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Biomass-based gasifiers for internal combustion (IC) engines—A review

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Abstract. The world is facing severe problems of energy crisis and environmental problem. This situation makes people to focus their attention on sustainable energy resources for their survival. Biomass is recognized to be the major potential source for energy production. There are ranges of biomass utilization technologies that produce useful energy from biomass. Gasification is one of the important techniques out of direct combustion, anaerobic digestion – Biogas, ethanol production. Gasification enables conversion of these materials into combustible gas (producer gas), mechanical and electrical power, synthetic fuels, and chemical. The gasification of biomass into useful fuel enhances its potential as a renewable energy resource. This paper gives a comprehensive review of the techniques used for utilizing biomass, experimental investigation on biomass fuels, characterization, merits, demerits and challenges faced by biomass fuels.

Keywords. Biomass; gasification; producer gas.

1. Introduction

A large population in the world are still not being serviced with energy needs at the minimum level even in the 21st century. This is true with the developing nations like India, Bangladesh, Sri Lanka, Pakistan, Latin American countries like Chile, Costa Rica, Brazil, etc., African countries like Zambia, Uganda, Zimbabwe, etc. and many others. Most of these countries are characterized by a large part of the population in scattered locales – in villages and hamlets. These remote locations make it uneconomical to extend the centralized grid. In addition, their economic structure is not strong towards importing oil for power generation applications. Further, the environmental considerations to reduce GHG have forced conservation of the use of fossil fuel. This has become one of the factors for the nations to reduce the use of fossil fuel and adopt suitable renewable energy device. In the renewable energy scenario dominated by solar, wind and micro/mini hydel, biomass is beginning to look promising in the view of new emerging technologies. Even though each of the above energy sources has a niche market, biomass has been playing a key role

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in the renewable energy sector. The modern bio-energy has received comparatively little fiscal and financial incentive unlike its counterpart, namely the solar photovoltaics. However, for reasons like the cost effectiveness and availability factor, biomass-based technologies are becoming popular as they have edge over other renewable. India is an oil-importing country, with nearly 70% of its population living in half million villages and hamlets across the country and rich in bio-resources is ideally suited for biomass-based technologies. The term biomass is used for all organic materials which are combustible in nature, mainly plant and animal origin present in land and aquatic environments. Biomass includes by-product and residue of crop farming and processing industries such as straw, husk, cobs, stalks, leaves, bark, fruits, cutting vines, etc., in addition to animal refuses and plant products used in agro-industrial processing such as grains, bean, flower and some special products such as cassava, seaweeds, etc. (Klass 1998; McKendry 2002; Rathore *et al* 2009).

With respect to global issues of sustainable energy and reduction in emission of greenhouse gases, biomass is getting increased attention as a potential for power generation. Biomass is not yet competitive with fossil fuels. Fossil fuel contributes to the major part of world's total energy consumption. According to the World Energy Assessment report, 80% of the world's primary energy consumption is contributed by fossil fuel, 14% by renewable (out of which biomass contributes 9.5%) and 6% by nuclear energy sources (McKendry 2002; Rathore *et al* 2009).

The process of gasification to produce combustible from organic feeds was used in blast furnaces over 180 years ago. The possibility of using this gas for heating and power generation was soon realized and there emerged in Europe producer gas systems, which used charcoal and peat as feed material. At the turn of the century, petroleum gained wider use as a fuel, but during both world wars and particularly World War II, shortage in petroleum supplies led to widespread re-introduction of gasification. By 1945 the gas was being used to power trucks, buses and agricultural and industrial machines. It is estimated that there were close to 9000,000 vehicles running on producer gas all over the world.

After World War II, the lack of strategic impetus and the availability of cheap fossil fuels led to general decline in the producer gas industry. Biomass gasifiers are being developed around the world today to produce CO_2 neutral energy. Gasification is a thermo chemical process where biomass is converted into a combustible producer gas. The main components in producer gas are N_2; H_2; CO; CO_2 and CH_4, and it is often used as fuel in an internal combustion (IC) engine (Bridgewater 2003). Gasification of woody biomass has been a well-known technology for more than five decades. Section 2 deals with biomass utilization, section 3 contains details on gasifiers. Sections 4 and 5 present review of past experiments and conclusion, respectively.

2. Biomass utilization techniques

There are wide ranges of biomass utilization technologies that produce useful energy from biomass.The commonly used techniques for utilizing biomass are elaborated below.

2.1 *Direct combustion*

Combustion, which is used in many applications, is the most direct process for converting biomass into usable energy. Since pre-historical inhabitants of this planet learnt how to make fire, they converted biomass to useful energy by burning wood in a fireplace or woodstove. Ever since the earliest inhabitants of this planet burned wood in their fireplaces, direct biomass burning has been a source of energy for meeting human needs until the present time. Direct combustion is a thermo chemical conversion process utilizing the major feedstock such as wood, agricultural waste, municipal solid waste.

The energy produced by direct combustion process is heat and steam. Despite its apparent simplicity, direct combustion is a complex process from a technological point of view. High reaction rates and high heat release and many reactants and reaction schemes are involved. In order to analyse the combustion process, a division is made between the place where the biomass fuel is burned (the furnace) and the place where the heat from the flue gas is exchanged for a process medium or energy carrier (the heat exchanger).

Properly designed industrial biomass combustion facilities can burn all types of above listed biomass fuel. In combustion process, volatile hydrocarbons (C_xH_y) are formed and burned in a hot combustion zone. Combustion technologies convert biomass fuels into several forms of useful energy for commercial and/or industrial uses. In a furnace, the biomass fuel converted via combustion process into heat energy. The heat energy is released in the form of hot gases to heat exchanger that switches thermal energy from the hot gases to the process medium (steam, hot water or hot air).

Direct combustion systems are of either fixed bed or fluidized-bed systems. Fixed-bed systems are basically distinguished by types of grates and the way the biomass fuel is supplied to or transported through the furnace. In stationary or travelling grate combustor, a manual or automatic feeder distributes the fuel onto a grate, where the fuel burns. Combustion air enters from below the grate. In the stationary grate design, ashes fall into a pit for collection. In contrast, a travelling grate system has a moving grate that drops the ash into a hopper.

Fluidized-bed combustors (FBC) burn biomass fuel in a hot bed of granular, non-combustible material, such as sand, limestone, or other. Injection of air into the bed creates turbulence resembling a boiling liquid. The turbulence distributes and suspends the fuel. This design increases heat transfer and allows for operating temperatures below 970°C, reducing NO_x emissions. Depending on the air velocity, a bubbling fluidized bed or circulating fluidized bed is created. The most important advantages (comparing to fixed bed systems) of fluidized-bed combustion system are:

- Flexibility to changes in biomass fuel properties, sizes and shapes
- Acceptance of biomass fuel moisture content up to 60%
- Can handle high-ash fuels and agricultural biomass residue (>50%)
- Compact construction with high heat exchange and reaction rates
- Low NO_x emissions
- Low excess air factor, below 1.2 to 1.4, resulting in low heat losses from flue gas.

Two cycles are possible for combining electric power generation with process steam production. Steam can be used in process first and then re-routed through a steam turbine to generate electric power. This arrangement is called a bottoming cycle. In the alternate cycle, steam from the boiler passes first through a steam turbine to produce electric power. The back-pressure (or extracted) steam from the steam turbine is then used for processes or for heating (or cooling) purposes. This arrangement is called a topping cycle, which is the more common cycle.

2.2 *Biomass gasification*

Gasification, production of combustible gas from carbon containing materials, is already an old technology. The first record of its commercial application origins from so called dry distillation (or pyrolysis – heating of feedstock in the absence of O_2, resulting in thermal decomposition of fuel into volatile gases and solid carbon) dates back to 1812 (Gas Company in London). The first attempt to use producer gas to fire the internal combustion engine was carried out in 1881. Biomass gasification was reintroduced during the World War II as the consequence of unavailability of petroleum. After the end of the war gasifier systems were substituted with engines driven by liquid fossil fuels again. It was not before the 1970s energy crisis when gasification came back for the third time through its history. Biomass gasification is other thermo chemical conversion process utilizing the following major feedstock: wood, agricultural waste, municipal solid waste.

Chemical process of gasification means the thermal decomposition of hydrocarbons from biomass in a reducing (oxygen-deficient) atmosphere. The process usually takes place at about 850°C. Because the injected air prevents the ash from melting, steam injection is not always required. A biomass gasifier can operate under atmospheric pressure or elevated pressure. The resulting gas product, the synthetic gas, contains combustible gases – hydrogen (H_2) and carbon monoxide (CO) as the main constituents; by-products are liquids and tars, charcoal and mineral matter (ash or slag). In general, the gasifying agent can be air, oxygen (O_2) or oxygen-enriched air. For biomass gasification, air is normally used as oxidant (oxygen as the oxidant agent is preferred in high capacity fossil fuel gasification systems). The net product of air gasification can be found by summing up the partial reactions, as follows:

$$\text{Carbohydrate matter } (C_6H_{10}O_5) + O_2 \rightarrow C_XH_Y + C_LH_MO_N + CO + H_2 + \text{Heat.}$$

The biggest advantage of gasification is the variety of feed stocks as well as products. The produced synthetic gas can be utilized not only as the fuel for power generation but also as the feedstock for chemical industry.

2.3 *Anaerobic digestion – Biogas*

As per records, Alessandro Volta first discovered biogas in 1776 and Humphrey Davy was the first to pronounce the presence of combustible gas methane in the farmyard manure in as early as 1800. Anaerobic digestion is a biological process that produces a gas principally composed of methane (CH_4) and carbon dioxide (CO_2), known as biogas. The biogas is produced from the following major organic wastes:

- Solid and liquid animal manure
- Agricultural plant waste
- Waste from agricultural products processing industry
- Organic components in town waste
- Waste waters
- Landfills.

Anaerobic digestion can be used to produce valuable energy from waste streams of natural materials or to lower the pollution potential of a waste stream. Biogas plant has a self-consumption of energy to keep the sludge warm. This is typically 20% of the energy production for a well-designed biogas plant. Anaerobic digestion is a complex biochemical reaction carried out in a number of steps by several types of microorganisms that require little or no oxygen to live. During the process of biogas, principally approximately 65% methane (CH_4) and about 30% carbon dioxide (CO_2), is produced. The amount of biogas produced varies with the amount of organic waste fed to the digester and temperature influences the rate of decomposition. Several different types of bacteria work in stages together, to break down complex organic wastes, resulting in the production of biogas. Controlled anaerobic digestion requires an airtight chamber, called a digester. A mixture of CH_4 with CO_2 is making up more than 90% of the total biogas composition. The remaining gases are usually smaller amounts of H_2S, N_2, H_2, methylmercaptans and O_2.

2.4 *Ethanol production*

Starch content of biomass feed stocks like corn, potatoes, beets, sugarcane, wheat, barley, and similar can be converted by fermentation process into alcohol (ethanol). Fermentation is the biochemical process that converts sugars into ethanol (alcohol). In contrast to biogas production, fermentation takes place in the presence of air and is, therefore, a process of aerobic digestion.

Ethanol producers use specific types of enzymes to convert starch crops such as corn, wheat and barley to fermentable sugars. Some crops, such as sugar cane and sugar beets, naturally contain fermentable sugars. Hydrolysis is the technology, which converts cellulose to alcohols through fermentation. Ethyl alcohol can be produced from a Variety of sugars by fermentation with years. Molasses is diluted with water to a sugar content of about 20% by weigh acidified to pH 4.5 and then mixed with yeast culture in a fermentor. Ammonia is used to reduce acidity. When 8–10 percent alcohol is accumulated, then liquid is distilled, fractionated and rectified 2.5 litres of cane molasses produces about one litre of alcohol.

Ethanol is easier to transport and store than hydrogen, fuel reforming (using a chemical process to extract hydrogen from fuel) may be a practical way to provide hydrogen to fuel cells in vehicles or for remote stationary applications. Latin America, dominated by Brazil, is the world's largest production region of bio-ethanol. As the value of bio-ethanol is increasingly being recognized, more and more policies to support development and implementation of ethanol as a fuel are being introduced.

Among all the alternatives of technology used, gasification is the best suitable alternative in view of the following points (Khan 2009):

- Gasification offers high flexibility in terms of various biomass materials as feedstock.
- Gasification has thermo-chemical conversion efficiencies in the range of 70% to 90%, which is highest among various alternative.
- Gasification output capacity, especially in the high output ranges, is controlled only by availability of adequate feed materials rather than technical consideration.
- The area requirement for gasification equipment is lowest per unit output of energy in the form of heat and/or electricity.
- The gasification equipment has high turn down ratios comparable to biogas and higher than steam turbine systems.

3. Gasifiers

The production of generator gas (producer gas) by gasification is partial combustion of solid fuel (biomass) which takes place at temperature of about 1000°C. The reactor is called a gasifier. The combustion products from complete combustion of biomass generally contain nitrogen, water vapour, carbon dioxide and surplus of oxygen. However in gasification where there is a surplus of solid fuel (incomplete combustion) the products of combustion are combustible gases like Carbon monoxide (CO), Hydrogen (H_2) and traces of Methane and non useful products like

Table 1. Significant differences between fixed bed and fluidized bed.

Fixed bed	Fluidized bed
(−) Higher investment (about 10%), two lines	(+) Lower investment
(−) Feedstock fines must be agglomerated	(+) No problems with feedstock fines
(−) Particle size as uniform as possible	(+) Broad particle size distribution
(+) Very great particle size possible (up to 100 mm)	(−) Limited Particle size (up to 50 mm)
(+) Nearly tar free gas	(−) Tar (1 g/m3n); high tar content in the gas
(+) High carbon conversion rate (90–99%)	(−) Low carbon conversion rate (90%)
(+) Discharge of liquid slag	(−) Ash fusion by low-softening ash

(+) indicates positive aspects; (−) indicates negative aspects

tar and dust. The key to gasifier design is to create conditions such that (i) biomass is reduced to charcoal and, (ii) charcoal is converted to CO and H_2 at suitable temperature to produce. Basically gasifiers are classified as fixed bed and fluidized bed type gasifiers similar to fixed bed or fluidized-bed systems in combustion technology. The significant differences concerned with these gasifiers are given below (Hindsgaul *et al* 2000) (table 1).

Since there is an interaction of air or oxygen and biomass in the gasifier, fixed bed gasifiers are classified according to the way air or oxygen is introduced in it. There are two types of gasifiers: downdraft and updraft. These are also called cocurrent and countercurrent, respectively (figure 1).

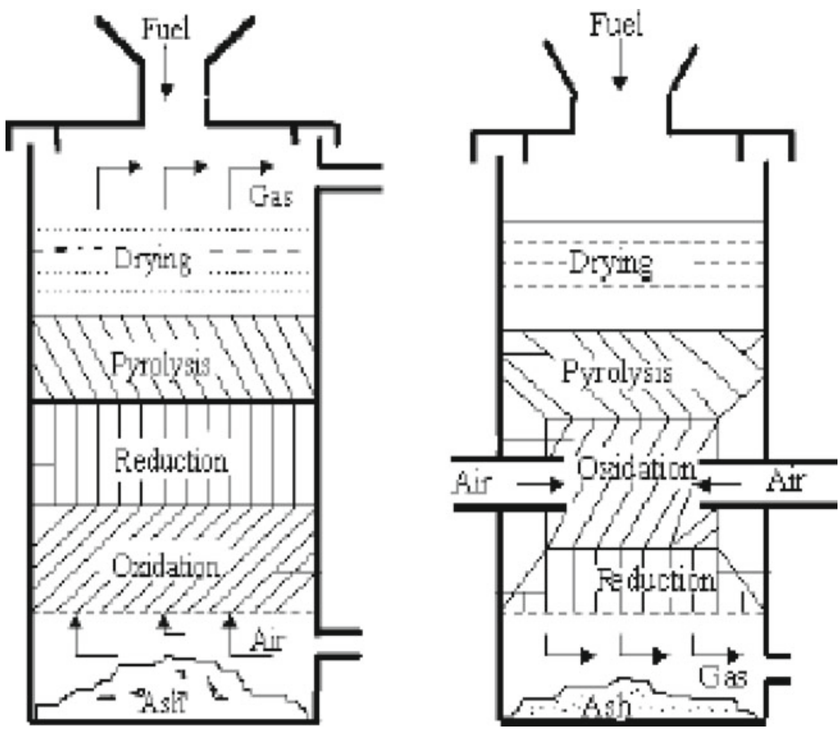

Figure 1. Updraft and downdraft gasifiers.

Table 2. Advantages and disadvantages of various fixed bed gasifiers.

S. No.	Gasifier type	Advantage	Disadvantages
1.	Updraft	Small pressure drop	Great sensitivity to tar and moisture and moisture content of fuel
		Good thermal efficiency	Relatively long time required for start up of IC engine
		Little tendency towards of slag formation	Poor reaction capability with heavy gas load
2.	Downdraft	Flexible adaptation of gas Production to load	Design tends to be tall
		Low sensitivity to charcoal dust and tar content of fuel	Not feasible for very small particle size of fuel

And as the classification implies updraft gasifier has air passing through the biomass from bottom and the combustible gases come out from the top of the gasifier. Similarly, in the downdraft gasifier the air is passed from the tuyers in the downdraft direction. With slight variation almost all the gasifiers fall in the above categories. The fuel, its final available form, its size, moisture content and ash content, dictates the choice of one type of gasifier over other. The advantages and disadvantages generally found for various classes of gasifiers are listed in table 2.

3.1 *Chemical reactions in the gasifier*

Gasification is a highly complex chemical process. Bridgewater described the gasification sequence as drying and evaporating processes of biomass followed by pyrolysis, and finally oxidation and reduction (Bridgewater 2003). However, the overall process can be reasonably described by the reactions described below (Bridgewater 2003; McKendry 2002).

$$Biomass \xrightarrow{heat(300\text{–}400^\circ C)} gases\,(CO,\, CO_2,\, H_2,\, light\ HC's) + pyrolysed\ vapors + char \tag{1}$$

$$Pyrolysed\ vapors \xrightarrow{(heat+high\ residence\ time)} gases\,(CO,\, CO_2,\, H_2,\, light\ HC's) \tag{2}$$

$$C + O_2 \leftrightarrow CO_2,\, \Delta H = -393.5\ kJ/mol \tag{3}$$

$$C + (1/2)\, O_2 \leftrightarrow CO,\, \Delta H = -110.5\ kJ/mol \tag{4}$$

$$C + CO_2 \leftrightarrow 2CO,\, \Delta H = 172.4\ kJ/mol \tag{5}$$

$$C + H_2O \leftrightarrow H_2 + CO,\, \Delta H = 131.3\ kJ/mol \tag{6}$$

$$C + 2H_2 \leftrightarrow CH_4,\, \Delta H = -74.8\ kJ/mol \tag{7}$$

$$CO + H_2O \leftrightarrow H_2 + CO_2,\, \Delta H = 41.1\ kJ/mol \tag{8}$$

$$CO + 2H_2 \leftrightarrow CH_4 + H_2O,\, \Delta H = 206.1\ kJ/mol. \tag{9}$$

Among the reactions described above, the char-oxidation (Eq. 3) and partial-oxidation (Eq. 4) reactions are slowest, and consequently the rate controlling factor in the overall gasification process (McKendry 2002). Pyrolysis also results in liquid which is resistant to the cracking due to temperature increase though most of the pyrolyzed liquid does so at higher temperature. This requires subsequent cleaning set-up for the tar, which can be a substantial investment in many cases (Bridgewater 2003).

3.2 *Gasifier fuel characteristics*

Almost any carbonaceous or biomass fuel can be gasified under experimental or laboratory conditions. However, the real test for a good gasifier is not whether a combustible gas can be generated by burning a biomass fuel with 20–40% stoichiometric air but that a reliable gas producer can be made which can also be economically attractive to the customer. Towards this goal the fuel characteristics have to be evaluated and fuel processing done.

A gasifier fuel can be classified as good or bad according to the following parameters.

3.2a *Energy content and bulk density of the fuel*: The higher the energy content and bulk density of fuel, the similar is the gasifier volume since for one charge one can get power for longer time (Livingston 2007; Ciolkosz 2010).

3.2b *Moisture content*: It is desirable to use fuel with low moisture content because heat loss due to its evaporation before gasification is considerable and the heat budget of the gasification reaction is impaired. Besides impairing the gasifier heat budget, high moisture content also puts load on cooling and filtering equipment by increasing the pressure drop across these units because of condensing liquid. Thus in order to reduce the moisture content of fuel some pretreatment of fuel is required. Generally, the desirable moisture content for fuel should be less than 20% (http://www.fao.org/docrep/t0512e/T0512e17.htm).

3.2c *Dust content*: All gasifier fuels produce dust. This dust is a nuisance since it can clog the internal combustion engine and hence has to be removed. The gasifier design should be such that it should not produce more than 2–6 g/m^3 of dust (Livingston 2007). The higher the dust produced, more load is put on filters necessitating their frequent flushing and increased maintenance (Warneck 2002; Ptasinski *et al* 2007).

3.2d *Tar content*: Tar is one of the most unpleasant constituents of the gas as it tends to deposit in the carburetor and intake valves causing sticking and troublesome operations. It is a product of highly irreversible process taking place in the pyrolysis zone. The physical property of tar depends on temperature and heat rate and the appearance ranges from brown and watery (60% water) to black and highly viscous (7% water). There are approximately 200 chemical constituents that have been identified in tar so far. A well-designed gasifier should put out less than 1 g/m^3 of tar (Warneck 2002; Ptasinski *et al* 2007).

3.2e *Ash and slagging characteristic*: The mineral content in the fuel that remains in oxidized form after complete combustion is usually called ash. Ash basically interferes with gasification process in two ways:

(i) It fuses together to form slag and this clinker stops or inhibits the downward flow of biomass feed.

(ii) Even if it does not fuse together it shelters the points in fuel where ignition is initiated and thus lowers the fuel's reaction response.

Ash and tar removal are the two most important processes in gasification system for its smooth running. Various systems have been devised for ash removal. In fact some fuels with high ash content can be easily gasified if elaborate ash removal system is installed in the gasifier. Only two fuels have been thoroughly tested and proven to be reliable. They are charcoal and wood. Besides with the present energy crisis where most countries do not have enough supply of wood it is advantageous and attractive to use agricultural residues. For the agricultural sector this is an extremely attractive alternative (Rathore & Panwar 2009).

3.2f *Biomass type*: Biomass elemental composition has a significant effect on syngas composition. The release of pyrolysis gas is highly dependent on hydrogen/carbon ratio as well as oxygen/carbon ratio and increases when these ratios increase, especially with an increase in hydrogen/Carbon ratio. A higher oxygen concentration in biomass needs lower ER for gasification because of its inherent oxygen that will also be available for gasification (Mishra *et al* 2010).

4. Review of past experiments

A large number of researches were carried out with biomass as a replacement of internal combustion (IC) engine fuel by researchers from various parts of the world. Most of these experiments were reported from US, Europe, India, Malaysia, China and Germany. A summary of these experimental results is given below.

Vyarawalla *et al* (1984) have designed and developed a 9 kW capacity biomass-based gasifier engine system for laboratory experiments and a field trail of nearly 1000 h for saw dust and toor stalks as biomass. They could achieve the diesel saving up to 75% by compression ignition type engines by producer gas from gasifier. A topless wood gasifier running a 3.75 kW diesel engine pump set for water pumping was tested and developed for wood by Rajvanshi & Joshi (1989). It was found that to produce 1 kWh of energy 1.33 Kg of wood and 125 ml of diesel were used and also economic analysis reveals that with a Low (60%) diesel substitution, gasifier system is economically on par with a diesel only fuel.

Parikh *et al* (1989) have compared the performance of direct injected and indirect injected diesel engine running with producer gas from downdraft biomass gasifier. They used Subabool tree (*Leucaena lecucocephala*) as a biomass sample. They achieved a diesel replaces of 68 to 80% at 80% of rated load by changing the volume of gas cooling – cleaning system. It has been established that dual fuel operation results in substantial increase in engine exhaust CO content more so at part load. Coffee husk as biomass for gasification was used to analyse the performance of diesel engine on dual fuel mode. It could achieve the maximum diesel replacement of 31% only. Krishna & Kumar (1994) suggested that this is due to clinkers formation and a low density of biomass. Jorapur & Rajvanshi (1997) suggested the commercial scale (1080 MJ/h) development of a low density biomass gasification system for thermal application. The gasifier can handle fuels like sugarcane leaves, bajra stalks, sweet sorghum stalks and bagasse, etc. From the results, it is demonstrated that low density biomass gasifier running on sugarcane leaves or bagasse can be successfully retrofitted to existing oil fired furnace/boilers in metallurgical and other industries, if the cost of biomass is less than Rs.1350 T^{-1} for capacity of 1080 MJ/h.

Availability of eight selected agricultural residues as raw material for biomass gasification in India with due consideration to their seasonal and geographical availability dimensions were discussed by Tripathi *et al* (1998). Biomass residues of arhar stalk, maize stalk, maize cobs, cotton stalk, mustard stalk, jute and mesta sticks, rice husk and groundnut shells have been assessed. It is reported that more than eight million tonnes of these residues were produced in the year with a primary energy potential of about 1200 Peta Joules. Cost estimates of biomass residues vary from Rs. 132/tonne to Rs. 628/tonne, depending on the agricultural residue cost and the transporting distance. These cost figures were much lower than the prevailing cost of coal in India. Hence, these agricultural residues may be profitably used as feedstock in biomass gasification and briquetting plants.

Martin *et al* (1997) studied the gasification of wood from the mill, which is integrated with a combined cycle for power production, as well as with the fuel synthesis. This combination makes better use of the gasifier, since the synthesised gas can be used to generate excess electricity during the winter season when electricity prices are high, whereas it can be used to produce transportation fuels at other times. The criteria for comparison of fixed bed and fluidized bed gasifier were worked out as technology, use of material, use of energy, environment and economy. A utility analysis for thermo chemical processes are studied also shows fixed bed gasifier is the best in the plants having 10 MW_{th} capacity and also they have high carbon conversion rate (99%) as compared to fluidized bed gasifier with nearly tar-free gas (Warneck 2000). The usage of producer gas, a lower calorific gas as a reciprocating engine fuel at a high compression ratio (17:1) is technically feasible (Sridhar *et al* 2001). The effect of moisture on the various characteristics of gas produced from different biomass fuel has been investigated. They give the idea about carbon conversion, tar emission, product gas heating value and cold gas efficiency (Drift *et al* 2001).

Equivalence ratio plays an important role on the gas composition, calorific value and the gas production in downdraft biomass gasifier. Optimum equivalence ratio for the best performance of downdraft biomass gasifier comes out to be 0.38. Gas flow rate per unit weight of fuel increases linearly with equivalence ratio. The specific consumption of the biomass materials (furniture wood and wood chips) is found to be of the order of 2 kg/kWh, while the overall efficiency of the biomass electrical power producing system is of the order of 10–11% and the cold gas efficiency is of the order of about 80% (Zainal *et al* 2002). Feed rate also effects on Calorific value/composition of the product gas and the associated variations of gasifier zone temperatures (Dogru *et al* 2002). Optimum operation of the gasifier was found to be between 1.44 and 1.47 Nm^3/kg of air fuel ratios at the values of 4.06 and 4.48 kg/h of wet feed rate which gives the producer gas with a good gross calorific value of about 5 MJ/m^3 at a volumetric flow of 8–9 N m^3/h product gas.

A gasifier has been fabricated in Sri Lanka for the tea industry. Experimental testing of the design under various conditions has produced data that has then been used to calibrate a computer program, developed to investigate the impact of design parameters and features of gasifier on conversion efficiency. It was concluded that a wood chip size of 3–5 cm with moisture content below 15% (dry basis) should be used in that gasifier. Feed material with a fixed carbon content of higher than 30% and heat losses of more than 15% should be avoided. For the above parameters, the gasification zone should be 33 cm long to achieve an acceptable conversion efficiency (Jayah *et al* 2003). Technical performance and sustainability of the largest biomass gasifier-based power plant (500 kW) in India has been reviewed with respect to diesel replacement, fuel wood supply, cost of electricity generation and environmental pollution. The overall efficiency of that plant is about 19% and the diesel replacement obtained at the optimum load condition was 64% (Sonaton *et al* 2004). Concentration of pollutants such as carbon monoxide (CO), oxides of nitrogen (NO_x), sulphur dioxide (SO_2), hydrocarbons (HC) and particulates in the flue gas were monitored and emission factors have been derived using kikar wood as biomass fuel in downdraft biomass gasifier clubbed with dual fuel diesel engine. In addition to the emission characteristics, diesel replacement rate at different loads were estimated. The diesel engine is capable of running with dual fuelling with 67–86% diesel replacement rate. Also engine performance decreases with increase in emissions at part load conditions both at diesel and dual fuel mode. For optimum load condition (80% of the rated capacity) the emissions were generally below the emission norms except for carbon monoxide emission from dual fuel operation, which exceeds the standard due to combination of factors such as low heating value of gas, low adiabatic flame temperatures, and low mean effective pressures. Carbon monoxide emissions from dual fuel engines were higher than diesel engines at all operated load condition. Dual fuel operation reduces NO_x and SO_2 emission without increasing particulate emission (Uma *et al* 2004). It is reported that the higher capacity of the engine than the required capacity must be selected because the producer gas dual fuel engine could run only at a maximum of 50–60% of maximum load condition. The engine performance decreases with increase in emissions at part load conditions both at diesel and dual fuel mode of operation. At optimized conditions, the exhaust emissions are found to be closer irrespective of the fuel used. In the dual fuel mode of operation, while using wood chips higher diesel savings is achieved when compared to coir pith. The diesel replacement while using coir pith in the gasifier could be improved by briquetting (Ramadhas *et al* 2006).

Effect of woody biomass components on air-steam gasification were also investigated using the downdraft fixed-bed gasifier at 1173 K and at atmospheric pressure. The gasification conversions in cellulose, xylem and lignin were 97.9%, 92.2%, and 52.8% on a carbon basis, respectively. The product gas composition in cellulose were 35:5 mol% CO, 27:0 mol% CO_2, and 28:7 mol% H_2, and the CO compositions were higher than the CO_2 or H_2 compositions, which is similar to that in the Japanese Oak, of which the main component was cellulose. In contrast, the product gas compositions in xylem and lignin were approximately 25 mol% CO, 36 mol% CO2, and32 mol% H_2, and the CO composition is lower than the CO_2 or H_2 compositions, which were similar to those in Japanese red pine bark, of which the main component were lignin. The fundamental information obtained in the gasification of each component could possibly be used to predict the composition of product gas generated in air-steam gasification of different woody biomass (Hanaoka *et al* 2005). The fuel properties of Jatropha seed husk and its gasification feasibility is investigated for open core down draft gasifier. Performance is evaluated in terms of fuel consumption rate, calorific value of producer gas and gasification efficiency at different gas flow rates. Producer gas calorific value and concentration of CO, along with gasification efficiency, increased with the increase in gas flow rate. The maximum gasification efficiency is found to be 68.31% at a gas flow rate of 5.5 m^3/h and specific gasification rate of 270 kg/ m^2 h which is comparable to that of wood (Vyas & Singh 2007). In dual fuel mode (fossil diesel, FD + producer gas), the concentration of pollutants like carbon monoxide (CO), carbon dioxide (CO_2), nitric oxide (NO), nitrogen dioxide (NO_2) reduced by 55%, 19.7%, 82% and 83%, respectively, while hydrocarbon (HC) increased by 67.2% as compared to FD. Operated in dual fuel mode of (FD+ refined rice bran oil, RRBO), the concentration of pollutant like CO, CO_2 and HC reduced by 60%, 0.86% and 91%, respectively whereas NO_x increased by 23.48% as compared to FD. In mixed fuel mode (pre-heated blends of RRBO+FD in the proportion of 3:1 and producer gas) the concentration of pollutants like HC, NO and NO_2 reduced by 48.28%, 61.57% and 80.48%, respectively, while CO increased by 16.31% as compared to FD (Singh *et al* 2005, 2007). Engine has also been run with diesel, rubber seed oil, diesel + coir pith and rubber seed oil + coir pith combinations. The engine performance decreases in dual mode operation with diesel or rubber seed oil as pilot fuel. The pilot fuel consumption of rubber seed oil is higher than that of diesel in dual fuel mode operation. Carbon monoxide emission of rubber seed oil-producer gas operation is higher than diesel-producer gas operation under all load conditions because of higher fuel consumption with lower calorific value fuels. Moreover, higher carbon dioxide emissions are observed with rubber oil-producer gas operation. Also exhaust emissions were found to be closer irrespective of the fuel used (Sridhar *et al* 2001). Brake thermal efficiency values of 24.25%, 22.25% and 23% were obtained with producer gas–diesel, producer gas–Honge oil and producer gas–Honge oil methyl ester, respectively. In dual fuel operation emissions like smoke and NO_x were reduced whereas CO and HC increased considerably (Banapurmath & Tewari 2009).

The increase of oxygen content in fuel blend increased the Brake specific fuel consumption of engine. The more oxygenated fuel is added in the fuel, the more reduction is achieved in smoke and particulate matter (PM) while slight increase in NO_x is witnessed (Chen *et al* 2008). Effects of air flow rate and moisture content on biomass consumption rate and quality of the producer gas generated is evaluated in terms of equivalence ratio, producer gas composition, calorific value of the producer gas, gas production rate, zone temperatures and cold gas efficiency. Biomass consumption rate decreases with the increase in moisture content of biomass while increase as there is increase in the air flow rate. Molar fraction of N_2 and CO_2 decrease till equivalence ratio (ϕ) = 0.205, and for higher values of ϕ, they increase. The fraction of CO and H_2 shows exactly opposite trend to that of N_2 and CO_2. The calorific value, pyrolysis zone temperature and the oxidation zone temperature is maximum at $\phi = 0.205$. However, the calorific value decreases for an equivalence ratio ranging from 0.205 to 0.35. The production rate of producer gas continuously increases with an increase in ϕ. The value of cold gas efficiency 0.25 is almost double as $\phi = 0.17$ changes to 0.035. The effect of ϕ on cold gas efficiency is comparatively lower for higher values of ϕ. For the downdraft biomass gasifier optimum equivalence ratio is 0.205 (Sheth & Babu 2009).

A one-dimensional stationary model of biomass gasification in a fixed bed downdraft gasifier was based on the mass and energy conservation equations and includes the energy exchange between solid and gaseous phases, and the heat transfer by radiation from the solid particles was proposed. The proposed model is used as tool to study the influence of process parameters, such as biomass particle mean diameter, air flow velocity, gasifier geometry, composition and inlet temperature of the gasifying agent and biomass type, on the process propagation velocity (flame front velocity) and its efficiency. The maximum efficiency was obtained with the smaller particle size and lower air velocity (Tinaut *et al* 2008). Combustible gas production from biomass materials such as coconut shell, groundnut shell and rice husk were experimentally investigated at 800°C using gasification technique by a downdraft gasifier. The calorific value of coconut shell is 23.01% higher than ground nut shell and 45.45% higher than rice husk. Hydrogen amount in the producer gas for ground nut shell is more than coconut shell and rice husk. But carbon monoxide is 17.55% and 21.22% higher than ground nut shell and rice husk as compared to coconut shell. Also 6.15% and 38.71% methane are more in coconut shell as compared to other tested biomass. The coconut shell have more carbon content also in producer gas. Coconut shell is the best suitable fuel for gasifier compared to the other two biomass materials (Sivakumar & Krishna 2010).

4.1 *Advantages*

From the review of literature available in the field of biomass usage, many advantages are noticeable. The following are some of the advantages of using biomass as fuel with diesel in I.C. engine in India (Tewari 1999; Sheng 1989).

- India is an agriculture-based country so agricultural waste obtained domestically helps to reduce costly petroleum imports.
- Development of the biomass usage machinery would strengthen the domestic, and particularly the rural, agricultural economy of agricultural based countries like India.
- It is biodegradable and non-toxic.
- It is a renewable fuel that can be made from agricultural crops and or other feed stocks that are considered as waste.
- It contains no aromatics.
- It has a reasonable cetane number and hence possesses less knocking tendency.
- Environment friendly due to absence of sulphur content.
- No major modification is required in the engine.
- Personal safety is improved (flash point is higher than that of diesel).
- It is usable within the existing petroleum diesel infrastructure (with minor or no modification in the engine).

4.2 *Challenges*

The major challenges that face the use of Biomass as I.C. engine fuels are listed below (Kohli & Ravi 2003; Bridgewater 1995; Sheng 1989).

- The price of biomass is dependent on various factors like availability, transportation, and drying, etc.
- Feed stock homogeneity, consistency and reliability are questionable.
- Storage and handling is difficult (particularly stability in long term storage).
- Flash point in blends is unreliable.
- Compatibility with I.C. engine material needs to be studied further.
- Acceptance by engine manufacturers is another major difficulty.
- Continuous availability of the particular type of biomass needs to be assured before embarking on the major use of it in I.C. engines.

4.3 *Technical difficulties*

The major technical areas (with respect to the use of biomass as fuels in I.C. engines), which need further attention are listed below (Kohli & Ravi 2003; Bridgewater 1995; Sheng 1989).

- Development of less expensive quality tests.
- Emission testing with a wide range of biomass feed stocks.
- Studies on developing specific markets such as mining, municipal water supplies, etc. which can specify bio-diesel as the fuel choice for environmentally sensitive areas.
- Co-product utilization like ash produced in a beneficial manner.
- Efforts to be focused on responding to fuel system performance, material compatibility and low fuel stability under long term storage.

- Continued engine performance, emissions and durability testing in a variety of engine types and sizes need to be developed to increase consumer and manufacturer confidence.
- Environmental benefits offered by biomass over diesel fuel needs to be popularized.
- Studies are needed to reduce cost and identify potential markets in order to balance cost and availability.

5. Conclusion

Researchers in various countries carried out many experimental works using producer gas derived biomass as I.C. engine fuel substitutes. These results have shown that thermal efficiency was comparable to that of diesel with small amounts of power loss while using producer gas. The particulate emissions of producer gas are lesser than that of diesel fuel with a reduction in NO_x and producer gas from biomass gave performance characteristics comparable to that of diesel. Hence, they may be considered as diesel fuel substitutes. The use of producer gas derived from biomass as I.C. engine fuels can play a vital role in helping the developed world to reduce the environmental impact of fossil fuels.

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