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Co-Gasification of Mesquite and Coal Blend in an Updraft Fixed Bed Gasifier

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ABSTRACT

In order to reduce the emission of NO_x, SO_x, and CO_2 and mitigate the dependence on the fossil fuel, the use of renewable energy, especially the biomass energy, has been explored. Since most biomass fuels are hard to grind to the very fine size, gasification is the preferred technology of energy conversion. Updraft fixed bed gasification using partial oxidation process is adopted where air less than the stoichiometric quantity is admitted to oxidize the char to CO. The temperature profile within the bed reveals a characteristic temperature peak. The results reveal a correlation between the higher heating value (HHV) of producer gas and the peak gasification temperature (T_{peak}). Coal with higher char content (~45%) is blended with biomass of low char content (~20%) in order to produce high quality gas. In this study, the Texas-based mesquite fuel was blended with Wyoming Power River Basin (PRB) coal with mass ratios of 100:0, 90:10, and 80:20 and fired downward into the gasifier. It was found that at a given mesquite to the coal mass ratio, the peak gasification temperature decreased with the increase in ER. With the increase of the coal ratio in the mesquite: coal blend and the peak temperature increased significantly; more combustible gases such as CO, CH_4 were generated at the end of product gas, and the HHV of the product gas increased by 10% - 20%.

Keywords: Gasification; Bioenergy; Coal; Heating Value; Sustainability

1. Introduction

The utilization of wastes as a renewable energy source in a thermo-chemical process to generate electricity or heat has been widely used. The US independent biomass energy industry today provides for the disposal of approximately 22 million tons/yr of solid biomass waste [1]. Brian *et al.* [2] reported that approximately 60% of biomass energy consumption occurs in the forest products industry in US. The forest products industry produces its own sources of biomass such as bark, sawdust, wood scraps/shavings, and waste water treatment sludge. Normally, bio-chemical and thermo-chemical are the two main ways to convert biomass into energy. Gasification is a thermo-chemical process where a solid fuel was converted into gaseous species through a series of chemical reactions and physical transformation. Air, steam, and pure oxygen are the three main gasifying media, although other agents like CO_2 or H_2 are also being studied.

The gasifiers can generally be classified into two different types: fixed bed and fluidized bed gasifier. For fixed bed gasifier, the flow velocity is low; there is a grate at the bottom of the gasifier and ash was disposed through the grate while the flow velocity is high and there is no grate for the fluidized bed gasifier. The fixed bed gasifier can be classified as updraft, downdraft, and crossdraft. The updraft fixed bed gasifier is a counterflow reactor in which fuel is fed into the top and the air or the steam is supplied at the bottom. The ash was removed through the grate. In a downdraft fixed bed gasifier, fuel and gases both flow in the same direction. Fixed bed gasifiers are well suited for small-scale applications (Power < 10 MW) [3]. Fluidized bed gasifier usually has a large scale size and is used for industrial applications. For mesquite and coal co-gasification, the updraft fixed bed gasifier is used since it is easy to construct and operate. The temperature of gas coming out from the updraft gasifier is less than 200˚C [4].

2. Literature Review and Objective

Extensive studies have been carried out on the biomass gasification using air, steam, or air-steam mixture as gasification media. Kumabe *et al.* [5] carried out the co-gasification experiments using Japanese cedar and Mulias coal in a downdraft gasifier by using air and steam as gasification media. It was found that with an increase in the biomass ratio in the mixture, the H_2 % decreased and the CO_2% increased while the CO % was independent of the biomass ratio. A low biomass ratio led to the production of a gas favorable for methanol and hydrocarbon fuel synthesis, and a high biomass ratio led to the production of a gas favorable for Dimethyl Ether (DME) synthesis. The cold gas efficiency of the co-gasification ranged from 65% to 85%.

Pan *et al.* [6] mixed the pine chips with black coal and Sabero coal, in the ratio range of 0/100 - 100/0, respectively. Experimental tests were carried out using air and steam as gasification agent at gasification temperatures of 840˚C - 910˚C and superficial fluidized gas velocities of 0.7 - 1.4 m/s using fludized bed gasifier. It was found that the dry product gas heating value increases with increasing blend ratio from 3700 to 4560 kJ/Nm^3 for pine chips/black coal, and from 4000 to 4750 kJ/Nm^3 for pine chips/Sabero. Dry product gas yield raised with the increase of the blend ratio from 1.80 to 3.20 Nm^3/kg (pine chips/black coal), and from 0.75 to1.75 Nm^3/kg (pine chips/Sabero coal), respectively. About 50% co-gasification processes overall thermal efficiency can be achieved for the two types of blend.

Lu *et al.* [7] studied the effect of the equivalence ratio on the co-gasification of pine sawdust and bituminous coal in a bubbling fluidized bed. It was found that when blending fuel ratio is 50% - 50%, with ER increasing from 0.2 to 0.28 the volume concentration of H_2 rose from 14.1% to 26.9%, and CO% decreased from 28.9% to 21.8%. The CO_2% showed an increasing tendency in the range of ER, while those of CH_4 and C_nH_m kept decreasing. The maximum of the lower heating value (LHV), is about 7180 kJ/m^3 when ER is 0.25. The gasification efficiency ranged from 44% - 53% and the carbon con- version rate was between74% to 76%.

Chen *et al.* [8] used the mesquite wood chips as feedstock for a fixed bed gasification experiment. It was found that the HHV of the gas produced from the mesquite fuel decreased when equivalence ratio (ER) increased from 2.7 to 4.2 and the HHV was in a range of 2400 kJ/Nm^3 to 3500 kJ/Nm^3.

Gerado *et al.* [9] used a mixture of dairy biomass (DB) and Wyoming sub-bituminous coal (WYC) with a ratio of 90:10 for co-gasification study in a 10 kW updraft gasifier using air-steam as gasification media. Due to the presence of higher amount of fixed carbon in the WYC, the peak gasification temperature and the % of CO in the end produced gas increased and the HHV of the producer gas increased correspondingly. The HHV of the gases varied from 3649 to 4793 kJ/ Nm^3.

In these studies, the variation of HHV of the gases produced and the gasification efficiency with ER and mesquite: coal ratios were investigated. It was also found that the HHV of the product gas increased as coal % was increased in the blends. In the current study, the Texas based mesquite was blended with PRB coal for air gasification in order to produce higher quality gas (*i.e.* increased HV gas) and convert more volatile matter into combustible gases (e.g. reduce the tar content in the product gas due to higher T_{peak}). The effect of the ER and coal% in mesquite: coal blend (MCB) on the gasification temperature, gas compositions, and HHV were investigated. The main objective of this study was to use the Texas based Mesquite and PRB coal blended fuel to produce higher quality gas (*i.e.* increased HV gas) and convert more volatile matter into combustible gases (e.g. reduce the tar content in the product gas due to higher T_{peak}) in an air gasification process. The effect of the ER and coal percentage in mesquite: coal blend (MCB) on the gasification temperature, gas compositions, and HHV were investigated.

3. Sustainabilityof Mesquite

The sustainability of any energy source must satisfy the following requirements: Abundance of energy sources, maintaining integrity of environment including air, land (soil) and water, renewability and affordability (*i.e.* low cost)[10]. Most biomass fuels satisfy the requirement including mesquite. The Mesquite (*Prosopis glandulosa*) is a deciduous wood which can reach a height of 6 to 9 m (20 to 30 ft), grows rapidly and furnish shade and wildlife habitat where other trees will not grow [11]. It is an extremely hardy, drought-tolerant plant growing on semi-arid non-cultivated lands because it can draw water from the water table through its long taproot and thus it can be harvested nearly year round [11,12]. Depending upon availability, mesquite can also use water in the upper part of the ground. Mesquite trees have very strong regrowth after top-kill damage [12]. Like many members of the Legume Family, it fixes nitrogen in the soil where it grows and therefore satisfies most of its nutrient needs [13]. It is estimated that of the 21 M total ha of mesquite in Texas alone [14,15] , about 20%, or 4.2 M ha, could be harvested for bioenergy needs. At an average of 18 dry Mg/ha [12], this could amount to over 75 teragrams (Tg) of total mass available. There is no planting, cultivation, irrigation and fertilization costs for this naturally occurring, nitrogen-fixing species [12]. This species can be used as feedstock to produce syngas and bio-oil in small scale gasification units [4]. Since coal has higher amount of char compared to mesquite, then the heat value of gas produced could be enhanced by blending small amount of coal with mesquite; such a process increases the usage of gas produced from gasification of

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mesquite, reduces the transportation cost of gas per GJ and makes it more affordable.

4. Preparation of Solid Fuel

Mesquite trees used in this gasification study were 3 - 4 m tall and had multiple basal stems. Basal stem diameter ranged from 5 - 15 cm. Tree ring counts indicated that above ground portions of these trees were 15 to 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 [8]. 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. In this study, the mesquite particles with size of 2 - 6 mm were selected for gasification. At the time of harvest, the moisture content of fresh cut wood was between 30% - 45% [Jim Ansley unpublished data]. After chipping and sieving process, the moisture content of the fuel declined to 10% - 20%. The moisture content of the mesquite fuel in this study was in a range of 10% - 12%.

5. Experimental Facility and Procedure

The gasifier (72 cm tall) was divided into four sections which are joined by using ring type flanges of 12.7 × 35.6 × 50.8 mm (**Figure 1**). The gasifier was constructed of castable alumina refractory tube. The inner and outer diameters of tube are 13.9 cm and 24.5 cm, respectively. The tube was surrounded by 4.45 cm insulating blanket in order to minimize heat losses. The layer was then surrounded by a steel outer tube with an inner diameter of 34.3 cm. An ash disposal system is installed to maintain quasi-steady operation. A conical gyratory cast iron grate drilled with large number of holes with diameter of 6.4 mm is coupled to a pneumatic vibrator of variable frequency that vibrates the grate in order to dispose the ash continuously from the bed. The rate of ash removal can be controlled by changing the vibration frequency in the vibrator [16].

At the beginning of the experiment, the empty bed was preheated to 600˚C using a propane torch. After the temperature reached 600˚C, the torch was turned off and biomass samples were gradually added to the gasifier. This addition continued until the bed height of the gasifier reached 22 cm (8.5 in). Afterwards, the fuel port was closed and air or the mixture of air and steam was sent into this system at the desired rate. Because mesquite has low ash content (<3%), the vibrator operated for <1 minute to dispose the ash from the plenum before it reached steady state. Afterwards, the grate was vibrated over a short period of 5 to 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

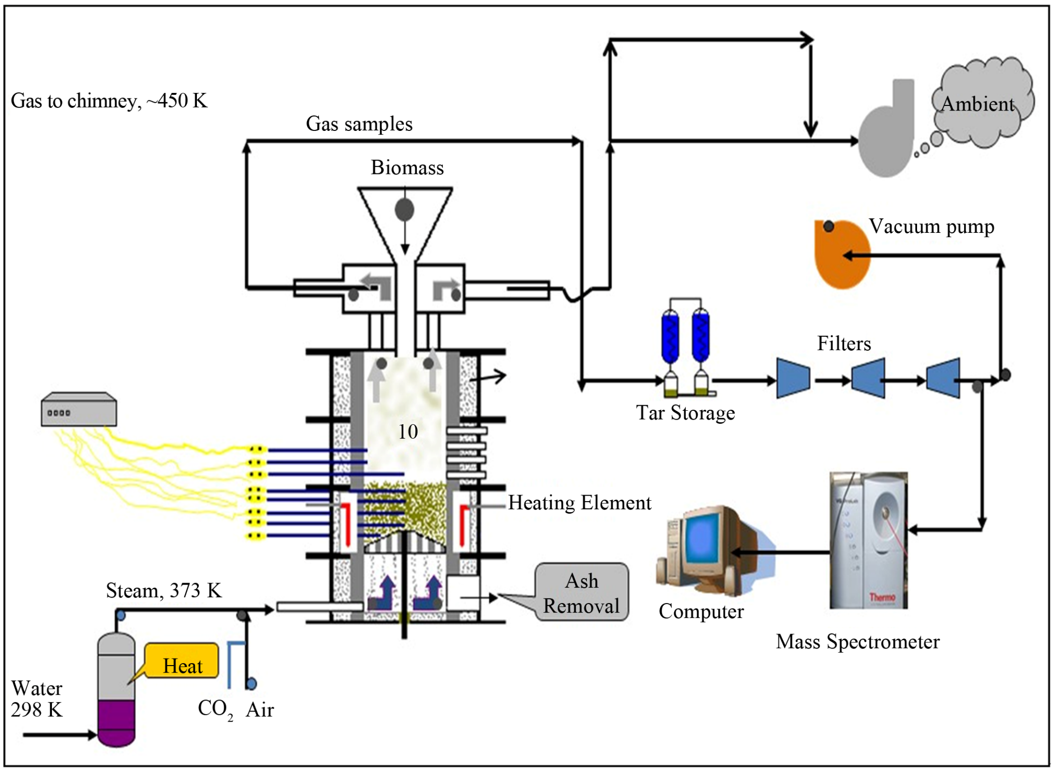

Figure 1. Gasification facility. Adapted from [16].

reached by varying the air flow rate. Fuel was fed at the top of the gasifier while air was supplied from the bottom. As fuels gasified in the reactor chamber, negative pressure was maintained using vacuum fan in order to exhaust the gases from the gasifier. It took approximately 60 minutes for experiments to reach steady state, this being when T_{peak} varied lesser than 10˚C over the period of 15 minutes and the location of the T_{peak} remained at the same position. Once the steady state condition was achieved the gas analysis was started and the gas compositions were recorded for 8 - 10 minutes.

5.1. Temperature Measurement

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 during gasification process. The temperature was recorded every 60 seconds.

5.2. Gas Compositions Measurement

A mass spectrometer was used to measure the composition of the produced gases such as CO, CO_2, N_2, CH_4, C_2H_6, and H_2. After the steady state condition was reached within the reactor, the producer gas was analyzed for its composition. A small amount of gas was supplied to the mass spectrometer by using a vacuum pump. The gas first passed through a condenser to remove tar and condensable vapors, and then was passed through a series of filters to capture particulates suspended in the gas. Afterwards, a small amount of gas was sent 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 an inert gas (Helium) once in every three days in order to get accurate measurements [8].

6. Results and Discussion

6.1. Fuel Properties

Figures 2(a) and **(b)** show the mesquite and PRB coal used for the gasification study. **Table 1** presents the proximate and ultimate analyses of the mesquite and PRB coal.The ultimate and proximate analysis of mesquite which was used for the present study is shown in **Table 1**.

It can be found that the mesquite fuel had very high VM content (>80%) while volatile matter of the PRB coal was less than 50% under DAF basis, which means less gas would be liberated from PRB coal during the gasification process. However, the FC (DAF basis) for the Wyoming coal is significantly higher than that of mesquite. Higher C element implies more C is available to form the gas such as CO_2, CO and CH_4. It can be found from **Table 1** that the C/O atom ratio for the PRB coal is 4.12 while it was only 1.48 for mesquite fuel on dry, ash free basis, and thus the HHV of the PRB coal is much higher than that of mesquite. On a dry ash free (DAF) basis the higher heating value (HHV) of mesquite is 19,902 kJ/kg and the PRB coal has a HHV of 29,593 kJ/kg. Generally the HHV of the biomass is roughly 2/3 of HHV of coal.

(a) (b)

Figure 2. (a) Mesquite chips; (b) PRB coal.

Table 1. Mesquite fuel and Wyoming PRB coal proximate and ultimate analysis [17].

As received	PRB	Mesquite
Moisture	12.2	10.86
Ash	7.39	3.19
Volatile Matter	37.7	70.63
Fixed carbon	43.15	15.32
Carbon	60.85	47.7
Oxygen	14.77	32.28
Hydrogen	3.57	5.17
Nitrogen	0.86	0.72
Sulfur	0.35	0.08
HHV (kJ/kg)	23800	20191
Dry, Ash Free (DAF)		
Moisture	0	0
Ash	0	0
Volatile Matter	46.34	82.17
Fixed Carbon	53.66	17.83
Carbon	75.67	55.51
Oxygen	18.36	37.54
Hydrogen	4.44	6.02
Nitrogen	1.07	0.84
Sulfur	0.45	0.09
Empirical formula	$CH_{0.70}N_{0.02}O_{0.18}S_{0.002}$	$CH_{1.3582}O_{0.577}N_{0.0122}S_{0.0003}$
HHV of VM (kJ/kg)	25921	16933
HHV (kJ/kg)	29593	19902

+Estimated using the relation $HHV_{DAF} = FC_{DAF} \times HV_{FC} + VM_{DAF} \times HHV_{DAF}$ [18].

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6.2. Temperature Profile of the Mesquite and PRB Coal Blends

Figures 3-5 present the temperature profiles for the mesquite and coal mixtures with ratio of 100:0, 90:10, and 80:20 at different ER. It was found that all the temperature profile share the same trend. Along the axis of the gasifer, the temperature increased first and reached a maximum value (above 3 - 5 cm from the grate) due to the accumulation of the ash at the bottom, and then decreased. In addition, as ER increased the gasification temperature decreased due to less air being supplied into the gasifier.

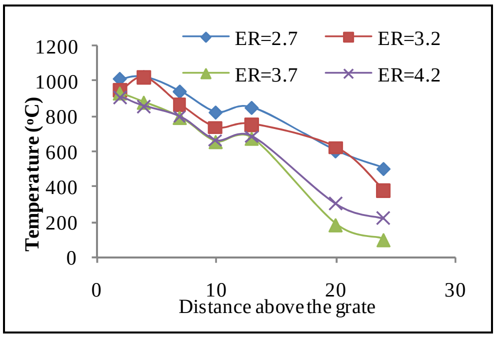

Figure 3. Temperature profile for mesquite:coal (100:0) mixture.

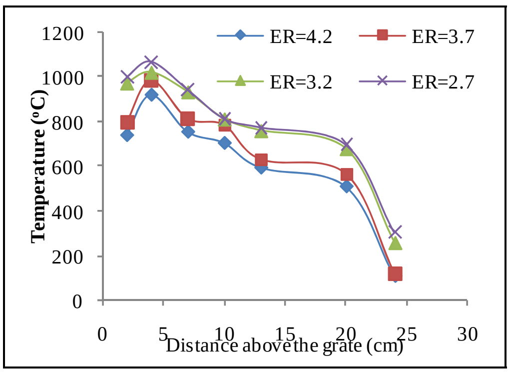

Figure 4. Temperature profile for mesquite:coal (90:10) mixture.

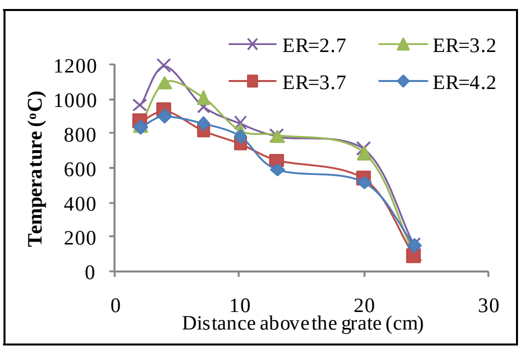

Figure 5. Temperature profile for mesquite:coal (80:20) mixture.

Figure 6 shows the T_{peak} for the mesquite: coal blend with ratios of 100: 0, 90:10, and 80:20. It was found that T_{peak} increased with the increase of the coal percentage in the blend. The temperature increased from 989˚C to 1200˚C when PRB coal percentage increased from 0 to 20% at ER = 2.7. Since coal is a higher quality fuel, more char is in the coal compared to woody biomass. In **Table 1**, the C/O ratio for the PRB coal is 4.12 while only 1.48 for mesquite fuel. Temperature is expected to be higher for mesquite and coal blend due to higher amount of heatreleased from coal.

6.3. Gas Composition

The main gas compositions in the end product are CO, CO_2, CH_4, H_2, and N_2. **Figure 7** gives the gas composition of the producer gas as a function of ER for mesquite gasification. Temperature is expected to be higher for mesquite and coal blend due to higher amount of heat released from coal. It can be seen that the concentration of CO and H_2 decreases with the increase of ER, while CO_2 content increases with the increase of ER. And the amount of change in CH_4 and C_2H_6 at different ER is negligible. This is because high gasification temperature favors the formation of CO and H_2 [9]. Lower ER implies that more air was supplied into the gasifier which promotes the oxidation of the carbon which results in high temperature.

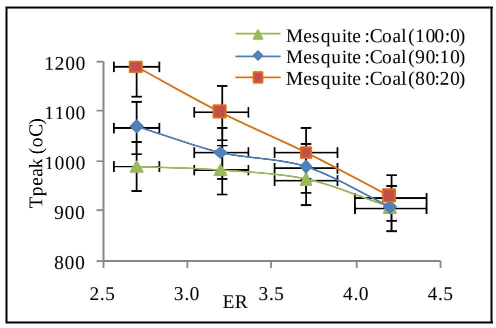

Figure 6. T_{peak} for the coal and mesquite blend ratio.

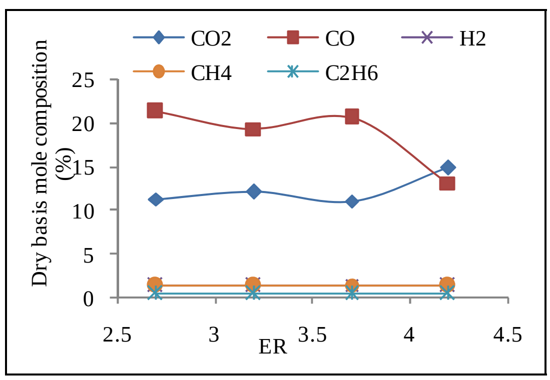

Figure 7. Mesquite gas compositions (dry basis) vs. ER for air. Adapted from [8].

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Figures 8 and **9** present the CO_2 and CO concentration (dry basis) under different coal: mesquite ratio. It was found that the CO_2 concentration decreased while CO concentration increased when the PRB wt % increased in the blend. This is because higher gasification temperature favors the formation of the CO and decreases the percentage of CO_2 [16]. The CO_2 concentration was between 6% - 18% and the CO percentage was between 14% - 23% when ER decreased from 4.2 to 2.7.

Figure 10 presents the H_2 and CH_4 concentration with blend ratio as a parameter. The solid and dotted lines represents the H_2 and CH_4 percentage, respectively. It was found that H_2 mole faction was in a range of 2.5% - 4% and the CH_4 mole fraction was between 0.7% - 2.5%. Increase of the coal ratio in the mixture resulted in slight increases of the CH_4 concentration because more char was available to react with H_2 to form CH_4.

6.4. HHV of Gas

When producer gas is used as a fuel in internal combustion engines or other applications, the optimal gasification conditions are those that yield the highest HHV and have a high thermal efficiency. **Figure11** gives HHV of the gas from coal and mesquite mixture. It was found that HHV increased with the increase of the coal:mesquite ratio. From **Figure 12**, it was seen that HHV of gas produced from mesquite gasification is between 2000 - 3000 kJ/Nm^3;It increased to 2900 - 3600 kJ/Nm^3(20% to 45% increased) with 10% PRB coal in the mixture;HHV of gas can increase up to 4000 kJ/m^{3}at ER = 2.7 with 20% PRB coal in the mixture. The low HHV of gas is due to a high % of N_2 originating from air.

As discussed before, with an increase in the coal % in the blend, T_{peak} and gas HHV increased.In order to obtain the correlation between the T_{peak} and HHV, T_{peak} vs. HHV was plotted in **Figure 12**. It was seen that higher T_{peak} would result in increase of HHV of the producer gas. It is because more combustible gases such as CH_4 and CO were produced under the high gasification peak temperature.

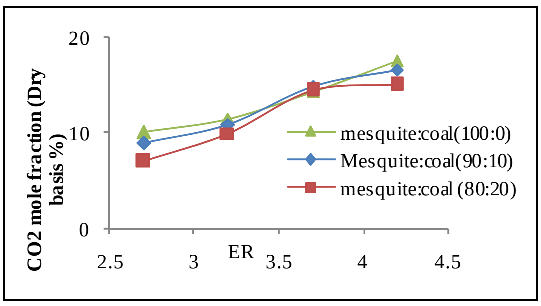

Figure 8. CO_2 concentration for different mesquite and coal blend.

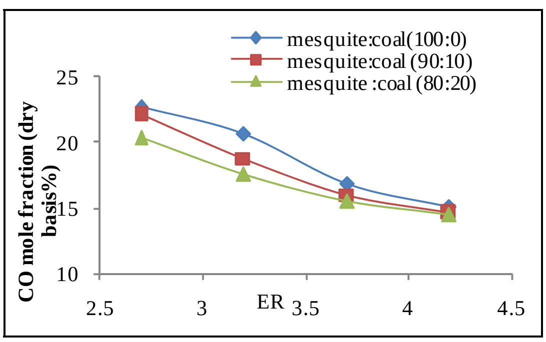

Figure 9. CO concentration for different mesquite and coal blend.

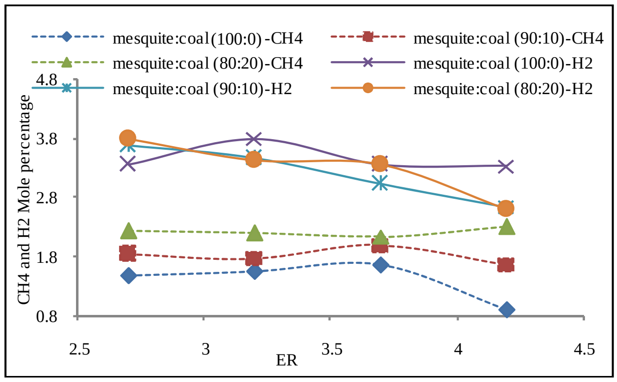

Figure 10. H_2 and CH_4 concentration for different mesquite and coal blend.

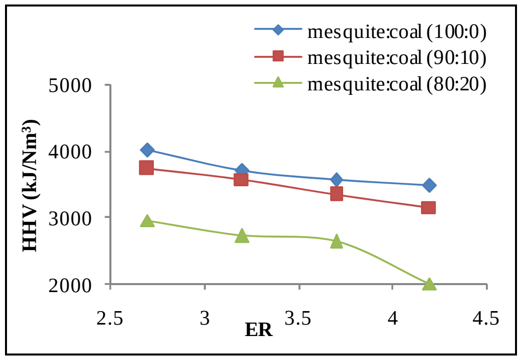

Figure 11. HHV for the PRB and mesquite mixture gas.

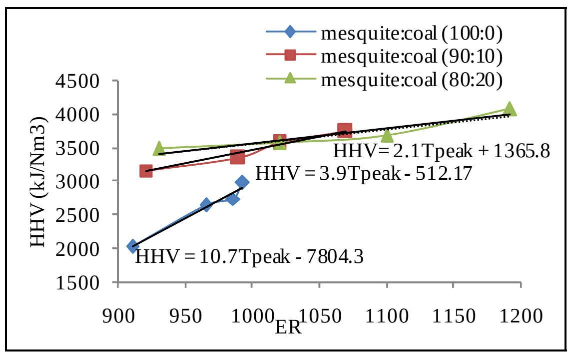

Figure12. HHV vsT_{peak} for mesquite andcoal blend gasification.

7. Conclusions

In this study, PRB coal was blended with mesquite for air gasification. The gasification temperature, gas compositions, and gas HHV were regarded as functions of mesquite, and coal ratios were investigated. The results of the experiments are summarized as follows:

1) When PRB coal was mixed with mesquite fuels at ratios of 10:90 and 20:80 for gasification experiment, T_{peak} increased significantly due to the higher HHV of the PRB coal. The T_{peak} of coal and mesquite blend was 1200˚C at ER = 2.7 and blend ratio 20:80.

2) For Co-gasification, T_{peak} increased with the increase of the PRB coal percentage, and CO_2 concentration decreased while CO and CH_4 percentage increased at the end of product gases. When the coal wt. % increased from 0 to 20%, the end product gases contained 14% - 23% CO, 6% - 18% CO_2, 2.5% - 4% H_2, and 0.7% - 2.5% CH_4.

3) The HHV of gases from the mesquite and PRB coal blend increased with the coal% in the mixture due to the higher peak temperature and carbon content in the coal which resulted in more combustible gas being released. The higher the gasification temperature is, the higher will be the HHV of the gases. The HHV increased around 20% when the coal percentage was 10% in the blend.

8. Acknowledgements

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Nomenclature

CO: Carbon Monoxide
CO_2: Carbon Dioxide
CH_4: Methane
C_2H_6: Ethane
DAF: Dry, Ash Free Basis
DME: Dimethyl Ether
ER: Equivalence Ratio
FC: Fixed Carbon
HHV: Higher Heating Value
LHV: Lower Heating Value
MCB: Mesquite to Coal Blend
N_2: Nitrogen
O_2: Oxygen
PRB: Powder River Basin
T_{peak}: Peak Gasification Temperature
VM: Volatile Matter