Updraft fixed bed gasification of mesquite and juniper wood samples

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\section*{A B S T R A C T}

Biomass gasification is being considered as one of the most promising technologies for converting biomass into gaseous fuel. Here we present results of gasification, using an adiabatic bed gasifier with air as gasification medium, of mesquite (\textit{Prosopis glandulosa}) and redberry juniper (\textit{Juniperus pinchotii}), two woody species that dominate uncultivated lands in the Southern Great Plains, U.S.A., that may have potential for bioenergy utilization. The effects of equivalence ratio (ER), particle size, and moisture content on the temperature profile, gas composition (CO, CO\textsubscript{2}, H\textsubscript{2}, N\textsubscript{2}, CH\textsubscript{4}, and C\textsubscript{2}H\textsubscript{6}), and higher heating value (HHV) were investigated. As ER decreased from 4.2 to 2.7, the mole composition of the end product gas for mesquite contained: 13\textendash{}21\% CO, 1.6\textendash{}3\% H\textsubscript{2}, 1\textendash{}1.5\% CH\textsubscript{4}, 0.4\textendash{}0.6\% C\textsubscript{2}H\textsubscript{6}, 60\textendash{}64\% N\textsubscript{2}, 11\textendash{}25\% CO\textsubscript{2}, and 1\textendash{}2\% O\textsubscript{2}. The mole composition of the end product gas for juniper consisted of 21\textendash{}25\% CO, 2.5\textendash{}3.5\% H\textsubscript{2}, 1.5\textendash{}1.8\% CH\textsubscript{4}, 0.3\textendash{}0.5\% C\textsubscript{2}H\textsubscript{6}, 58\textendash{}61\% N\textsubscript{2}, 9\textendash{}12\% CO\textsubscript{2}, and 1\textendash{}2\% O\textsubscript{2}. The H\textsubscript{2} and CO mole percentages decreased with increasing ER while the CO\textsubscript{2} and N\textsubscript{2} mole percentage increased. After removing N\textsubscript{2}, the HHV of the end-product gas for mesquite and juniper reached 26 and 27.5\% of natural gas HHV, respectively, when ER = 2.7.

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\section*{1. Introduction}

In order to reduce greenhouse gas (GHG) emissions, different sources of biomass, such as forests and agriculture residues, have been widely studied as an alternative energy to replace fossil-fuels. These biomass sources which have different moisture contents, usually less than 50\%, can be either pyrolyzed in absence of oxygen to produce liquid and gaseous fuels or gasified with air, oxygen, and/or steam to produce syngas [1\textendash{}3]. Syngas (mainly H\textsubscript{2} and CO) and tar (liquid product) can be used as fuel, fertilizers or other chemical products [1]. Synthetic or substitute natural gas and hydrogen can also be obtained from syngas. The emerging biomass gasification energy technologies are expected to play an important role in the future development of energy systems.

Due to limitations of land area for growing biomass for large biofuel conversion facilities in the upper Midwest and the high cost of feedstock transportation in regions that have lower biomass density, it would be beneficial to develop a small scale, less expensive, and localized conversion facilities that require less feedstock and have lower feedstock transportation costs. Woody species (brush) growing on semi-arid non-cultivated lands (rangelands), such as mesquite (\textit{Prosopis glandulosa}) and juniper (\textit{Juniperus spp.}), may have potential as bioenergy feedstock. These species occur on over 20 million ha in Texas alone and can achieve standing biomass of 50 dry metric tons ha\textsuperscript{\textendash}1 [4]. They are perceived as noxious plants that are detrimental to rangeland ecosystems and their removal and use as a bioenergy feedstock would result in improvements in ecosystem quality as well as services from these lands such as increased income from livestock grazing [5]. These species may be ideal candidates to produce syngas and bio-oil in small scale gasification units that can be located near the fuel source to reduce feedstock transport costs.

Biomass gasification can be classified depending on the gasification medium. The main gasification agents are air, steam, air\textendash{}steam mixture, or oxygen\textendash{}steam mixture. Natural gas (NG) which is mostly CH\textsubscript{4} has a volumetric HHV of 37,000 kJ/Nm\textsuperscript{3}, where N stands for normal temperature (20 \degree C) and pressure (101 kPa). When air is used as the medium, the producer gas has low heating value (around 4000\textendash{}7000 kJ/Nm\textsuperscript{3}, 11\%\textendash{}19\% NG) due to the presence of a significant amount of N\textsubscript{2} (50\%\textendash{}60\%) [6]. On the other hand, the use of pure oxygen results in higher quality gas (10,000\textendash{}18,000 kJ/Nm\textsuperscript{3}, 27\%\textendash{}49\% of NG), however, pure oxygen gasification is expensive and requires a complicated reactor [6]. In addition to air and oxygen, steam is usually mixed with air to promote the steam-reforming reaction in order to produces H\textsubscript{2}\textendash{}rich gas mixtures.

Abbreviations: HHV, higher heating value; GHG, greenhouse gas; NG, natural gas; LHV, lower heating value; ER, equivalence ratio; VC, volatile matter; FC, fixed carbon; FR, feedlot biomass; DA, daily biomass; DAF, dry ash free; N, nitrogen.

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In directly heated gasification (with air or pure O₂), the high local temperature near the oxidation zone create problems in bed agglomeration and clogging. Steam minimizes the formation of ash agglomeration by lowering the local reactor temperature since steam carbon reaction is endothermic. The production of the steam from water requires an external heat input which can be provided by using sensible heat of producer gas.

In pure steam gasification called indirectly heated gasification, external heat input is provided for promoting endothermic steam carbon reaction. An advantage is that the heat value of producer gas is enhanced to 15,000 kJ/Nm³ (40% NG) due to the absence of N₂ [7].

Lv et al. [8,9] studied air-stream gasification of pine sawdust in a fluidized bed and found that the highest hydrogen yield reached 71 g/kg biomass (wet basis) at a reactor temperature of 900 °C, ER of 0.22 and steam to biomass of 2.7. Also, the gas LHV ranged between 6700 and 9140 kJ/Nm³ when ER varied from 0.19 to 0.27 and steam to biomass ratio varied from 0 to 4.

Sommas et al. [10] have carried out experiments of rubber wood chip gasification in a 100 kW bubbling fluidized bed gasifier to investigate the equivalence ratio (ER) on the yield and properties of synthesis gas. They found that increasing the ER resulted in a decrease of syngas product and lower product gas heating value. The producer gas had low heating value (9.41 MJ/Nm³) at 950 °C and with ER of 0.42.

Dogru et al. [11] used hazelnut shells as feedstock to investigate the air gasification gas quality in a down draft fixed-bed gasifier. It was reported the major combustible product were H₂, CO, CH₄, C₂H₆, C₂H₂ and the total percentages of these gases were approximately 24.8–36.2% of the total gas when air-to-fuel ranging from 1.38 to 1.64. Two different moisture content (8.3% and 16.2%) were observed when Yang wood was gasified in a two-stage gasifier by Bhattacharya [12]. He reported that higher moisture resulted in an increase of CO₂ and H₂ while decrease of the CO concentration in the producer gas. Blasi et al. [13] carried out beechwood biomass gasification experiments at a laboratory scale updraft fixed-bed using air as media. The beechwood feedstock content with 5–6% moisture was cut into size of 3–5 mm. It was found that the produce gas composition (vol%) was 28.6–30% CO, 7–5.5% CO₂, 7–7% H₂, 18–1.8% CH₄, and 55.6–55.7% N₂ when the air-to-fuel ratio varied from 1.267 to 1.055.

Fuel moisture content is another important parameter which affects the temperature profile in the gasifier. Typically, freshly cut wood biomass usually contains 30–60% moisture. For mesquite biomass, 47.2% moisture was found in the first 24 h after harvest [14,15].

Based on current literature review, there is no available data regarding gasification of mesquite and juniper. Our objective was to determine the effects of ER and particle size, as well as moisture content on the temperature profile, gas composition, and higher heating value of mesquite and juniper biomass samples and obtain gasification performance data for mesquite and juniper using a small scale updraft gasifier.

2. Methods

2.1. Mesquite and juniper harvest

Mesquite and juniper samples were harvested from native rangeland areas in north central Texas near Vernon (annual precipitation 665 mm). Trees were 3–4 m tall and had multiple basal stems. Basal stem diameter ranged from 5 to 15 cm. Tree ring counts indicated that aboveground portions of these trees were 15–35 years old. Tree branches (5–10 cm diameter) were chain sawed down and then passed through a Vermeer wood chipper. Leaf and small twigs were removed from branches before chipping. Chipped material was then passed through a motorized sieve system to separate into different particle sizes. No attempt was made to separate heartwood, sapwood and bark in either species. At the time of harvest, fresh wood moisture content was between 20 and 35% [Ansley, unpublished data]. During the chipping and sieving process, wood moisture content declined to between 10 and 20%. Wood chips were subsequently stored in cellulose bags and transferred to College Station for gasification trials.

2.2. Proximate and ultimate analysis of fuel

Proximate and ultimate analyses of each solid fuel type were conducted. Proximate analysis provides the composition of a material in terms of moisture, volatile matter (VM), fixed carbon (FC), mineral matter and ash, as well as heating value [16]. Ultimate analysis provided elemental-mass-based compositions including C, H, N, O, S, moisture and mineral matter.

2.3. Gasification facility

Gasification behavior was conducted using a small scale (10 kW) batch type fixed-bed gasifier (Fig. 1). The experimental facility is the
same as the one used by Gordillo [2,3] for cattle manure feedlot biomass (FB) gasification. The gasifier (72 cm tall) is divided into four sections which are joined by using ring type flanges of 12.7 × 35.6 × 50.8 mm. The gasifier is constructed of alumina refractory tube. The inner and outer diameters of tube are 13.9 cm and 24.5 cm, respectively. The tube is surrounded by 4.45 cm of insulating blanket in order to minimize heat losses. The layer is then surrounded by a steel outer tube with an inner diameter of 34.3 cm. An ash disposal system was installed to maintain quasi-steady operation [3]. A conical gyratory cast iron grate drilled with large number holes with diameter of 6.4 mm was coupled to a pneumatic vibrator of variable frequency that vibrates the grate in order to dispose the ash continuously from the bed. Table 2 gives a comparison of the ash weight of different fuels for 30 min accumulation after the experiment reached a steady state at a fuel flow rate of 1 kg/h. It can be observed that both mesquite and juniper ash weight is significantly lower than dairy biomass (DB) and FB, as well as chicken litter. Thus, the ash bed height in the reactor chamber was correspondingly much lower than that of animal biomass.

Because mesquite and juniper have low ash content (<2%), the vibrator operated for <1 min to dispose the ash from the plenum before it reached steady state. Afterward, the grate was vibrated over a short period of 5–10 s to dispose of the ash, maintain a constant bed height, and obtain a steady temperature profile within the reactor. Air was used as the source of oxygen for gasification. The desired ER can be reached by varying the air flow rate. As fuel gasified in the reactor chamber, negative pressure was maintained inside the chamber by using a vacuum fan to exhaust the gases from the gasifier. The gas was first passed over water-gas heat exchanger which is installed on the top of the gasifier in order to lower the gas temperature and then exhausted to the ambient. It took approximately 60 min for experiments to reach steady state, this being when $T_{\text{peak}}$ varied less than 10 °C over the 15 min period and the location of the $T_{\text{peak}}$ remained in the same place.

### 2.4. Gas composition measurement

A mass spectrometer was used to measure the composition of the product gases. The gas was first passed through a condenser to remove tar and condensable vapors, and then passed a series of filters to capture associated particles. Typically, tar produced by the updraft gasifier is in the 100 g/Nm³ range. Detail experiments are in progress to determine tar content as a function of ER and moisture content with and without catalyst and the results will be reported elsewhere. After steady state operation was achieved a small amount of clean and cooled gas was supplied into the gas analyzer. The gas analyzer was pre-calibrated using a standard mixture of gas (N₂, CO, CO₂, H₂, C₂H₆, and CH₄) and the inert gas (Helium) every three days in order to improve its accuracy. The gas compositions were recorded every 10 s when $T_{\text{peak}}$ fluctuation was less than 10 °C by the gas analyzer when gasifier reached steady state.

### 2.5. Particle size

Wood samples were screened to a suitable size for the gasification experiments. In order to better understand the effect of the
particle size on the gasification behavior, two sizes of mesquite and juniper samples (2–4 and 4–6 mm) were selected (Figs. 3 and 4). In order to test the sample density and their compactness, both samples were filled in separate plastic cups until they reached a volume of 600 ml. The mass of both samples was measured and recorded before shaking. The 4–6 mm sample had a mass of 167 g and the 2–4 mm sample has a mass of 179 g, respectively. The larger size particles had lower density (278.3 kg/m$^3$) compared to small size particles (298.3 kg/m$^3$) as shown in the Table 3. Afterward, both containers were covered with a flat alumina plate and shaken for 70 s and the volumes of the both samples were measured again. For the large size particles the volume reduced from 600 ml to 520 ml while the small size particles reduced slightly from 600 ml to 580 ml. The difference between volume changes was due to the spacing between the particles. The larger particle size had more spacing between particles and hence bulk density is lower.

### Results and discussion

#### 3.1. Proximate and ultimate analysis of fuel

On a dry ash free (DAF) basis the higher heating values (HHV) of mesquite and juniper are 20128 kJ/kg (8653 BTU/lb) and 20584 kJ/kg (8849 BTU/lb), respectively, as received (Table 1).

Ulich et al. [14] performed the ultimate analysis of mesquite with moisture content of 19.0%. The results based upon weight percent were as follows: carbon 53.49%, oxygen 36.33%, hydrogen 6.45%, nitrogen (N) 1.065%, and sulfur 0.086%.

<table>
<thead>
<tr>
<th>Juniper sample</th>
<th>2–4 mm</th>
<th>4–6 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume (ml)</td>
<td>600</td>
<td>600</td>
</tr>
<tr>
<td>Mass (g)</td>
<td>179</td>
<td>167</td>
</tr>
<tr>
<td>Density (kg/m$^3$)</td>
<td>298.3</td>
<td>278.3</td>
</tr>
<tr>
<td>Volume (ml) (after shaking)</td>
<td>520</td>
<td>580</td>
</tr>
</tbody>
</table>

Table 3

The empirical chemical formulas for the mesquite and juniper samples are CH$_{1.3582}$O$_{0.5779}$N$_{0.0122}$S$_{0.0003}$ and CH$_{1.3708}$O$_{0.5637}$N$_{0.0049}$S$_{0.0001}$, respectively. From these formulas it can be observed that juniper has a slightly lower O/C ratio than mesquite and as a result, its HHV was slightly higher. Mesquite and juniper are better quality fuel with higher HHV compared to cattle manure FB which has more than 14.5%–45% (depending on collection methods) ash content and low HHV (12,843 kJ/kg) [17]. The N in juniper is significantly lower compared to mesquite, thus juniper would be expected to release less NOx during combustion compared to mesquite. Mesquite is a legume that fixes its own N and would be expected to have higher N. Juniper is known to accumulate nutrients from grass areas in interstitial spaces between juniper plants [19], but this process did not increase wood N content over that of mesquite. Bituminous coal has approximately 30%–40% VM and lignite has approximately 40%–50% VM [20]. However, both mesquite and juniper have almost twice the VM of coal, but HHV of both is less
From the above information, under pure pyrolysis almost 80% of the DAF biomass of both mesquite and juniper is released as gases while coal can only release 40–50% as gas. Gas yield during gasification is typically higher for wood biomass compared to coal.

### 3.2. Temperature profile in the gasifier

All of the temperature profiles share the same trend: temperature increases first along the height of the gasifier, reaching a peak value at 3–6 cm above the grate (Fig. 5). After that, the temperature decreased gradually and dropped significantly when the distance is 22 cm above the bed height. The peak temperature \( T_{\text{peak}} \) occurred a few cm above the bottom of the gasifier since char oxidation occurred when there was an abundant supply of \( \text{O}_2 \). Above the combustion zone, the \( \text{O}_2 \) concentration decreased and most of the reactions that occurred in this zone were endothermic processes which decreased the temperature. Once air was used completely, the pyrolysis zone follows the reduction zone in which organic materials were chemically decomposed by heat in

**Table 4**  
Gasification temperature (°C) profile above the grate for juniper sample.

<table>
<thead>
<tr>
<th>Distance (cm)</th>
<th>2</th>
<th>4</th>
<th>7</th>
<th>10</th>
<th>13</th>
<th>20</th>
<th>24</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture (20.16%)</td>
<td>794</td>
<td>1014</td>
<td>936</td>
<td>721</td>
<td>630</td>
<td>297</td>
<td>196</td>
</tr>
<tr>
<td>Moisture (12.6%)</td>
<td>735</td>
<td>1094</td>
<td>865</td>
<td>782</td>
<td>701</td>
<td>351</td>
<td>261</td>
</tr>
</tbody>
</table>

**Table 5**  
Gas composition (dry basis) for different moisture juniper sample.

<table>
<thead>
<tr>
<th>Gas</th>
<th>CO2</th>
<th>CO</th>
<th>N2</th>
<th>H2</th>
<th>CH4</th>
<th>C2H6</th>
<th>O2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture (20.16%)</td>
<td>14.96</td>
<td>20.78</td>
<td>56.42</td>
<td>5.56</td>
<td>1.9</td>
<td>0.37</td>
<td>0</td>
</tr>
<tr>
<td>Moisture (12.6%)</td>
<td>9.8</td>
<td>27.4</td>
<td>54.1</td>
<td>5.3</td>
<td>1.9</td>
<td>0.4</td>
<td>0.8</td>
</tr>
</tbody>
</table>

**Table 6**  
HHV of the gas for juniper biomass (kJ/kg).

<table>
<thead>
<tr>
<th>Moisture</th>
<th>All gases included</th>
<th>( \text{N}_2 ) free</th>
</tr>
</thead>
<tbody>
<tr>
<td>20.16%</td>
<td>3379</td>
<td>7689</td>
</tr>
<tr>
<td>12.6%</td>
<td>4129</td>
<td>9266</td>
</tr>
</tbody>
</table>

**Table 7**  
HHV of the gas for juniper biomass (kJ/STPm³).

<table>
<thead>
<tr>
<th>Moisture</th>
<th>All gases included</th>
<th>( \text{N}_2 ) free</th>
</tr>
</thead>
<tbody>
<tr>
<td>20.16%</td>
<td>3928</td>
<td>8991</td>
</tr>
<tr>
<td>12.6%</td>
<td>4663</td>
<td>10,225</td>
</tr>
</tbody>
</table>

**Fig. 6.** Temperature profile for different size juniper at \( \text{ER} = 3.7 \).

**Fig. 7.** The effect of \( \text{ER} \) on gasification temperature profile of juniper (2–4 mm size) with moisture content 13.5%.

**Fig. 8.** The effect of \( \text{ER} \) on gasification temperature profile of mesquite (2–4 mm size) with moisture content 12.9%.

**Fig. 9.** The average temperature for mesquite and juniper in the gasifier vs \( \text{ER} \).
the absence of oxygen. The lowest temperature occurred in the drying zone in which the moisture in the fuel was removed by absorbing heat from the gases. Peak temperature in the combustion and reduction zones was slightly higher for juniper than for mesquite.

3.3. Particle size effects

Particle size affected the degree to which air was drawn around the particles in the gasification process. The pressure in the gasifier was kept slightly negative compared to atmosphere and a smaller amount of air was exhausted without reacting with char from the gasifier. Generally, more air as sucked out from the larger particles due to large spacing between them. Fig. 6 gives the steady state gasification temperature profile for three different size juniper samples. The gasification temperature increased with the increase of particle size in the combustion zone. This conclusion was confirmed with the theoretical and experimental studies of wood chips in a fixed-bed reactor [21].

3.4. The effect of moisture content

The $T_{\text{peak}}$ varied with the moisture content, 1094 °C and 1014 °C for juniper samples with moisture content of 12.6% and 20.14%, respectively (Table 4). The juniper with lower moisture generated higher CO% and slightly lower H$_2$% (dry basis) in the end product gas (Table 5). This is because $T_{\text{peak}}$ decreased with an increase of moisture content due to more energy was consumed in the moisture vaporization process which resulted in higher CO$_2$ mole percentage. Equation (1) describes the water–gas equilibrium reaction:

$$\text{CO}_2 + \text{H}_2 \rightleftharpoons \text{CO} + \text{H}_2\text{O} \quad \Delta H = 41,140 \text{ kJ/kmol}$$  (1)

Consider the equilibrium constant in Equation (2):

$$K_w = \frac{[\text{CO}] \cdot [\text{H}_2\text{O}]}{[\text{CO}_2] \cdot [\text{H}_2]}$$  (2)

where [CO], [H$_2$O], [CO$_2$], and [H$_2$] are mole concentrations for each gas, $K_w$ is the equilibrium constant. When temperature decreases, the reaction equilibrium will move toward the left side of Equation (1). As a result, the H$_2$ content slightly increases while CO content decreases. Tables 6 and 7 give the HHV of the end product gas of juniper fuels with different moisture content. The gas HHV increased 13% (volume basis) when moisture decreased from 20.16% to 12.6% after removing the N$_2$.

3.5. Equivalence ratio effects

ER is a crucial parameter affecting gasification temperature and the composition of producer gas. It is defined as the fuel-to-air weight ratio used divided by the fuel-to-air weight ratio of stoichiometric combustion. Gasification temperature profiles of mesquite and juniper sample were measured under four different ER conditions: 2.7, 3.2, 3.7, and 4.2. It can be seen from the Figs. 7 and 8 that $T_{\text{peak}}$ increased with the decrease of ER. This was because a lower value of ER means more amount of oxygen supplied to the gasifier. A high air flow rate promoted the oxidation reaction which results in more heat release and temperature raise in the gasifier.

In order to better understand the effect of ER on the gasification temperature, fifth order polynomial equations were generated
Based on the temperature profiles. The average temperature ($T_{ave}$) was also calculated by using these equations. The average gasification temperature for mesquite and juniper sample decreased with the rise of the ER (Fig. 9). Juniper had a higher average temperature than mesquite at a fixed ER because of its higher HHV. For juniper, the average temperature was 782 °C when ER was 2.7 and dropped to 658 °C when ER increased to 4.2. Lowest $T_{ave}$ for mesquite occurred at ER 3.7 and did not decrease further at higher ER.

Increasing ER (lower $T_{ave}$) resulted in an increase in CO2 mole percentage, while CO and H2 mole percentage decreased (Figs. 10 and 11). These trends occurred because higher temperature shifts the equilibrium of the endothermic reaction (e.g., $CO_2 + H_2 \leftrightarrow CO + H_2O$) to the products and that of the exothermic reaction (e.g., $CO + H_2O \leftrightarrow CO_2 + H_2$) to the reactants. As a result, a series of biomass gasification endothermic and exothermic reactions could be used to explain the gasification mechanism [22]:

\[
C + H_2O \leftrightarrow CO + H_2 \quad \Delta H = 131,160 \text{ kJ/kmol} \quad (3)
\]
\[
CH_4 + H_2O \leftrightarrow CO + 3H_2 \quad \Delta H = 206,000 \text{ kJ/kmol} \quad (4)
\]
\[
C + CO_2 \leftrightarrow 2CO \quad \Delta H = 172,320 \text{ kJ/kmol} \quad (5)
\]
\[
C + O_2 \leftrightarrow CO_2 \quad \Delta H = -393,180 \text{ kJ/kmol} \quad (6)
\]
\[
CH_4 + 2H_2O \leftrightarrow CO_2+4H_2 \quad \Delta H = 165,000 \text{ kJ/kmol} \quad (7)
\]

Increasing the gasification temperature would result in equilibrium of reactions (3), (4), and (7) move forward to favor the formation of H2 direction. Also, the endothermic reaction (3), (4), and (5) would prevail over the reaction (8) and thus result in increase of CO concentration [22]. Additionally, equation (6) was favored at low temperature and thus more CO2 was generated [3]. The end product gas of juniper had a higher CO and H2 percentage and lower N2 and CO2 content compared to mesquite under same experiment conditions (Table 8). This difference was mainly due to the higher HHV of the juniper fuel that resulted in higher gasification temperature in favor of CO and H2.

### 3.6. Gas HHV

When gas is used as a fuel in internal combustion engines or other applications, the optimal gasification performance conditions are those that yield the highest HHV. In order to better understand the synthesis gas HHV, the concentration of each combustible gas species was converted to an N2 free basis to eliminate the dilution effect of N2. Figs. 12 and 13 give gas HHV of mesquite and juniper in kJ/kg and kJ/Nm3 units as a function of ER. The gas produced from juniper generally yielded higher HHV in both N2 and N2-free conditions.

As it is well known, CH4 is a high quality fuel which almost “mimics” natural gas with HHV 55,509 kJ/kg and is often used as reference for HHV. Fig. 14 provides a comparison of HHV for syngas and CH4. The dry gas can reach almost 11% of HHV of CH4 for juniper when ER is 2.7 when all the gas composition is included in the end product. Also, the HHV percentage decreased with the increase of ER for both mesquite and juniper. After removing the N2, the heating value of gas increased to 27% of CH4 HHV for juniper and 25.82% of CH4 HHV for mesquite when the ER is set to 2.7, respectively. Increasing ER resulted in a decline in the heating value percentage.

### 3.7. The gas yield from per kilogram biomass

Fig. 15 shows the gas yield from per kg biomass as a function of ER. The yield gas volume was calculated using the nitrogen tracer method [23]. Since N2 is inert gas and assuming no nitrogen comes out from the fuel during the gasification process, knowing the amount of N2 in the air supplied to the gasifier, the volume of the producer gas can be calculated from the N2 percentage in the gas. It was found that the gas yield decreased with the increase of ER due to less air being sent into the gasifier. The juniper fuel appears to
4. Conclusions

1. The peak temperatures during combustion of both mesquite and juniper samples were above 1000°C and occurred at a distance of about 3–6 cm above the grate in the gasifier. Gas mole percentage was very sensitive to $T_{\text{peak}}$, moisture content and ER.

2. High moisture content decreased $T_{\text{peak}}$ and lowered CO and H2 mole percentage in the final production gas, but large particle size increased $T_{\text{peak}}$ which would result in increasing the CO to a smaller extent.

3. When ER decreased from 4.2 to 2.7, the mole composition of the end product gas for mesquite contained $13–21\%$ CO, $1.6–3\%$ H2, $1–1.5\%$ CH4, $0.4–0.6\%$ C2H6, $60–64\%$ N2, $11–25\%$ CO2, and $1–2\%$ O2. The mole composition of the end product gas for juniper consisted of $21–25\%$ CO, $2.5–3.5\%$ H2, $1.5–1.8\%$ CH4, $0.3–0.5\%$ C2H6, $58–61\%$ N2, $9–12\%$ CO2, and $1–2\%$ O2. For both mesquite and juniper samples, increasing ER decreased the CO and H2 mole percentage and raised the CO2 and N2 mole percentage.

4. The HHV ranged from 3500 kJ/Nm3 to 3900 kJ/Nm3 for juniper and from 2400 kJ/SATPm3 to 3500 kJ/Nm3 for mesquite when ER increased from 2.7 to 4.4. And, producer gas was between 2.4 and 1.44 Nm3/kg biomass and 2.4–1.37 Nm3/kg biomass for juniper and mesquite, respectively, when ER increased from 2.7 to 4.4. If N2 was removed from the end-product gas, the HHV of mesquite and juniper samples can reach 26% and 28% of CH4 at ER = 2.7, respectively.

5. Based on carbon conversion efficiency and energy consumption required for grinding wood chips into smaller size, a solid wood particle size of 4–6 mm appeared to be the best option for the gasification experiment for both mesquite and juniper.

6. Both wood types generated high quality gas, but the juniper end product gas quality was greater than mesquite primarily due to lower N content and higher HHV under both N2 and N2-free conditions.

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References


