(Published as a Chapter (No. 4) in book "Alternative Energy in Agriculture", Vol. II, Ed. D. Yogi Goswami, CRC Press, 1986, pgs. 83-102.). (Author's comments: Since publication of this chapter lot of work in gasification has taken place in our lab. Please see; http://www.nariphaltan.org/Gasifier.pdf)

BIOMASS GASIFICATION

By

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I INTRODUCTION

Modern agriculture is an extremely energy intensive process. However high agricultural productivities and subsequently the growth of green revolution has been made possible only by large amount of energy inputs, especially those from fossil fuels[1]. With recent price rise and scarcity of these fuels there has been a trend towards use of alternative energy sources like solar, wind, geothermal etc.[2] However these energy resources have not been able to provide an economically viable solution for agricultural applications[3].

One biomass energy based system, which has been proven reliable and had been extensively used for transportation and on farm systems during World War II is wood or biomass gasification[4].

Biomass gasification means incomplete combustion of biomass resulting in production of combustible gases consisting of Carbon monoxide (CO), Hydrogen (H_2) and traces of Methane (CH_4). This mixture is called producer gas. Producer gas can be used to run internal combustion engines (both compression and spark ignition), can be used as substitute for furnace oil in direct heat applications and can be used to produce, in an economically viable way, methanol – an extremely attractive chemical which is useful both as fuel for heat engines as well as chemical feedstock for industries[5]. Since any biomass material can undergo gasification, this process is much more attractive than ethanol production or biogas where only selected biomass materials can produce the fuel.

Besides, there is a problem that solid wastes (available on the farm) are seldom in a form that can be readily utilized economically e.g. Wood wastes can be used in hog fuel boiler but the equipment is expensive and energy recovery is low[6]. As a result it is often advantageous to convert this waste into more readily usable fuel from like producer gas. Hence the attractiveness of gasification.

However under present conditions, economic factors seem to provide the strongest argument of considering gasification[7, 8]. In many situations where the price of petroleum fuels is high or where supplies are unreliable the biomass gasification can provide an economically viable system – provided the suitable biomass feedstock is easily available (as is indeed the case in agricultural systems).

II HISTORICAL BACKGROUND

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[9] .

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. However Sweden continued to work on producer gas technology and the work was accelerated after 1956 Suez Canal crisis. A decision was then made to include gasifiers in Swedish strategic emergency plans. Research into suitable designs of wood gasifiers, essentially for transport use, was carried out at the National Swedish Institute for Agricultural Machinery Testing and is still in progress[10] .

The contemporary interest in small scale gasifier R&D, for most part dates from 1973 oil crisis. The U.S. research in this area is reviewed by Goss[11]. The manufacturing also took off with increased interest shown in gasification technology. At present there are about 64 gasification equipment manufacturers all over the world[11,36]. The present status of gasification technology and R&D activities will be discussed in chapter VII.

III THEORY OF GASIFICATION

The production of generator gas (producer gas) called gasification, is partial combustion of solid fuel (biomass) and takes place at temperatures of about 1000^0C. The reactor is called a gasifier.

The combustion products from complete combustion of biomass generally contain nitrogen, water vapor, carbon dioxide and surplus of oxygen. However in gasification where there is a surplus of solid fuel (incomplete combustion) the products of combustion are (Figure 1) combustible gases like Carbon monoxide (CO), Hydrogen (H_2) and traces of Methane and nonuseful products like tar and dust. The production of these gases is by reaction of water vapor and carbon dioxide through a glowing layer of charcoal. Thus the key to gasifier design is to create conditions such that a) biomass is reduced to charcoal and, b) charcoal is converted at suitable temperature to produce CO and H_2.

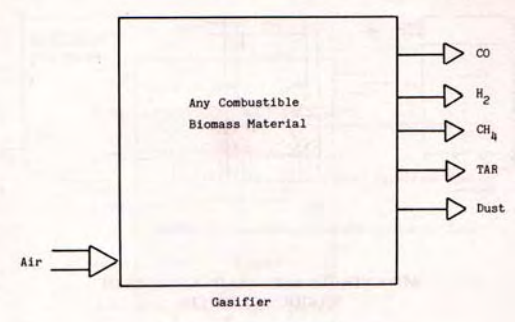

FIGURE 1. Products of gasification.

A. *Types of Gasifiers*

Since there is an interaction of air or oxygen and biomass in the gasifier, they are classified according to the way air or oxygen is introduced in it. There are three types of gasifiers (Figure 2); Downdraft, Updraft and Crossdraft. 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.

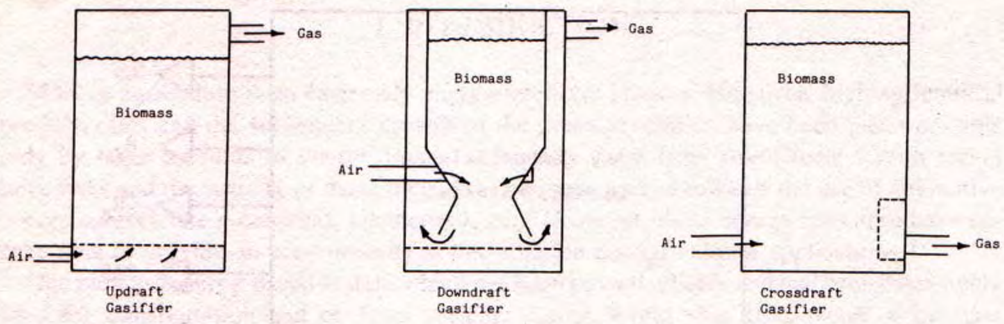

FIGURE 2. Various types of gasifiers.

With slight variation almost all the gasifiers fall in the above categories.

The choice of one type of gasifier over other is dictated by the fuel, its final available form, its size, moisture content and ash content[12]. Table 1 lists therefore, the advantages and disadvantages generally found for various classes of gasifiers.

Table 1. Advantages and Disadvantages of various Gasifiers

Sr. No.	Gasifier Type	Advantage	Disadvantages
1.	Updraft	- Small pressure drop - good thermal efficiency - little tendency towards slag formation	- Great sensitivity to tar and moisture and moisture content of fuel - relatively long time required for start up of IC engine - poor reaction capability with heavy gas load
2.	Downdraft	- Flexible adaptation of gas production to load - low sensitivity to charcoal dust and tar content of fuel	- Design tends to be tall - not feasible for very small particle size of fuel
3.	Crossdraft	- Short design height - very fast response time to load - flexible gas production	- Very high sensitivity to slag formation - high pressure drop

B. Process Zones

Four distinct processes take place in a gasifier as the fuel makes its way to gasification. They are :

a) Drying of fuel
b) Pyrolysis – a process in which tar and other volatiles are driven off
c) Combustion
d) Reduction

Though there is a considerable overlap of the processes, each can be assumed to occupy a separate zone where fundamentally different chemical and thermal reactions take place. Figure 3 shows schematically an updraft gasifier with different zones and their respective temperatures. Figure 4 and 5 show these regions for downdraft and crossdraft gasifiers respectively.

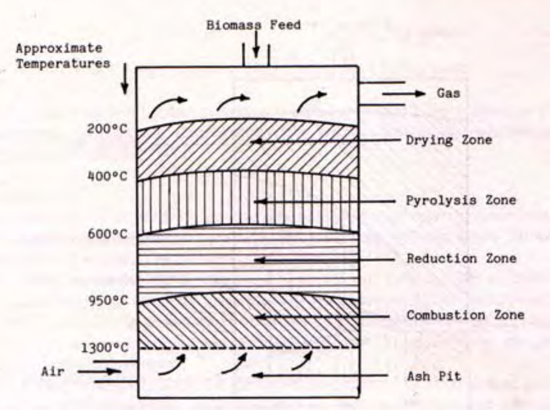

FIGURE 3. Various zones in updraft gasifier. (From Foley, G. and Barnard, G., Biomass Gasification in Developing Countries, Technical Report No. 1, Earthscan, London, 1983. With permission.)

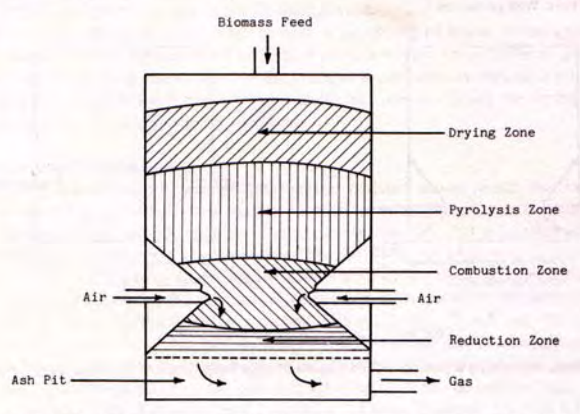

FIGURE 4. Gasification process in downdraft gasifier. (From Foley, G. and Barnard, G., Biomass Gasification in Developing Countries, Technical Report No. 1, Earthscan, London, 1983. With permission.)

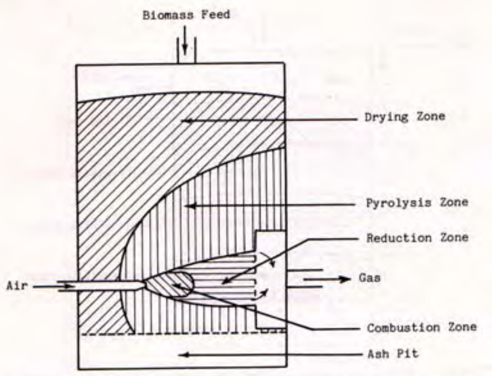

FIGURE 5. Gasification process in crossdraft gasifier. (From Foley, G. and Barnard, G., Biomass Gasification in Developing Countries, Technical Report No. 1, Earthscan, London, 1983. With permission.)

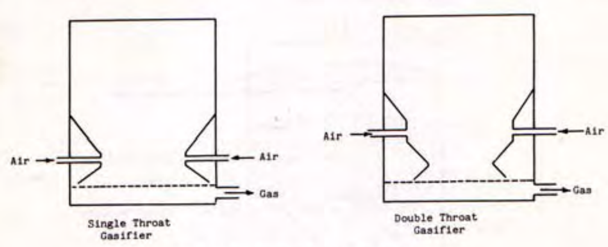

FIGURE 6. Single and double throat gasifiers.

In the downdraft gasifiers there are two types :

a) Single throat and, b) Double throat (Figure 6).

Single throat gasifiers are mainly used for stationary applications whereas double throat are for varying loads as well as automotive purposes.

C. Reaction Chemistry

The following major reactions take place in combustion and reduction zone[12].

1. Combustion zone

The combustible substance of a solid fuel is usually composed of elements carbon, hydrogen and oxygen. In complete combustion carbon dioxide is obtained from carbon in fuel and water is obtained from the hydrogen, usually as steam. The combustion reaction is exothermic and yields a theoretical oxidation temperature of 1450^0C[14]. The main reactions, therefore, are:

$$C + O_2 = CO_2 \quad (+ 393 \text{ MJ/kg mole}) \qquad (1)$$
$$2H_2 + O_2 = 2H_2O \quad (- 242 \text{ MJ/kg mole}) \qquad (2)$$

2. Reaction zone

The products of partial combustion (water, carbon dioxide and uncombusted partially cracked pyrolysis products) now pass through a red-hot charcoal bed where the following reduction reactions take place[12].

$$C + CO_2 = 2CO \quad (- 164.9 \text{ MJ/kg mole}) \qquad (3)$$
$$C + H_2O = CO + H_2 \quad (- 122.6 \text{ MJ/kg mole}) \qquad (4)$$
$$CO + H_2O = CO + H_2 \quad (+ 42 \text{ MJ/kg mole}) \qquad (5)$$
$$C + 2H_2 = CH_4 \quad (+ 75 \text{ MJ/kg mole}) \qquad (6)$$
$$CO_2 + H_2 = CO + H_2O \quad (- 42.3 \text{ MJ/kg mole}) \qquad (7)$$

Reactions (3) and (4) are main reduction reactions and being endothermic have the capability of reducing gas temperature. Consequently the temperatures in the reduction zone are normally 800-1000^0C. Lower the reduction zone temperature (~ 700-800^0C), lower is the calorific value of gas.

3. Pyrolysis zone

Wood pyrolysis is an intricate process that is still not completely understood[14]. The products depend upon temperature, pressure, residence time and heat losses. However following general remarks can be made about them.

Upto the temperature of 200^0C only water is driven off. Between 200 to 280^0C carbon dioxide, acetic acid and water are given off. The real pyrolysis, which takes place between 280 to 500^0C, produces large quantities of tar and gases containing carbon dioxide. Besides light tars, some methyl alcohol is also formed. Between 500 to 700^0C the gas production is small and contains hydrogen.

Thus it is easy to see that updraft gasifier will produce much more tar than downdraft one. In downdraft gasifier the tars have to go through combustion and reduction zone and are partially broken down.

Since majority of fuels like wood and biomass residue do have large quantities of tar, downdraft gasifier is preferred over others. Indeed majority of gasifiers, both in World War II and presently are of downdraft type.

Finally in the drying zone the main process is of drying of wood. Wood entering the gasifier has moisture content of 10-30%. Various experiments on different gasifiers in different conditions have shown that on an average the condensate formed is 6-10% of the weight of gasified wood[14]. Some organic acids also come out during the drying process. These acids give rise to corrosion of gasifiers.

*D. **Properties of Producer gas***

The producer gas is affected by various processes as outlined above hence one can expect variations in the gas produced from various biomass sources. Table 2 lists the composition of gas produced from various sources. The gas composition is also a function of gasifier design and thus, the same fuel may give different calorific value as when used in two different gasifiers. Table 2 therefore shows approximate values of gas from different fuels.

Table 2. Composition of Producer Gas from various fuels

Fuel	Gasification method	Volume Percentage					Calorific value MJ/m^3	Ref.
		CO	H_2	CH_4	CO_2	N_2		
Charcoal	Downdraft	28-31	5-10	1-2	1-2	55-60	4.60-5.65	12
Wood with 12-20% moisture content	Downdraft	17-22	16-20	2-3	10-15	55-50	5.00-5.86	12
Wheat straw pellets	Downdraft	14-17	17-19	-	11-14	-	4.50	15
Coconut husks	Downdraft	16-20	17-19.5	-	10-15	-	5.80	15
Coconut shells	Downdraft	19-24	10-15	-	11-15	-	7.20	15
Pressed Sugarcane	Downdraft	15-18	15-18	-	12-14	-	5.30	15
Charcoal	Updraft	30	19.7	-	3.6	46	5.98	16
Corn cobs	Downdraft	18.6	16.5	6.4	-	-	6.29	17
Rice hulls pelleted	Downdraft	16.1	9.6	0.95	-	-	3.25	17
Cotton stalks cubed	Downdraft	15.7	11.7	3.4	-	-	4.32	17

The maximum dilution of gas takes place because of presence of nitrogen. Almost 50-60% of gas is composed of noncombustible nitrogen. Thus it may be beneficial to use oxygen instead of air for gasification. However the cost and availability of oxygen may be a limiting factor in this regard. Nevertheless where the end product is methanol – a high energy quality item, then the cost and use of oxygen can be justified[5].

On an average 1 kg of biomass produces about 2.5 m^3 of producer gas at S.T.P. In this process it consumes about 1.5 m^3 of air for combustion[14] . For complete combustion of wood about 4.5 m^3 of air is required. Thus biomass gasification consumes about 33% of theoretical stoichiometeric ratio for wood burning.

The average energy conversion efficiency of wood gasifiers is about 60-70% and is defined as

$$\eta_{Gas} = \frac{\text{Calorific value of gas/kg of fuel}}{\text{Avg. calorific value of 1 kg of fuel}} \qquad (8)$$

Example :

1 kg of wood produces 1.5 m^3 of gas with average calorific value of 5.4 MJ/m^3. Average calorific value of wood (dry) is 19.8 MJ/kg[18] .

Hence

$$\eta_{Gas} = \frac{2.5\ (m^3) \times 5.4\ (MJ/m^3)}{19.80\ (MJ/kg) \times 1\ (kg)} = 68\%$$

E. Temperature of Gas

On an average the temperature of gas leaving the gasifier is about 300 to 400^0C [16]. If the temperature is higher than this (~ 500^0C) it is an indication that partial combustion of gas is taking place. This generally happens when the air flow rate through the gasifier is higher than the design value.

IV **GASIFIER FUEL CHARACTERISTICS**

Almost any carbonaceous or biomass fuel can be gasified under experimental or laboratory conditions[19]. 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.

Many a gasifier manufacturers' claim that a gasifier is available which can gasify any fuel. There is no such thing as a universal gasifier[19]. A gasifier is very fuel specific and it is tailored around a fuel rather than the other way round.

Thus a gasifier fuel can be classified as good or bad according to the following parameters :

1) Energy content of the fuel
2) Bulk density

3) Moisture content
4) Dust content
5) Tar content
6) Ash and slagging characteristic

A. Energy content and Bulk Density of 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.

B. Moisture content

In most fuels there is very little choice in moisture content since it is determined by the type of fuel, its origin and treatment. 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. For example, for fuel at 25^0C and raw gas exit temperature from gasifier at 300^0C, 2875 KJ/kg moisture must be supplied by fuel to heat and evaporate moisture[20].

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 desirable moisture content for fuel should be less than 20%.

C. 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[19] . Figure 7 shows dust produced as a function of gas production for wood generators used during World War II [21].

The higher the dust produced, more load is put on filters necessitating their frequent flushing and increased maintenance.

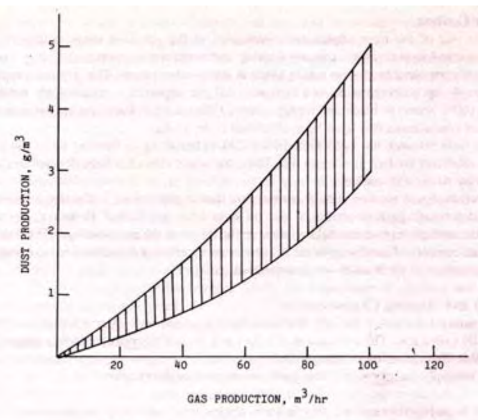

FIGURE 7. Dust content as a function of gas production.

D. 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[22] . It is a product of highly irreversible process taking place in the pyrolysis zone. The physical property of tar depends upon temperature and heat rate and the appearance ranges from brown and watery (60% water) to black and highly viscous (7% water)[19]. There are approximately 200 chemical constituents that have been identified in tar so far.

Very little research work has been done in the area of removing or burning tar in the gasifier so that relatively tar free gas comes out. Thus the major effort has been devoted to cleaning this tar by filters and coolers. A well-designed gasifier should put out less than 1 g/m^3 of tar[21]. Usually it is assumed that a downdraft gasifier produces less tar than other gasifiers[25]. However because of localized inefficient processes taking place in the throat of the downdraft gasifier it does not allow the complete dissociation of tar[19]. More research effort is therefore needed in exploring the mechanism of tar breakdown in downdraft gasifiers.

E. Ash and Slagging Characteristics

The mineral content in the fuel that remains in oxidized form after complete combustion is usually called ash. The ash content of a fuel and the ash composition have a major impact on trouble free operation of gasifier.

Ash basically interferes with gasification process in two ways :

a) It fuses together to form slag and this clinker stops or inhibits the downward flow of biomass feed.
b) 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[23]. In fact some fuels with high ash content can be easily gasified if elaborate ash removal system is installed in the gasifier[19].

Slagging, however, can be overcome by two types of operation of gasifier[20] :

1) Low temperature operation that keeps the temperature well below the flow temperature of the ash.
2) High temperature operation that keeps the temperature above the melting point of ash.

The first method is usually accomplished by steam or water injection while the latter method requires provisions for tapping the molten slag out of the oxidation zone. Each method has its advantages and disadvantages and depends on specific fuel and gasifier design.

Keeping in mind the above characteristics of fuel, only two fuels have been thoroughly tested and proven to be reliable. They are charcoal and wood. They were the principal fuels during World War II and the European countries had developed elaborate mechanisms of ensuring strict quality control on them[24].

Charcoal, specifically, because of being tar free and having relatively low ash content property was the preferred fuel during World War II and still remains so[25]. However there is a major disadvantage of charcoal in terms of energy. Charcoal is mostly produced from wood and in conversion of wood to charcoal about 50% of original energy is lost[12] . When made by pit method (as is normally made in most developing countries) the losses can be as high as 80%[7]. 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.

Many agricultural residues and fuels have, therefore, been gasified. However the operating experience is very limited and most of the work has been on laboratory scale[15,17]. Table 3 lists the characteristics of these fuels. More research needs to be done in order to make gasification systems running on these fuels on a large scale.

Table 3. Gasification characteristics of various fuels

Fuel	Treatment, bulk density, moisture (m.c.)	Tar produced g/m^3	Ash content %	Gasifier	Experience	Ref.
Alfalfa straw	Cubed, 298 kg/m^3 m.c. = 7.9%	2.33	6	downdraft	No slagging, some bridging	17
Bean straw	Cubed, 440 kg/m^3 m.c. = 13%	1.97	10.2	downdraft	Severe slag formation	17
Barley straw (75% straw; 25% corn fodder and 6% orza binder	Cubed, 299 kg/m^3 m.c. = 4%	0	10.3	downdraft	Slag formation	17
Coconut shell	Crushed(1-4 cm), 435 kg/m^3 m.c. = 11.8%	3	0.8	downdraft	Excellent fuel. No slag formation	15
Coconut husks	Pieces 2-5 cm, 65 kg/m^3	Insignificant tar coconut	3.4	downdraft	Slag on grate but no operational problem	15
Corn cobs	304 kg/m^3 m.c. = 11%	7.24	1.5	downdraft	Excellent fuel. No slagging	17
Corn fodder	Cubed, 390 kg/m^3 m.c. = 11.9%	1.43	6.1	downdraft	Severe slagging and bridging	17
Cotton stalks	Cubed, 259 kg/m^3 m.c. = 20.6%	5	17.2	downdraft	Severe slag formation	17
Peach pits	Sundried, 474 kg/m^3 m.c. = 10.9%	1.1	0.9	downdraft	Excellent fuel. No slagging	17

Peat	Briquettes, 555 kg/m^3 m.c. = 13%	-	-	downdraft	Severe slagging	15
Prune pits	Air dried, 514 kg/m^3 m.c. = 8.2%	0	0.5	downdraft	Excellent fuel	17
Rice hulls	Pelleted, 679 kg/m^3 m.c. = 8.6%	4.32	14.9	downdraft	Severe slagging	17
Safflower	Cubed, 203 kg/m^3 m.c. = 8.9%	0.88	6.0	downdraft	Minor slag formation	17
Sugarcane	Cut 2-5 cms, 52 kg/m^3	Insignificant	1.6	downdraft	Slag on hearthring. Bridging	15
Walnut shell	Cracked, 337 kg/m^3 m.c. = 8%	6.24	1.1	downdraft	Excellent fuel. No slagging	17
Walnut shell	Pelleted.	14.5	1.0	downdraft	Good fuel	17
Wheat straw	Cubed, 395 kg/m^3 m.c. = 9.6%	-	9.3	downdraft	Severe slagging, bridging. Irregular gas production	15
Wheat straw and corn stalks	Cubed (50% mix), 199 kg/m^3 m.c. = 15%	0	7.4	downdraft	Slagging	17
Wood blocks	5 cm cube, 256 kg/m^3 m.c. = 5.4%	3.24	0.2	downdraft	Excellent fuel	17
Wood chips	166 kg/m^3 m.c. = 10.8%	6.24	6.26	downdraft	Severe bridging and slagging.	17

V GASIFICATION SYSTEMS

The combustible gases from the gasifier can be used a) in internal combustion engines, b) for direct heat applications and c) as feedstock for production of chemicals like methanol.

However in order for the gas to be used for any of the above applications it should be cleaned of tar and dust and be cooled. As previously mentioned cooling and cleaning of the gas is one of the most important processes in the whole gasification system. The failure or the success of producer gas units depends completely on their ability to provide a clean and cool gas to the engines or for burners. Thus the importance of cleaning and cooling systems cannot be overemphasized.

A. Cooling and Cleaning of Gas

The temperature of gas coming out of generator is normally between 300-500^{0}C. This gas has to be cooled in order to raise its energy density. Various types of cooling equipment have been used to achieve this end[21]. Most coolers are gas to air heat exchangers where the cooling is done by free convection of air on the outside surface of heat exchanger. Since the gas also contains moisture and tar, some heat exchangers provide partial scrubbing of gas[22]. Thus ideally the gas going to an internal combustion engine should be cooled to nearly ambient temperature.

Cleaning of the gas is trickier and is very critical. Normally three types of filters are used in this process. They are classified as dry, moist and wet[22] .

In the dry category are cyclone filters. They are designed according to the rate of gas production and its dust content[26]. The cyclone filters are useful for particle size of 5 μm and greater[26]. Since 60-65% of the producer gas contains particles above 60 μm in size the cyclone filter is an excellent cleaning device[21].

After passing through cyclone filter the gas still contains fine dust, particles and tar. It is further cleaned by passing through either a wet scrubber or dry cloth filter. In the wet scrubber the gas is washed by water in countercurrent mode. The scrubber also acts like a cooler[27], from where the gas goes to cloth or cork filter for final cleaning.

Since cloth filter is a fine filter, any condensation of water on it stops the gas flow because of increase in pressure drop across it. Thus in quite a number of gasification systems the hot gases are passed through the cloth filter and then only do they go to the cooler[28]. Since the gases are still above dew point, no condensation takes place in filter. Figure 8 shows schematically a downdraft gasification system with cleaning and cooling train.

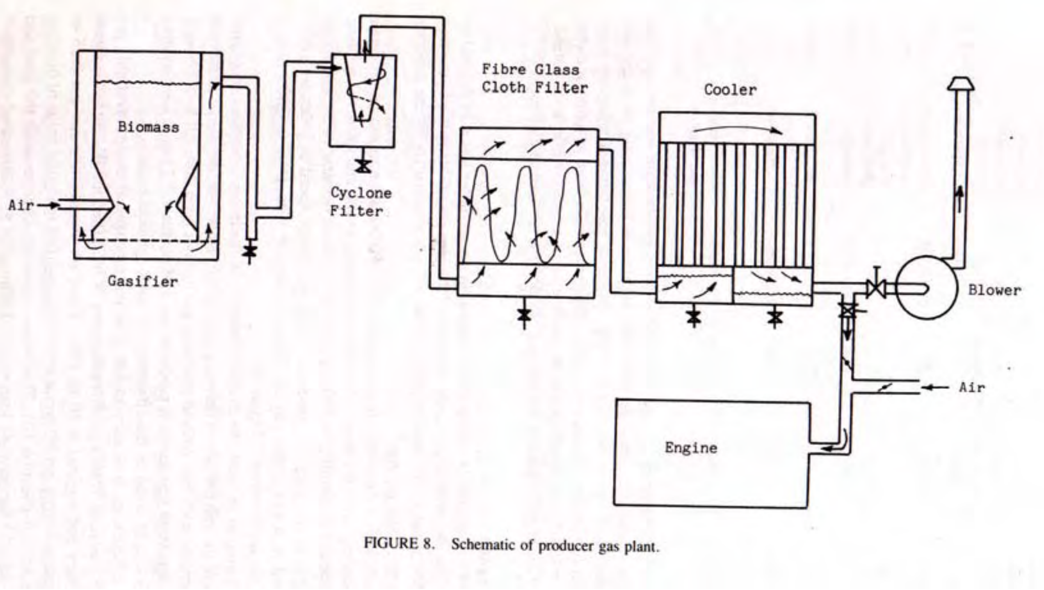

FIGURE 8. Schematic of producer gas plant.

There is quite a substantial pressure drop across the whole gasification system and the design is usually done such that the pressure drop should not exceed 100 cm of water[7] .

B. Shaft Power Systems

The biggest application of producer gas has been in driving IC engines. Both spark ignition and compression ignition engines have been driven by it. In principle any IC engine can be converted to run completely or partly on the gas. However in actual practice running the engines uninterrupted and for long periods of time without any problem is difficult to achieve[19].

The trend at present is therefore, to use available IC engines and run them on producer gas. However since the producer gas plant is tailor-made for a specific engine it is worthwhile to look at the engine itself. Producer gas being a relatively low energy gas has certain combustion characteristics that differ markedly from gasoline or diesel oil. Thus in future R&D in gasification it is worthwhile to do considerable work to make an engine specific for the gas. At present no such engine exists.

1. Spark Ignition Engine

When a spark ignition engine is converted to operation on producer gas it is derated to about 40-50%[29] . The deration is primarily because of low energy density of producer gas. This accounts for about 30% loss of power. The rest is accounted for by the pressure drop in the intake valves and piping[30] . A spark ignition engine on the whole requires very little modification to run on producer gas. Generally depending upon the make of engine (compression ratio and rpm), the ignition timing has to be advanced by about 30-40 degrees. This is done because of low flame speed of producer gas as compared to gasoline[30] . The low flame speed of producer gas is more efficiently used in low speed engine. Thus an engine with 1500-2500 rpm is ideal for producer gas application[30] . (Figure 9).

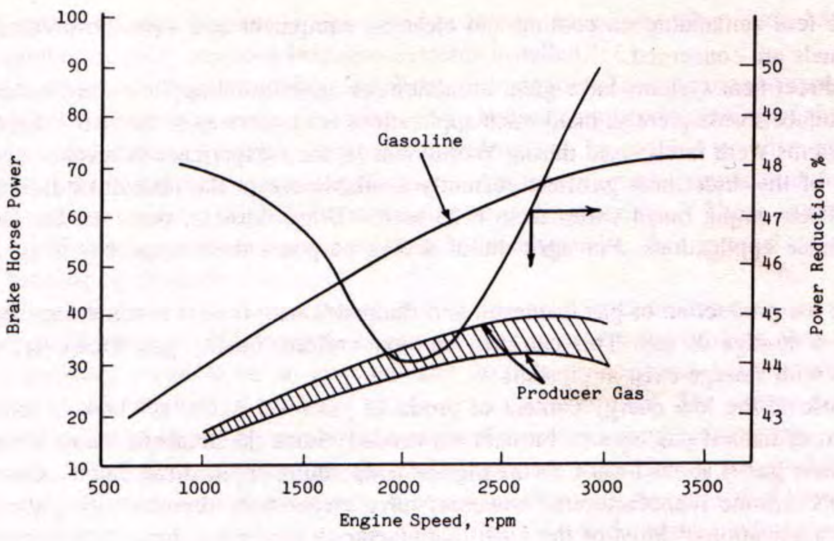

FIGURE 9. Power reduction as function of engine speed. (From Kaupp, A. and Goss, J. R., *Small Scale Gas Producer Engine Systems*, Deutsche Gesellschaft für Technische Zusammenarbeit, 1984. With permission.)

It should be noted that in general the overall efficiency of the IC engine itself does not change though the power derating takes place. However, detailed comparison of the engine efficiencies with and without producer gas has not been done till now because of insufficient data and large variations in producer gas composition[30]. Thus a conservative figure of 15-20% can be used as efficiency of spark ignition engines.

With the above efficiencies it is easy to calculate the mechanical energy available per kg of biomass gasified. With gasifier efficiency of 68% (Section III) the total system efficiency (gasification and engine) is 10-13%. Thus on an average one can get 0.55-0.75 kWh of mechanical energy per kilogram of biomass gasified (calorific value of biomass is taken to be 19.6 MJ/kg (Section III). This value however changes with the load and can go as low as 0.22 kWh/kg for 10% load to 0.73 kWh/kg for 87% load rated capacity[31]. Nevertheless for purpose of sizing a system, a good number is 0.7 kWh/kg.

2. Compression Ignition Engine

A compression ignition or diesel engine cannot be operated on producer gas completely without injection of small amount of diesel. This is because the producer gas cannot ignite by itself under prevailing pressure. Thus for compression ignition engines to run on producer gas they have to be either.

a) a dual fuel engine or, b) converted into spark ignition engines.

Since diesel engines have compression ratio between 16-20 and are run at lower rpm than gasoline engines they are ideally suited to run on producer gases with spark ignition. However, conversion of the engine to spark ignition is costly and elaborate affair and the advantages are nullified by the cost.

Thus most of the diesel engines running on producer gas have been dual fuel type. Especially in developing countries, where the proliferation of diesel engines has been because of dual pricing structure (diesel is subsidized).

Because of high compression ratio and low speeds, the derating of diesel engines running on producer gas is only between 15-30%. This is far superior to the gasoline engine’s derating. Even if gasoline engines are used in dual fuel mode their derating is still between 40-50%[30] .

On an average the diesel engine can run on 15-20% (of the original consumption) diesel and rest on producer gas. Generally the engine is started on diesel and as the gas generation builds up the diesel consumption is then kept at the idling level. The engine efficiency in this case is about 25%. Thus as a thumb rule the dual fuel engine producing 1 kWh requires 1 kg of biomass and consumes 0.07 liters of diesel[10] .

In both the diesel and gasoline engines the introduction of producer gas to the engine is by a T valve where, from one section of the T air is sucked in. Thus the complicated carburetor is greatly simplified by the above arrangements. Many arrangements have been developed for introduction of air/gas mixture in the engine[30] .

C. Direct Heat Systems

Direct heat systems are those in which the producer gas is burnt directly in furnace or boiler. The advantage of this as compared to direct combustion of biomass is in obtaining controlled heating and higher flame temperatures than those obtainable otherwise. Because of direct burning, the gas quality is less critical than in shaft power systems and consequently they are less demanding on cooling and cleaning equipment and have more versatility as far as fuels are concerned[7].

The direct heat systems have great attraction for agricultural applications like drying of farm produce and consequently many such applications are underway in U.S.[11]. Since direct heat systems were rarely used during Second World War, their experience is recent.

Most of the direct heat gasifiers currently available are of updraft or fluidized bed types. Their output range varies from 0.25-25 GJ/hr[7]. Most of these are for large kiln and furnace applications. For agricultural drying purposes their range has to be brought down.

Since the production of gas is uneven and fluctuates with time it is sometimes necessary to have a storage of gas. This can provide very uniform quality gas. However no such systems with storage exist at present.

Because of low energy content of producer gas (~ 5 MJ/m^3) which is about 10-15% that of natural gas, special burners are needed. Since the adiabatic flame temperature of producer gas is about 1400^0C [32]. The highest temperature applications can be around $1000\text{-}1200^0C$. Some manufacturers however have erroneously reported using the gas for 1600^0C applications[7]. Most of the U.S. manufacturers producing direct heat systems have been summarized by Goss[11].

D. Fluidized Bed Systems

For fuels which have high ash content and the ash has low melting point, fluidized bed combustion seems to gasify them[33].

In fluidized bed gasifiers the air is blown upwards through the biomass bed. The bed under such conditions behaves like boiling fluid and has excellent temperature uniformity and provides efficient contact between gaseous and solid phase. Generally the heat is transferred initially by hot bed of sand[23]. The major advantage of fluidized bed gasifier over, say, downdraft is its flexibility with regard to feed rate and its composition. Fluidized bed systems can also have high volumetric capacity and the temperature can be easily controlled.

However these advantages are offset by the complexity of the system with large blowers for blowing air and augers for feeding biomass. Besides, fluidized bed systems produce more dust and tar as compared to downdraft gasifiers[33]. This puts a heavy load on the cooling and cleaning train.

Nevertheless quite a number of research projects are underway to study and optimize biomass residue-based fluidized bed gasification systems[8,23,34]. However no large scale manufacturing facility for such systems exists today.

VI **APPLICATIONS**

As was mentioned earlier the main applications of biomass gasifier are :

a) Shaft power systems
b) Direct heat applications
c) Chemical production

In the shaft power systems the main agriculture applications are driving of farm machinery like tractors, harvesters etc. There are quite a number of manufacturers catering to the on-farm machinery gasification systems[33]. Small scale electricity generation systems also provide an attractive alternative to utilities.

Another useful application of producer gas units is in irrigation systems. This seems to be the most to be the most important application in developing countries[7]. There is no reason why such systems cannot become popular in developed countries especially when there have been quite a number of solar powered irrigation systems installed[37].

Direct heat systems, because of their simplicity, may prove to have biggest applications in agriculture. Among them are grain drying, green house heating and running of absorption refrigeration and cooling systems. Again these systems can be coupled to other renewable energy systems like solar for thermal applications. Another interesting application for direct heat (external combustion) application is running of Stirling engines[38]. These engines have very high efficiencies and may prove to be a better alternative than internal combustion engine running on producer gas.

Production of chemicals like Methanol and Formic acid from producer gas is a recent phenomenon[5]. However with fossil fuels getting scarcer, production of these chemicals by producer gas may prove to be an economically feasible proposition. Another interesting application may be use of producer gas to run a fuel cell plant. The energy density of such a plant would be highly favorable as compared to IC engine systems.

However for all these applications the most important ingredient is the availability of biomass fuel. For on farm applications biomass residues are attractive proposition. However, before any large scale application of gasification is undertaken the fuel availability is to be critically ascertained.

As an example it is instructive to look at the land area required, for a gasifier to run on cotton stalks (biomass residue) as fuel. On an average, quantity of stalks harvested is 1.5 tons/acre/yr[35]. Thus a 100 kW gasifier running at 8 hours per day for 300 days/year will require about 213 acres of cotton plantation to produce the required cotton stalks. Against such background all the future applications of gasifiers should be evaluated.

If the biomass residue availability is not adequate then the decision has to be made about running it on wood. However such decisions can only be made at specific sites and for specific applications.

Just like in any other alternative energy source it is advisable to use hybrid systems, similarly in biomass gasifications systems also it will be worthwhile to use them in conjunction with other energy systems. For example, grain drying can have biomass gasifier/solar coupling.

Only in specific cases of methanol or chemical production, should the gasification system be used as separate one.

VII CURRENT STATUS OF GASIFICATION TECHNOLOGY

Excellent survey of current status of gasification technology has been carried out by Foley and Barnard[41]. They have reviewed the status in both developed and developing countries.

However there is confusion regarding the number of manufacturers of gasification equipment. Quite a number of these manufacturers have just produced few units, which are still in experimental stages. There are therefore, close to 64 manufacturers all over the world[39, 11]. In U.S. alone there are 27 manufacturers and about 13 Universities and USDA research stations working on various aspects of biomass gasification[11].

The world's largest gasification manufacturing facility is Gasifier and Equipment Manufacturing Corporation (GEMCOR) in Philippines. They produce about 3000 units/year ranging in size from 10-250 kW. Besides they have recently started producing gasifiers for direct heat applications[43]. Their primary applications have been for irrigation pumps and power generating sets. To date about 1000 units have been installed within Philippines running on charcoal, wood chips and briquettes[43]. Brazil is another country where large scale gasification manufacturing program has been undertaken[42]. About 650 units of various sizes and applications have been installed.

In both the Brazilian and Philippines program the gasifiers are mostly charcoal powered. In this a strict quality control of the fuel has to be maintained. Thus the companies involved in gasifier manufacturing also supply the quality fuel. Inadequate fuel quality is the biggest problem in running these gasifiers[43].

In Europe there are many manufacturers especially in Sweden, France, West Germany and Netherlands who are engaged in manufacturing gasification systems for stationery applications. Most of market for these European manufacturers has been in developing countries[7].

The U.S. and North American manufacturing activities have been summarized by Goss[11]. In the research area the most active program in gasification is at University of California, Davis and University of Florida, Gainesville[11]. Many systems in the range of 10-100 kW have been developed at Davis. U.S. also is ahead of the rest of world in direct heat application gasifiers. Both fluidized and fixed bed gasifiers have been developed for this purpose.

In other countries of Asia and Africa the work is being carried out in research institution and few prototypes have been made and tested [7]. Interestingly enough no mention of Japan is there in any world wide gasification literature. However if the gasification technology does pick up it will be only a matter of time before Japan flexes its economic muscle and mass produces the gasifiers at cheaper rates.

Most of the gasifiers (upto 100 kW range) being sold by different manufacturers show a leveling off price of \$ 380/KW_e for plant prices and about \$ 150 KW_e for basic gasifier price[39] . This leveling off comes at about 100 kW system. However, for small systems the prices are extremely high. Thus a 10 KW_e gasifier plant costs about \$ 840/KW_e while the basic gasifier is \$ 350/KW_e. To this must be added the transportation costs (especially for shipment to developing countries). These prices therefore can make the gasifiers uneconomic. This explains the big gasifier manufacturing push being given in countries like Philippines, Brazil etc.

Unfortunately with all the activities going around the world the impact of gasification technology till todate on the economy has been negligible and far smaller than that of other renewable energy namely Solar. However gasification is a recently rediscovered technology and most of the development is still on learning curve.

VIII **CONCLUSIONS**

1. Biomass gasification offers the most attractive alternative energy system for agricultural purposes.

2. Most preferred fuels for gasification have been charcoal and wood. However biomass residues are the most appropriate fuels for on-farm systems and offer the greatest challenge to researchers and gasification system manufacturers.

3. Very limited experience has been gained in gasification of biomass residues.

4. Most extensively used and researched systems have been based on downdraft gasification. However it appears that for fuels with high ash content fluidized bed combustion may offer a solution. At present no reliable and economically feasible systems exist.

5. Biggest challenge in gasification systems lies in developing reliable and economically cheap cooling and cleaning trains.

6. Maximum usage of producer gas has been in driving internal combustion engine, both for agricultural as well as for automotive uses. However direct heat applications like grain drying etc. are very attractive for agricultural systems.

7. A spark ignition engine running on producer gas on an average produces 0.55-0.75 kWh of energy from 1 kg of biomass.

8. Compression ignition (diesel) engines cannot run completely on producer gas. Thus to produce 1 kWh of energy they consume 1 kg of biomass and 0.07 liters of diesel. Consequently they effect 80-85% diesel saving.

9. Future applications like methanol production, using producer gas in fuel cell and small scale irrigation systems for developing countries offer the greatest potentialities.

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