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Down Draft Gasification Modelling and Experimentation of Some Indigenous Biomass for Thermal Applications

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Abstract

Five locally available biomassesnamely Bamboo (Banbusea Tulda), Gulmohar (Delonix regia), Neem (Melia Azedarach L), Dimaru (Ficus lepidosa wall), and Shisham (Delbergia sissoo) had been characterized with CHN analysis. The elemental characterization results were used to model a downdraft gasification (10 $kW_{thermal}$) process in terms of producer gas composition. A thermodynamic equilibrium modelling had been presentedfor a throated downdraft gasifier, based on equilibrium constants with appropriate assumptions. The gas compositions of the above bio-fuels had been studied with varying moisture content from (0-30) percentage at a gasification temperature of 850 °C. Highest calorific value (18.40 MJ kg^{-1}) was obtained for bamboo chip with fixed carbon 48.69 percentages. Gulmohar yielded maximum value of Hydrogen (24.50 %) in downdraft gasification among all fuels for same moisture. Bamboo gasification gave overall best quality of producer gas for same moisture. The compositions of producer gas thus generated from these five woody biomasses had been determined by gas chromatography analysis. The results obtained from equilibrium modelling study were fairly in good agreement with experimental results.

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Keywords: Biomass; Gasification; Equilibrium modelling; Downdraft ; Thermal application

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1. Introduction

1.1 Background of studies

Technologically ever developing world is stressed due to the shortage of reserved fossil fuels and related environmental pollution, natural imbalance; global warming, etc. Moreover, occurrence of number of natural disasters Tsunami, Cyclone, Floods, Draught, etc. creates environmental turbulence [1]. Presently, conventional energy sources in the world are dominated by different fossil fuels (80%; equals to 400 EJ/year). About (10-15) percentage of energy demand is covered by biomass [2]. The major factors that cause biomass as an alternative energy source is because of its comparatively low impact on environment, low content of N_2 and sulphur or carbon neutral benefit. This gives rise to practically negligible fraction of NO_x and SO_2 emission [3]. Fischer and Schrattenholger estimated the global biomass prospective as (91-675) EJ/year for the years 1990-2060 [4].

Biomass may be converted into more useful bio-fuels by thermo-chemical transformation techniques, such as Combustion, Gasification, and Pyrolysis, etc. Direct combustion of biomass may generate heat and power with right conversion devices. Pyrolysis takes place in absence of O_2that is a highly endothermic and irreversible phenomenon. Pyrolysis produces liquid, gas and solid residues as final products. Biomass gasification energy may be conveniently used for generation of both heat and power. Gasification utilizes heat of partial oxidation to pyrolyze the biomass feedstock. Biomass gasification converts low-value feedstock into useful heat or electricity. Moreover, this may be applied to produce SNG (synthetic natural gas), methanol, green diesel (Fischer-Tropsch), etc. Advanced technology such as gas turbines and fuel cells with the synthetic gas generated from gasification may result in increased overall system efficiency [4]. Combined heat and power generation from biomass is especially beneficial for agricultural based rural process industry, and rural electrification in developing countries to replace diesel. The major challenges that come as a restriction in commercialization of small-scale gasification systems are appropriate, reliable and cheap producer gas cleaning technology for long duration operation, development of robust purely producer gas fired engines; multi-fuel effective biomass conversion capability by development of advanced gasifier at lower capital cost [5,6].

Biomass gasification processes are composite coinciding bio-chemical reactions inside a gasifer in limited supply of air. Gasification performance depends on quality of feed stock (i.e, moisture, CHN fraction, equivalence ratio, type of gasifier used, etc.) Improper selection of these parameters may lead to development of disproportionate tar and soot in the product gas. This may destabilize continuous operation of gas engine, gas cleaning system or heat exchanger [7, 8]. Downdraft gasifier is one of the most auspicious options for decentralized power generation due low tar and particulates present in product gas. However, it needs additional research in area of suitable modelling for a specific gasifier with available biomass feed stocks locally available. The most widely used modelling approach for the effective prediction of the gas concentration, heating value and efficiencies for downdraft biomass gasification may be either by reaction kinetic approach or by thermodynamic equilibrium approach.

The present paper deals with an equilibrium modelling of a downdraft gasification process for investigating the effect of moisture content on gas composition of five biomass samples namely*: Bamboo (Banbusea Tulda), Gulmohar (Delonix regia), Neem (Melia Azedarach L), Dimaru (Ficus lepidosa wall) and Shisham (Delbergia sissoo)*. Proximate and ultimate analysis data have been presented and a comparative study has been done for calorific values of above biomass samples.

1.2 Biomass potential in India

India has an incredible prospective for energy generation with biomass. Major part of rural areas of India tends to depend on conventional biomass (firewood, animal dung, and agricultural residue) for cooking, heating and lighting, etc., activities. Notwithstanding the global economic turndown, the gross domestic product (GDP) annual growth rates in India were 6.90% in 2011. The few Indian industries use biomass in power generation application. According to the Ministry of New and Renewable Energy, India has 288 biomass power and co-generation plants with 2.7 GW of installed capacity. It has a potential biomass based electricity generation capacity of 18 GW. The biomass energy technology may add one-third of total energy consumption in India [9, 10]. The availability of biomass in India is estimated about 500 MTs/year including residues from agriculture, agricultural industries and forest products. Maharashtra, Madhya Pradesh, Punjab, Gujarat, and Uttar Pradesh have highest potential for biomass. Total biomass power installed capacity in India is about 829 MW [11, 12].

1.3 Downdraft gasification of biomass

Fixed bed gasification is the most common technology for solid biomass conversion. During biomass gasification process, feed stocks are subjected to different thermo-chemical reactions. First, the biomass is dried up and it is followed by pyrolysis process. Lignin and cellulose are decomposed in to hydrocarbon, H_2, CO and water. The solid fraction vegetal char is combusted in presence of oxygen to generate process heat. In limited air fuel equivalence ration, vegetal char is gasified by pyrolysis and oxidation gases [13]. There are many types of fixed bed gasifiers with variable arrangements for both reactor design and reaction. The fixed bed gasifier may be classified according to the ways the gasifying agent enters into the gasifier i.e. updraft, downdraft, cross draft, and two stage gasifier. Commercially, about 75% of the gasifiers sold are downdraft gasifiers, 20% are fluidized bed, 2.5 % updraft and 2.5% of the other types [14]. Atmospheric downdraft gasifier is an attractive for small-scale application up to about 1.5 MW_{th} [15-17].

The producer gas may be used for different thermal applications like drying of food products, medium temperature industrial process heat generation, institutional cooking, etc. A 5x100 kW downdraft gasifier for remote electrification of five villages in Gosaba Islands in West Bengal, India has been reported [18]. Downdraft gasifier was operated in China with straw as feed stock for domestic cooking. It had gasification efficiency 75 percentage. The output power of gasifier ranged from (60-200 kW). The heating value of producer gas was (3.8-4.6) MJ/m^3 [19]. M/S Phosphate India Pvt. Limited, Udaipur has been using downdraft gasifier for heating and concentrating phosphoric acid. Biomass consumption rate of the gasifier was varied from (100-120) kg/h. The average air and gas flow rate was (92.69-99.20 and 204-210.26) m^3/h respectively. The temperature was varied from (800-1143) °C at 20 mm above gate. The quality of gas samples were analysed and heat value of the producer gas observed 4.35 MJ/Nm^3 [20].

A (6-7) kW downdraft biomass gasifier (JRB-1) was designed developed and tested at Durham University, UK. The thermal efficiency was calculated as (90.1-92.4) percentage. Temperature inside the reaction zone was (950-1150) °C, primary airflow rate was (0.0015 m^3/s) and exit temperature of the producer gas was (180-220°C) [21]. TERI (The Energy and Resources Institute) has been working on the development of various biomasses gasifier designs (downdraft, updraft, and natural draft) for both thermal as well as decentralized power generation over two decades. More than 350 TERI gasifier systems have been successfully installed throughout India. The collective installed capacity of over 13MW_{th} has been reported [22]. A modular design of a 125 kg/h biomass gasifier system was subsequently scaled up to 375 kg/h. This was a throated type, downdraft system intended for thermal application. The system was reported to produce good quality of fuel gas consistently [23]. Downdraft gasifier with internal cyclonic chamber has been reported. The turbulent, swirling high temperature combustion takes place to convert biomass and to crack tars [24].

1.4 Modelling approach

Thermodynamic equilibrium modelling predicts maximum achievable yield of desired products from a reacting system. This considers reaction alone without taking into account of the geometry of the gasifier [25]. Kinetic modellingis used for practical applications that study the progress of reactions in the reactor. This gives the product compositions at different positions along the gasifier. It takes into interpretation reactors geometry as well as its hydrodynamics [26]. Thermodynamic equilibrium calculations are independent of gasifier design and therefore it is convenient to study the influence of fuel and process parameters. Generally, equilibrium models are comparatively easy to implement with faster convergence [27].

Chemical equilibrium is determined by equilibrium constant or minimization of Gibbs free energy. There are many results available for downdraft gasifier with an equilibrium modelling approach. An equilibrium model was reported for reduction zone of a downdraft biomass gasifier. This predicted the composition of producer gas under steady state [28]. Combined chemical and thermodynamic equilibriums of the global reactions had been presented. This could predict the final composition of the producer gas [29]. An equilibrium gasification modelling based on equilibrium constants has been studied to simulate the gasification process in a downdraft gasifier. This study confirmed that the residence time of the reactants could be considered high enough to reach chemical equilibrium [30]. A similar conclusion has been reported regarding the influence of air fuel (A/F) ratio in addition to biomass moisture content on adiabatic temperature, gas compositions, and efficiencies [29, 31]. A parametric study of the influence of the gasifying agent, relative fuel air ratio (F/A) and moisture contents of the biomass on the characteristics of the process and the product gas composition with a downdraft gasifier based on thermodynamic equilibrium model has been presented. Using rubber wood as a feedstock with 14.7% moisture, a cold gasification efficiency of 80% was achieved. Another parametric study in terms of initial moisture content in the feed stocks and the temperature in the gasification zone has been investigated. This is based on equilibrium model to predict the gasification process in downdraft gasifier [30]. Furniture waste gasification experiment in a downdraft gasifier had been reported. The effect of airflow rate, moisture content on biomass consumption rate and quality of produced gas were studied [32]. Thermodynamic equilibrium is presented for downdraft gasifier, which uses MSW (Municipal Solid Waste) in Thailand. It was found that mole fraction of H_2 gradually increased; CO decreased; CH_4, which had a very low percentage in the producer gas increased; N_2 slightly decreased; and CO_2 increased with moisture contents [33]. Gasification of four samples namely wood, paddy husk, paper and municipal waste were investigated using equilibrium model and variation of gas composition especially for H_2,CO and CH_4 with respect to moisture content was studied [30, 34]. Gasification system with chemical equilibrium has been reported [35].

2. Materials and Methods

A zero dimensional model has been presented in this analysis. It takes the advantages of thermochemical equilibrium approach that is based on equilibrium constants. The equilibrium model is used to predict the variation of gas composition for five biomass samples at 850°C with the moisture varying from (0-30) percentage.
The main assumptions of this model are:

- The residence time of the reactants is supposed to be high enough to establish chemical equilibrium.
- Char formation is neglected and gasifier is considered adiabatic.
- Ash does not take part in chemical reaction and tar content is negligible for downdraft gasifier.
- Nitrogen gas is inert.

The following simplified chemical formulas (Eq.1) describe the basic gasification process at 25 °C [26].

Boudouard reaction	$: C + CO_2 \leftrightarrow 2CO + 172\ kJ/mol$	(1a)
Water gas or steam	$: C + H_2O \leftrightarrow 2CO + H_2 + 131\ kJ/mol$	(1b)
Hydrogasification	$: C + 2H_2 \leftrightarrow CH_4 - 74.8\ kJ/mol$	(1c)
Oxidation reactions	$: C + O_2 \rightarrow CO_2 - 394\ kJ/mol$	(1d)
	$: CO + 0.5O_2 \rightarrow CO_2 - 284\ kJ/mol$	(1e)
	$: CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O - 803\ kJ/mol$	(1f)
	$: H_2 + 0.5O_2 \rightarrow H_2O + 242\ kJ/mol$	(1g)
Shift reaction	$: CO + H_2O \rightarrow CO_2 + H_2 - 41.2\ kJ/mol$	(1h)
Methanation reaction	$: 2CO + 2H_2 \rightarrow CH_4 + CO_2 - 247\ kJ/mol$	(1i)
	$: CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O - 165\ kJ/mol$	(1j)
Steam reforming	$: CH_4 + H_2O \leftrightarrow CO + 3H_2O + 206\ kJ/mol$	(1k)
	$: CH_4 + 0.5O \leftrightarrow CO + 2H_2O - 36\ kJ/mol$	(1l)

For the development of an equilibrium model approach, the numbers of independent reactions have to be determined by applying phase rule, as described by Tassios [36]. Considering equilibrium to be achieved when no solid carbon remains in the equilibrium state and this is taken care by only two reactions called Water-gas shift and Hydrogenating gasification. The equilibrium constant for Water-gas shift reaction and Hydrogenating gasification are as follow [37]:

$$K_1 = \frac{P_{CH_4}}{(P_{H_2})^2} \quad (2)$$

$$K_2 = \frac{P_{H_2}P_{CO_2}}{P_{CO}P_{H_2O}} \quad (3$$

The typical chemical formula of the bamboo feedstock, based on a single carbon atom is $CH_{1.65}O_{0.71}$ and it was obtained from CHN analysis of the biomass.
The global gasification reaction may be written as:

$$CH_{1.65}O_{0.71} + wH_2O + m(O_2 + 3.76N_2) \rightarrow x_1H_2 + x_2CO + x_3CO_2 + x_4H_2O + x_5CH_4 + 3.76mN_2 \quad (4)$$

Where w is the amount of water per kilo mol of wood, m is the amount of oxygen per kilo mol of wood, x_1 to x_5 are the coefficients of constituents of the products.If MC is moisture content of per mol biomass and it is assumed as constant, then we have the relationship:

$$MC = \frac{mass\ of\ water}{mass\ of\ dry\ biomass}(100\%) => MC = \frac{18w}{25.01+18w}(100\%),\quad w = \frac{25.01MC}{18(1-MC)} \quad (5)$$

For a known value of MC, the value of w becomes a constant and m can be found out from the airflow rate per kilo mol of wood. There are six unknowns x_1 to x_5, and T in global reaction, representing the five unknown species of the product and the temperature of the reaction. Now six equations are required, which can be obtained from the following material and energy balances:

Carbon Balance:

$$1 = x_2 + x_3 + x_5 \quad (6)$$

Hydrogen Balance:

$$2w + 1.65 = 2x_1 + 2x_4 + 4x_5 \quad (7)$$

Oxygen Balance:

$$w + 0.71 + 2m = x_2 + 2x_3 + x_4 \quad (8)$$

The heat balance for the gasification process (assumed adiabatic) is:

$$\begin{bmatrix} H^0{}_{fwood} + w(H^0{}_{fH_2O(l)} + H_{(vap)}) + mH^0{}_{fO_2} \\ +3.76mH^0{}_{fN_2} + \Delta T'(mC_pO_2 + 3.76mC_pN_2) \end{bmatrix} = \begin{bmatrix} x_1H^0{}_{fH_2} + x_2H^0{}_{fCO} + x_3H^0{}_{fCO_2} \\ +x_4H^0{}_{fH_2O(vap)} + x_5H^0{}_{fCH_4} + \Delta T(x_1C_{pH_2} + \\ x_2C_{pCO} + x_3C_{pCO_2} + x_4C_{pH_2O(vap)} + x_5C_{pCH_4} \\ +3.76mC_{pN_2} \end{bmatrix} \quad (9)$$

$H^0_{fx}$is the enthalpy of formation of substance X and it is zero for all gases at ambient temperature.

Where $\Delta T = T_2\text{'} - T_1$ and $\Delta T\text{'} = T_2\text{'} - T_1$

T_1 ,T_2 and $T_{2'}$ represents the temperature of inlet, temperature of reduction zone and air inlet temperature From Eq. (6)

$$x_5 = 1 - x_2 - x_3 \qquad (10)$$

From Eq. (7)

$$x_4 = w + 0.82 - x_1 - 2x_5 \qquad (11)$$

Substituting the value of x_5 from the Eq. (10) into Eq. (11)

$$x_4 = - x_1 + 2x_2 + 2x_3 + w - 1.175 \qquad (12)$$

From Eq. (2)

$$x_1^2 K_1 = 1 - x_2 - x_3 \qquad (13)$$

Substituting the value of x_4 from the Eq. (12) into Eq. (8)

$$- x_1 + 3x_2 + 4x_3 = 2m + 1.885 \qquad (14)$$

Substituting the value of x_4 from the Eq. (12) into Eq. (3)

$$x_1 x_3 = K_2 x_2 [- x_1 + 2x_2 + 2x_3 + w - 1.175] \qquad (15)$$

From Eq. (9)

$$T_2 = T_1 + \frac{\begin{bmatrix} H^0{}_{fwood} + w(H^0{}_{fH_2 0(l)}) + H_{(vap)}) + H^0{}_{fO_2} + 3.76mH^0{}_{fN_2} + \Delta T'(mC_{pO_2} + 3.76mC_{pN_2}) \\ -x_1 H^0{}_{fH_2} + x_2 H^0{}_{fCO} + x_3 H^0{}_{fCO_2} + x_4 H^0{}_{fH_2O(vap)} + x_5 H^0{}_{fCH_4} \end{bmatrix}}{\left[(x_1 C_{pH_2} + x_2 C_{pCO} + x_3 C_{pCO_2} + x_4 C_{pH_2O(vap)} + x_5 C_{pCH_4} + 3.76mC_{pN_2}) \right]} \qquad (16)$$

The general equation for $\ln K_1$ is given by

$$\ln K_1 = \left[\frac{7082.848}{T} + (-6.567)\ln T + \frac{7.466\times10^{-3}}{2} T + \frac{-2.164\times10^{-6}}{6} T^2 + \frac{0.701\times10^{-5}}{2T^2} + 32.541 \right] \qquad (17)$$

The general equation for $\ln K_2$ is given by

$$\ln K_2 = \left[\frac{5870.53}{T} + 1.86\ln T - 2.7\times10^{-4} T - \frac{58200}{T^2} - 18.007 \right] \qquad (18)$$

3. Results and Discussions

3.1 Characterization of biomass samples

Present study deals with five type biomass [Fig.1. (a)toFig.1. (e)] samples namely *Bamboo (Banbusea Tulda), Gulmohar (Delonix regia), Neem (Melia Azedarach L), Dimaru (Ficus lepidosa wall), and Shisham (Delbergia sissoo).* Bamboo is a fast growing and widely available plants in the North East India. Around two third of the growing stocks of bamboo in India is found in the North East Indian States. Madhya Pradesh has the second highest area under bamboo, estimated at 20.3% of the area and with 12% of the growing stock [38]. Shisham is very popular in north India with nearly 10% to 15% of total forest cover. Shisham is mostly found in northern Indian states like Himachal Pradesh, Utter Pradesh, and Uttrakhand. The *Neem* tree is a tropical evergreen tree native to

Indian sub-continent [39, 40]. There are estimated 25 million trees growing all over India. Karnataka has 5.5%trees in third rank next to Utter Pradesh(55.7%) and Tamilnadu (17.8%) occupying the first two places respectively [41]. Gulmohar is a very popular roadside tree whereas*Dimaru* is mostly found in North-eastern region like Assam, Arunachal Pradesh etc.

The results obtained from ultimate, proximate analysis have been presented in Table 1, and Table 2 [42].The woody biomass was chipped to appropriate sizes and then dried with moisture less than 20% on wet basis. The Higher Heating Value for different biomass is calculated with established co-relation using Carbon, Hydrogen, Nitrogen, and Oxygen weight fraction. These results were obtained using a CHN Analyser (PerkinElmer precisely, Series II, CHNS/O Analyser, 2400). Producer gas compositions at variable feed stock moisture contents (5 to 20) % were determined by Gas Chromatogram (Thermo fisher: Trace: 600, Fig. 6).

Fig.1.(a)Bamboo

Fig.1.(b) Gulmohar

Fig.1.(c) Neem

Fig.1.(d) Neem

Fig.1.(e) Shisham

Table 1. Ultimate analysis of five-biomass samples

Feedstock	C% by weight	H% by weight	N% by weight	O% by weight
Bamboo	48.39	5.86	2.04	39.21
Gulmohar	44.43	6.16	1.65	41.90
Neem	45.10	6.00	1.70	41.50
Dimaru	44.85	5.98	1.65	41.84
Sisham	45.85	5.80	1.60	40.25

Table 2.Proximate analysis of five-biomass sample

Feedstock	Volatiles % db	Ash % db	Fixed Carbon % db
Bamboo	80.30	4.50	15.20
Gulmohar	81.25	5.50	13.25
Neem	81.75	5.60	12.65
Dimaru	82.00	5.80	12.20
Sisham	80.00	4.60	15.40

From ultimate analysis (Table 1.) of above biomass samples, it was found that *bamboo* had highest carbon by weight (48.39 %) and Nitrogen (2.04 %). Hydrogen and Oxygen contents were comparatively higher in *Gulmoha*r. Results of proximate analysis (Table 2) show that *Dimaru* has highest percentage of volatiles (82.00% db) and ash content of 5.80% on dry basis. The moisture content is same in all biomass samples.

The calorific values of the samples were obtained in an adiabatic constant volume bomb calorimeter (Make: Changsha, China, Model: 5E-AC8018, Range: Maximum 40 MJ kg-1 (Fig.7), Temperature Resolution: 0.0001, Analysis time: 15 min). The lower heating value of *Bamboo* sample was measured 18.4 MJ kg^{-1}, *Gulmohar* 16.20 MJ kg^{-1}, *Neem* 16.60 MJ kg^{1}, *Dimaru* 15.95 MJ kg^{-1}, *Shisham* 17.15 MJ kg^{-1} respectively. It has been observed that lower heating value was highest for bamboo species compared to other woody biomass for same moisture contents. The gross calorific values of biomass (Higher heating value) fuels usually vary between (18-22) MJ kg^{-1} (db). The following empirical relation may be used to compute theoretical GCV of a typical biomass [43].

$$GCV = 0.3491X_C + 1.1783X_H + 0.1005X_S - 0.0151X_N - 0.1034X_O - 0.0211X_{ash}\ [MJ\ kg^{-1}\ db] \quad (19)$$

Where X_i is the contents of Carbon, Hydrogen, Sulphur, Nitrogen, Oxygen and ashes in wt % (wb) and it is clear from the formula that C, H and S contribute positively for heating value and N, O and ash contents affect negatively to the heating value. The net calorific value may be calculated from the following correlation.

$$NCV = GCV\left[\left(1 - \frac{w}{100}\right)\right] - 2.44\frac{w}{100} - 2.444\frac{h}{100}8.936\left(1 - \frac{w}{100}\right)\ MJ\ kg^{-1}\ wb \quad (20)$$

Where *w* is moisture content of fuel in wt % (wb) and *h* is concentration of hydrogen in wt % (db).

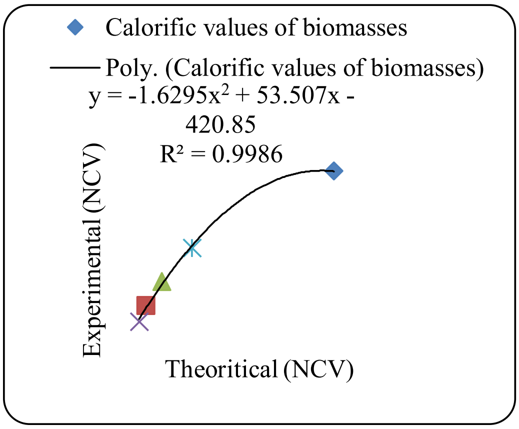

Fig. 2. Studies of theoretical and experimental (NCV)

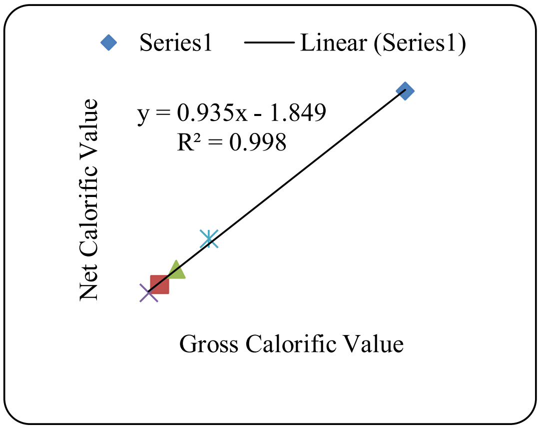

Fig.3. Variation of GCV and NCV

Fig.2. represents variation of theoretical net heating value and experimental values for the all samples. The relationship may be best described with the curve fitting expression:

$$[NCV]_{exp.} = -1.692(NCV)^2_{theor} + 53.50(NCV)_{theor}) -420.8 \quad (21)$$

Fig.3 shows variation of gross calorific value with net calorific value. It is clear from curve fitting that the relationship between the two variables follows liner relationships given by the Eq. (22). The relationship between net calorific value and gross calorific value is linear with slope equals to 0.935.

$$NCV = 0.935GCV -1.849 \quad (22)$$

3.2Modelling results

It was observed from that the composition of hydrogen in the fuel gas for all biomass samples had increased continuously with the moisture content [Fig. 4. (a) to Fig.4 (e)]. A similar increasing trend was also observed for the carbon dioxide. However, the percentage of carbon monoxide reduced for the same variation of moisture content for all samples. Theses all variations were obtained at a temperature of 850° C. The experimental down draft gasifier is shown in Fig. 5.

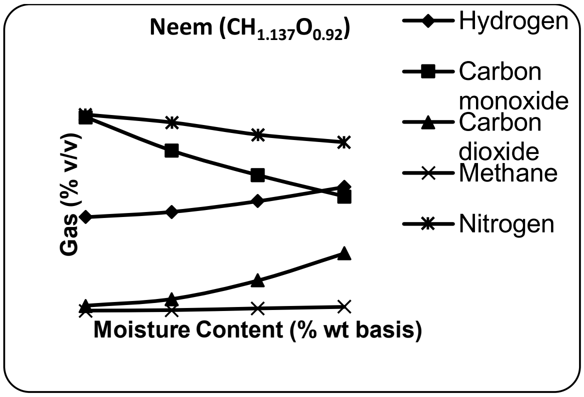

Fig. 4.(a) Gas composition with moisture (Neem)

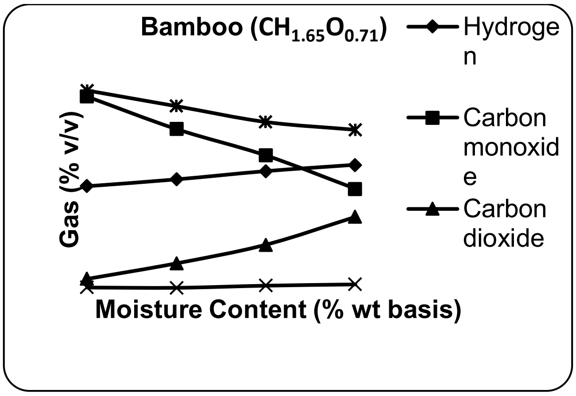

Fig. 4.(b) Gas composition with moisture (Bamboo)

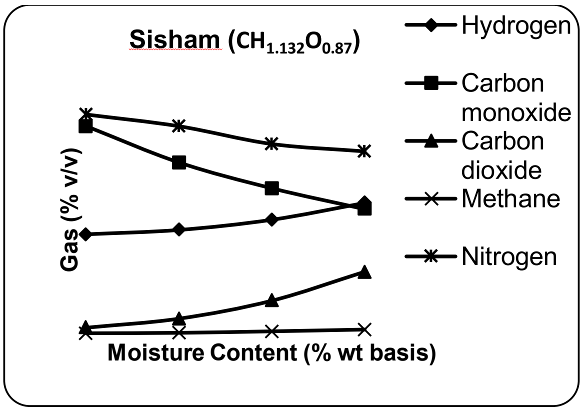

Fig. 4(c) Gas composition with moisture (Shisham)

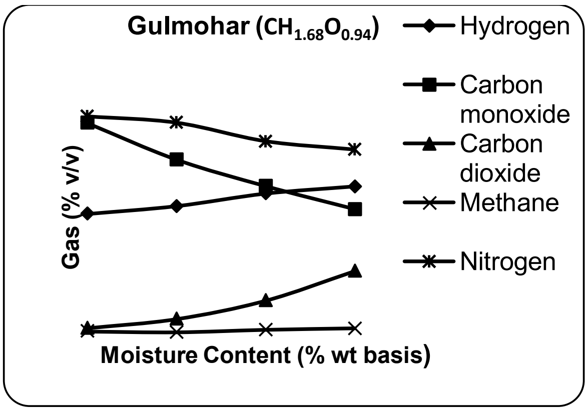

Fig. 4.(d) Gas composition with moisture (Gulmohar)

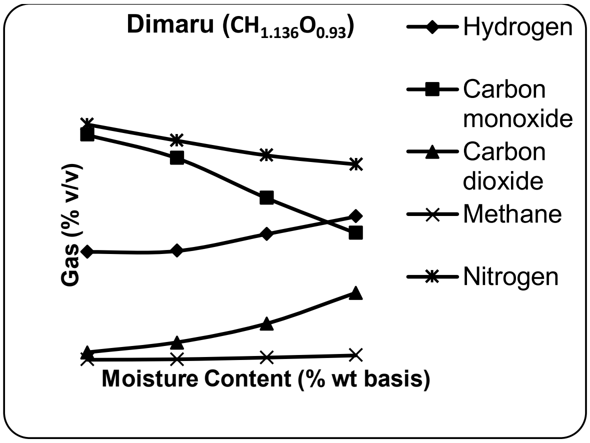

Fig. 4.(e) Gas composition with moisture (Dimaru)

Fig. 5. Downdraft gasifier experimental setup

Fig.6 Gas chromatograph

Fig.7. Automatic bomb calorimeter

Table 3a. Experimental gas composition of *Neem* with feed stock moisture

Moisture (db)	ER	CO	H_2	CO_2	CH_4	N_2	Gas flow rate (Nm^3/h)
5	0.3	19.2	17.5	10.3	1.2	51.5	10
10	0.3	19	17.6	10.5	1.25	51.3	10
15	0.3	18.7	17.8	10.8	1.25	51	10
20	0.3	18.5	18.2	11	1.35	50.5	10

Table 3b. Experimental gas composition of *Bamboo* with feed stock moisture

Moisture	ER	CO	H_2	CO_2	CH_4	N_2	Gas flow rate (Nm^3/h)
5	0.3	20.5	17.8	10.5	1.15	48.5	10
10	0.3	20.2	18	10.8	1.15	48	10

15	0.3	20	18.5	11	1.25	47.5	10
20	0.3	19.5	18.8	11.2	1.25	46	10

Table 3c. Experimental gas composition of *Shisham* with feed stock moisture

Moisture	ER	CO	H_2	CO_2	CH_4	N_2	Gas flow rate (Nm^3/h)
5	0.3	20.2	18	11	1.20	49.1	10
10	0.3	20	18.5	10.9	1.20	48.8	10
15	0.3	19.5	18.5	11.5	1.25	48.6	10
20	0.3	19	19	11.4	1.30	48.9	10

Table 3d. Experimental gas composition of *Gulmohar* with feed stock moisture

Moisture	ER	CO	H_2	CO_2	CH_4	N_2	Gas flow rate (Nm^3/h)
5	0.3	18.5	17	10.7	1.2	52.4	10
10	0.3	18.5	17	10.8	1.25	52.3	10
15	0.3	18.2	17.5	11	1.25	51.8	10
20	0.3	18	17.5	11.5	1.35	51.5	10

Table 3e. Experimental gas composition of *Dimaru* with feed stock moisture

Moisture	ER	CO	H_2	CO_2	CH_4	N_2	Gas flow rate (Nm^3/h)
5	0.3	17.5	16.5	11.5	0.85	53	10
10	0.3	17.5	16.5	11.5	0.88	52.3	10
15	0.3	17	17	12	0.88	52.5	10
20	0.3	17	17	12	0.95	52.5	10

Modelling results reveal that*bamboo* yielded producer gas composition CO (24.28 %), H_2 (21.43 %), CH_4 (0.78 %), CO_2 (8.19 %) and N_2 (44.99 %) at feedstock moisture of 20 percentage. The corresponding minimum values for *Dimaru* was CO (23.92 %), H_2 (18.59 %), CH_4 (0.52 %), CO_2 (7.56 %) and N_2 (49.13 %) respectively. It was observed that yield of Hydrogen content was more for *Gulmohar* when moisture content increased, as compared to all other biomass. This might be because of more number of hydrogen fractions are available in *Gulmohar* (1.68 atoms). Variation of Hydrogen with moisture content has a linear trend in case of bamboo. Trend of Carbon mono-oxide for all biomass has almost same variation. Carbon di-oxide composition increases with increase in moisture content. The corresponding experimental producer gas compositions have been presented in (Table 3a-3e) for feed stock moisture of (5, 10, 15 and 20) % respectively at constant air fuel equivalence ratio (ER) and output gas flow. It is clear from these tables that the experimental and modelled producer gas compositions are fairly in agreement. However, actual production of CO is somewhat less that the predicted may be because of combustion of a fraction of CO in combustion zone of gasifer at higher woody biomass moisture level.

4. Conclusions

- The present paper investigated the fuel characteristics of five locally available biomass samples. Ultimate analysis results show that *Bamboo* has highest Carbon percentage (48.39 %) by weight and from proximate analysis it is found that, *Dimaru* has highest volatile matter (82.00 % db).
- It was observed that *Bamboo* samples had highest calorific values (18.4 MJ kg^{-1}) and *Dimaru* had minimum (15.95 MJ kg-1) for same moisture. Out of four main types of woody biomass, *Shisham* gave maximum calorific value (15.15 MJ kg^{-1}).

- Gasification of these chipped feed stocks gave producer gas yields similar to a commercially available wood gasification as per manufacturer specification.
- Modelling studies observed that H_2 and CO_2 composition had increased and a decreasing trend was seen for CO and N_2 when moisture content varies from (0-30) % for all above samples. CH_4 variation is almost same for all biomass samples with moisture content varying from (0-30) percentage.
- *Bamboo* gave maximum yield of all gaseous constituents (H_2 = 21.43 %, CO = 24.28 %, CH_4 = 0.78 % at 20 % moisture) contributing to calorific value of producer gas. The corresponding minimum values for *Dimaru*were (H_2 = 18.59 %, CO = 23.92 %, CH_4 = 0.52 % at 20 % moisture). However, increase of H_2 content was more in case of *Gulmohar* as compared to all other samples probably because of more Hydrogen fraction (1.68) was available against one atom of carbon in molecular formula ($CH_{1.68}O_{0.94}$). The gaseous fuel compositions generated from other three biomasses were in between *Bamboo* and *Dimaru*.
- Experimental results of producer gas compositions (H_2 = 18.80 %, CO = 19.5 %, CH_4 = 1.25 moisture for Bamboo and H_2 = 17.00 %, CO = 17.00 %, CH_4 = 0.95 for Dimaru at 20 % moisture) were fairly in good agreement with modelling results at feed stock moisture contents (5, 10, 15, and 20) % respectively.

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