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Biomass Gasification: A Modern Approach for Renewable Energy Utilization

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Abstract

The World is facing crucial time for energy due to consumption of fossil fuels (natural gas, coal, and oil), rise in fuel price, and unacceptable environmental effect in recent years. Biomass is a renewable potential energy source which can reduces dependency on fossil fuels. Biomass is available in various forms throughout year in India. It accumulates solar energy by photosynthesis method from sunlight. Gasification is a chemical process that converts carbonaceous material such as biomass and coal into gaseous fuel or chemical feedstock. This gaseous fuel is known as producer gas or syngas which contains CO2, H2, CO, H2O, CH4 and N2 compounds. An attempt has been made to give basic idea about gasification, gasification mechanism, types of gasifier and characteristics of different biomass in this paper.
Keywords- Gasification, Biomass, Gasification Mechanism, Gasifier

I. INTRODUCTION

Gasification is a thermo chemical approach, explored by Thomas Shirley in 1659. The final product of gasification is known as producer gas which is made up mainly of hydrogen, carbon monoxide, methane, carbon dioxide, nitrogen and small amount of hydrocarbon compounds [6]. Producer gas can be utilized to run internal combustion engine or can be used as a fuel for furnace [11]. During 1973, OPEC organization banned oil exports to the western countries and USA, which created a strong motivation to develop alternative technology such as gasification to cut down reliability of imported oil. Gasifier was extensively used for the farm systems and transportation during World War II [6].

Coal and biomass are the popular feedstock for the various gasifiers.

The overall biomass resources can be broadly categorized into:

1) Agricultural: sugarcane bagasse, food grain, corn stalks, straw, bajra stalks, cashew nutshells, rice hulls, rice straw, sweet sorghum stalks, cotton stalks, and manure from cattle.
2) Forest: bamboo, sawdust, gulmohar, neem, wood waste, shisham bark, dimaru, timber slash, and mill Scrap.
3) Municipal: sewage sludge, food waste, refuse-derived fuel (RDF), paper.
4) Biological: biological waste, algae, water plant, animal waste.

II. GASIFICATION PROCESS

A. Air Gasification

Air is used as a gasifying agent in this gasification process. Surplus char which is formed from pyrolysis process is heated by supplying limited amount of air in the gasifier. Temperature of the reactor is reliable on the feedstock feed rate and air flow rate. Higher tar and lower gas is produced by supplying low inlet air. Lower heating gas (3 - 7 MJ/Nm^3) is produced which is appropriate for engine and boiler application [11][13].

B. Steam Gasification

Steam is utilized only as a gasifying agent, exterior heat source is needed and it will produce carbon dioxide and hydrogen by reacting with carbon monoxide. Water gas shift reaction is the basic reaction in the steam gasification which is as below:

$$CO+H_2O \rightarrow CO_2+H_2 \qquad (2)$$

Steam gasification yields producer gas having higher heating value as compared to air gasification [13].

C. Oxygen Gasification

Oxygen is utilized as a gasifying agent, available from plant or nearby source. Medium heating gas (12 - 21 MJ/Nm^3) is achieved through this gasification. Capital cost of the plant installation is higher [10].

D. Hydrogen Gasification

Hydrogen is utilized as a gasifying agent to convert biomass feedstock into gaseous products under higher pressure. It is unfavourable process [13].

Gasifying agent	*Gasification products*	*Gas heating value (MJ/m^3)*	*Advantages*	*Disadvantages/Limitations*
Air	*CO, CO_2, H_2, CH_4, N_2, Tar*	*~ 5*	– *Moderate tar and char content*	– *Low heating value of gas* – *Large number of N_2 (>50% by volume)* – *Gas suitable only for boiler and engine applications* – *Gas transportation through pipeline is difficult* – *Gas utilization problem can arise in combustion, particularly in gas turbine*
Oxygen	*CO, CO_2, H_2, CH_4, Tar*	*~10-12*	– *Moderate heating value of gas*	– *Additional cost of providing and using oxygen*
Steam	*CO, CO_2, H_2, CH_4, Tar*	*~15-20*	– *High heating value of gas,* – *H_2 rich syngas*	– *Lower overall efficiency due to loss of carbon in the second reactor* – *High tar content in syngas* – *Require catalytic tar reforming*

III. GASIFICATION MECHANISM

Drying, pyrolysis, gasification and oxidation are the four main zones in the gasifier depending upon the relative movement of gasifying agent and feedstock [28]. Different temperature and different reactions occurred in the different zones. Each zone is relying up on feedstock, gasifying agent, temperature, particle size, moisture content, and chemical composition.

A. Drying Zone

It receives energy from the other zones through heat transfer to reduce moisture content up to 5%. Drying process occurred at 100 ºC -150 ºC. Chemical reaction is not taking place in this zone [6].

B. Pyrolysis Zone

It is known as DE volatilization zone and process occurred in this zone at 150°C-700°C. DE volatilization of feedstock is occurred due to the heat transfer from reduction zone. Higher temperature difference occurred due to hot gases and cold feedstock. Thermal and physical properties of biomass feedstock are changed due to higher temperature. Gases, liquid (oil and tars), and char are the products of this zone [13].

C. Oxidation Zone

It is known as combustion zone. In this zone, feedstock carbon is burned through oxygen. Temperature of the zone is at 700°C to 1500°C which is highest among all zone and exothermic reactions are occurred in this zone. Air which is gasifying agent is entered in this zone into the biomass feedstock bed. Carbon dioxide proportion is increased and oxygen percentage is decreased while using air as gasifying medium [28]. Following chemical reactions take place:

$$C+O_2\text{------------>}\ CO_2\ -401.9\ kJ/mol \qquad (3)$$

$$H+1/2O_2\ \text{-------->}H_2O\text{-}241.1\ kJ/mol \qquad (4)$$

D. Gasification Zone

It is known as reduction zone. temperature of this zone is from 800°C to 1100°C. Reaction are mostly endothermic as follows [9] :

Reaction 1: $C+H_2O\ \text{-------->}CO+H_2+\ 131\ kJ/mol$ (5)

Reaction 2: $C+CO_2\text{--------->}2CO+\ 172\ kJ/mol$ (6)

Reaction 3: $CO+H_2O\ \text{------->}CO_2+H_2\text{-}41.2\ kJ/mol$ (7)

Reaction 4: $C+2H_2\text{--------->}CH_4\text{-}74.8\ kJ$ (8)

IV. GASIFIER TYPES

Based on relative displacement of feedstock or gasification agent, fluidized bed and fixed bed are the main two type of gasifier [6] [10] [13].

A. Fixed Bed Gasifier

In this type of gasifier, bed remains fixed. Design of reactor is simple in the comparison with fluidize bed. It is applicable for power generation. Temperature of this type of gasifier is variable. Updraft, cross draft and downdraft are the main three types of gasifier.

1) Updraft Gasifier

It is known as counter current gasifier because gasifying agent is inserted at bottom and proceed from bottom to top while feedstock proceed from top to bottom. The feedstock descends through drying, pyrolysis, reduction and oxidation zone. Producer gas is dispersing from the top side while ash is removed from bottom side. The product gas restrains more CO, but low CH_4, acetylene and ethane than product gas from the other gasifiers. It has high thermal efficiency. Lower heating value is 5-6 Mj/Nm^3. Tar production level is 50 g/Nm^3 [6].

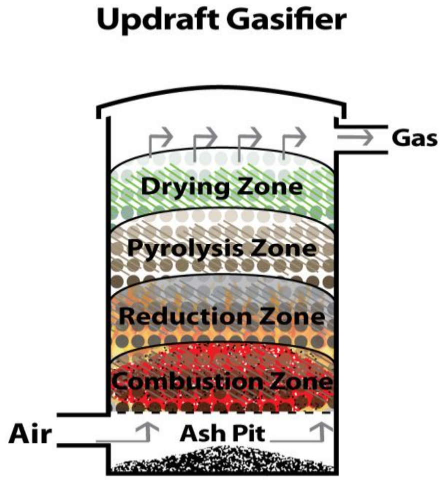

Fig. 1: Updraft Gasifier

2) Downdraft Gasifier

Location of the reduction zones and oxidation are interchanged. The biomass feedstock descends through drying, pyrolysis, oxidation and reduction zone. Gasifying agent is inserted at side of the reactor while biomass feedstock proceeds from top to bottom. Producer gas is dispersing from the bottom side, Lower heating value is 4.5-5 Mj/Nm^3 and Tar production level is 1 g/Nm^3 [10].

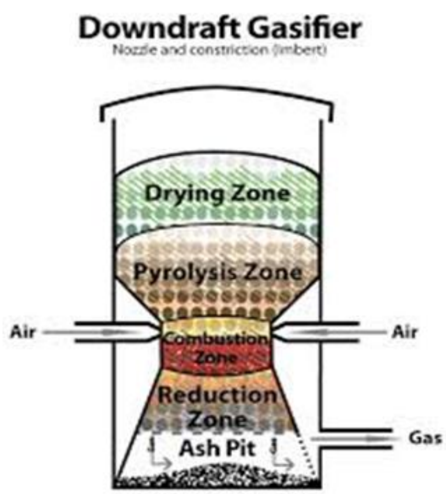

Fig. 2: Downdraft Gasifier

3) Cross Draft Gasifier

Gasifying agent is inserted from side of the reactor near bottom part while producer gas is available from opposite side. The reduction and oxidation zones are both having small volume. Lower heating value is 4-4.5 Mj/Nm^3. Tar production level is 0.01–0.1 g/ Nm^3.

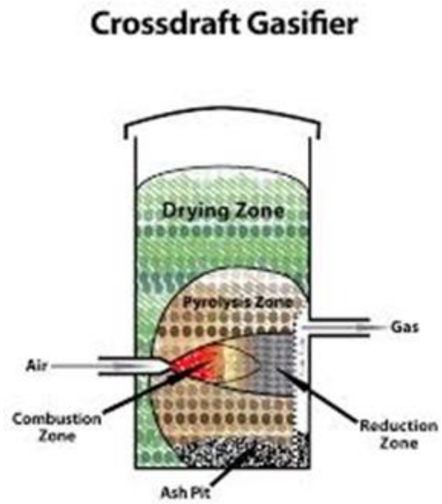

Fig. 3: Cross Draft Gasifier

B. Fluidized Bed Gasifier

Drying process, pyrolysis process and gasification process are occurred simultaneously inside in the reactor. It is classified according to the configuration and velocity of the gasifying agent, e.g. bubbling, circulating. Silica is used in the form of granular solids, called bed materials. It can be useful for coal gasification [6].

1) Bubbling Fluidized Bed Gasifier

It was discovered by Fritz Winkler in 1921 having two types- high-temperature and low temperature. Biomass pulverizes up to less than 10 mm is inserted into a bed of hot materials. It can be performed at elevated or atmospheric pressures. Bubbling fluidized bed work at below 1 m/s gas velocity. It can be suitable for power production up to <25 MWth. Cold gas efficiency is up to 90% [10].

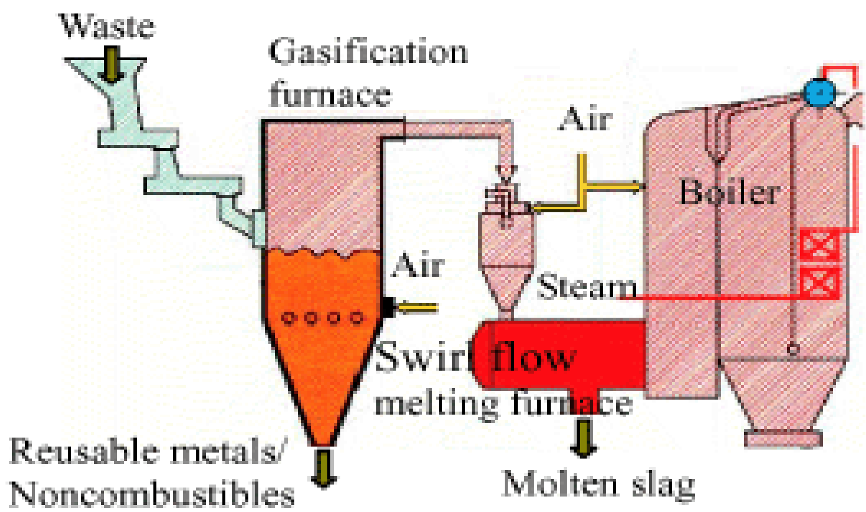

Fig. 4: Bubbling Fluidized Bed Gasifier

2) Circulating Fluidized Bed Gasifier

In this type of gasifier, circulating bed work at 3-10 m/s gas velocity. Biomass pulverizes up to less than 06 mm is inserted into a bed of hot materials. Tar concentration is up to 8 g/Nm^3 (lower than BFB). Cold gas efficiency is up to 96%. It provides long residence time. It is applicable for high volatiles fuels [13].

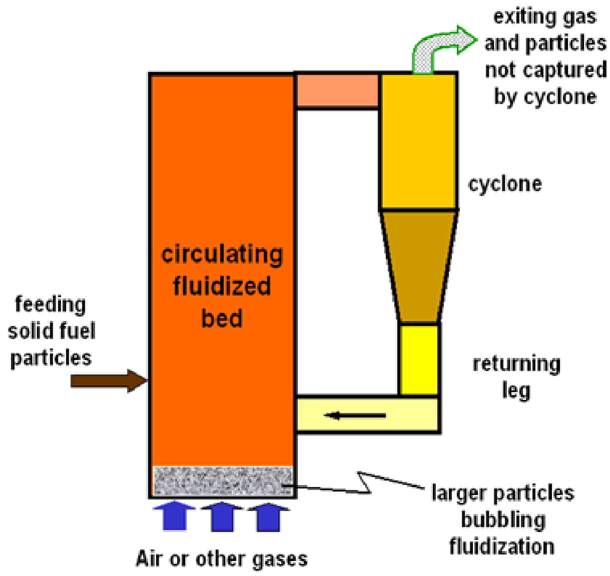

Fig. 5: Circulating Fluidized Bed Gasifier

V. PROPERTIES OF BIOMASS

A. Proximate Analysis

it is used to measure moisture content (M), Ash content (A), Volatile Matter(VM), Fixed carbon content(FC) of biomass using standard ASTM tests [6]. Proximate and ultimate analysis measured same value for moisture and ash content. But for fixed carbon it is differ. Carbon does not include in the volatile matter but taken as the char product after DE volatilization in proximate analysis.

1) Moisture Content

Biomass holds moisture content internally by its nature, and externally in which moisture content is absorbed from the surrounding environment [28]. It is the percentage volume of water, expressed as a part of the biomass's weight fraction. ASTM (American society for testing and materials) Standards E-871 representing wood; E-949 representing Refuse-derived fuel (RDF); D-3173 representing coal are used for measuring moisture content. It can be referred as on dry ash free and on wet basis [6].

The wet-basis moisture is describing by Moisture content wet (MCW) = (weight of wet - weight of dry)/ weight of wet and dry weight basis is describe by Moisture content dry (MCD) = (weight of wet - weight of dry)/ weight of dry. Wet and dry moisture content is convertible through following relation Moisture content dry= Moisture content wet/ (1- Moisture content wet) and Moisture content wet = Moisture content dry / (1+ Moisture content dry) [11].

Table 1: Moisture content of biomass on wet basis [6][11]

Biomass	*Bagasse*	*Corn Stalks*	*Municipal refuse*	*Peat*	*Rice Straw*	*Rice Husk*	*Woody biomass dry*	*Woody biomass green*
Moisture (wet basis)	*70*	*40-60*	*35*	*90*	*50–80*	*7–10*	*15*	*40-60*

Table 2: Moisture content of biomass on dry basis [6][11]

Biomass	*Bagasse*	*Leather residue*	*Municipal refuse*	*Peat*	*Rubber wood*	*Sawdust wood*	*Woody biomass green*	*Woody biomass dry*
Moisture (dry basis)	*230*	*11.23*	*55*	*900*	*18.5*	*11*	*67-150*	*17*

2) Ash Content

Ash content is the inorganic residue left as solid form after entirely biomass combustion. It is indicated on dry basis. D-1102 representing wood, D-3174 representing coal and E-1755-01 representing other biomass are used for measurement of ash content [6]. Silica, aluminum, iron, and calcium are the prime constitutes for ash content and, magnesium, potassium, titanium, phosphorus, sodium are also in small amount to be present in it. Agglomeration, corrosion, fouling problem arise due to ash content.

Table 3: Ash content in biomass [6][11]

Biomass	*Bamboo*	*Neem*	*RDF*	*Rice husk*	*Rice straw*	*Sawdust*	*Sewage*	*Sisham*
Ash(% dry basis)	*4.50*	*5.60*	*13.9*	*15.5*	*19.2*	*1.0*	*26.5*	*4.60*

3) Volatile Matter

When the biomass is combusted (400-500°C), volatile matter release in the form of condensable and no condensable. Aggregation of volatile matter depends upon temperature and heating rate. E-872 representing for wood fuels and D-3175-07 representing for coal and coke tests are used for the measurement of volatile matter [6]. Biomass has higher (up to 80 percent) and coal has lower (less than 20 percent) volatile matter.

Table 4: Volatile Matter in biomass [6][11]

Biomass	Brown paper	Coconut husks	Lignite coal	Mangrove wood	Poplar wood	Sugarcane bagasse	Wheat straw
Volatile Matter	89.1	48.13	43	40.55	75	75.8	72

4) Fixed Carbon

It is measured in biomass by this equation

$$\text{Fixed Carbon(C)} = 1 - \text{M (moisture)} - \text{VM (volatile matter)} - \text{ASH} \tag{9}$$

Gasification rate and its output are measured through the conversion process of fixed carbon and slower conversion reaction is used to measure size of gasifier. Fixed carbon amount is equal to char yield in biomass like wood. With the rise in fixed carbon content, flaming pyrolysis zone temperature also increase the. So fixed carbon content more than 30% are not desirable [11].

Table 5: fixed carbons in biomass [6][11]

Biomass	Cahsewnut sell char	Cedar	Coconut husks	Lignite coal	Magazine paper	Mangrove wood	Sugarcane bagasse
Fixed carbon	19.26	13.1	40.73	46.6	7.3	40.46	11.35

B. Ultimate Analysis

It is the determination of element proportion, Hydrogen/ Carbon and Oxygen/ Carbon ratio in biomass feedstock [11]. It is relatively complex and overpriced as correspond to proximate analysis due to laboratory apparatus and highly experienced analysts. Carbon + Oxygen + Hydrogen + Nitrogen + ASH + Sulfur + MOISTURE = 100% in biomass. Carbon, hydrogen is measured by E-777 for RDF, Nitrogen is measured by E-778 for RDF, Sulfur is measured by E-775 for RDF, Moisture is measured by E-871 for wood fuels, Ash is measured by D-1102 for wood fuels [6].

Table 6: Ultimate analysis of different biomass [6][11]

Sr.No	Material	C (%)	H (%)	N (%)	S (%)	O (%)	Ash (%)	Ref
1	Animal waste	42.70	5.50	2.40	0.00	31.30	18.10	1
2	Bamboo	48.39	5.86	2.04	0.00	39.21	4.50	25
3	Cashew nutshell (CNS)	48.70	6.96	0.36	0.00	43.98	1.00	23
4	Charred Cashew nutshell (CNS)	63.00	3.60	6.40	0.00	27.00	6.00	23
5	Coal	61.10	3.00	1.35	0.40	8.80	22.10	11
6	Coconut husks	39.49	6.07	0.40	0.06	49.51	4.47	6
7	Coconut shell	50.20	5.70	0.00	0.00	43.40	-	8
8	Coir pith	44.00	4.70	0.70	0.00	43.40	-	8
9	Corn stalks	43.80	6.40	0.00	0.00	49.80	2.40	11
10	Dimaru	44.85	5.98	1.65	0.00	41.84	5.80	25
11	Grape marc	52.91	5.93	1.86	0.03	30.41	8.81	20
12	Grape stalks	46.143	5.737	0.366	0.00	37.59	10.16	20
13	Gulmohar	44.43	6.16	1.65	0.00	41.90	5.50	25
14	Ground nutshell	48.30	5.70	0.80	0.00	39.40	5.90	1
15	Mangrove woods	52.09	8.09	0.03	0.07	31.71	8.00	6
16	Municipal waste	47.60	6.00	1.20	0.30	32.90	12.00	31
17	Municipal solid waste	30.30	3.40	1.40	0.00	35.80	29.10	11
18	Neem	45.10	6.00	1.70	0.00	41.50	5.60	25
19	Oil palm fronds	48.43	8.32	0.34	0.02	35.93	6.96	6
20	Paddy husk	38.50	5.70	0.50	0.00	39.80	15.50	31
21	Paper	43.40	5.80	0.30	0.20	44.30	6.00	31
22	Peach pit	53.00	5.90	0.32	0.05	39.14	1.59	20

23	Pine sawdust	50.00	5.70	0.17	0.03	44.10	0.00	6
24	Rapeseed straw	44.50	5.50	0.00	0.00	49.40	4.00	11
25	Rice husk	36.42	4.91	0.59	0.00	35.88	22.20	4
26	Rice straw	39.20	5.10	0.60	0.10	35.80	19.20	6
27	Rubber wood	50.60	6.50	0.20	0.00	42.00	0.70	18
28	Saw dust	52.00	6.07	0.28	0.00	41.55	0.10	18
29	Sewage sludge	29.20	3.80	4.10	0.70	19.90	42.10	6
30	Sisham	45.85	5.80	1.60	0.00	40.25	4.60	25
31	Subabul	42.76	5.68	1.07	0.00	49.29	1.20	4
32	Sugarcane bagasse	45.78	5.43	0.20	0.07	45.84	2.69	27
33	Sugarcane leaves	39.81	5.50	0.19	0.00	46.80	7.70	27
35	Sunflower stalks	42.60	5.50	0.00	0.00	51.70	9.60	11
35	Wood	50.00	6.00	0.00	0.00	44.00	0.00	31

C. Heating Value
It is the amount of the heat produced during entire combustion. Experimental process and unified correlation method are used for measuring heating value [28]. Heating value of biomass feedstock is influenced by its moisture content. It is categorized as higher heating value and lower heating value.

D. Equivalence Ratio
It is the ratio of fuel to air ratio to stoichiometric fuel to air ratio.

VI. DIFFERENT BIOMASS GASIFICATION RESEARCH

Bhavanam et al. [1] used equilibrium model for solid waste (municipal solid waste, agriculture, animal waste) gasification for the production of synthesis gas. Influence of reaction temperature in the gasification zone, moisture content and equivalence ratio of solid waste on gas composition measured. Solid waste's chemical composition was considered as CHxOyNz. Matlab with newton Jacobi iteration method was used for the calculation. Percentage of hydrogen increased (for MSW 10.32-10.67vol%, AW 13.21-14.29vol%) with the rise in moisture content (0-28wt%).At temperature 800°C-900° C, carbon monoxide and hydrogen is higher. At equivalence ratio 0.3, carbon monoxide and hydrogen content in the synthesis gas is highest. When equivalence ratio increased from 0.2 - 0.8, carbon monoxide and hydrogen content in the synthesis gas lowered.
Kumar et al. [2] used chir pine needle as a biomass feedstock in the downdraft gasifier.

Khadse et al. [4] Presented thermodynamic equilibrium model for the gasification of Saw dust, Bagasse, Subabul, Rice husk and measuring gross calorific values. Air and Steam used as a gasifying agent and gas is produced in the form of CO, CO_2, H_2 and CH_4. Gross calorific value of bagasse is maximum and Gross calorific value of subabul is minimum at lower temperature (<1000 K). At temperature higher than 1100 K, Gross calorific values remain constant for Saw dust, Bagasse, Subabul, Rice husk. At air 0.1 moles and steam/air=8, Saw dust, Bagasse, Subabul, Rice husk produce higher gross calorific values.

Koroneous et al.[19] used thermodynamic equilibrium model to measure percentage composition of producer gas from cotton stalks with moisture content 0-30% at 800°C.

Echegaray et al. [20] presented thermodynamic Equilibrium model for the gasification of peach pit, grape marc and grape stalk in fluidize bed gasifier. Air and mixed air-steam (gasifying agent) was used to measure ideal value of equivalence ratio (ER), moisture content, operating temperature, and steam to biomass ratio (SBR). The ideal value of equivalence ratio is 0.1 and when equivalence ratio is increased H_2 and CO contents decreases. The ideal value of moisture content is 30%.The ideal value of gasification temperature for the biomass (peach pit, grape marc and grape stalks) is between 650°C -750°C. The ideal value of steam to biomass ratio is 2.5 (at operating temperature 800°C, ER 0.1, moisture content 10%, steam temperature 400°C). Hydrogen production is more in air-steam gasification than air gasification.

Vaezi et al. [22] presented zero dimensional thermo chemical mathematical models based on equilibrium constants to find out correct biomass for certain units. And also studied range of variety of oxygen content and carbon/hydrogen ratio from ultimate scrutiny of 55 different biomasses. As rise in C/H ratio to about 8.2 tends to rise of higher heating value of produced gas. Highest cold gas efficiency is achieved with lowest oxygen content and C/H ratio. Average value of cold gas efficiency is 80% and doesn't fall down below 75% and carbon conversion efficiency is about to more than 86%. 9m^3 of syngas volume can be produced form 1kg of biomass.

Ramanan et al. [23] presented equilibrium model for the gasification of cashew nut shell char and measuring effect of equivalence ratio (ER), reaction temperature (RT) and moisture content (MC) on producer gas composition. For the gasification system equivalence ratio (ER) is taken between 0.15- 0.30 but when the equivalence ratio is lower than 0.15, model intimate inaccurate producer gas composition data. With the enlargement of equivalence ratio, ($H_2O + N_2$) and CO_2 are enhancing and H_2, CH_4 and CO are diminishing. With the enlargement of reaction temperature, H_2 and CO are enhancing and CH_4, (N_2+ H_2O) and CO_2 are diminishing. With the enlargement of moisture content, H_2, CH_4, CO_2 and (N_2+ H_2O) are enhancing and CO is diminishing. Dutta et al. [25] used five biomasses (Bamboo, gulmohar, neem, dimaru and shisham) in thermodynamic equilibrium model with downdraft throated gasifier. Gasification of bamboo gives highest producer gas components (H_2 = 21.43 %, CO = 24.28 %, CH_4 = 0.78 % at 20 % moisture) and gives highest calorific value (18.4 MJ/kg) and Dimaru gives minimum producer gas components (H_2 = 18.59 %, CO = 23.92 %, CH_4 = 0.52 % at 20 % moisture) and gives minimum calorific value (15.95 MJ/kg) for same moisture. When moisture content increase, H_2, CO_2 increase and CO, N_2 decrease.

Jorapur et al. [27] describe commercial scale (1080Mj/h) progress of a low density biomass (sugar cane bagasse, leaves, bajra stalks, sweet sorghum stalks) gasification system for thermal units.

Zainal et al. [31] used thermodynamic equilibrium model for the intimation of composition of producer gas for different biomass in downdraft gasifier and determined calorific value. The influence of moisture content in the wood and influence of temperature on calorific value in the gasification zone analyze. Newton raphson method is used to solve equation. With the rise in moisture content, calorific value of product gas decrease and with the rise in temperature, calorific value of product gas decrease.

VII. CONCLUSION

Biomass gasification strives against direct liquefaction, coal combustion, and biochemical conversion (fermentation).

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