Gasification of Furniture Waste Sawdust in a Cyclone Gasifier

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Abstract. Sawdust is one of the major biomass that was produced over 1 million ton per year in Thailand. A large amount of sawdust can be used as renewable energy. Gasification is one of the high-efficiency processes to convert biomass to the gaseous product. Sawdust is suitable to be converted to the gaseous product due to its high proportion of volatile (73%). In this work, sawdust thermal conversion was investigated by using a stairmand type cyclone gasifier with 100 mm diameter. The operation of the cyclone with short residence time and high efficiency of particulate separation from the gaseous product is suitable for a small particle like sawdust. The influences of equivalence ratio (0.15-0.60) and reactor temperature (700° C, 800° C and 900° C) on the waste conversion performance were determined. The gas composition (CO, CO₂, CH₄, H₂, and CₙHₘ), carbon and hydrogen conversions, lower heating value and cold gasification efficiency were reported. The data analysis indicated the optimum equivalence ratio is 0.45. Excessively lower or higher equivalence ratio negatively affected the gas composition and heating value of gaseous product. The optimum of reactor temperature is 900° C. The lower temperature also adversely affected the gaseous product, conversion of carbon and hydrogen. The lower heating value of product gas is range from 0.95-3.45 MJ/m³ and the cold gasification efficiency is range from 28-68%. The optimal condition of sawdust gasification in cyclone gasifier is equivalence ratio of 0.45 and temperature of 900° C at which total carbon and hydrogen conversions are 90% and 60%, respectively.

1. Introduction
Several types of agricultural waste, forestry products and industry residue in Thailand are used as feedstock for gasification process. Thai government of supports this technology for heat and power purposes [1]. Gasification is the thermal conversion process that is suitable for producing gaseous product from carbonaceous raw materials. Here, the input material should be small or long reaction time is needed to ensure effective conversion to fuel gas. Sawdust from furniture industry is of small particle size and has appropriate characteristics to be converted to the fuel gas products because of its high volatile matter (around 70%) and carbon content (around 50%) with low moisture content (around 6%). From previous researches, sawdust was gasified in several reactor types such as spout-fluid bed reactor [2] and entrained-flow reactor [3, 4]. Though problems of small particle being carried away or short-circuited through the reactor before complete reaction resulted in contamination of the product gas. Furthermore, some alkalis were found to exit the gas stream by attaching to the surface of those small particles [2]. Thus, in order to mitigate these problems, a cyclone reactor was selected due
The purpose of the present work is to investigate the gasification parameters during the conversion of sawdust to fuel gas product by cyclone gasification process. The performance was evaluated in terms of gas composition (CO, CO₂, CH₄, H₂ and CₙHₘ), carbon and hydrogen conversions, lower heating value and cold gasification efficiency.

2. Material and Methods

The biomass feedstock in this study is sawdust which comes from a furniture plant located in an eastern province of Thailand. The particle size between 150 - 250 μm was used and kept at 105 °C in an oven for 24 hours prior to any experiments to vaporize the moisture. The feedstock was collected in one batch to minimize the characteristic variation.

The characteristics of biomass feedstock, proximate analysis, ultimate analysis and lower heating value are shown in Table 1. The main characteristics of feedstock consists of high carbon content (45%), high volatile matter (73%), low moisture content (6%) and low ash content (6%). Note that the ultimate analysis was determined by following ASTM-D5373 using C-H-N analyzer except the oxygen composition was assumed by difference and the proximate analysis was determined by following ASTM-D5142-02. Bomb calorimeter was used to analyze lower heating value that resulted in the value of 19.2 MJ/kg which is typical for lignocellulosic materials.

As shown in Figure 1, the major particle size distribution of this feedstock is in range of 150-250 μm. This size of feedstock is optimum for gasifying particles according to Moghiman et al. [5] who reported the satisfactory range for wood particle size in the cyclone gasification of wood powder of 150-600 μm because the particle with small size of less than 150 μm may leave the cyclone and carry away the alkali compound with the producer gas. The bigger particle size of more than 600 μm may leave the cyclone before the complete gasification. Another reason is heat transfer, the smaller particles could be heated more rapidly and evenly with minimized temperature gradient which leads to higher rate of gasification reactions.

The Stairmand type cyclone design yielded a reactor with 100 mm diameter and 400 mm height. This design was selected because it is suitable for small particle that required short residence time and high efficiency of particulate separation from the gaseous product. The gasifier was made from stainless steel grade 310S which can withstand high temperature and corrosive nature of expected by-products.

The experimental set up is shown in Figure 2 which consists of six major parts: carrier gas preheating system, biomass feeding system, cyclone reactor, electric heater, tar condenser and sampling gas train for analysis. To begin the experiment, carrier gas, nitrogen and oxygen, was heated up to 200°C prior to entering and flowing through the feeding tube to the cyclone reactor. The biomass feeding system which located perpendicular to the feeding tube fed the sawdust continuously to the feeding tube by screw conveyor. Then, the sawdust was mixed with the carrier gas and entrained to the cyclone reactor where it came into contact with the hot cyclone wall and rapidly heated up. After that, the producer gas left the reactor through the upper section while the char product was separated to char box at the bottom of the cyclone. The producer gas moved into the tar condensation system to extract tar content and to decrease its temperature. Then the producer gas was sampled by peristaltic pump for analysis of the gas compositions (CO, CO₂, CH₄, CₙHₘ and H₂) before released to the atmosphere.

Table 1. Proximate, Ultimate Analysis and Lower heating of feedstock.

| Ultimate analysis ( % dry basis) | C   | H   | N   | Oa  |
|---------------------------------|-----|-----|-----|-----|
|                                 | 44.99 | 6.31 | 0.32 | 48.38 |
| Proximate analysis ( % wet basis) | Moisture | Volatile matter | Fixed carbon | Ash content |
|                                 | 6.12 | 72.7 | 14.8 | 6.38 |
| Lower heating value (MJ/kg)     | 19.2 |

* by difference
Figure 1. The particle size distribution of biomass feedstock.

Figure 2. Diagram of the cyclone gasification system.

This study is focused on gasification temperature and equivalence ratio that may affect the gas product distribution. The gasification temperature was varied from 700°C, 800°C and 900°C and the equivalence ratio (ER) was varied from 0.15, 0.30, 0.45 and 0.60. The carrier gas consists of nitrogen and pure oxygen that acted as the gasification agent. The biomass feed rate was determined at 0.32-0.47 kg/h.

3. Result and Discussion
The varied experimental conditions are temperature and ER in which their effect on the main gasification parameters would be discussed here. The sawdust was fed to the feeding tube. Then combined with the carrier gas and move to the hot cyclone wall by centrifugal force. The hot cyclone wall provided the thermal energy to sawdust within short residence time resulting in the gasification process rapidly occurred which was summarized as several following reactions.
Oxidation reaction

\[
\begin{align*}
C + \frac{1}{2} O_2 &\rightarrow CO & \Delta H = -111 \text{ kJ/mol} \\
C + O_2 &\rightarrow CO_2 & \Delta H = -394 \text{ kJ/mol} \\
CO + \frac{1}{2} O_2 &\rightarrow CO_2 & \Delta H = -284 \text{ kJ/mol} \\
CH_4 + 2O_2 &\rightarrow CO_2 + 2H_2O & \Delta H = -803 \text{ kJ/mol}
\end{align*}
\]

Boudouard reaction

\[
C + CO_2 \rightarrow 2CO & \Delta H = +172.5 \text{ kJ/mol}
\]

Water-gas reaction

\[
C + H_2O \rightarrow CO + H_2 & \Delta H = +131.3 \text{ kJ/mol}
\]

Water-gas shift reaction

\[
CO + H_2O \rightarrow CO_2 + H_2 & \Delta H = -41.2 \text{ kJ/mol}
\]

Methanation reaction

\[
C + 2H_2 \rightarrow CH_4 & \Delta H = -74.9 \text{ kJ/mol}
\]

Steam reforming reaction

\[
CH_4 + H_2O \rightarrow CO_2 + 3H_2 & \Delta H = +206.2 \text{ kJ/mol}
\]

3.1. Effect of the ER

In this study, ER was varied from 0.15 to 0.60. The ER is the ratio of actual mole of oxygen input to the stoichiometric mole of oxygen for particular oxidation processes which depends on the biomass feeding rate. This means that the higher of ER, the higher amount of oxygen.

Oxygen content plays an important role in oxidation reaction (equation(1-4)) which produces CO\textsubscript{2} as the main product. Higher oxygen availability led to increased CO\textsubscript{2} generation as shown in Figure 3. At 700°C, 800°C, and 900°C, the ER increased, the CO\textsubscript{2} conversion increased from 6.78% to 28.27%, 11.54% to 21.16 and 11.41% to 27.59, respectively. In contrast, the CH\textsubscript{4} composition was slightly decreased because it can react with oxygen to produce CO\textsubscript{2} and H\textsubscript{2}O according to the oxidation reaction (equation(4)). However, when the ER was increased up to the optimum level, the CO conversion decreased because the CO was used in the interaction (equation(3)) in which it would combine with O\textsubscript{2} and convert to CO\textsubscript{2}. As a result, the optimum ER of reactor temperature 700°C, 800°C and 900°C is 0.30, 0.45 and 0.45, respectively. Hence the increase rate of oxidation reaction led to greater sawdust degradation which decrease amount of char products as shown in Table 2.
Figure 3. Effective of equivalence ratio on carbon conversion to CO$_2$ at 700°C, 800°C and 900°C.

The cold gas efficiency depends on the composition of producer gas, CO, CH$_4$ and H$_2$ and hence the producer gas at optimum ER cause the highest value of the cold gas efficiency at 700°C, 800°C and 900°C of 38.96%, 48.33% and 67.66%, respectively. Figure 4 shows cold gas efficiency data from the experiments.

A similar trend of CO, CO$_2$ and H$_2$ was also reported by Yijun on the experiment with rice husk using a cyclone reactor [6]. The result indicated that when the ER increased to 0.3, greater CO, CO$_2$ and H$_2$ could be observed. On the other hand, the carbon conversion of sawdust (33.30-60.17%) was higher than that of rice husk (27.1 – 39.7%) at 700 °C in cyclone reactor which resulted from oxidation reactions (equation(1-4)).

At 800°C, the results displayed similar trend to that of Shaozeng who studied on cyclone air gasification of wood powder [7]. The results showed that H$_2$ and CO$_2$ increased with high ER. The gasification in an entrained-flow reactor [3] of sawdust has a similar trend of carbon conversion when compared with the gasification of sawdust in cyclone reactor. At high temperature (800°C – 900°C), the ER had little effect on carbon conversion.

3.2. Effect of reaction temperature

The increasing of reactor temperature is the option to enhance the energy input to the system which leads to greater chemical reaction rate of gasification reactions, particularly, the endothermic ones, Boudouard and water-gas reactions. The Boudouard and water-gas reactions have a faster reaction rate with the high temperature. The high effectiveness of these reactions can be observed via the CO and H$_2$ composition increased as shown in Figure 5. At greater ERs from 0.15 to 0.60, the higher temperature resulted in increased CO and H$_2$ conversions from 20% to 50% and 3.7% to 26%, respectively. Furthermore, the oxidation reaction (equation(1)) and steam reforming reaction (equation(9)) were also increased the CO and H$_2$ composition.

The synthesis gas, CO and H$_2$, greatly influence the LHV and cold gas efficiency. High synthesis gas generation leads to increased LHV and cold gas efficiency as shown in Figure 6. At ER 0.45, the LHV and cold gas efficiency increase from 1.46 to 3.45 MJ/m$^3$ and 38.96% to 67.66%, respectively. If oxygen is readily available, CO$_2$ composition would increase with temperature but at 800°C and 900°C the composition of CO$_2$ was relatively steady. This probably due to the reaction rate of the equation(1-4) which may already reached the maximum.
At high temperature, the methanation reaction (equation(8)) produces more CH\(_4\) but the steam reforming reaction (equation(9)) also consumes CH\(_4\) as the raw material in the reaction. This may explain the relatively stable CH\(_4\) composition in the produce gas with increasing temperature.

**Figure 5.** Effect of temperature on carbon conversion to CO\(_2\) and hydrogen to H\(_2\) at ER 0.45.

**Figure 6.** Effect of temperature on LHV and cold gas efficiency at ER 0.45.

**Table 2.** The gasification parameters for ER 0.15, 0.30, 0.45 and 0.60 at different temperature.

| Temperature | 700°C | 800°C | 900°C |
|-------------|-------|-------|-------|
| ER          | 0.15  | 0.30  | 0.45  | 0.60  | 0.15  | 0.30  | 0.45  | 0.60  | 0.15  | 0.30  | 0.45  | 0.60  |
| Feeding rate (kg/h) | 0.36  | 0.41  | 0.39  | 0.39  | 0.42  | 0.38  | 0.46  | 0.34  | 0.41  | 0.44  | 0.47  | 0.32  |
| Carbon conversion (%) |       |       |       |       |       |       |       |       |       |       |       |       |
| CO          | 20.01 | 33.23 | 33.74 | 28.58 | 34.44 | 30.53 | 35.83 | 28.67 | 41.45 | 46.19 | 50.15 | 44.49 |
| CO\(_2\)    | 6.78  | 12.70 | 19.18 | 28.27 | 11.54 | 12.83 | 21.16 | 20.40 | 11.41 | 17.05 | 27.59 | 23.64 |
| CH\(_4\)    | 6.51  | 9.42  | 7.24  | 7.76  | 10.60 | 9.56  | 9.94  | 6.32  | 13.28 | 12.53 | 12.56 | 10.19 |
| Total       | 33.30 | 55.35 | 60.16 | 64.61 | 56.58 | 52.92 | 66.93 | 55.39 | 66.14 | 75.77 | 90.30 | 78.32 |
| Hydrogen conversion (%) |       |       |       |       |       |       |       |       |       |       |       |       |
| CH\(_4\)    | 17.29 | 25.03 | 19.24 | 20.63 | 28.18 | 25.40 | 26.41 | 16.79 | 35.29 | 33.29 | 33.38 | 27.09 |
| H\(_2\)     | 3.68  | 7.62  | 6.73  | 6.11  | 10.62 | 14.19 | 13.39 | 12.89 | 14.69 | 20.52 | 25.97 | 20.70 |
| C\(_\text{H}_m\) | 0.55  | 0.58  | 0.36  | 0.36  | 0.78  | 0.52  | 0.47  | 0.85  | 0.85  | 0.52  | 0.24  | 0.08  |
| Total       | 21.52 | 33.23 | 26.33 | 27.03 | 39.58 | 40.11 | 40.27 | 30.53 | 50.83 | 54.33 | 59.59 | 47.87 |
| LHV (MJ/m\(^3\)) | 0.95  | 1.65  | 1.46  | 1.30  | 2.06  | 1.75  | 2.29  | 1.27  | 2.66  | 3.02  | 3.45  | 1.97  |
| Cold gas Efficiency (%) | 27.52 | 41.70 | 38.96 | 34.61 | 47.87 | 44.55 | 48.33 | 37.12 | 59.29 | 63.05 | 67.66 | 57.10 |
| Char product (%) | 9.52  | 8.62  | 5.58  | 4.03  | 8.19  | 5.61  | 4.02  | 3.65  | 6.40  | 3.83  | 3.76  | 5.17  |

**4. Conclusions**
Investigation of the performance of cyclone gasification of furniture waste sawdust was carried out in this work. The parameters used to define the process efficiency were carbon and hydrogen conversions, product gas heating value and cold gas efficiency. The operating parameters investigated was temperature and equivalence ratio. Generally, the increasing of ER has an effect to the oxidation reactions which increase carbon conversion to favourable CO gas product. Meanwhile the increasing of reaction temperature significantly effects the endothermic reactions which enhanced carbon to CO and hydrogen to H\(_2\). Thus the optimum conditions that produce high performance synthesis gas is 900°C at ER 0.45 when the highest carbon to CO, hydrogen to H\(_2\), LHV and cold gas efficiency can be achieved.

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References
[1] Laohalidanond K, Chaiyawong P and Kerdsuwan S 2015 Energy Procedia 79 385
[2] Thamavithya M, Jarunghammachote S, Dutta A and Basu P 2012 Int. J. Energ. Res. 36 204
[3] Zhao Y, Sun S, Zhou H, Sun R, Tian H, Luan J and Qian J 2010 Fuel. Process. Technol. 91 910
[4] Weiland F, Hedman H, Marklund M, Wiinikka H, Ohrman O and Gebart R 2013 Energy Fuels 27 932
[5] Moghiman M, Hashemi T, Zahmatkesh I and Daghighi Y 2007 J. Energy. Inst. 80 (1) 29
[6] Zhao Y, Sun S, Che H, Guo Y and Gao C 2012 Int. J. Hydrogen. Energ. 37 16962
[7] Sun S, Zhao Y, Tian H, Ling F and Su F 2009 Bioresource. Technol. 100 4047