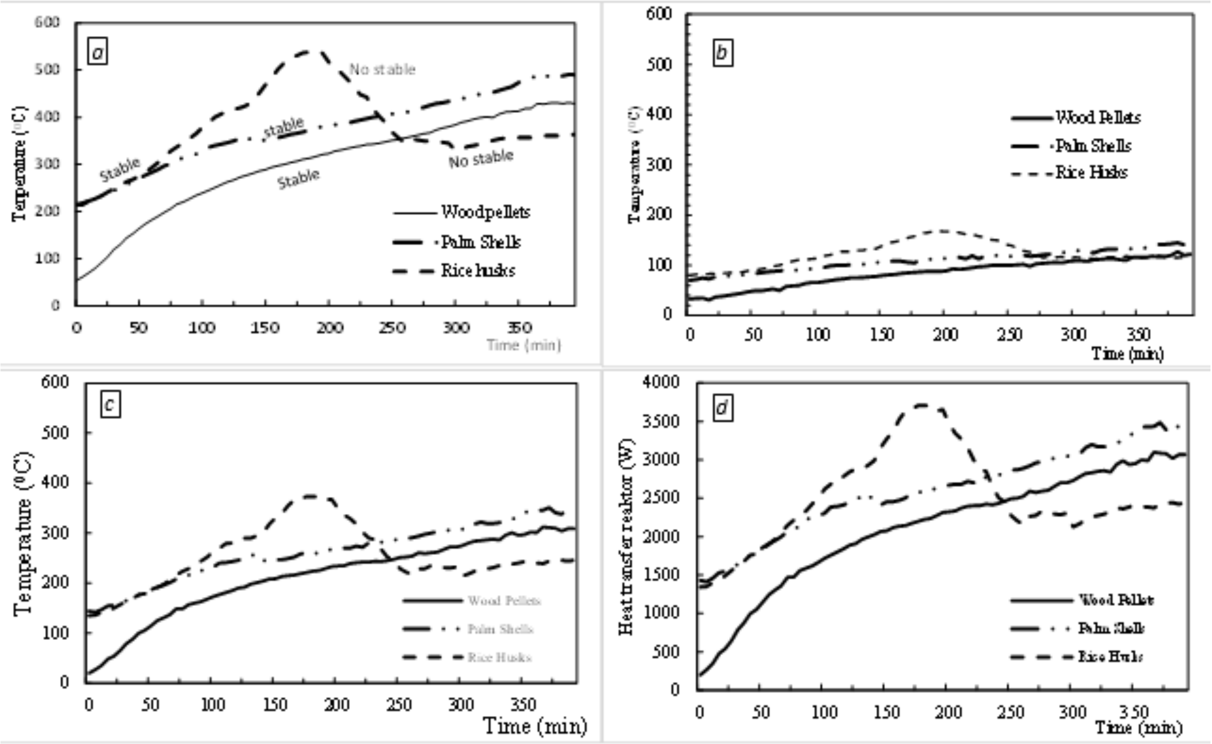

Figure 5. Reactor temperature profile and heat transfer rate for three different biomass (a) temperature T_2, (b) temperature T_3, (c) temperature differential T_2-T_3, and (d) heat transfer rate of the reactor wall.

The air entering the reactor (Oxygen) will be less due to the small air cavity gaps and rice husk ash inhibition. Diminished production of synthetic gas results from reduced oxygen, a slower combustion process, and a drop in temperature. An unstable flame is the first sign of synthetic gas decrease (Fig 6). The air cavity gaps are larger, and the airflow is greater in palm shells and wood pellets because of their larger shapes. A plentiful supply of air (oxygen) will keep the combustion process running smoothly, resulting in the stable generation of synthetic gas. A cash flame served as evidence. Accordingly, rice husk is not appropriate for this gasification.

Both palm shells and wood pellets can maintain the flare's flame while also keeping the reactor's temperature high (Fig. 6). Accordingly, gasification will proceed well if the reactor temperature can be kept high.

Figure 6. Flames produced by burning synthesis gases for three types of biomass.

System Performance

In order to keep the reactor's biomass level from overflowing during the vacuum gasification experiment, water was needed. Without water spraying, the biomass will gradually dwindle and transform into charcoal in the experiment. According to Eq. (3), the gasification reduction reaction, this process requires water.

Water spraying was carried out when the reactor was full of burning biomass charcoal (Fig. 7). When the fresh biomass has all turned into hot (smoldering) charcoal, the production of H2O gasification agents will run out. Lack of water can be remedied by adding water by spraying. This is in accordance with the reduction reaction (Eq. 2). In addition, it will increase the production of syngas. The effect of spraying water is that the temperature of the reactor will drop, and the low temperature is too low, so the spraying of water stops. When the temperature of the reactor is very high again and the reactor is full of hot biomass charcoal, the spraying of water will be carried out again.

Figure 7. The reactor is full of hot biomass charcoal ((914°C).

The problem with the vacuum gasification process is that the reactor is full of hot biomass charcoal. A reactor full of hot biomass charcoal will make it difficult for fresh biomass to enter the reactor. Fresh biomass must be added to the reactor; otherwise, the flame in the beacon will become unstable. In order for this experimental process to continue, water was added to replace fresh biomass by spraying it. The addition of water can significantly reduce the hot charcoal biomass in the reactor. This reduction of hot biomass charcoal will cause the vacuum gasification process to run continuously. Another effect is that the flame in the flare becomes stable again. This treatment was carried out during the 6-hour flame test and 30-minute steam boiler test.

During the 6.5-hour experiment, the use of wood pellet biomass consumed 25.82 kg, 24 kg of palm shells, and 22.50 kg of rice husk. The experimental time of 6.5 hours was started after the initial charcoal was used up in the reactor and the reactor temperature became very high. The charcoal used for preheating the reactor is not counted because it is assumed to have run out (Fig. 8). In comparison to wood pellets and palm shells, rice husk is the least used biomass since it is the lightest. The reduction reaction will result in a large amount of charcoal turning into gas at the bottom of the reactor. If this area is not filled with the above biomass, then the bottom of the reactor becomes empty. The mass of rice husk, which is lighter than other biomass, causes the risk husk to be unable to push it down to the bottom of the reactor so that it becomes empty. This massive event will cause the biomass and temperature in the reactor to drop suddenly. Palm shells and wood pellets have almost the same dimensions and caloric value, so the amount of mass consumed in the experiment is almost the same. Due to the different physical characteristics of the three biomass, the mass of water consumed is also different (Fig. 8).

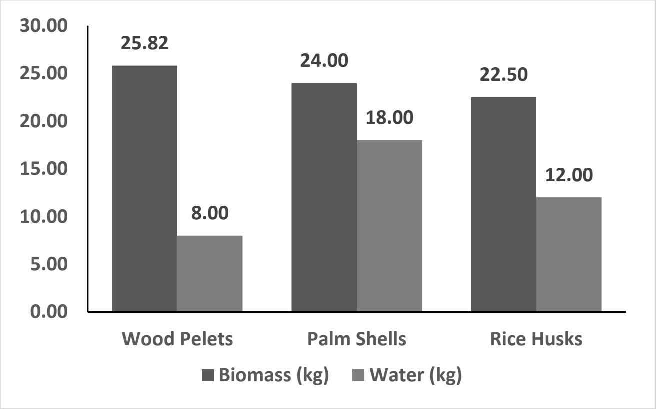

Figure 8. Use of biomass and spraying water in a vacuum gasification experiment

Unless they have transformed into charcoal, Wood pellets are made from compacted sawdust. Wood pellets will be easily damaged if exposed to water because they are less dense. Wood pellets can be sprayed with water when they have turned into charcoal. Wood pellet charcoal is harder and denser than fresh wood pellets. The water consumption of wood pellets is at least 8 kg. Compared to 18 kg of palm shells, rice husks require just 12 kg of water to be sprayed (Fig. 8). This is in contrast to palm shells; rice husks have the ability to absorb water. Water that has been caught in rice husk grains becomes challenging to evaporate and challenging to dry, reducing its need. Because of their hardness, palm shells are the best biomass for spraying because water evaporates fast, and it dries out soon.

Calculation of the heat generated in the reactor using the equation Eq. (6) obtained values of 18.77 kW and 18.52 kW for palm shells and wood pellets (Fig. 8). The calorific value of wood pellets is almost the same as that of palm shells because the calorific value is higher even though the number of wood pellets used is less. With a rating of 10.50 kW, the rice husk has the lowest generating heating value (Fig. 9). At the reactor temperature, the rice husk dropped drastically, and the flame was unstable (Fig. 5a). As a result, of these experiments rice husks were more difficult to vacuum gasification and took longer to convert to charcoal, reducing the total amount.

In the experiment: the heat consumption of the steam boiler and the heat generated by the gasification of wood pellets and palm shells were almost the same. The calculation uses Eq. (2), a value of 5.41 kW for wood plates and 5.62 kW for palm shells. Synthesis gas production can be kept constant while high reactor temperatures are maintained using wood pellets and palm shells. This is shown by the graphic of a large flame (Fig. 6), high heat generation (Fig. 8), and relatively stable reactor temperature (fig. 5a). Rice husk has a reactor temperature that drops drastically and a small flame. The results of calculating heat output using Eq. (5), rice husk has the lowest heat-used value of all materials at 2.65 kW.

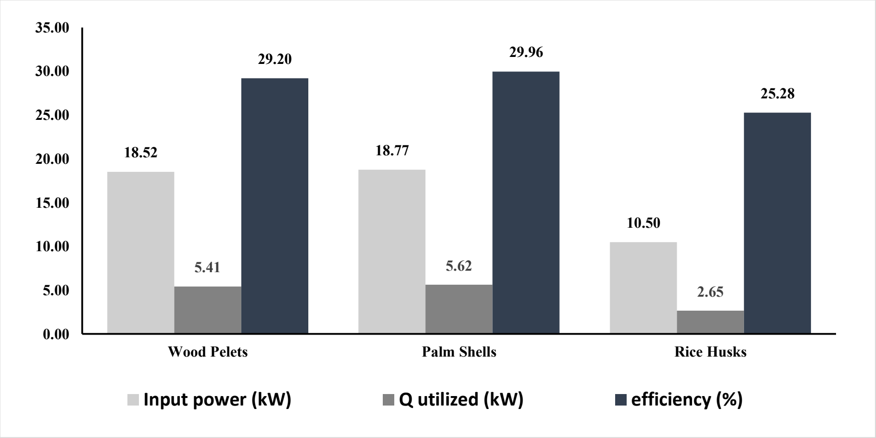

Figure 9. Vacuum gasification system performance with 3 variations of biomass

In thermal system efficiency calculation using Eq. (4) the efficiency values for husks were 25.28%, and wood pellets and palm shells were fairly good, namely 29.20% and 29.96%. Compared to the steam power system, the efficiency value of wood pellets and palm shells is still above 20% which is considered good. Rice husk is considered a failure because the flame is unstable. If the value is above 20%, the efficiency of the system using palm shells and wood pellets is better than the standard efficiency of a steam power system. The efficiency of wood shells and pellets is still below the efficiency standards of gas turbine systems or engines.

CONCLUSIONS

Flames have been successfully produced by the vacuum gasification system using wood pellets, palm shells, and rice husks. The flame test experiment produced by rice husks is less stable when compared to palm shells and wood pellets. The flame became unstable because the rice husk was unable to keep the reactor temperature high, despite the fact that it dropped significantly. In comparison to wood pellets and palm shells, which produced 5.41 kW and 5.62 kW, respectively, rice husk had the lowest calorific value at 2.65 kW. The lowest efficiency value is 25.28% for rice husk. Both wood pellets and palm shells have very high-efficiency values, respectively 29.20%, and 29.96%. Palm shells can be treated wetly with up to 18 kg of water sprayed on them. In comparison to rice husks and wood pellets, palm shells perform vacuum gasification and wet conditions most effectively. When compared to a steam power system, the vacuum gasification system for wood pellets and shells still performs quite well (efficiency above 20%). When compared to gas turbines and combustion engines, the vacuum gasification system still performs poorly (efficiency below 38%).

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