Effectiveness Study on The Vacuum Biomass Gasification System Using Variation of Suction Pump Rotation Power and Biomass Wetness

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Abstract: - Environmental damage and depletion of fossil fuels trigger the development of biomass conversion technology to produce environmentally friendly fuels. One of them, biomass conversion technology is vacuum pressure biomass gasification technology. Previous research has succeeded in converting biomass energy into electricity, but the results are still not effective. In this regard, the effectiveness of the gasification system needs to be improved in this research. The combination of dry biomass and soaked biomass, as well as the combination of suction pump rotation at 1400 and - 2800 rpm, is the focus of this study. Based on the experimental results, the larger the motor rotation, the higher the vacuum pressure. The soaked biomass is more stable in maintaining the level of the amount of biomass in the reactor and the reactor is never overflowing. The combination of 2800 rpm rotation with drenched biomass can maintain the reactor temperature maintained at 800-1000 °C, the most stable and highest evaporation rate is around 23.0 x 10^{-4} kg/s, and produces the highest heat rate of 5.19 kilowatts. Based on this, the combination of soaking biomass with a rotation of 2800 rpm produces the best effectiveness.

Key-Words: - Biomass, gasification, syngas, vacuum, heat, effectiveness

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1 Introduction

As an agricultural country, Indonesia has a great potential to utilize biomass from agricultural wastes and convert them to a huge amount of energy. Until now only 1.81 GW (5.55%) of 32.6 GW of energy from biomass has been utilized overall in Indonesia [1][2]. Biomass as a renewable energy source can replace fossil fuels, which will be exhausted in the next 70 years [3][4]. As an environmentally friendly renewable energy source biomass can reduce greenhouse gases (CO_2) that are able to cause global warming [5][6][7]. The conversion of biomass into energy as a substitute for fossil fuels involves gasification process [4][8][9][10]. Biomass gasification is the process of converting solid materials from living things into combustible gases through thermochemical processes. The gasification process goes through four stages, viz. biomass drying process, pyrolysis, oxidation, and reduction [11] [9].

In the biomass drying stage, the water content of the fuel is converted into steam through evaporation [12][13]. At this stage, heat transfer by conduction occurs from the surface to the center of the biomass particles. The biomass particles are made small to reduce heating and drying time [12]. Also, dry biomass is usually preferred once the heat required in this stage is proportional to the moisture of the feeds stock [8]. The drying process temperature is in the range of 150-250 °C [14]. Thus, the biomass drying process is directly related to the biomass pre-treatment procedure [9].

The pyrolysis process, also known as devolatilization, is a thermochemical decomposition process of dry biomass to evaporate volatiles such as CO, CO_2, light hydrocarbons, and tar with residual charcoal and ash as by-products [9]. Equation (1) shows the pyrolysis reaction [8][15]:

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

The pyrolysis reaction is endothermic and occurs at temperatures between 200 and 700 °C [8]. Phenomena involved in this step include heat transfer, product diffusion from the pore of biomass to the gas phase, and series reactions [9]. The pyrolysis reaction can be classified into primary and secondary processes. The primary process occurs at temperatures between 200-600 °C and corresponds to the initial decomposition of the biomass into tar, char, and volatiles. The secondary process takes place above 600 °C and consists of cracking tar in light to hydrocarbons [12].

Oxidation, also referred to as combustion, is the only exothermic step of gasification. Consequently, oxidation can provide heat energy for the other endothermic processes. The exothermic nature of oxidation reaction contributes to an increase of temperature in the gasifier to about 800-1100 °C [8]. Oxidation requires the presence of oxygen under stoichiometric conditions to oxidize only part of the fuel. Char and hydrogen are the main reactants in this step, which are rapidly converted to CO_2 and H_2O. Besides charcoal and H_2, condensed products are also oxidized [12][13][9].

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 [8]. In this endothermic process, care must be taken by removing the ash when the ash is going to cover the charcoal leading to overheating [12][9]. The gasification steps described above proceed through the basic solid-gas complex reaction processes (heterogeneous reactions) and gas-phase reactions (homogeneous reactions) whose reaction pathways are not fully understood [9][12]. The general reduction reaction is shown in equation (2-3) [7][9][8][10][15]:

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

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

In the final process, the char produced before the end of pyrolysis is converted into syngas by reacting the biomass with hot gases from the upper zone. These gases are reduced to form larger proportions of H_2 and CO [14]. When leaving the reactor at a temperature between 200 °C and 300 °C, the syngas carries some dust, pyrolytic products (tar), and water vapor, which have to be removed by thermal or mechanical processes [14].

Nowadays, the technology of gasification uses two types of reactor, namely fixed and fluidized bed. Both types have an open and close system making it difficult to supply biomass [8][16]. This technology uses high pressure because the higher the pressure, the more optimal the process is. It will increase the efficiency of syngas production. The disadvantage of this technology is the complex operation especially for small-scale systems [8], which is prone to explosion. The research conducted by Susastriawan et al. [17] shows the gasification process temperature ranging from 600 to 800 °C during the experiment duration of 30 min. The efficiency of biomass gasification systems using steam is usually less than 20 %. For comparison only, the efficiency of gas motor/turbine engines is around 38 – 50 % [18].

System performance can be characterized using a thermal efficiency approach. The thermal efficiency of the system is calculated using equation (4) [19][20]:

$$\eta_{sys} = \frac{Q_{use}}{Q_{in}} \quad (4)$$

Calculation of the heat rate used $\dot{Q}_{use}$ with the equation (5) [1][2] :

$$\dot{Q}_{use} = \dot{m_w}(h_g - h_f) \quad (5)$$

where $\dot{m_w}$ is the water mass rate, h_g = enthalpy of steam at 100 °C and 1 atm (2676.1 kJ/kg) , h_f = enthalpy of liquid water at 100 °C and 1 atm (519.04 kJ/kg)[3].

The rate of heat entering the system $\dot{Q}_{in}$ can be calculated using equation (6) [1][2]

$$\dot{Q}_{in} = \dot{m}_b \, LHV \quad \text{.........................(6)}$$

where $\dot{m}_b$ is biomass rate, LHV= palm shell calorific value (14.88 MJ/kg) [4].

The gasification reactor has refractory insulation layers inside and outside the surface of the reactor wall. This measure can maintain the heat of combustion, but the syngas production was still less stable [5]. On that basis, it is necessary to improve the process of biomass gasification reaction in order to produce syngas continuously and stablely, indicated by the presence of flames on the torch. The stability and continuity of syngas production can be guaranteed if the reactor temperature ranges from 800 - 1000 °C.

2 Materials and Methods

2.1 Palm Shell Biomass

The biomass used in this study is palm shell from palm oil processing waste found abundantly around the research site. As shown in Figure 1, the palm shells used in this study were treated in two different ways: soaked in water and dried by the solar heat (humidity of 13.0%). Palm shells are selected to obtain a more uniform length and width of about 0.5 – 1.5 cm.

The properties and chemical composition of the palm shells are listed in Table 1.

(a) (b)

Figure 1. Soaked (a) and dry palm shells (b)

Table 1. Characteristics of Palm Shells [4]

Values Property	Unit	Value	Method
Proximate analysis			
Moisture content	wt%	13.00	
Ash content	wt%	3.77	
Ultimate analysis (macro elements)			
Carbon	wt%	39.91	Measured
Hydrogen	wt%	5.49	Measured
Oxygen	wt%	37.47	Calculated
Nitrogen	wt%	0.35	Measured
Sulfur	wt%	0.02	Measured
Halides	wt%	Rest	Calculated
Net calorific value (LHV)	MJ/kg	14.88	Measured
Gross calorific value (HHV)	MJ/kg	16.40	Measured
HHV Milne	MJ/kg	16.27	Calculated

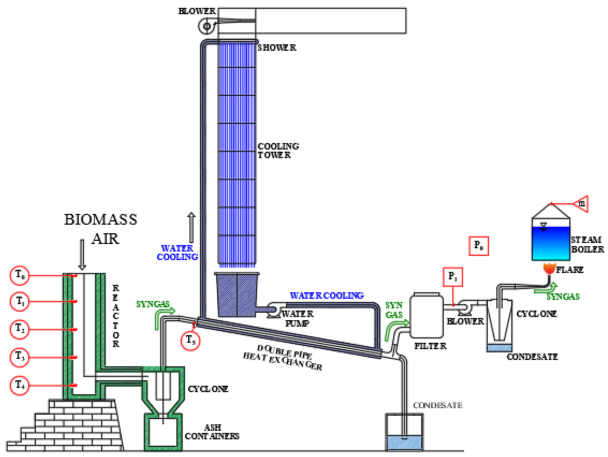


Figure 2. Schematic diagram of the vacuum biomass gasification system

2.2 Experimental Facilities

The research activity was carried out at the Manufacturing Laboratory, Department of Mechanical Engineering, Faculty of Engineering, University of Subang. Figure 2 is the schematic diagram of vacuum biomass gasification system used in this study. The temperatures were measured using 2 different types of thermocouples at 6 positions. The K-type thermocouples were used to measure the temperatures T_0 and T_5 and the S-type for measuring the temperatures T_1, T_2, T_3, and T_4. The thermocouple for T_0 is placed on the top surface of the reactor followed by the thermocouples for T_1, T_2, T_3, and T_4

as shown in Figure 2. The distance between the thermocouples was 20 cm. The thermocouple for T_5 was used to measure the exit temperature of the cyclone exhaust gas. The data from K-type and S-type thermocouples were recorded using data loggers Lutron BTM-420SD and Lutron TM-947SD respectively. The air blower was driven using an electric motor. Two electric motors with power/rotational speed of 0.25 hp/1400 rpm and 1 hp/2800 rpm were used in this study.

The BMP180 pressure sensor is used to monitor the measured pressure in the gasification system at P_0 and P_1. P_1 is measuring the vacuum pressure near before the suction pump, while P_0 is measuring the air pressure. The FTU DLP4SD data logger was used to record the pressure at P_0 and P_1. In addition, to calibrate the BMP180 pressure sensor, a U-tube water manometer is installed.

YZC131 load cell was used to measure the mass of water converted to steam, and the mass sensor was recorded using the FTU DLM-2101 data logger.

2.3 Experimental Procedure

The experimental procedure is as follows, first fill the reactor with charcoal and leave 15 cm from the top surface; turn on the suction pump and cooling system; burning charcoal as preheating until the gasification temperature is obtained (800 – 1000 ^{o}C) and the flare is burned with a lighter so that synthetic gas, especially CO gas, is toxic after burning; temperature and pressure data logger starts recording test data; the reactor has reached the gasification temperature, the dry/drenched palm shells biomass is fed into the reactor; the fire has been burning stable then the light is turned off; a steam boiler is prepared for testing the utilization of the heat of combustion of synthetic gases; mass data logger records the mass loss of water into water vapor; add water to the steam boiler when it runs out; The test is carried out by a period of about 5.0 hours or the fire goes out.

There are four combinations of biomass and suction pump rotation evaluated in this experiment. The combination is shown in Table 2.

Table 1. Combination of biomass and suction pump rotation used in the experiment

No.	Biomass	Power and rotate the motor
1	Dried palm shells	0.25 HP & 1400 rpm
2.	Soaking palm shells	0.25 HP & 1400 rpm
3.	Dried palm shell	1 HP & 2800 rpm
4.	Soaking palm shells	1 HP & 2800 rpm

3 Results and Discussion

3.1 Pressure Profile

The pressure measured at point P_1 (Figure 2) during the test are represented in Figure 3. Compared to the pump speed of 1400 rpm, the vacuum pressure is greater than the pump speed of 2800 rpm. According to fluid engine performance theory [23], the higher the rotation, the higher the suction pressure.

Comparing the vacuum pressure at the same pump rotation speed, dry biomass tends to produce a higher vacuum pressure than the immersed one. Because by using dry biomass, the reactor is full of biomass and overflows so that the suction flow becomes blocked, and the vacuum pressure rises. Different submerged biomass will produce a lower vacuum pressure. This is because the soaked biomass does not cause the reactor to be full/overflowing due to the soaked biomass giving more H_2O so that the charcoal reduction reaction process becomes higher (equation 3) and the level of the amount of biomass in the reactor is relatively stable.

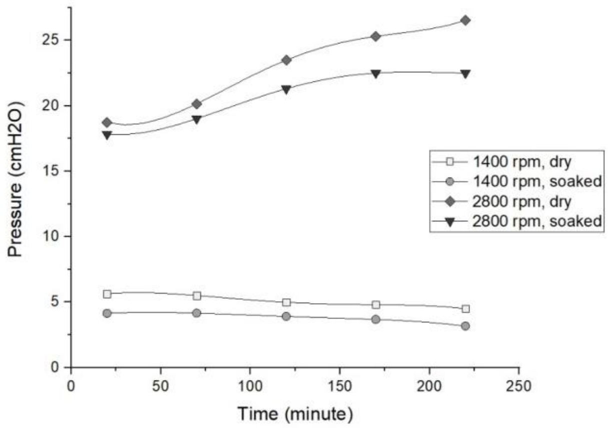


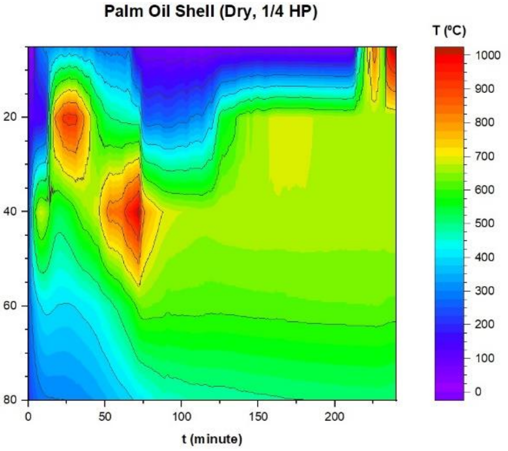
Figure 3. Pressure profile

From these experiments, it can be concluded that soaked biomass has a better ability to maintain the vacuum that results in the stable syngas production.

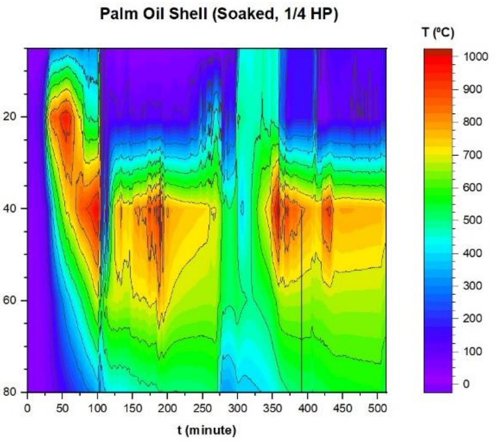
3.2 Temperature Profile

Figure 4 describes the temperature profile throughout the reactor as a function of time with 0 cm being the position at the very top of the reactor. In general, the reactor temperature fluctuated during the experiment. The 2800 rpm suction pump rotation produces and maintains a higher temperature than the 1400 rpm suction pump rotation. This is because the higher the rotation, the greater the air/oxygen that is inhaled. The more oxygen, the greater the oxidation reaction and the greater the heat produced. The more heat generated, the easier it is for the reactor to reach and maintain the gasification temperature (800-1000 °C). This is different from the 1400 rpm suction pump, the temperature is difficult to maintain at a temperature of 800 - 1000 °C. This is because the oxygen supply is less so that the oxidation reaction is less and there is less heat.

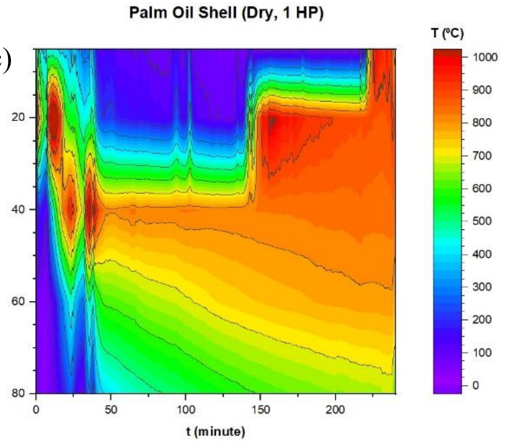
(a)



(b)



(c)



(d)

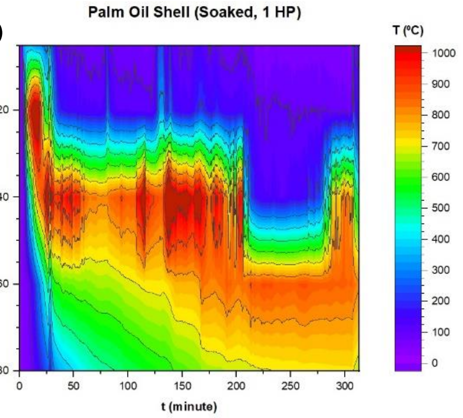


Figure 4. Temperature profile in the reactor, a) dry palm shells - 1400 rpm, b) soaked palm shells - 1400 rpm, c) dry palm shells - 2800 rpm, d) soaked palm shells 2800 rpm

Reactor temperature profile, dry biomass produces a high-temperature profile will move up. This is because the rate of reduction of chars is slower than the rate of dry biomass into embers and finally the reactor is full of embers. While the soaked biomass is better able to maintain a high-temperature profile in the middle of the reactor. This is because the rate of charcoal reduction is relatively the same as the rate of biomass to embers because the addition of H_2O will increase the rate of the reduction reaction (equation 3).

With the combination of soaked biomass and rotation of 2800 rpm (figure 4d), the temperature profile can maintain a temperature of 800-1000 C in the middle of the reactor. This is because the high rotation causes a greater supply of oxygen so that the oxidation reaction is more and produces more heat. The more heat, the higher the temperature in the reactor. In addition, the soaked biomass will add H20 so that the reaction rate of the reduction of charcoal to gas (CO and H_2) becomes greater. The combination of increasing the supply of oxygen and H_2O will make the effectiveness of biomass gasification better than just increasing the supply of oxygen or H_2O.

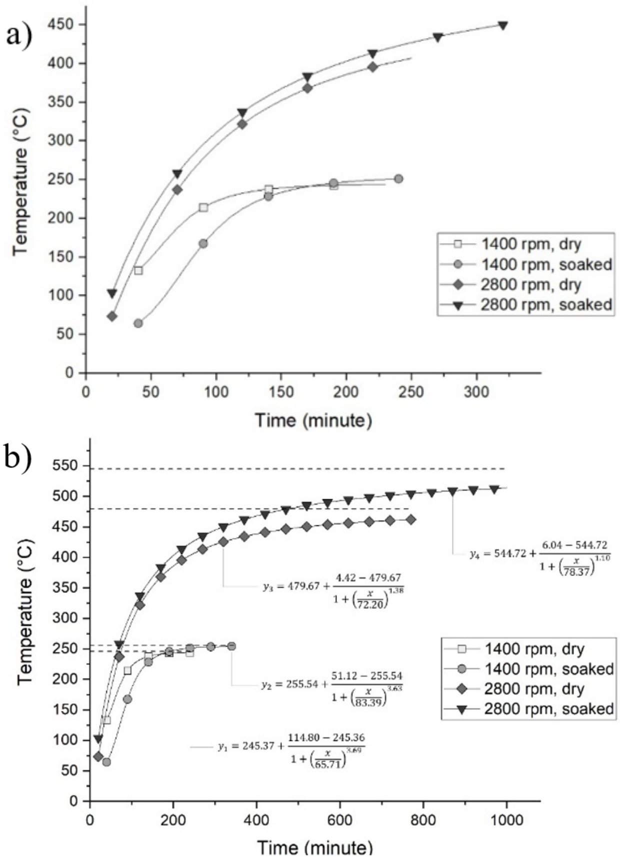


Figure 5. Temperature profile of syngas when exiting the cyclone for four test conditions, a) measured during the experiments, b) modeling using regression analysis.

Figure 5a depicts the temperature profiles of the syngas measured when exiting the cyclone for four different parameter combinations. At the beginning of the process, the temperature of the syngas leaving the cyclone rises rapidly. The temperature rate depends much on the rotary speed of the pump. No matter how wet the biomass is, the higher the rotary speed of the pump, the higher the rate of increase in syngas temperature during the first 100 minutes of the gasification process. The rate of increase in the syngas temperature reduces over time and will reach a value of zero at a certain temperature level. The syngas temperature profiles can be modeled using equation 7.

$$y = A2 + \frac{A1 - A2}{1 + \left(\frac{x}{x_0}\right)^p} \quad (7)$$

According to modeling results shown in Figure 5b, the highest temperature of syngas when leaving the cyclone depends not only on the pump's rotary speed but also on the wetness of biomass. Compared to the other three parameter combinations, the syngas's exit temperature of about 545 °C for soaked biomass with a pump rotary speed of 2800 rpm is the highest during the entire experiment. Because the biomass inside the reactor does not accumulate, the gasification system uses soaked biomass and a pump with a rotary speed of 2800 rpm can provide the system with more oxygen and lower flow resistance (equilibrium reaction). In this case, the more oxygen added to the combustion reaction, the more heat is generated, and thus the temperature rises. This temperature reference can be used to construct a syngas cooling system.

3.3 Evaporation Rate

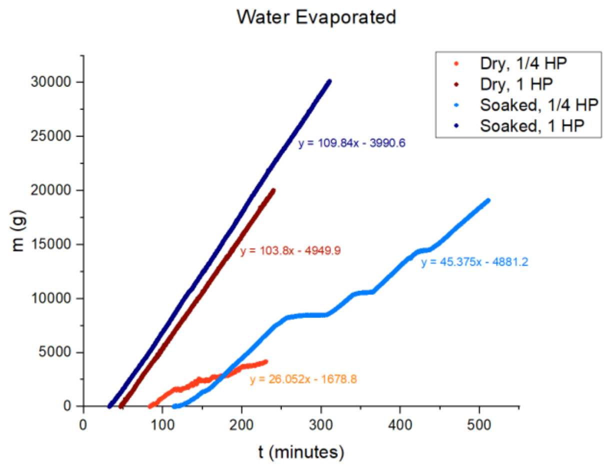


Figure 6. Mass of evaporating water as a function of time for four testing conditions

The effectiveness of the gasification process in creating syngas can be determined by burning syngas using a flame, as shown in Figure 2. In a boiler with a mass sensor, the heat from syngas combustion is used to evaporate water. Equation 5 can be used to compute the heat value by knowing the quantity of mass of water that evaporates. A graph depicting the quantity of mass that evaporates as a function of time is shown in Figure 6. It can be shown which combination of tests generates the highest and most consistent mass rate by comparing these graphs.

Soaked biomass with a suction pump rotation of 2800 rpm obtained a straight curve and the highest slope (model equation $y = 109.84x + 3990.6$). This shows that the syngas production is more abundant and constant during the test. Higher rotation will cause more oxygen supply. The more oxygen supply, the greater the heat generated from the oxidation reaction. With a greater amount of heat, the reduction reaction produces more syngas. In addition, the addition of H_2O will increase the production of syngas from the reduction reaction of equation 3.

The curve of dry biomass rotated at 2800 rpm is comparable to that of wet biomass rotated at 2800 rpm, however, the curve is shorter. This is because the reactor will be full/overflowing with charcoal. The 1400 rpm suction pump rotation does not produce a straight curve like the 2800 rpm rotation. This shows that the syngas production is not stable because the heat generated by the oxidation reaction is not able to maintain the temperature in the 800 - 1000 °C range (the amount of oxygen supply is small).

3.4 System Performance

Table 3 shows the system performance with four test combinations. The combination of soaked biomass with 2800 rpm has the highest values compared to the other three combinations, although the efficiency is lower. The superiority of the performance of soaked biomass - 2800 rpm is that it has the largest calorific value of biomass combustion (51.5 kW), the largest calorific value use (5.19 kW), and the highest mass production rate of steam (23.0×10^{-4} kg/s).

This is because the higher the suction pump rotation will cause the oxygen supply to be greater and the oxidation reaction will produce more heat. Furthermore, the heat generated will be able to produce high temperatures (800 - 1000 °C) and this high temperature is the ideal temperature for the perfect gasification process. The more perfect the gasification process, the richer the syn-gas production will be and the added supply of H_2O will further enrich the syn-gas production. This is indicated by the highest calorific value use.

Table 3. Performance of the system with four test combinations

Description	Dry-1400 rpm	Soaked-1400 rpm	Dry-2800 rpm	Soaked-2800 rpm
Biomass (kg)	5.2	28.8	10.1	58.5
Rate of biomass ($\times 10^{-4}$ kg/s)	4.6	11.5	8.5	34.6
Input power (kW)	6.8	17.1	12.6	51.5
Mass of steam (kg)	6.7	18.1	15.7	38.9
Rate of steam water ($\times 10^{-4}$ kg/s)	5.9	7.2	13.2	23.0
Heat rate employed (10^2 W)	13.3	16.3	29.7	51.9
Efficiency (%)	19.4	9.5	23.6	10.1

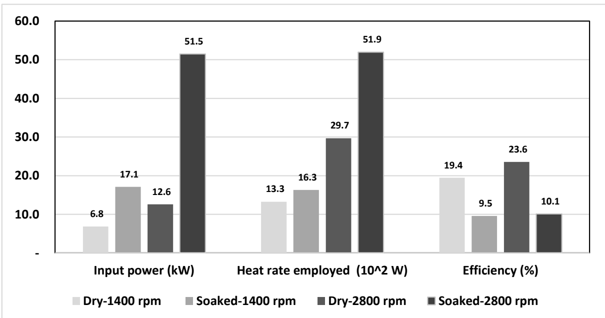


Figure 7. Graph of system performance with four test combinations

Based on a series of four experimental combinations, it was found that the soaked biomass increased the effectiveness of the vacuum pressure biomass gasification system. In this case, the input process into the vacuum pressure biomass gasification system is divided into three components: biomass, air (oxygen), and liquid H_2O, resulting in the following equation for the pyrolysis reactions:

$$CH_xO_y \text{ (Biomass)} + O_2 + H_2O_{(liquid)} \rightarrow CO + CO_2 + H_2O_{(steam)} + H_2 + CH_4 + \text{hydrocarbons} + \text{tar} + \text{char} + \text{asher} \quad (8)$$

4 Conclusion

This study aims to make the vacuum pressure biomass gasification process more effective. Vacuum pressure biomass gasification will be more effective by using soaked biomass with a suction pump rotation of 2800 rpm compared to the other three combinations. The indicators are a relatively stable vacuum pressure, the ability to maintain the temperature in the reactor at 800-1000 °C, the highest evaporation rate of water, and the largest heat utilization rate.

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Contribution of individual authors to the creation of a scientific article (ghostwriting policy)

All authors work together to get the results and have the same contributions in all areas of experimentation.

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