Updraft fixed bed gasification of mesquite and juniper wood samples

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ABSTRACT

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 (*Prosopis glandulosa*) and redberry juniper (*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_2, H_2, N_2, CH_4, and C_2H_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: 13–21% CO, 1.6–3% H_2, 1–1.5% CH_4, 0.4–0.6% C_2H_6, 60–64% N_2, 11–25% CO_2, and 1–2% O_2. The mole composition of the end product gas for juniper consisted of 21–25% CO, 2.5–3.5% H_2, 1.5–1.8% CH_4, 0.3–0.5% C_2H_6, 58–61% N_2, 9–12% CO_2, and 1–2% O_2. The H_2 and CO mole percentages decreased with increasing ER while the CO_2 and N_2 mole percentage increased. After removing N_2, the HHV of the end-product gas for mesquite and juniper reached 26 and 27.5% of natural gas HHV, respectively, when ER $\approx$ 2.7.

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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 [1–3]. Syngas (mainly H_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 bio-fuel 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 (*Prosopis glandulosa*) and juniper (*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^{-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–steam mixture, or oxygen–stream mixture. Natural gas (NG) which is mostly CH_4 has a volumetric HHV of 37,000 kJ/Nm^3, where N stands for normal temperature (20 °C) and pressure (101 kPa). When air is used as the medium, the producer gas has low heating value (around 4000–7000 kJ/Nm^3, 11%–19% NG) due to the presence of a significant amount of N_2 (50%–60%) [6]. On the other hand, the use of pure oxygen results in higher quality gas (10,000–18,000 kJ/Nm^3, 27%–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_2-rich gas mixtures.

In directly heated gasification (with air or pure O_2), the high local temperature near the oxidization 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/Nm^3 (40% NG) due to the absence of N_2 [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/Nm^3 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 product gas had low heating value (9.41 MJ/Nm^3) 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 H_2, CO, CH_4, C_2H_6, C_2H_2 and the total percentages of these gases were approximately 24.8–36.23% 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 CO_2 and H_2 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% CO_2, 7–7% H_2, 1.8–1.8% CH_4, and 55.6–55.7% N_2 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 30 and 45% [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
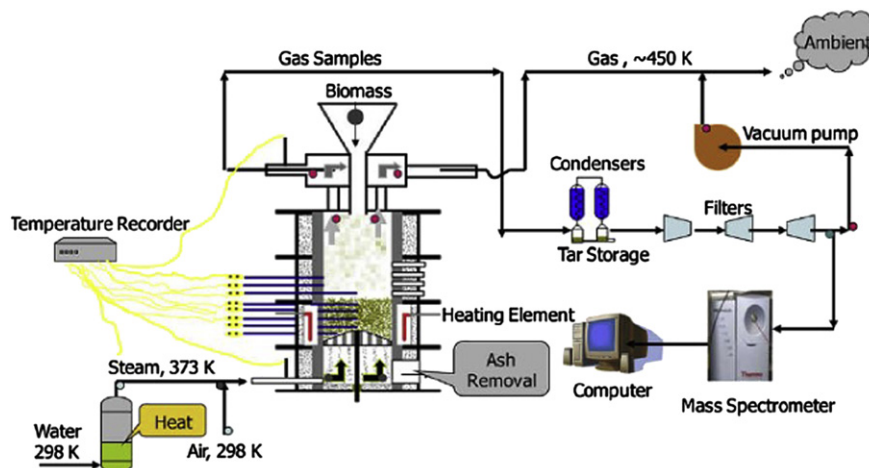

Fig. 1. Schematic of gasification facility. Adapted from [3].

Table 1
Mesquite and juniper proximate and ultimate analysis.

	Mesquite	Juniper
	as received	
Moisture	15.53	5.85
Ash	1.67	1.91
VM	66.09	77.99
FC	16.71	14.25
Carbon	43.60	49.27
Oxygen	33.57	37.00
Hydrogen	4.98	5.68
N	0.62	0.28
Sulfur	0.03	0.01
HHV (kJ/kg)	16,666	18,987
	Dry, ash free	
Moisture	0	0
Ash	0	0
VM	79.82	84.55
FC	20.18	15.45
Carbon	52.66	53.42
Oxygen	40.54	40.11
Hydrogen	6.01	6.16
N	0.75	0.30
Sulfur	0.04	0.01
HHV (kJ/kg)	20,128	20,584
Volatile HHV (kJ/kg)[a]	16,933	18,358
Chemical formula	$CH_{1.3582}O_{0.5779}N_{0.0122}S_{0.0003}$	$CH_{1.3708}O_{0.5637}N_{0.0049}S_{0.0001}$

[a] Estimated using the relation $HHV_{DAF} = FC_{DAF} * HV_{FC} + VM_{DAF} * HHV_{DAF}$ [16].

Fig. 2. Preheat grate and k type thermocouples along the height of the gasifier.

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. Fuel was fed at the top of the gasifier while air was supplied from the bottom. Eight K type thermocouples were located at 2 cm, 4 cm, 7 cm, 10 cm, 13 cm, 20 cm, 24 cm, and 28 cm along the gasifier axis to measure the temperature in the gasification chamber (Fig. 2).

At the beginning of the experiment, the empty bed was pre-heated to 600 °C using a propane torch. Later the torch was turned off and biomass samples were gradually added to the gasifier when the fuel bed height reached 22 cm above the grate. Afterward, the fuel port was closed and air was sent into this system at the desired 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_{peak} varied less than 10 °C over the 15 min period and the location of the T_{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 (N_2, CO, CO_2, H_2, C_2H_6, and CH_4) and the inert gas (Helium) every three days in order to improve its accuracy. The gas compositions were recorded every 10 s when T_{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

Table 2
Ash weight (as received) for different biomass in the down draft gasifier [17,18].

	Mesquite	Juniper	Low-ash dairy manure	High-ash dairy manure	Low-ash feedlot manure	High-ash feedlot manure	Chicken litter biomass
Ash (Mass %)	1.67	1.91	14.9	59.9	9.6	32.9	44
Ash weight (kg)	0.00835	0.00955	0.0745	0.2995	0.048	0.1645	0.22

Fig. 3. Juniper size 2–4 mm (left), 4–6 mm (middle) and 6–9.5 mm (right). The dark portions are due to the bark, the light portions are sapwood.

Fig. 4. Mesquite chips size 2–4 mm (left) and 4–6 mm (right). The dark portions are due to the bark, the light portions are sapwood.

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.

3. 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 3
The volume changes of different size juniper samples.

Juniper sample	2–4 mm	4–6 mm
Volume (ml)	600	600
Mass (g)	179	167
Density (kg/m^3)	298.3	278.3
Volume (ml) (after shaking)	520	580

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
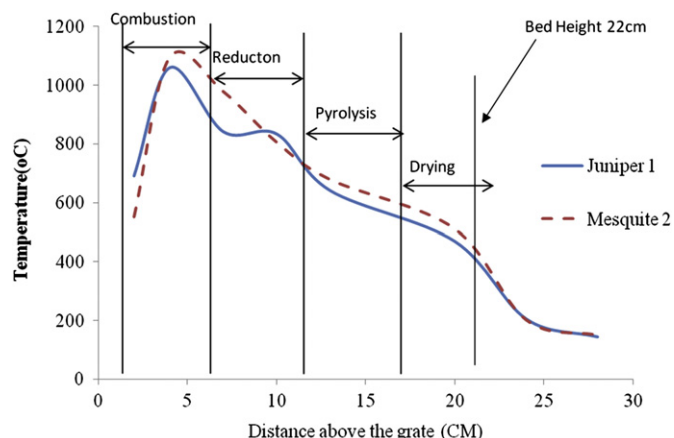

Fig. 5. Temperature profile of mesquite and juniper (2–4 mm sample size) at ER = 3.7.
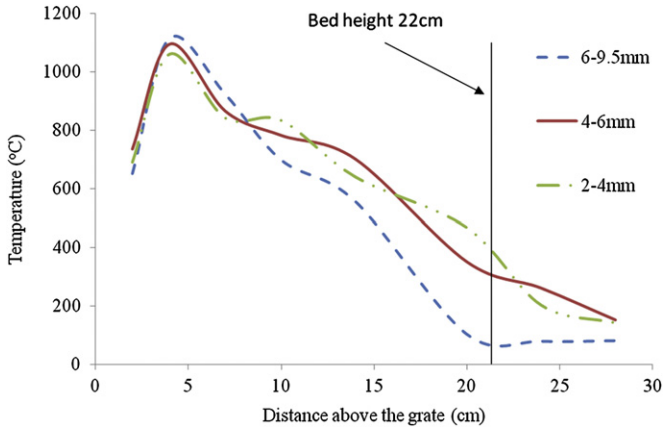
Fig. 6. Temperature profile for different size juniper at ER = 3.7.

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

Distance (cm)	2	4	7	10	13	20	24
Moisture (20.16%)	794	1014	936	721	630	297	196
Moisture (12.6%)	735	1094	865	782	701	351	261

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

Gas	CO_2	CO	N_2	H_2	CH_4	C_2H_6	O_2
Moisture (20.16%)	14.96	20.78	56.42	5.56	1.9	0.37	0
Moisture (12.6%)	9.8	27.4	54.3	5.3	1.9	0.4	0.8

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

Moisture	All gases included	N_2 free
20.16%	3379	7689
12.6%	4129	9266

Table 7
HHV of the gas for juniper biomass (kJ/SATPm^3).

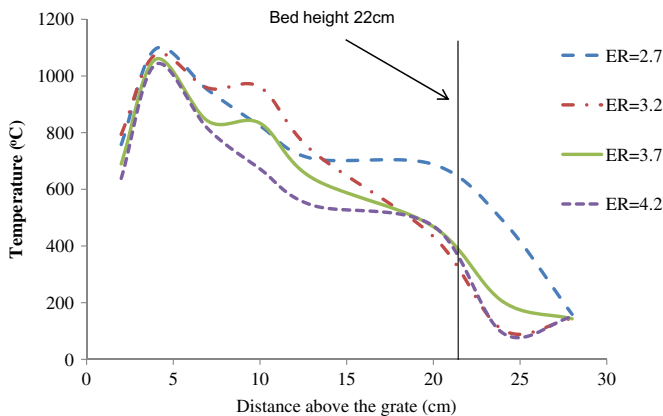| Moisture	All gases included	N_2 free
20.16%	3928	8991
12.6%	4663	10,225

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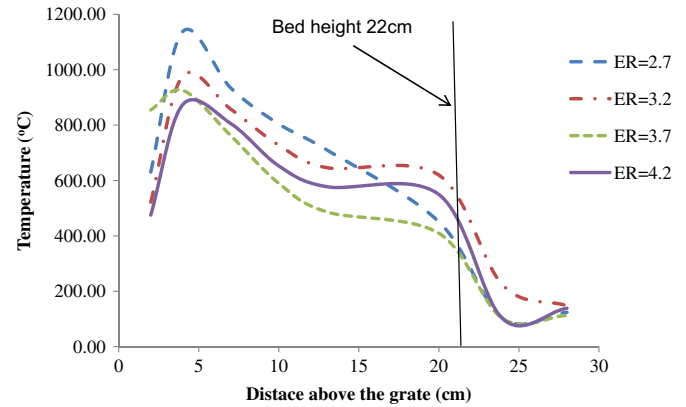

Fig. 8. The effect of ER on gasification temperature profile of mesquite (2–4 mm size) with moisture content 12.9%.

than coal. 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_{peak}) occured a few cm above the bottom of the gasifier since char oxidation occured when there was an abundant supply of O_2. At the bottom of the bed, ash was accumulated and the temperature would be correspondingly low. Above the ash, char reacted with oxygen to produce CO and CO_2, as well as the heat for the gasification process. T_{peak} highly depended on the concentration of O_2, CO, and CO_2. T_{peak} in the combustion zone can rise above 1000 °C depending upon HHV and oxygen concentration. Above the combustion zone, the 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
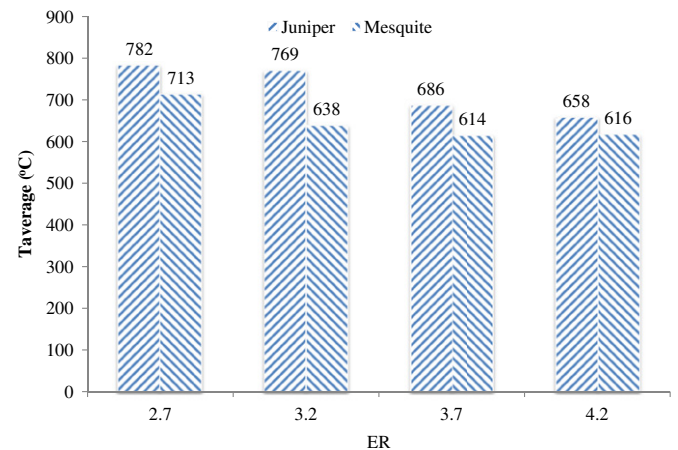

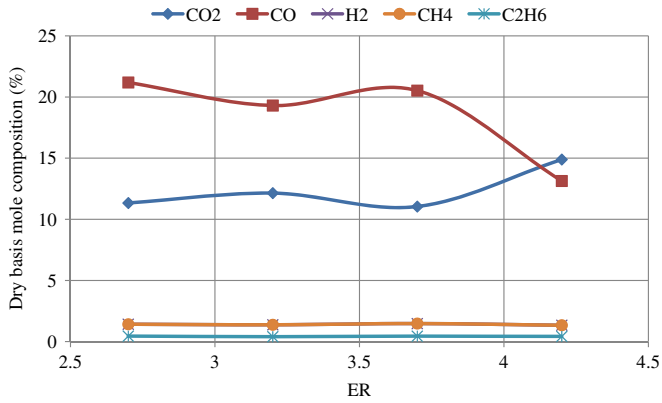**Fig. 9.** The average temperature for mesquite and juniper in the gasifier vs ER.

Fig. 10. Mesquite gas composition (dry basis) vs. ER.

Table 8
The range of gas yields of mesquite and juniper on a percent basis (dry basis) when ER increased from 2.7 to 4.2.

Molecule	Juniper (2–4 mm)	Mesquite (2–4 mm)
N_2 (%)	58–61	62–64
CO (%)	21–25	13–21
CO_2 (%)	9–11	11–15
H_2 (%)	2.6–3.3	1.6–3
CH_4 (%)	1.5–1.7	1.2–1.5
C_2H_6 (%)	0.3–0.5	0.4–0.6
O_2 (%)	1–2	1–2

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_{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_{Peak} decreased with an increase of moisture content due to more energy was consumed in the moisture evaporation process which resulted in higher CO_2 mole
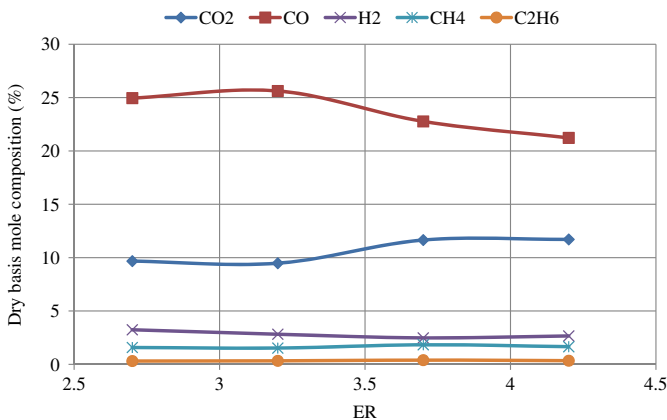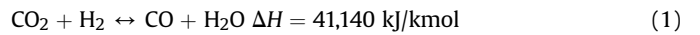
percentage. Equation (1) describes the water–gas equilibrium reaction:

$$CO_2 + H_2 \leftrightarrow CO + H_2O \quad \Delta H = 41,140 \text{ kJ/kmol} \tag{1}$$

Consider the equilibrium constant in Equation (2):

$$Kw = ([CO] * [H_2O])/([CO_2] * [H_2]) \tag{2}$$

where [CO], [H_2O], [CO_2], and [H_2] are mole concentrations for each gas, Kw 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_{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 oxidization 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
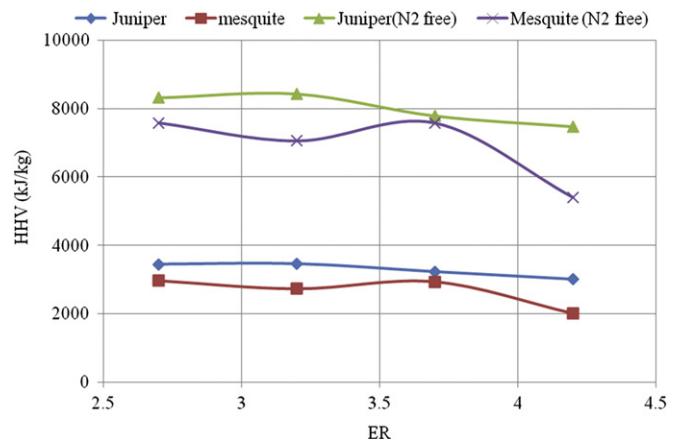

Fig. 11. Juniper gas composition (dry basis) vs. ER.

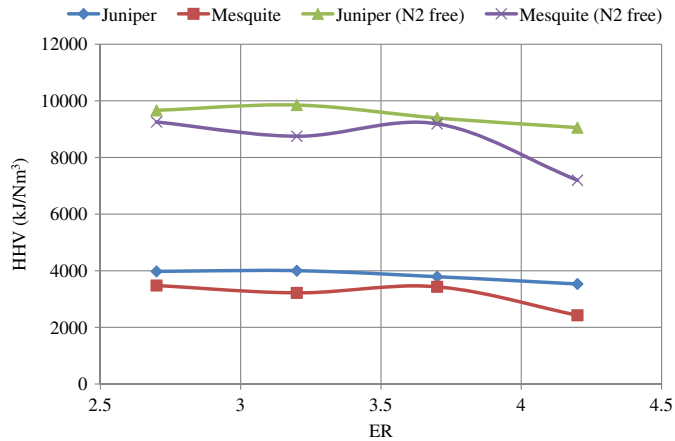**Fig. 12.** HHV (in kJ/kg) mesquite and juniper gas with moisture content 12.9% and 13.5%, respectively, vs. ER.

Fig. 13. HHV (in kJ/Nm³) of mesquite and juniper gas with moisture content 12.9% and 13.5%, respectively vs. ER.

Fig. 15. Gas yield per kg biomass for mesquite and juniper vs. ER.

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 CO_2 mole percentage, while CO and H_2 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]:
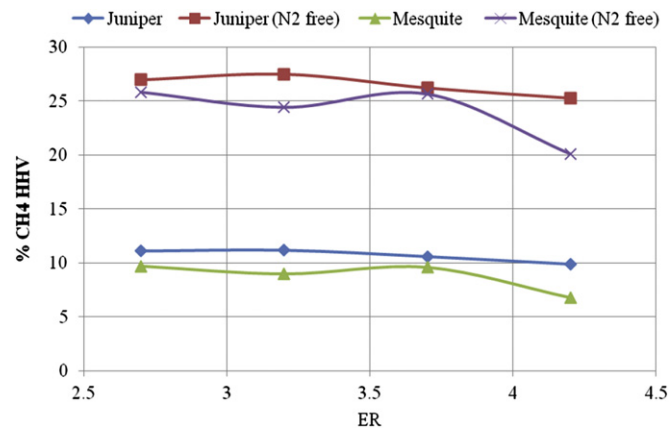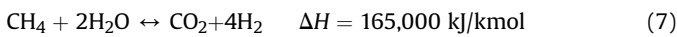
$$C + H_2O \leftrightarrow CO + H_2 \qquad \Delta H = 131,160 \text{ kJ/kmol} \qquad (3)$$

$$CH_4 + H_2O \leftrightarrow CO + 3H_2 \qquad \Delta H = 206,000 \text{ kJ/kmol} \qquad (4)$$

$$C + CO_2 \leftrightarrow 2CO \qquad \Delta H = 172,320 \text{ kJ/kmol} \qquad (5)$$

$$C + O_2 \leftrightarrow CO_2 \qquad \Delta H = -393,180 \text{ kJ/kmol} \qquad (6)$$

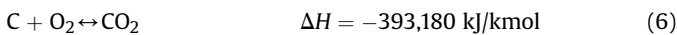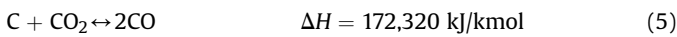$$CH_4 + 2H_2O \leftrightarrow CO_2 + 4H_2 \qquad \Delta H = 165,000 \text{ kJ/kmol} \qquad (7)$$

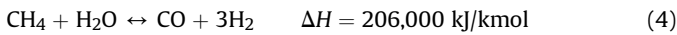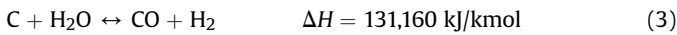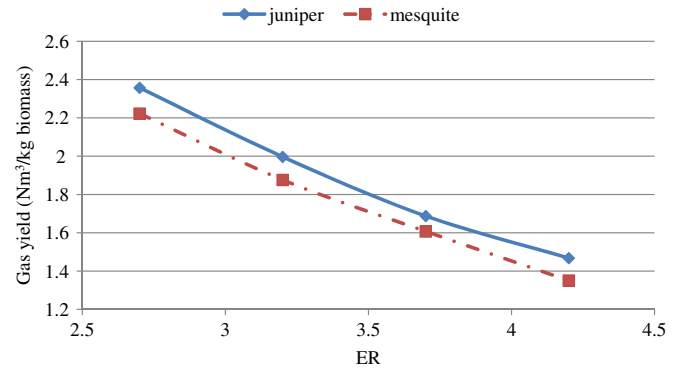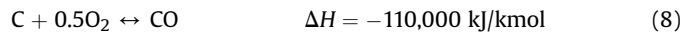Fig. 14. Percent of CH₄ HHV vs. ER (kJ/kg basis).

$$C + 0.5O_2 \leftrightarrow CO \qquad \Delta H = -110,000 \text{ kJ/kmol} \qquad (8)$$

Increasing the gasification temperature would result in equilibrium of reactions (3), (4), and (7) move forward to favor the formation of H_2 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, reaction (6) was favored at low temperature and thus more CO_2 was generated [3]. The end product gas of juniper had a higher CO and H_2 percentage and lower N_2 and CO_2 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 H_2.

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 N_2 free basis to eliminate the dilution effect of N_2. 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 N_2 and N_2-free conditions.

As it is well known, CH_4 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 CH_4. The dry gas can reach almost 11% of HHV of CH_4 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 N_2, the heating value of gas increased to 27% of CH_4 HHV for juniper and 25.82% of CH_4 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 N_2 is inert gas and assuming no nitrogen comes out from the fuel during the gasification process, knowing the amount of N_2 in the air supplied to the gasifier, the volume of the producer gas can be calculated from the N_2 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

yield slightly more producer gas than that of mesquite because there is more volatile on DAF basis (Table 1).

4. Conclusions

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

2 High moisture content decreased T_{peak} and lowered CO and H_2 mole percentage in the final production gas, but larger particle size increased T_{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% H_2, 1–1.5% CH_4, 0.4–0.6% C_2H_6, 60–64% N_2, 11–25% CO_2, and 1–2% O_2. The mole composition of the end product gas for juniper consisted of 21–25% CO, 2.5–3.5% H_2, 1.5–1.8% CH_4, 0.3–0.5% C_2H_6, 58–61% N_2, 9–12% CO_2, and 1–2% O_2. For both mesquite and juniper samples, increasing ER decreased the CO and H_2 mole percentage and raised the CO_2 and N_2 mole percentage.

4 The HHV ranged from 3500 kJ/Nm^3 to 3900 kJ/Nm^3 for juniper and from 2400 kJ/SATPm^3 to3500 kJ/Nm^3 for mesquite when ER increased from 2.7 to 4.4. And, producer gas was between 2.4 and 1.44 Nm^3/kg biomass and 2.4–1.37 Nm^3/kg biomass for juniper and mesquite, respectively, when ER increased from 2.7 to 4.4. If N_2 was removed from the end-product gas, the HHV of mesquite and juniper samples can reach 26% and 28% of CH_4 at ER $\approx$ 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 N_2 and N_2-free conditions.

Acknowledgments

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