Experimental study of wood downdraft gasification for an improved producer gas quality through an innovative two-stage air and premixed air/gas supply approach

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This study conducted experiments on three different downdraft gasification approaches: single stage, conventional two-stage, and an innovative two-stage air and premixed air/gas supply approach. The innovative two-stage approach has two nozzle locations, one for air supply at combustion zone and the other located at the pyrolysis zone for supplying the premixed gas (air and producer gas). The producer gas is partially bypassed to mix with air and supplied to burn at the pyrolysis zone. The result shows that producer gas quality generated by the innovative two-stage approach improved as compared to conventional two-stage. The higher heating value (HHV) increased from 5.4 to 6.5 MJ/Nm\textsuperscript{3}. Tar content in producer gas reduced to less than 45 mg/Nm\textsuperscript{3}. With this approach, gas can be fed directly to an internal combustion engine. Furthermore, the gasification thermal efficiency also improved by approximately 14%. The approach gave double benefits on gas qualities and energy savings.

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1. Introduction

Biomass can be converted to biofuel by mainly two routes, one is the biochemical route and the other is the thermochemical route to which the gasification process falls under (Damartzis and Zabaniotou, 2010). Gasification of solid biomass converts it to gas often referred to as producer gas or syngas which is mainly composed of CO, CO\textsubscript{2}, CH\textsubscript{4}, H\textsubscript{2} and N\textsubscript{2} (if the gasification agent is air). The useful gas or combustible gas components are CO, CH\textsubscript{4} and H\textsubscript{2}, which if available in sufficient quantity, can be used as fuel for internal combustion engines (ICE). In a typical downdraft gasifier, the generated producer gas will have total combustible gas percentage varying on the range of 20–35% and have higher heating value (HHV) of around 5.0 MJ/Nm\textsuperscript{3} (Dutta, 1998; McKendry, 2002). Higher HHV can better operate an ICE but the tar content in should also be considered. For direct application into an ICE, it should be lower than 50 mg/Nm\textsuperscript{3} (Bhattacharya et al., 2001). Other literatures mentioned that tar content can be tolerated up to 100 mg/Nm\textsuperscript{3} (Stassen and Knoef, 1995; Karuppaswamy et al., 1993). An appropriate gas cleaning unit should be installed if tar content is unsatisfactory.

Downdraft gasification process consists of drying, pyrolysis or devolatilization, combustion or oxidation and gasification or reduction. The flame initiated at the combustion zone releases and transfer heat to both upper (pyrolysis and drying zones) and lower (reduction zone) directions. As feedstock gets consumed, the feedstock moves downward closer to the high temperature combustion zone. At the location that has temperature of 100 °C and more, the moisture in the feedstock is completely vaporized and this zone is identified as the drying zone. The dried feedstock continues to move downward and the volatile matter in feedstock is devolatilized as it enters the pyrolysis zone which temperature ranges from 250 to 550 °C (Jaojaruek and Kumar, 2009). Products that come out of this sub-process are volatile gas (CO, CO\textsubscript{2}, CH\textsubscript{4}, H\textsubscript{2} and tar), char and water vapor. The char and volatile gas will then mix with the injected air and partially burn at the combustion zone. Un-burnt portion of the char flows further down until it is gasified in the reduction zone. This gas is called producer gas and has the same composition as volatile gas but the quantities of combustible gas (CO, CH\textsubscript{4} and H\textsubscript{2}) are improved and the tar content is lower. The producer gas leaves the system through the bottom of the gasifier. This can then be used to serve thermal applications and if the quality is sufficiently good, it can be used for ICE application or gas-powered electricity generators.
The gasification process is a series of chemical reactions. The chemical kinetic model shows that the degree of complete reaction depends on temperature and reaction duration (Turns, 1996) and these have direct impacts to the gas quality. Water–gas shift depends on temperature and reaction duration (Turns, 1996) and chemical kinetic model shows that the degree of complete reaction (Jarungthammachote, 2008).

2. Methodology

2.1. Two-stage air and premixed air/gas supply approach

The multi-stage or two-stage downdraft gasification in a single reactor approach was already studied at the Asian Institute of Technology, Thailand (Devi et al., 2003; Jarungthammachote, 2008) with a reactor designed to have two locations of air supply nozzles located at combustion and pyrolysis zones. Compared to single-stage, this method improved the temperature profile in the reactor, increased the HHV by more than 25%, and reduced tar by more than 1000 mg/Nm³. However, it was reported that the secondary flame in pyrolysis zone was unstable and had the tendency to move down to merge with the flame in the combustion zone. This made the control of the required flame position more difficult especially when a relatively wet feedstock is used (Jarungthammachote, 2008).

To further improve gas quality and flame location stability at the pyrolysis zone, an innovative two-stage approach was developed, designed and presented in this study. The approach is, instead of supplying only air at the pyrolysis zone, air is premixed with bypassed producer gas as shown in Fig. 1. This premixed gas is burned at the pyrolysis zone and it is expected that this approach can create higher temperature profile and better stability of the flame location. The ultimate objective of this two-stage approach is to improve producer gas quality in terms of higher HHV and lower tar content for ICE application. The improvement of biomass conversion efficiency in terms of thermal efficiency is also a target.

2.2. Gas qualities and thermodynamic analysis

The gas quality normally is presented in terms of HHV, tar content, and total combustible gas percentage in the producer gas. The total combustible gas percentage can be evaluated as follows:

\[
GAS_{comb} = \frac{Y_{CO} + Y_{CO_2} + Y_{CH_4} + Y_{H_2}}{C_2} \times 100\%
\]

(1)

The HHV of producer gas is dependent on the percentage quantities of CO, CH₄ and H₂ in producer gas and it can be calculated from the equation:

\[
HHV_g = Y_{CO}HHV_{CO} + Y_{CH_4}HHV_{CH_4} + Y_{H_2}HHV_{H_2}
\]

(2)

where \( Y \) is the mole fraction of each gas species that can be obtained from experiment measurements and the heating value of each gas species is presented in the Table 1 (Reed and Das, 1988).

Tar content in producer gas can be measured using a technique of Brandt et al. (2000) as shown in Fig. 1 (tar sampling set). In this technique, the producer gas will be allowed to flow through a condenser and the residue tar in the liquid condensate will be collected in a beaker per 1 m³ of the producer gas that passed. The weight of tar can then be measured after the liquid in beaker is properly dried in a certain time (Brandt et al., 2000). The tar content can be calculated using the equation:
Tar content = \frac{m_{\text{tar}}}{V_{\text{sampling gas}}}

(3)

where \( m_{\text{tar}} \) is a weight of tar and \( V_{\text{sampling gas}} \) is a corresponding volume of sampling gas during tar is collected in the tar container.

The thermodynamic analysis is applied to evaluate the thermal capacity and thermal efficiency of generated gas. The thermal capacity means the available heat per unit time that the producer gas contain which can then be used for any thermal application purpose. The thermal capacity can be evaluated when gas leaving temperature, gas percentage of each species and gas flow rate are known. These parameters are obtained from the experiment data and the following equation is applied to calculate the thermal capacity:

\[ H_{\text{cap, g}} = m_g (HHV_g + h_g) \]

(4)

here, \( m_g \) refers to the mass flow rate of gas in kg/s, while \( h_g \) is the enthalpy of gas in kJ/kg.

The conversion thermal efficiency is the quantity of heat obtained after the gasification process against the heat input. It is the ratio of useful heat of the generated gas and total heat input of feedstock and air supply. It can be calculated from:

\[ \eta_{\text{th}} = \frac{\text{heat}_{\text{out}}}{\text{heat}_{\text{in}}} = \frac{m_g (HHV_g + h_g)}{m_f (HHV_f + h_f) + m_a h_a} \]

(5)

The specific enthalpy \( (h) \) for each corresponding parameters are calculated based on the temperature and pressure of 25 °C and 1 atm (NTP), respectively. The mass flow rate of gas \( (m_g) \) can be estimated by applying the mass balance of \( N_2 \) in and out of reaction. However, the \( N_2 \) content in the ash and the other form of \( N_2 \) in the producer gas are very low (Jarungthammachote, 2008) and are treated as negligible. So, the \( N_2 \) mass balance equation is applied as follow:

\[ m_g y_{N_2, g} = m_f y_{N_2, f} + m_a y_{N_2, a} \]

(6)

The mass fraction of \( N_2 (y_{N_2}) \) in the feedstock can be obtained from the ultimate analysis on a sample of the feedstock, which for this work is the eucalyptus wood. The ultimate analysis was done with ThermoFinnigan (FlashEA™ 1112) to find the chemical composition percentage weight of C, H, O, N and S which are

Table 1

<table>
<thead>
<tr>
<th>Gas species</th>
<th>Higher heating value (MJ/Nm³)</th>
<th>Lower heating value (MJ/Nm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>13.1</td>
<td>13.1</td>
</tr>
<tr>
<td>CH₄</td>
<td>41.2</td>
<td>37.1</td>
</tr>
<tr>
<td>H₂</td>
<td>13.2</td>
<td>11.2</td>
</tr>
</tbody>
</table>

Source: Reed and Das (1988).

Fig. 1. Overall schematic diagram of the experiment apparatus and instrument set-up.
Kumar, 2009). The N2 mass fraction in the producer gas can then be calculated by mass balance of the producer gas as follow:

\[ y_{\text{N2}} = 1 - (y_{\text{CO}_2} + y_{\text{CO}} + y_{\text{CH}_4} + y_{\text{N2}}) \]  

(7)

The mass fraction of each gas species \((y_{\text{CO}_2}, y_{\text{CO}}, y_{\text{CH}_4}, y_{\text{N2}})\) in the producer gas can be obtained from the experiment measurements.

2.3. Experimental apparatus and measurement system

The experiment apparatus and measurement system is illustrated in Fig. 1. The mechanical apparatus consist of the gasification reactor (gasifier), cyclone, suction blower, piping and its associated devices such as fittings and valves. The data gathering system consisted of several measuring instruments, data acquisition (DAQ) device, communication devices and the computer. The installed measuring instruments are composed of air flow meter (rotameter), gas flow transmitter, level transmitter, gas flow counter and temperature sensor (type J thermocouple).

The gasifier reactor is constructed from steel. It is cylindrical in shape with 25 cm diameter and 100 cm height. The top of the reactor is the feedstock hopper (conical shape) which has top diameter of 50 and 70 cm height. The location of pyrolysis nozzle, combustion nozzle and gas exit nozzle along the height of reactor are 40, 30 and 10 cm from the bottom, respectively. The inner side of the reactor is insulated with a 1-inch thick refractory cement \((1200 \text{ °C grade})\).

As shown in Fig. 1, the air supply rate at combustion and pyrolysis nozzles were measured by rotameters 1 and 2, respectively. Eight thermocouple sensors (type-J) were installed to measure the temperature profile along the height of reactor. Thermocouple 1 \((T_1)\) was installed at gas exit position, \(T_3\) was at the combustion and \(T_5\) was at the pyrolysis. \(T_4\) was installed between \(T_3\) and \(T_5\) and finally \(T_6, T_7, T_8\) were installed at the upper level of the reactor, with 10 cm gaps from each other as shown in Fig. 1. A gas flow transmitter \((F1)\) was used to control the quantity of the bypassed gas required to mix with air at stoichiometric ratio. The premixed air/gas was supplied into the reactor through the pyrolysis nozzle. The percentages of gas components \((\text{CO}, \text{CO}_2, \text{CH}_4\), and \(\text{H}_2)\) in the producer gas were measured by an online gas analyser \((\text{NGA-2000, Fisher-Rosemount})\). The level transmitter \((L1)\) was also installed to monitor the feedstock feed rate. The gas was sampled by a tar sampling set to evaluate the tar content in the producer gas as also shown in Fig. 1. The tar sampling set consist of condenser tower, tar container (beaker), gas filter, gas flow counter and suction pump. The cooled water is supplied at bottom and exits at the top of condenser tower. The counter flow heat exchange between sampled gas (inner side) and cooling water (outer side) can lower down the gas temperature down to below 50 °C. Thus, the tar in the gas can be condensed and collected in the beaker. The volume of the gas is metered by a gas flow counter. One sampling is stopped when 1 m³ of the gas has already passed through the condenser. A new beaker is then replaced to start another sampling. The technique described by Brandt was applied to obtain the weight of tar in the beaker \((\text{Brandt et al., 2000})\).

The measuring instruments for the temperature, gas flow rate and feedstock level described above were connected to DAQ \((\text{HiLogger-1775, Hioki})\). The digital data from the DAQ and the gas percentage data from the gas analyser were then transmitted to the computer. This set-up allows data to be recorded instantly and perform some calculations automatically. Real time display of the measured values can also be seen in this set-up. The screen interface of human machine interface (HMI) as shown in Fig. 1 is programmed by LabView 6.0i. The data presented on the screen are in forms of graph, table, and in several styles of virtual gauge.

The measurement uncertainty of the experiment is also presented in this work and was considered based on systematic error and random error \((\text{Figliola and Beasley, 1995; ISO/IEC 17025, 2005})\). The random error was directly evaluated from the experimental data while the instrument's accuracy declared by manufacturer was treated as systematic error \((\text{Figliola and Beasley, 1995})\). The summary for each instrument's accuracy is shown in Table 2.

2.4. Experimental approach

The feedstock for this experiment is eucalyptus wood cut into 2 cm cubes approximately and has a bulk density of around 285 kg/m³. The wood cubes are loaded into the reactor at the feedstock hopper. The three gasification approaches namely: single-stage air supply, two-stage air and air supply (two-stage AA), and innovative two-stage air and premixed air/gas supply (two-stage AG) were studied in the same reactor. For the single-stage, air was supplied only at the combustion nozzles and valves V1 and V2 as shown in Fig. 1 were closed. For the two-stage approach, air was supplied at the combustion and pyrolysis nozzles and V1 was closed. In the innovative two-stage approach, air was supplied at combustion nozzles while the premixed air and bypass gas was supplied at the pyrolysis nozzles. The air supply rate was controlled by observing the flow rate at rotameters 1 and 2 to accordingly adjust CV1 and CV2. The controlled parameter in all three approaches was the air supply rate which was set at the same quantity. Its effect on the gas quality was analysed.

2.5. Experimental uncertainty

The uncertainty of each measured parameter of these experiments was evaluated by applying the standard uncertainty evaluations as in ISO/IEC 17025 (2005). The systematic error uncertainty \((u_{\text{s}})\) can be estimated by instrument uncertainty \((u_i)\) which can be taken from the value of the instrument's accuracy \((\text{Figliola and Beasley, 1995})\). These are shown in Table 2. The random error uncertainty \((u_r)\) can be evaluated directly from the measured data from the experiments. The standard deviation \((\text{SD})\) of each measured parameter is calculated based on the number of recorded data of more than 10 data. Then, \(t\)-distribution with \(SD\) was used to calculate the \(u_r\) and this evaluation was on 95% level of confidence. This means that at with 95% level confidence, the true value of the quantity being measured is expected to be between measured value ± the uncertainty value \((\text{APLAC, 2009})\). The uncertainty propagation analysis was also applied in the case of output parameter obtained from the calculation of multiple measured parameters \((\text{Chinsuwon, 2008})\). The total uncertainty \((u_t)\) can be calculated by \(\sqrt{u^2_r + u^2_i}\) and the result of temperature, total combustible gas percentage, tar content,
thermal efficiency, thermal capacity and HHV were $\pm 8.4 \, ^\circ C$, 1.1%, 7.8%, 7.4%, 4.3% and 4.1%, respectively.

3. Results and discussion

The temperature profile along the reactor height for the innovative two-stage air and premixed air and gas supply approach (two-stage AG approach) is presented in Fig. 2a. For this case, 70 LPM of air is supplied through the combustion nozzles and 70 LPM of premixed air/gas is supplied through the pyrolysis nozzles. From 20 to 40 cm above the combustion nozzles, the temperature was monitored to be around 40 $^\circ C$ and did not significantly change. However, the temperature increased significantly from 42 (at 10 cm above the pyrolysis nozzles) to 525 $^\circ C$ (at the pyrolysis nozzles). The temperature reached a maximum of around 800 $^\circ C$ at the combustion nozzle. After the combustion zone, the temperature gradually reduced due to heat transfer and gasification reactions. Gas exit temperature was around 405 $^\circ C$. It can be obviously observed in Fig. 2b that the temperature in the pyrolysis nozzle improved from 65 (in a single-stage approach) to 525 $^\circ C$ when two-stage AG approach is used. On the other hand, comparing the pyrolysis temperatures of two-stage AA approach against two-stage AG approach will give a temperature difference of 205 $^\circ C$ (from 320 to 525 $^\circ C$). As seen in Fig. 2b, the two-stage AG has a wider high temperature zone than the two-stage AA and single-stage approaches. Since the premixed gas can be burned itself and its flaming ability is independent from the feedstock, the temperature and flame are more stable. On the other hand, in a conventional two-stage AA method, only air is supplied into the reactor on the pyrolysis zone. Since air is the combustion agent and is supplied to help burn feedstock in the pyrolysis zone, the degree of burning in a conventional two-stage method would highly depend on the degree of mixing of the air and feedstock. Feedstock properties, for example, moisture would be crucial to this process. High moisture feedstock is more difficult to burn than drier feedstock and it affects the temperature on the pyrolysis zone. In the innovative approach, reactions take place under higher temperature for a longer distance. Therefore, the gases obtained from the two-stage AG approach had a higher quality in terms of high heating value (HHV) than from the others approaches. Furthermore, the energy utilization of two-stage AG was also observed to improve as compared to the other two approaches. Graphically, this observation can be indicated by the bigger area beneath the temperature profile of two-stage AG as compared to the other two. In this case, the thermal efficiency of an innovative two-stage approach also improved.

Comparison of the qualities of the producer gas from the three approaches is shown in Fig. 3. The tar content and total combustible gas percentage comparison between three approaches based on air supply of 160 LPM for the single-stage, 80 LPM at combustion nozzles and 80 LPM at pyrolysis nozzles for the two-stage AA, and 80 LPM at combustion nozzles and premixed air and gas 80 LPM at pyrolysis nozzles for the two-stage AG. The total combustible gas (CO, CH4 and H2) were 28.2%, 35.5% and 43.9% (single-stage, two-stage AA and two-stage AG, respectively). The output with higher useful combustible gas would obviously result to higher HHV. The HHV of the producer gas from the two-stage AG was improved by as much as 6.47 MJ/Nm3, while the two-stage AA and single stage can only reach HHV of 5.45 and 4.57 MJ/Nm3, respectively. Table 3 shows H2 percentage in the two-stage AG approach increased much with a value of more than 20%, which can
be attributed to water–gas shift reaction occurring well at higher temperature (Guo et al., 2009). As for the tar content, it was observed that the two-stage AA approach can reduce tar from 1270 (single-stage) to 114.4 mg/Nm³, while two-stage AG reduced tar to as low as 43.2 mg/Nm³ as shown in Fig. 3. The tar was reduced very well because of the high temperature of around 725–954 °C created in the two-stage AG as tar can be cracked well at higher temperatures (Li et al., 2009; Devi et al., 2003). In this approach, tar is under higher temperature in a longer residual time as compared to the other two and thus in this condition tar cracking can increase thermal efficiency as seen in Eq. (5).

The experiment result also indicated that the gas thermal capacity obtained from the single-stage was around 19.5 kW, while two-stage AG was around 22.0 kW and two-stage AG was around 27.5 kW. The two-stage AG approach increased the thermal capacity by more than 25% and 40% compared to two-stage AA and single-stage approaches, respectively. This improvement can be attributed to the higher temperature created by the two-stage AG approach. Higher temperature results in increased thermal efficiency (Guo et al., 2009). Since gas HHV, gas temperature and also gas generation rate were improved, it follows that gas capacity and efficiency were also improved because these parameters are directly affected by such improvements. The thermal efficiency also elevated from below 60% (single-stage) and 64.2% (two-stage AA) to 73.5% (two-stage AG). The innovative two-stage approach can increase thermal efficiency by around 10% compared with original two-stage AA.

The varying equivalence ratio (φ) has a direct impact to the HHV (Kumar et al., 2010) as plotted in Fig. 4. This plot shows that the optimum operation for single-stage approach takes place at φ range of 0.40–0.45. This corresponded well with φ value of single-stage gasifier (Zainal et al., 2002; Sharma, 2009) which normally operates on the range 0.35–0.60. The two-stage AA has an optimum φ range of 0.33–0.41 which also agree well with several previous works (Bui, 1996; Jarungthammachote, 2008). On the other hand, the two-stage AG can operate well on lower φ range of below 0.3. It means that the air supply for two-stage AG can be reduced by more than 10%. Air supply quantity is a factor that can increase thermal efficiency as seen in Eq. (5).

4. Conclusion

An innovative method of two-stage AG downdraft gasification was developed. This method by thermal utilization concept can improve high temperature zone in the reactor and results in higher producer gas qualities as compared to another two approaches. HHV and tar improved up to 6.5 MJ/Nm³ and down to 43.2 mg/Nm³, respectively. Therefore, this method can lower tar content sufficiently to feed the gas directly to internal combustion engine. The gas efficiency and capacity were also improved around 15% and 40% respectively when compared to a single-stage gasifier. This new method can operate well even with φ less than 0.3.

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References

APLAC (Asia Pacific Laboratory Accreditation Cooperation), 2009. General information on uncertainty of measurement. APLAC TC 010, Issue 1, February 2009.


Table 3

<table>
<thead>
<tr>
<th>Gasification approach</th>
<th>Air or premixed gas supply at pyrolysis (l pm)</th>
<th>Air supply at combustion (l pm)</th>
<th>Temperature at pyrolysis (°C)</th>
<th>Temperature at combustion (°C)</th>
<th>%CO</th>
<th>%H₂</th>
<th>%CH₄</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS</td>
<td>-</td>
<td>160</td>
<td>58</td>
<td>773</td>
<td>14.3</td>
<td>11.1</td>
<td>2.9</td>
</tr>
<tr>
<td>TS AA</td>
<td>80</td>
<td>80</td>
<td>423</td>
<td>842</td>
<td>17.1</td>
<td>15.7</td>
<td>2.7</td>
</tr>
<tr>
<td>TS AG</td>
<td>80</td>
<td>80</td>
<td>725</td>
<td>954</td>
<td>20.2</td>
<td>20.9</td>
<td>2.8</td>
</tr>
</tbody>
</table>

SS: Single-stage air supply.
TS AA: Two-stage air and air supply.
TS AG: Two-stage air and premixed air/gas supply.

Fig. 4. Comparison of the three approaches in terms of the effect different equivalent ratios (φ) to the HHV.