

BIOMASS DERIVED ENERGY CARRIERS AS FUELS IN ENGINES AND FUEL CELLS

P.J. Paul, S. Dasappa, G. Sridhar, and H.V. Sridhar*

Abstract

This paper reviews the use of biomass for power generation using IC engines or fuel cells. The different types of biomass and common features among them are examined. Their use in power generation is reviewed and gasification has been identified as a suitable means of electrical power generation for a wide variety of biomass. Some principles of gasification has been discussed and the requirements of quality of gas produced has been identified. The use of producer gas in IC engines has been explored and it has been shown that power generation through this route has reached commercial .scale of operation. Not only is the operation economical, hut the emission levels prescribed for power plants in various countries can easily be met with using producer gas engines. Different types of fuel cells available today have also been discussed and it is shown that two tapes, namely, molten carbonate and solid oxide fuel cells are suitable for operating with producer gas. Fuel cells, though have possibility of potentially high efficiency compared to IC engines, have not .vet reached commercial operation and their use with producer gas has not been adequately explored.

1. Introduction

Biomass has been a major energy source, prior to the discovery of fossil fuels like coal and petroleum. Even though its role is presently diminished in developed countries, it is still widely used in rural communities of the developing countries for their energy needs in terms of cooking and limited industrial use. Biomass contains stored solar energy, converted by plants through photosynthesis from carbon dioxide and water to solid form consisting mainly of cellulose, hemi-cellulose and lignin. On an average biomass has an empirical chemical formula $CH_1 4O_{0.6}$ and its variation is small among different forms of biomass on an ash free basis. On burning in presence of oxygen, it is converted to carbon dioxide and water, releasing the energy absorbed during the photosynthesis process. Thus the use of biomass for energy is CO_2 , neutral, if the usage is matched to the production of biomass. Biomass, besides its use in solid form, can be converted into gaseous fuel through gasification route.

2. Biomass Gasification

2.1 Types of Biomass

Biomass is classified into woody and powdery based on its availability in natural form. The former is taken to connote biomass whose average density is larger than about 200 kg/m³ and ash content limited to about 2%. Typical examples are fire wood, cotton stalk, mulberry stalk, corn cobs, coconut fronds and shells and weeds like eupatorium, lantana camera and other similar materials. The point to note here is that woody biomass is not limited to firewood, but several agricultural wastes also qualify for this title. All other biomass which are in loose form and ower densities are identified here are powdery. This includes several or most agricultural residues like sawdust, rice husk, straw, bagasse, sugarcane trash, groundnut shells, coir pith, prunes from tea/'coffee plantations and so on. The reason for the choice of the word powdery is that many such agricultural wastes are close to a form in which pulverization with a low power device (0.04-0.07 kWh/kg) can bring it into the form of powder. This also increases the bulk densities of the raw material helping in conveying at lower costs. The densities of such biomass is in the range 50-150 kg/m³ and ash content is up to 20%.

Since all biomass have roughly the same CHNO composition on an ash free basis. This also implies that the calorific value of biomass is about same for all biomasses excepting due to the effect of non-combustible mineral content. At sun dried condition (moisture content of 8-10%) the calorific value for all biomasses is in the range of 12-16 MJ/kg. The lower end belongs to rice husk and straw and the higher end belongs to wood/bagasse and such materials. If we note that the calorific value of coal found in India and a few other parts of the world having high ash content like 30-40% is about 15-20 MJ/kg. We come to a conclusion that biomass is comparable in the heating value to such coals. While coals have to be mined and transported over large distances for use, causing economic problems on the one hand and global warming effects on the other, biomass can be grown in most places except where the climate is most inhospitable.

2.2 Use of Biomass for Energy

The energy stored in biomass is released when it is burnt. When requirement is purely thermal, it can be met using combustion systems and appropriately transferring heat to the required devices. The use of biomass in cooking, boilers, achieved through boiler and steam turbines, though this route becomes efficient and economical only at large power levels, of the order of 5 MW or more. Gasification of biomass provides means for power generation at lower power levels at cost per mega watt comparable to large thermal power plants.

Gasification is a process by which the solid biomass residues are converted to a gaseous fuel, called producer gas. The producer gas thus generated can be used much like any other gaseous fuels, such as natural gas, for power generation in IC engines or gas turbines, or for thermal applications where clean and controlled combustion is necessary. There are also possibilities of converting this gas into liquid fuels like methanol; however this process is quite expensive and has not reached commercial application and hence not discussed further in this paper. Liquid fuels in the form of oils can also be obtained from certain oil seeds, which can also be used in engines.

2.3 Principles of Gasification

Gasification is the process of converting solid fuels to gaseous fuel. It is not simply pyrolysis; pyrolysis is only one of the steps in the conversion process. The other steps are combustion with air and reduction of the product of combustion (water vapour and carbon dioxide) into combustible gases, (carbon monoxide, hydrogen, methane, some higher hydrocarbons) and inerts, (carbon dioxide and nitrogen). The process leads to a gas with some fine dust and condensable compounds termed tar, both of which must be restricted to low values if the gas is to be used in internal combustion engines.

When biomass is heated it releases volatile matter at about 300-600°C temperature leaving fixed carbon. In presence of air these products burn to form carbon dioxide and water vapour and possibly carbon monoxide depending on the mixture ratio. This is an exothermic process releasing energy which can sustain the pyrolysis and combustion process continuously by transferring heat to the fresh biomass. This process takes place at temperatures of 1200-1400°C. The hot gases generated in the process, which contains CO₂ and H₂O, further react with the fixed carbon to convert CO₂ to CO and H₂O to H₂. These are called reduction reactions and are endothermic in nature. As a consequence, the temperature is reduced and the thermal energy is converted to chemical energy stored in CO and H₂ molecules. The process does not proceed until all the CO₂ and H₂O are converted to CO and H₂, since reduction reactions are not favoured below about 600-700°C. At the end of the process the gas, after cooling, would have a typical composition of 20% CO, 20% H₂, 2% CH₄, 12% CO₂ the rest being N₂ and equilibrium moisture. The unconverted H₂O remaining in hot gases is condensed while cooling the gas from about 600°C to ambient temperature. The gas may also contain other contaminants such as carbon dust picked up by the gases flowing past the hot charcoal bed and the residual volatile matter left unconverted during the process called tar. These contaminants, if not removed, causes difficulty in using the gas in IC engines since they get deposited in various engine parts. Hence, a good gasification system should produce as little of these contaminants as possible and an efficient gas cleaning system is required to remove the contaminants to the levels acceptable to the end use device.

2.4 Gasification Equipment

Various designs of gasifiers exist and they have been in use since during the second world war times. However, the interest in developing biomass gasifiers reduced in the post war years because of the easy availability of petroleum fuels. In the eighties, the interest picked up again consequent on the awareness of the limited nature of fossil fuel availability and the global warming problems created by the indiscriminate use of fossil fuels. India has a fair lead in the development of fixed bed gasification over the rest of the countries in terms of contaminant free gas generation, long hours of experience in operation of internal combustion engines and in commercial operation of gasification systems. One design of down draft fixed bed gasification system developed at the Indian Institute of Science is described briefly below

The development of the gasifier over a ranges of power levels of 3.7 to 100 kW and field experience are described in a series of earlier publications from this laboratory (Dasappa et al, 1989; Mukunda et al 1993; Mukunda et al, 1994; Mukunda et al, 1994; Ravindranath et al, 1990; Srinivas et al, 1991). Also described are the differences between the open top system and the classical closed top system. These are not addressed in detail here. However, a brief description is provided here. The principal element of woody biomass gasifier is the reactor with air drawn from top as well side air nozzles reduces the unreliable operation of the closed

top design particularly when the feed stock has high moisture content (around 25% or more) and also provide a good turn down ratio with little tar content (Mukunda et al, 1994). The reasons for the good performance of this system vis-a-vis the closed top design (Mukunda et al, 1994) are that the improvement in performance is related to the more homogeneous flow of air through the bed which is near one-dimensional, and to the fact that the approach to final fuel rich condition is from an initial lean state through stoichiometry. The second point leads to lower generation of tar and whatever is generated is cracked to smaller sized molecules as the gas traverses through a long uniformly arranged bed of hot charcoal without any low temperature zones.

The current design of the reactor consists of a vertical tubular reactor with an open top and a screw to extract the ash at the bottom. The high temperature portion of the reactor, i.e. where the reactor bed temperature which can reach upto 1400°C, is lined with a ceramic material of low thermal conductivity. For engine application, gas must be cooled to room temperature and must be much cleaner compared to thermal applications. The acceptable upper limit of particulate content appears to be around 50 mg m⁻³ irrespective of particle size, which is generally less than 10 micron. However, if the particle sizes are smaller than about one micron, this limit is unimportant as the particulate matter flows along with the gas without deposition at bends, corners and passages. In order to increase the density of the gas, the gas is cooled to ambient temperature by indirect and/or direct means and is filtered adequately to reduce the particulate content. Cooling and cleaning of gas is achieved by a series of scrubbers, including a chilled water scrubber followed by a fine filter. This procedure reduces the contaminants in the gas to less than 5 ppm. Typical schematic of the system for engine applications is shown in figure 1.

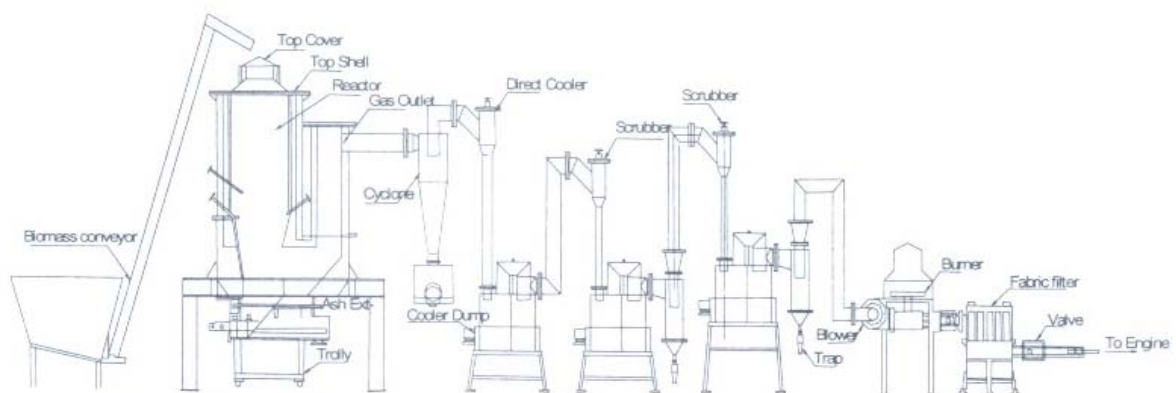


Figure 1 : Schematic of the gasifier system for power generation

2.5 Properties of Producer Gas

Producer gas derived from biomass typically contains 18-20 per cent each of H₂ and CO, 2 per cent of CH₄ and the rest inert gases such as CO₂ and N₂. The lower calorific value varies between 4.5 and 4.9 MJ/kg, with the stoichiometric air to fuel ratio being 1.35:1.00 on a mass basis. Some of the fundamental data relating to producer gas are compared with pure gases in Table 1. The comparison of producer gas with methane is more vital with regard to the internal combustion engine operation. This is because most of the engines operating on gaseous fuels are either close to pure methane (natural gas) or diluted methane (biogas, land-fill gas). The fuel-air equivalence ratio Φ (actual fuel-air ratio)/(stoichiometric fuel-air ratio), at the flammability limits (Kanitkar et al, 1993) compares closely for both the gases, but the laminar burning velocity for producer gas at the lean limits is much higher. The laminar burning velocity for producer gas (at 0.1 MPa and 300 K) is about 0.5 m/s (Kanitkar et al. 1993), which is about 30 per cent higher than methane. It is argued that this feature demands lower advancement in the ignition timing, which needs consideration when arriving at the optimum ignition timings for the producer gas fuel.

Table 1: Properties of Producer Gas (PG) Compared with Pure Combustible Gases.

Fuel + Air	LCV MJ/kg (MJ/m ³)	A/F at $\Phi=1$ mass (Mole)	Mixture MJ/kg (MJ/m ³)	Φ (limit)		S _L at $\Phi =$ 1 cm/s	Flame temp. K
				Lean	Rich		
H ₂	121	34.4 (2.38)	3.41 (3.2)	0.01	7.17	270	2130
CO	10.2	2.46 (2.38)	2.92 (3.8)	0.34	6.80	45	2130
CH ₄	50.2	17.2 (9.52)	2.76 (3.4)	0.54	2.26	35	1940
C ₃ H ₈	46.5	15.6 (23.8)	2.80 (3.7)	0.52	2.26	44	1980
PG	5.0 (5.6)	1.35 (1.12)	2.12 (2.6)	0.47	1.60	50	1530

Like any other gaseous fuel, producer gas can be used for internal combustion engine operation provided the gas is sufficiently clean that contaminant does not accumulate in the intermediary passages to the engine cylinder. However, this fuel has largely been left unexploited due to additional perceptions, namely (a) an auto-ignition tendency at a higher CR and (b) a large de-rating in power due to the energy density being low. These perceptions need re-examination and clarification. The arguments against the classical view in favour of better knock resistivity are as follows. Firstly, the fact that the laminar burning velocity is high due to the presence of hydrogen (more so, with the gasifier system adopted in this work) might reduce the tendency for knock. Secondly, the presence of inert gases in the raw gas (CO_2 and N_2) might suppress the pre-flame reactions that are responsible for knocking on account of increased dilution. Also, as the maximum flame temperature attainable with the producer gas is lower compared to conventional fuels like methane, better knock resistivity could not be expected. An examination of the literature shows that producer gas has not been subjected to study on knock behaviour. Further, there is a general perception that as producer gas is a low-density energy fuel, the extent of de-rating in power would be large when compared to high-energy density fuels like natural gas and liquefied petroleum gas. This could be misleading because what needs to be accounted for by way of comparison is the mixture energy density (Fluscher et al, 1981) and not the fuel energy density per se. Compared with CH_4 , the mixture energy density for producer gas is lower by 23 per cent, as reflected in Table 1. The product-reactant mole ratio for producer gas is less than one. These two parameters could contribute to de-rating of engine output. However, it might be possible to reduce de-rating by working with engines of higher CR, perhaps higher than what has been examined by Das and Watson (Das and Watson, 1997) using natural gas (CR=15.8).

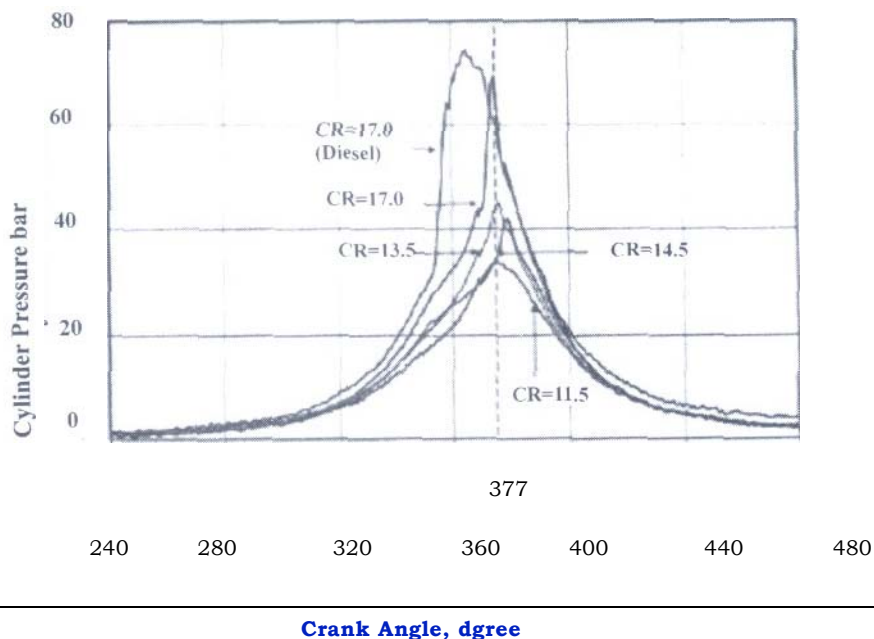


Figure 2: Comparison of p - θ curves at different compression ratios

3. Performance of Producer Gas in IC Engines

Producer gas has been tested on engines of various capacities ranging from 1 kW to 300 kW at conditions of varying compression ratios. Fair amount of field experience is also available currently (Sridhar et al, 2005). No deleterious effects on the engine has been observed on the engine after many thousands hours of operation on producer gas. The effect of some of the operating parameters are described below.

3.1 Compression Ratio and Power Output

As has been mentioned earlier, producer gas can be used at much high compression ratios compared to the other fuels in spark ignition engines. Figure 2 shows the p - θ diagram for a 20 kW engine at various compression ratios. The engine has worked smoothly without any sign of knock up to a compression ratio of 17 as is evident from the diagram. This work has also identified the optimum ignition timing (MBT) as a function of compression ratio. It has been indicated in literature (J.B. Heywood, 1988 and C.M. Wu et al, 1993) that MBT correspond to value wherein the peak cylinder pressure should occur at 16-17° ATC (after top centre). The MBT for

different ignition timings are given in Table 2.

Table 2: Maximum Engine Power Output, Optimum Ignition Timing, and Engine Efficiency at Various Compression Ratios

CR	MBT (°)	ϕ	Electrical power (kWe)	Break power (kW)	Gas to shaft efficiency (%)
17.0	06	1.10	17.5	20.0	30.8
14.5	10	1.10	16.4	18.8	29.0
13.5	14	1.06	16.2	18.6	29.3
11.5	17	1.07	15.3	17.6	27.5

3.2 Energy Balance

The useful energy in the engine is the shaft output, the rest being lost as friction, cooling and exhaust. Figure 3 gives the percentages of various components of these at various compression ratios. As can be seen the useful power and loss in the cooling water increase with compression ratio, while the loss in exhaust reduces with compression ratio.

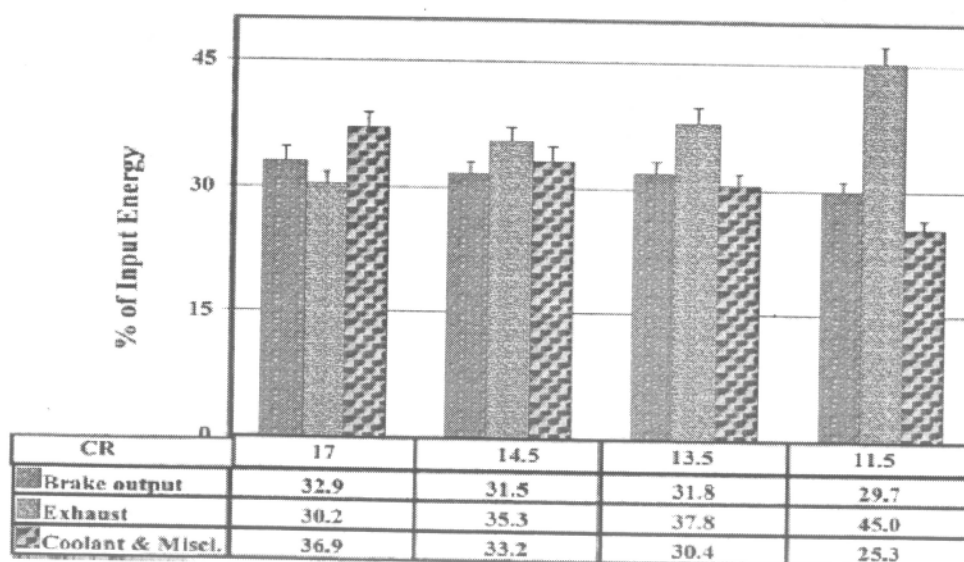


Figure 3 : Comparison of energy balance at various CRs with the producer gas corresponding to the maximum brake output. The marker refers to the error band.

3.3 Emissions

Currently emissions are a serious concern on any power generation operation. The emission norms for various countries are given in Table 3. The results of some of the tests conducted on producer gas engines is given in Fig 4. As can be seen. NO emission with producer gas is lower than all the existing norms. CO emission is large initially due tuning of the carburetor for arriving at the right mixture ratio. Subsequently, the CO emission comes down and is within many existing norms. which implies environmental friendly operation of producer gas operation.

Table 3: Comparison of Emission (g/MJ) with Producer Gas Operation against Existing Emission Norms in Various Countries

Parameter	Country			
	USA	EU	Japan	India
CO	3.06	1.4 - 1.6	1.67	1.25
NO _x	2.56	2.56	2.6 - 3.06	2.22
HC	0.36	0.36	0.4 - 0.56	0.3
PM	0.15	0.15 - 0.24	-	0.1 - 0.2

Source: <http://app10.internet.gov/scripts/nea/cms/htdocs/article.asp>

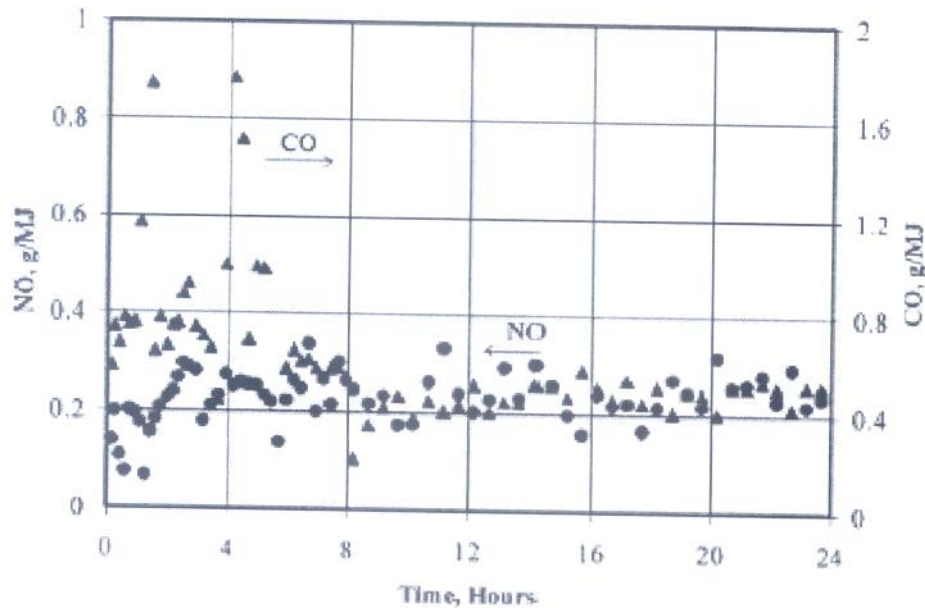


Figure 4 : Variation of emission in the case of engine E3 at 90 per cent load during 24 hours of continuous operation.

3.4 Summary of IC Engine Operation of Producer Gas

Producer gas derived from biomass can be operated reliably in IC engines and can provide long hours of operation meeting most of the emission requirements of most countries. The technology is reasonably matured so that commercial operation of power generation from biomass is currently a viable option.

4. Fuel Cells

While the IC engine option for power generation is reasonably matured technology, its efficiency is limited by the inherent efficiency of the internal combustion engine. The internal combustion engines have an efficiency of about 35%, which may be stretched to 40% in the case of large low speed engines, and the overall efficiency, including the gasification efficiency is limited to about 28-32%. Fuel cells provide a means of improving the efficiency significantly since the chemical energy stored in the fuel is converted directly to electrical energy without converting to thermal energy as in the case of IC engines.

4.1 What Is Fuel Cell?

A fuel cell has four basic components, two electrodes (anode and cathode), one electrolyte and a catalyst (enzyme) between the electrodes and the electrolyte in the centre. These components are made of different kinds of materials in different types of fuel cells. The process of generating electricity from a fuel cell requires four basic steps. First, hydrogen enters the fuel cell through the anode electrode. Then, the catalyst splits the electron and proton apart in the hydrogen and produces a hydrogen ion ($2\text{H}_2 \rightarrow 4\text{H}^+ + 4\text{e}^-$). After that, the proton travels to the cathode through the electrolyte while the hydrogen ion creates a flow of electricity. After the energy has been utilized, the electron is sent back to the cathode through external circuit and it is combined with the proton and oxidizes to form a water molecule ($4\text{e}^- + 4\text{H}^+ + \text{O}_2 \rightarrow 2\text{H}_2\text{O}$). Some of the types of fuel cells are described below :

Phosphoric Acid:

This fuel cell is the most commercially developed. It operates at about 204°C. The normal energy efficiency of this type of fuel cell is around 40%, but the cell can achieve as high as 85% if the steam produced from the cell is used properly.

Proton Exchange Membrane (PEM) or Solid Polymer:

This type of fuel cell is named after the material used for the electrolyte, polymer membrane. The catalyst of a PEM cell is made of platinum. This type of cell has the most potential on small applications according to the Department of Energy of the United States of

America. The reasons for their comments are that this type of cell can vary output. This type of fuel cell also operates at a relatively low temperature, 85°C, when compared with the other types of fuel cells.

Molten Carbonate:

This is a pretty new technology had its first test and demonstration in California in 1996. It operates at about 650°C. The ability of consuming CO is the unique characteristic of the Molten Carbonate Fuel Cell.

Solid Oxide:

Similar to the PEM fuel cell, this type of fuel cell got its name from its electrolyte material. The Solid Oxide Fuel Cell uses hard ceramic material for the electrolyte. This type of fuel can generate large amounts of energy at the efficient rate of 60%, which are suitable for power-plant type of operations. However, the cell's operating temperature is extremely high. It is around 980°C.

Alkaline Fuel Cell:

NASA uses alkaline Fuel Cells for space missions because it can achieve upto 70% of fuel-to-electricity efficiency. However, this cell has a big disadvantage, which is the extremely costly and can use only hydrogen.

Some of the features of the fuel cells are summarized in Table 4. Since producer gas contains nearly equal amounts of CO and H₂, the fuel cells suitable for this is either the solid oxide fuel cell or the molten carbonate fuel cell. So far very little work is done to combine the fuel cell and gasification technologies. Considering the significantly improved overall efficiencies obtainable through gasification fuel cell route, investigation into these technologies is likely to yield dividends. The high cost of fuels presently is one of the factors prohibiting their wider spread use. However, costs may come down in future with increased use of fuel cells.

Table 4 : Properties of Fuel Cells and Fuel Requirements

Fuel cell	Electrolyte	Operating temperature	Fuel gas	Catalyst poisons
AFC	KOH solution	70 – 260°C	Pure H ₂	CO, CO ₂
PEM	Polymer membrane	50 – 120°C	Pure H ₂	CO > 10 ppm
PAFC	H ₃ PO ₄	180 – 210°C	H ₂	CO > 0.5% H ₂ S > 50 ppm
MCFC	Molten alkaline carbonates	650°C	H ₂ /CO	H ₂ S > 0.5 ppm
SOFC	Solid oxide ceramics	800 – 1000°C	H ₂ /CO/CH ₄	H ₂ > 1 ppm

5. Conclusion

This paper has examined the aspects of using biomass derived gaseous fuel in IC engines and fuel cells. The IC engine route is fairly well established and has reached commercial scale of operation. Fuel cell has potential for much higher efficiencies and is a promising route for the future. However, it requires much development and experience on biomass generated fuels is minimal.

References

1. Das, A. and Watson, H.C. 1997. Development of a natural gas spark ignition engine for optimum performance. *Proc. Instn. Mech Engrs. Part D : J. Automobile Engineering*, 211(D5) : 361-378.
2. Dasappa, S., Shrinivasa, U., Baliga, B.N. and Mukunda. H.S. 1989. Five-kilowatt wood gasifier technology : Sadhana. Indian Academy of Sciences. *Proceedings in Engineering*, pages 187-212.

3. Fleischer, F., Grosse, W. and Zapf, H. 1981. Fuels from biomass and their rational utilization in internal combustion engines. *In: Proceedings of the International Conference on New Energy Conversion Technologies and Their Commercialization, volume 2*, pages 1334-1340.
4. Heywood, J.B. 1998. *Internal Combustion Engine Fundamentals*. McGraw-Hill, Maidenhead, International Edition.
5. Kanitkar, S., Chakravarty, P., Paul, P.J., and Mukunda, H.S. 1993. The flame speeds, temperature and limits of flame propagation for producer gas-air mixture - experimental results. In P.J. Paul and H.S. Mukunda, editors. *Proceedings of the Fourth National Meeting on Biomass Gasification and Combustion, volume 4*, pages 50-62.
6. Mukunda, H.S., Dasappa, S. and Shrinivasa, U. 1993. Open top wood gasifiers. 1993. *In: Renewable Energy, sources for fuels and electricity*, pages 699-728. Island Press.
7. Mukunda, H.S., Dasappa, S., Paul, P.J. and Shrinivasa U. 1994. Gasifiers and combustors for biomass technology field studies. *Energy for Sustainable Development*, 1:27-38
8. Mukunda, H.S., Paul, P.J., Dasappa, S., Rajan, N.K.S., Shrinivasa, U. Sharan. H., Beuhler, R., Hasler, P. and Kaufmann. H. 1994. Results of an indo-swiss programme for qualification and testing of a 300 kW IISc-dasag gasifier. *Energy for Sustainable Development*, 1:46-49.
9. Ravindranath, N.H., Dattaprasad. H.L., and Somashekar, H.I. 1990. A rural energy system based on forest and wood gasifier. *Current Science*, 59:557-560.
10. Sridhar, G., Sridhar, H.V., Dasappa, S., Paul, P.J., Rajan, N.K.S. and Mukunda, H.S. 2005. Development of producer gas engines. Proceedings of the Institution of Mechanical Engineers, *Journal of Automobile Engineering*.
11. Srinivas, S.N., Ravindranatha, N.H., Shrinivasa, U., Dasappa, S., and Mukunda, H.S. 1991. A gasifier based rural power generation system : Performance and problems. *In: Proc. Third :National Conference on Biomass, Baroda*.
12. Wu, C.M., Roberts, C.E., Matthews, R.D. and Hall, M.J. 1993. Effects of engine speed on combustion in SI engines : comparison of predictions of a fractal burning model with experimental data. SAE 932714, 102:2277-2291.