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Effects of Heating Temperature and Moisture on Indirect Gasification of Rubber Wood in Closed Gasifier Chamber

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Abstract

Rural area in Indonesia of which electrification ratio is still low has a strong demand for off-grid electric power supply. On the other hand, Indonesia is a leading natural rubber production country and these rubber wood trees are cultivated in vast plantation farms. A rubber wood tree is woody biomass resource which can be stably supplied because a lot of trees aged more than 25 years are logged and nursery trees are planted constantly. Woody biomass is burned directly as solid fuel and the generated thermal energy can be applied only for room heating or cooking. Otherwise, direct conversion of biomass to electric energy requires a large scale equipment such as a boiler and a steam turbine, whereas gasified woody biomass can be easily handled and can have wide application. A closed gasifier chamber which was kept vacuum and fulfilled with gas yield during gasification was recently developed by the authors for indirect gasification. It was confirmed that generated gas by the gasifier is clean and can be directly used to drive an engine generator to supply electricity. In this study, planer dust of rubber wood is used as gasification feedstock for indirect gasifying in the closed gasifier chamber, and effects of heating temperature and moisture content on gasification performance are discussed to examine characteristics of the closed gasifier chamber in details.

Keywords

Indirect Gasification, Rubber Wood, Closed Gasifier Chamber, Moisture Content, Gas Component

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1. Introduction

Economic growth in ASEAN (Association of Southeast Asian Nations) countries is significant in recent years. Primary energy demand in ASEAN is about 594 million tons of crude oil equivalent in 2013 [1]; it is up to 4.5% of the global primary energy demand [2]. Indonesia has the largest territory and population in ASEAN member countries and there are abundant deposits of fossil fuels such as coal, natural gas and oil. Indonesia fossil fuel consumption is 177 million tons of crude oil equivalent in 2013 [3]. In addition, there are abundant biomass resources of which 147 million tons are produced in a year [4]. Rubber wood is the majority of woody biomass in Indonesia. Indonesia is the second largest natural rubber production country in the world, and there are huge rubber wood plantations in Sumatra and Kalimantan. Rubber wood trees of more than 25 years old are logged for lumber in the plantation. However, 41 million tons of nursery trees are replanted every year, and thus, rubber wood logs can be supplied stably. As a result, rubber wood is the promised woody biomass for energy resource. In Indonesia, electrification rate is still low as 81% and 46 million of people mostly in rural area cannot access electricity [3] [5]. From a different viewpoint, they may be those who can easily access woody biomass resource, and are in an advantageous situation for off-grid electric power supply using biomass gasification.

The simplest way to get thermal energy is to burn woody biomass directly as solid fuel. However, the generated energy can be only used for heating or cooking. On the other hand, if we try to generate electric energy by burning woody biomass, a steam turbine generator system must be installed. Considering the above shortcomings concerning the energy produced from direct combustion of woody biomass, change of solid woody biomass to gas or liquid should be developed from a viewpoint of versatile usage. Combustible gas extraction from biomass is one of the attractive ways. Gas can be easily utilized for a wide variety of purposes. Some type of gasifiers has been developed by use of direct heating [6]-[9] or indirect heating [10]-[14] in a pilot plant scale. Direct heating is widely used for gasification because the structure is simple. Thermal energy for the gasification is supplied from combustion of a part of biomass feedstock in a gasifier. Therefore, a certain volume of air intake is inevitable for the gasification, so that generated gas yield necessarily contains N_2 from air, CO_2 produced from the combustion and residual O_2. Such extra gases lower heating value of the gas yield per unit volume. In contrast, an indirect heating gasifier, for instance, a rotary kiln type of gasifier decomposes biomass feedstock into gas by an outside heating source. A modicum of N_2 and other incombustible gases may be contained in the generated gas on account of small air intake opportunities during feedstock feeding when a gasifier is operated under ambient pressure, but nevertheless, the high caloric gas yield can be produced by an indirect heating gasifier, and further, soot formation can be suppressed by easy diffusion of gasification agent in the gasifier. The generated gases are typically used to drive an engine generator to produce electric energy. In order to drive an engine, small heating value of generated gas may need following devices. To enhance effective gas combustion, homogeneous charge compression ignition [15]-[18] and combustion in combination with other fuel [19]-[22] are contrived.

The current authors proposed a new woody biomass gasification method using a closed gasifier chamber [23] [24]. The closed gasifier chamber is a stainless steel vessel closed by flanges and used for a vacuum and pressurized vessel that is initially vacuumed and then pressurized during gasification process. This system has the following advantages: 1) gas produced in an indirect heating gasifier does not contain inert gas because of pre-vacuuming process before gasification and high calorie gas is obtained; 2) reduction of tar content in gas yield is a tradeoff between increase in reaction time and deterioration of energy efficiency; 3) if a biomass stove is used for heat source, it is no need to supply electricity for the gasifier operation except for pre-vacuuming; 4) the gasifier can be used for a temporary gas storage tank after gasification is terminated. Thus, it can be expected that generated gas is used without any treatment to drive a small gasoline engine generator for electric power.

This system is supposed to use rubber wood for gasification feedstock and to supply off-grid electricity at rural areas in Indonesia. Several studies on gasification of rubber wood by direct heating have been reported [25] [26], but research on gasification by indirect heating is very few [27]. In order to enhance efficiency of the gasifier developed by the current authors, usage of gasification agent is considered. H_2O or CO_2 is often added as gasification agent for woody biomass gasifier by indirect heating. Naruse *et al.* [28] studied effect of gasification agent on decomposition reaction using N_2 as a carrier gas in a drop tube type of gasifier heated indirectly by electric furnace. They reported that H_2O was effective in gasification at the temperature of lower than 1000˚C while CO_2, in gasification above 1000˚C. This study aims to enhance gasification efficiency of the indirect heating gasifier, which was developed by the current authors and operated at temperature below 1000˚C. One way for enhancement of the efficiency is to use a gasification agent. According to Naruse's result mentioned above, H_2O is selected as a gasification agent for this study. Heretofore, there is no study on effect of moisture content in feedstock on gasification characteristics of woody biomass under no oxygen, no carrier gas and pre-vacuumed condition. Therefore, to examine effects of heating temperature and moisture content on gasification characteristics, experiments are carried out in the closed gasification chamber using planer dust of rubber wood for gasification feedstock.

2. Experimental Apparatus

The closed gasifier chamber was developed by the current authors to enable gasification under no oxygen and no inert gas condition in the way that the chamber is vacuumed prior to the initiation. The chamber is heated from outside, and this condition is called indirect gasification. Therefore, a structure of gasifier is rather simple and the chamber temperature can be easily controlled as compared with a conventional fix bed type of gasifier.

The experimental apparatus is shown in **Figure 1**. The gasifier chamber is a cylindrical vessel of which the bottom plate is welded and is made of stainless steel. The chamber dimensions are 89.1 mm in outer diameter, 719.0 mm in height, and 3.94×10^{-3} m^3 in internal volume. A compound gage with a vacuum range and valves are attached to a pipe line from a flange welded to the chamber top. A vacuum pump is used to vacuum the chamber prior to gasification, and a gas sampling bag is used to collect a gas yield after experiment. Gasification feedstock is put in a stainless steel cup and is placed at the bottom of the chamber. Then, the gasification is started after the chamber is placed in an electric furnace heated at a specified constant temperature.

3. Experimental Condition and Procedure

Rubber wood feedstock is prepared in shape of thin pieces produced by an electric planer, of which dimensions are 7 mm in length, 4 mm in width, and 0.2 mm in thickness. Result of ultimate analysis, ash and heating value of rubber wood are shown in **Table 1**. To remove moisture, the feedstock is heated up at 105˚C and kept at the temperature for more than 7 hours in oven. Experimental conditions are summarized in **Table 2**. Heating temperature is defined as preset temperature of the electric furnace. Distilled water as a gasification agent is poured over the dried feedstock of 10×10^{-3} kg to adjust prescribed moisture content. Moisture content is defined by Equation (1) on a wet state basis.

$$\text{moisture content} = \frac{\text{mass of distilled water}}{\text{mass of dried planer dust and distilled water}} \tag{1}$$

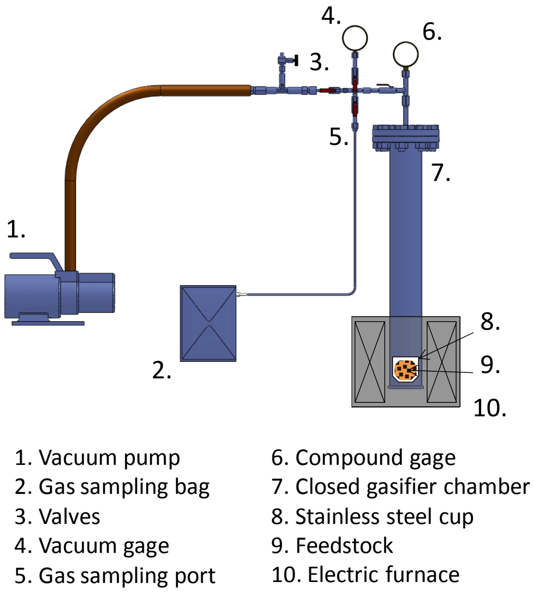

Figure 1. Experimental apparatus.

Table 1. Results of ultimate analysis, ash and heating value of rubber wood.

C [wt%]	42.3
H [wt%]	6.4
N [wt%]	0.3
O [wt%, by difference]	51.0
Ash [wt%]	1.7
Heating value [kJ/kg-dry]	18,047

Table 2. Experimental conditions.

Feedstock mass [10^{-3} kg]	10
Heating temperature [˚C]	600, 700, 800, 900
Moisture content [%]	0, 10, 20, 30, 40, 50

Experimental procedures are as follows:

- The feedstock sample is put into the stainless steel cup and distilled water is poured over it;
- The stainless steel cup is placed at the bottom of the chamber, then the chamber is closed with the flange;
- Air inside the chamber is suctioned by a vacuum pump until the vacuum reaches a certain level;
- The chamber is positioned in the electric furnace controlled at the preset temperature, and then gasification starts;
- When pressure inside the chamber increases and reaches plateau, small volume of generated gas is collected into the gas sampling bag to analyze gas components by a gas chromatography;
- Volume of remaining gas in the chamber is measured by downward displacement of water.

4. Experimental Result and Discussion

4.1. Total Gas Yield

Total gas yield generated per unit mass of feedstock in the gasification experiment is calculated as volume at standard ambient temperature and pressure (SATP) and shown in **Figure 2**. The largest gas yield of 1.32 m^3/kg is obtained at heating temperature of 900˚C. It is 2.3 times larger than the gas yield volume at 600˚C. Larger moisture content causes larger gas yield in the range of moisture between 0% and 30%. However, beyond this range, gas yield decreases with increase in moisture content. At 900˚C, gas yield for moisture content of 30% increases by 0.24 m^3/kg from that for 0%. Gas yield for 50% moisture is smaller than that for 30% and close to the result for 10%. High moisture content significantly increases pressure in the chamber due to expansion of steam volume vapored from the moisture. It is considered that high pressure may suppress gasification reaction in the chamber. At heating temperature of 800˚C, total gas yield is 1.20 m^3/kg for 30% moisture content. Increment of 0.38 m^3/kg is made from that for 0% moisture content, which is much higher than gas yield for other moisture contents at 800˚C. In addition, the gas yield is almost same as that for 20% moisture content at 900˚C. In general, high heating temperature can produce large gas yield, but if optimal gasification agent is not used, gas yield for high heating temperature maybe less than that for optimal gasification agent at low temperature.

After an experiment has been terminated, char, mostly composed of carbon remains in the stainless steel cup. Average char yield per unit mass of feedstock is slightly dependent on heating temperature as shown in **Figure 3**. The char yield is 19.0 wt% at 900˚C and increases to 25.0 wt% at 600˚C. The char yield can be an indicator for extent of decomposition reaction in a gasification process and is inversely related to gas yield. When heavy molecular hydrocarbon in decomposition products is cooled down, it is liquefied into tar. At low heating temperature, when gas yield was measured by the downward displacement method, flowing brown tar was observed together with condensed water vapor in a transparent tube. Furthermore, sticky tar adhered to the inner surface of the flange. At 900˚C, adherent tar was a little and flowing tar in the tube was also very little. This may indicate that heavy hydrocarbon is reformed into light gases at high temperature.

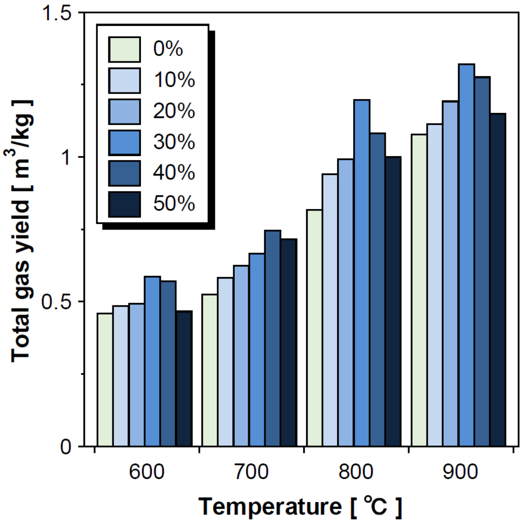

Figure 2. Total gas yield per unit mass of feedstock at SATP.

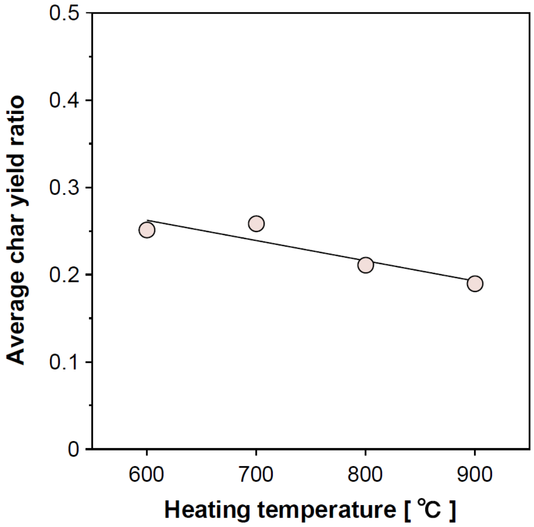

Figure 3. Average char yield ratio (char yield/feedstock mass) versus heating temperature.

4.2. Gas Compositions and Yield of Each Gas Component

Gas compositions of the generated gas at each heating temperature are shown in **Figure 4**. CH_4 is 17.0% and independent of the moister content except the case of heating temperature of 900˚C. In addition, H_2 is weakly dependent on the moisture content and increases slightly with the heating temperature. As a result, combined compositions of CH_4 and H_2 at above 700˚C are almost constant and nearly 55%, while CO_2 and CO are the rest gas components and total volume must be almost constant. Enhancement of moisture results in increase of CO_2 and decrease of CO at every temperature. It may be considered that the water-gas shift reaction, namely $CO + H_2O \rightarrow CO_2 + H_2$ is promoted by enhancement of moister and as a result, CO is converted to CO_2. On the other hand, high heating temperature yields decrease in CO_2 and eventually increase in combustible gases. The maximum combustible gas yield, 77%, is produced at 900˚C and 0% moisture, which is 23% higher than that at 600˚C.

Yield of each gas component is calculated as volume per unit mass of feedstock from total gas yield and gas component ratio, and is shown in **Figure 5**. Combustible gas yield besides CO_2 at 900˚C is around three times higher than that at 600˚C. The yield of CH_4 having high heating value is insusceptible against moisture content

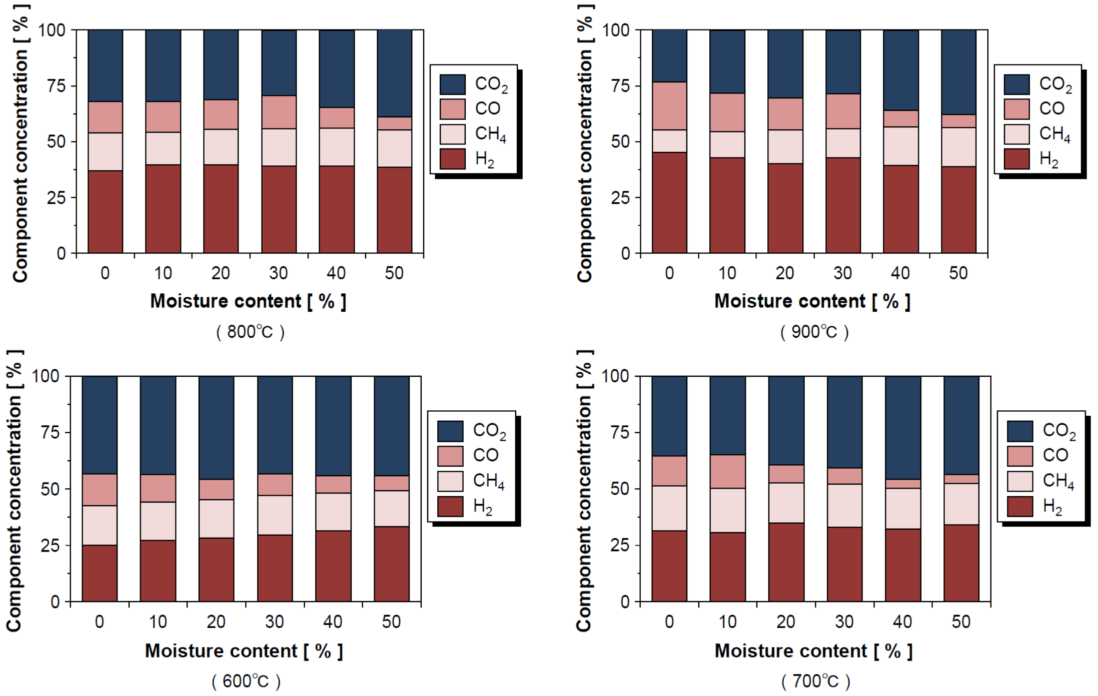

Figure 4. Component ratio of generated gas.

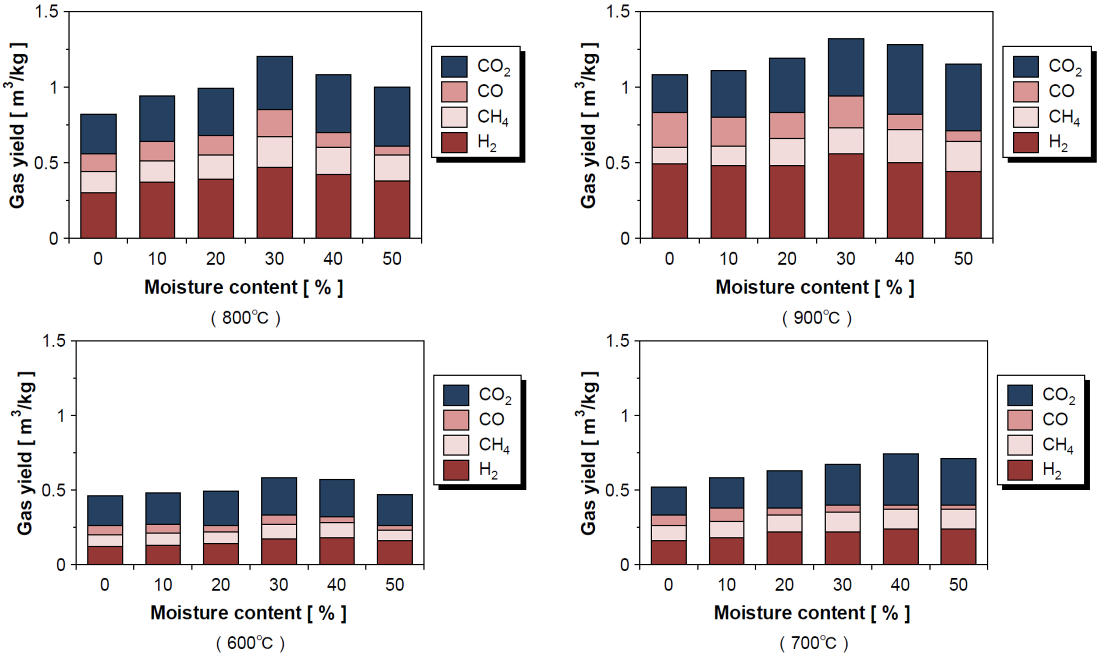

Figure 5. Yield for each component of generated gas per unit mass of feedstock.

and increases with the heating temperature up to 800˚C. At the heating temperature of 900˚C, the maximum yield of CH_4 is 0.22 m^3/kg for 40% moisture. At the heating temperature of 800˚C and 900˚C, the combustible gas yield decreases as the moisture exceeds 30%. Combustible gas yield reaches the peak, 0.94 m^3/kg at 900˚C and 30% moisture. At 800˚C, the largest combustible gas yield is 0.85 m^3/kg for 30% moisture and is higher than the yields at 900˚C and moisture of other than 30%. Moisture content of more than 30% and heating temperature of more than 800˚C produce less gas yield that results from reduction of CO yield and H_2 yield. The reduction in total gas yield is less than the reduction in combustion gas yield. Therefore, it is considered that decomposition reaction is suppressed due to increase in the chamber pressure resulted from vapored moisture, but the suppression is predominant over water gas shift reaction by moisture effect.

As compared with gas yield by rotary kiln gasifier using an indirect heating method, it should be noted that the current closed gasifier chamber produces almost same volume percent of CH_4, 2.5 times larger volume percent of CO_2 and H_2, and quarter times smaller volume percent of CO [29]. Downdraft type of gasifier and updraft type of gasifier that use a direct heating method with some air intake to burn biomass partially, produce gas yields containing N_2. Comparing the gas component yields produced by the current system with those produced by the downdraft or updraft type of gasifier, it should be noted that the current system produces 2 times larger volume percent of CH_4 and smaller volume percent of CO_2 [30]. The current closed chamber gasifier is characterized as H_2-rich gasifier, because the H_2 yield is significantly high as compared with that by other type gasifiers.

4.3. Heating Value of Generated Gas

Combustion of H_2, CO and CH_4 generates heat of 286 MJ/kmol, 284 MJ/kmol and 891 MJ/kmol, respectively. Gross heating value of generated gas yields per unit mass of feedstock can be calculated from these values and is shown in **Figure 6**. Cold gas efficiency is defined as a ratio of gross heating value of generated gas to heating value of feedstock. At 600˚C, averaged gross heating value is 5.4 MJ/kg, and the cold gas efficiency is lower than 30%. When heating temperature is higher than 800˚C, gross heating value is around twice higher than that at 600˚C and is larger than 9 MJ/kg. The cold gas efficiency exceeds 50%. Gross heating value is maximized at 900˚C and 30% moisture content where the largest gas yield is produced. The gross heating value is 15.1 MJ/kg and the cold gas efficiency is enhanced to 84%.

Specific heating value of generated gas per unit volume is shown in **Figure 7**. The values vary slightly over whole heating temperature and moisture. Because combustible gas ratio is reduced due to increase in CO_2 ratio, specific heating value is gradually declined as the moisture content increases. The specific heating value at 600˚C and 900˚C is lower than that at other heating temperature. This is because combustible gas ratio is low due to high CO_2 ratio at 600˚C, and due to low ratio of CH_4, which has the highest heating value, at 900˚C. In general, most of gases generated from woody biomass by direct heating are classified to low calorie gas. At 700˚C and 0% and 10% moisture content, and 800˚C and 30% moisture content, specific heating values of the generated gas exceed 12 MJ/m^3 and the gas produced by the current gasifier is classified into middle calorie gas.

5. Conclusions

In this study, indirect gasification experiment was carried out using thin robber wood pieces as gasification feedstock in the closed gasifier chamber proposed by the current authors. Experiments were carried out for various heating temperature and moisture contents, and following conclusions are obtained.

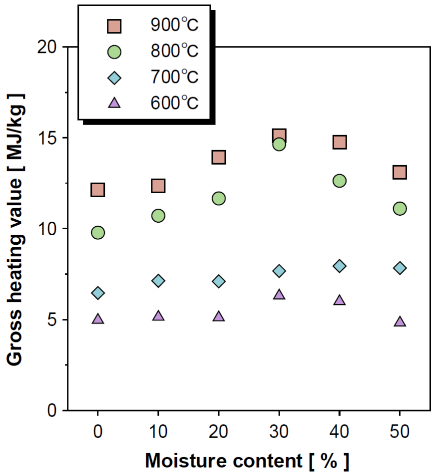

Figure 6. Gross heating value of generaed gas per unit mass of feedstock.

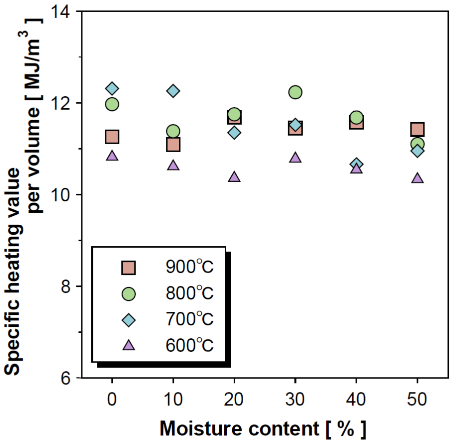

Figure 7. Specific heating value of generated gas per volume.

- Adding water as gasification agent brings increase in gas yield by promotion of gasification reaction. When heating temperature is high and moisture content is high, gas yield decreases due to suppression in gasification and high pressure in the gasifier chamber.
- CH_4 ratio of gas yield is insusceptible against heating temperature and moisture content. Sum of H_2 and CH_4 ratios is almost constant over all the experimental conditions. Higher moisture content brings higher CO_2 ratio and lower CO ratio. In addition, high heating temperature decreases CO_2 ratio, and then increases combustible gas ratio.
- Gross heating value of generated gas per unit mass of biomass is higher than 9 MJ/kg, and cold gas efficiency exceeds 50% at heating temperature of higher than 800˚C. On the other hand, specific heating value per volume at heating temperature of 900˚C falls below that at 800˚C, because combustible gas components other than CH_4 having the highest heating value are major. The maximum specific heating value of gas yield can surpass 12 MJ/m^3, which is the lower limit for a middle calorie gas, and thus it is definitely predicated that the developed gasifier can produce middle calorie gas.

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