

An Overview of Biomass Gasification

Introduction

As received, biomass can range from very clean wood chips at 50% moisture, to urban wood residues that are dry but contaminated with ferrous and other materials, to agricultural residues, to animal residues, sludges, and the organic component of municipal solid waste (MSW). Representative biomass compositions are compared to fossil fuel compositions in Table 1. The process of gasification can convert these materials into carbon- and hydrogen-rich fuel gases that can be more easily utilized, often with a gain in efficiency and environmental performance compared to direct combustion of the biomass.

Table 1: Representative Biomass and Fossil Fuel Compositions

	Poplar	Corn Stover	Chicken Litter	Black Liquor	IL No. 4 HvBb	Rosebud subB	Athabasca Bitumen
Proximate, wt% as received							
Ash	1.16	4.75	18.65	52.01	12.88	7.82	
Volatile Matter	81.99	75.96	58.21	32.56	37.54	33.32	
Fixed Carbon	13.05	13.23	11.53	6.11	42.04	41.91	
Moisture	4.80	6.06	11.61	9.61	7.54	16.94	
HHV, Dry (Btu/lb)	8,382	7,782	6,310	4,971	12,400	11,684	17,900
Ultimate, wt% as received							
Carbon	47.05	43.98	32.00	32.12	63.43	62.59	83.6
Hydrogen	5.71	5.39	5.48	2.85	5.10	6.27	10.3
Nitrogen	0.22	0.62	6.64	0.24	1.09	1.08	0.4
Sulfur	0.05	0.10	0.96	4.79	4.40	4.36	5.5
Oxygen	41.01	39.1	34.45	0.71	12.98	12.85	0.2
Chlorine	<0.01	0.25	1.14	0.07	0.11	0.11	
Ash	1.16	4.75	19.33	51.91	12.88	12.75	
H/C Atomic Ratio	1.45	1.46	2.04	1.06	0.96	1.19	1.47
Elemental Ash, wt% of fuel as received							
Si	0.05	1.20	0.82	<0.01			
Fe	--	--	0.25	0.05			
Al	0.02	0.05	0.14	<0.01			
Na	0.02	0.01	0.77	8.65			
K	0.04	1.08	2.72	0.82			
Ca	0.39	0.29	2.79	0.05			
Mg	0.08	0.18	0.87	<0.01			
P	0.08	0.18	1.59	<0.01			
As (ppm)			14				

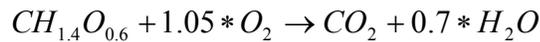
Gasifier systems incorporate a biomass fuel handling and feeding system, which is normally coupled by means of airlocks to the gasifier. The gasifier is usually a refractory lined vessel; and fluid-bed or entrained-flow gasification is carried at temperatures of 750-850°C at either atmospheric or elevated pressures. The product gas has to be treated so it matches the end-use application. For close-coupled gasifier-combustor systems there is no cleanup of the gases. For gas turbine applications in a power system the gas has to be free of particulates, tars, sulfur, chlorine compounds, and alkali metals to ensure the integrity of the turbine hot section. For internal combustion engines the gas must be cooled to ensure that a sufficient charge of energy can be put into each cylinder; and particular attention has to be given to tar and particulate contents to ensure that the valves and cylinders are protected. Fuel cell applications require the gas to be mainly hydrogen without any significant sulfur or chloride contamination to protect the electrodes. For synthesis operations such as ethanol, methanol Fischer Tropsch liquids, and hydrogen

production, tars, particulates and other contaminants (H₂S, ammonia, etc.) must be removed to prevent poisoning of downstream catalysts.

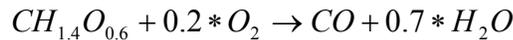
The conversion efficiency is high; gasification is typically 80-85% thermodynamically efficient in converting the organic content of the feed into a fuel gas mixture. Because biomass gasification results in a clean fuel gas, the efficiency for power is further enhanced by the use of combined cycles to generate electricity; biomass-to-electricity efficiencies greater than 45% are forecast. If the gases are converted to hydrogen, the limiting efficiency with fuel cells may be over 55%. The environmental advantage is that the fuel gas is a much smaller volume to be processed than the combustion stream from a boiler; this and the generally lower treatment temperature of the biomass results in retention of metals (including alkali) in the ash and cyclone as salts that can be disposed. The gas can easily be cleaned of acid gas components, including hydrogen chloride, before combustion and thus is environmentally superior to direct combustion.

Biomass is a complex mixture of organic compounds and polymers (Graboski and Bain 1979). The major types of compounds are lignin and carbohydrates (cellulose and hemicellulose) whose ratios and resulting properties are species dependent. Lignin, the cementing agent for cellulose, is a complex polymer of phenylpropane units. Cellulose is a polymer formed from d(+)-glucose; the hemicellulose polymer is based on hexose and pentose sugars. Biomass such as wood typically has low ash, nitrogen, and sulfur contents. However, some agricultural materials such as straws and grasses have substantially higher amounts. To estimate yields during gasification the complex material must be reduced to a simplified chemical formula, such as CH_{1.4}O_{0.6}. In this discussion, elements such as sulfur and nitrogen are considered to be present in very small amounts, and are not considered in terms of overall chemistry.

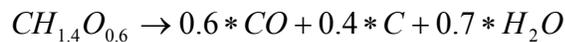
The combustion of biomass can be ideally represented by:



Oxygen-blown gasification can be thought of as incomplete combustion or partial oxidation. Gasification using a minimum amount of oxygen can be represented by:



In cases where no oxygen is used the gasification reaction can be represented by:



This pyrolysis reaction is endothermic, and heat is needed to make the reaction proceed. The heat is provided by the oxidation reactions shown above or by indirect heat transfer. Although these ideal reactions are simple, actual gasification is more complex. Intermediate compounds such as benzene, tars (organic compounds with boiling points higher than benzene), methane, and other light hydrocarbons are formed that must be further processed if the synthesis gas is to be used in high efficiency power applications or biofuels production.

Gasifier Medium

Gasification involves the thermal destruction of biomass in a reducing atmosphere of steam or air (or both) to produce a medium- or low-calorific value gas. If air is present, the ratio of oxygen to biomass is typically around 0.3. Air-blown, or directly heated gasifiers (also called partial oxidation gasifiers (POX)), use the exothermic reaction between oxygen and organics to provide the heat necessary to devolatilize biomass and to convert residual carbon-rich chars. For directly heated gasifiers, the heat to drive the process is generated inside within the gasifier. When air is used, the product gas is diluted with nitrogen and typically has a dry-basis calorific value of 5-6 MJ/Nm³. The dry-basis calorific value of the product gas can be increased to 13-14 MJ/Nm³ using oxygen instead of air. Oxygen production is expensive, however, and its use has been proposed only for applications involving the production of synthesis gas where nitrogen is not permitted in downstream synthesis conversion operations. Indirectly heated gasifiers heat and gasify biomass through heat transfer from a hot solid or through a heat transfer

surface. Because air is not introduced into the gasifier, little nitrogen is present and a medium-calorific gas is produced; dry-basis values of 18-20 MJ/Nm³ are typical.

Pressure

A second variable affecting gasification systems performance is operating pressure. Most gasification power applications will involve a gas turbine-based generation cycle. Turbines typically operate at compression ratios of 10 to 20, giving turbine inlet pressures of 1.0-2.5 MPa. A pressurized gasifier will produce gas at a pressure suitable for direct turbine application and provide the highest overall process efficiency, but process improvements are needed. Reliable, high-pressure feed systems have not been commercially proven. At gasifier conditions (825°C and 2 MPa) tars, chars, and volatile alkalis are generated. To maximize efficiency, these materials must be removed from the hot product gas without lowering the temperature below the tar dew point, typically about 540°C. Thus, hot-gas cleanup systems are required. Tars have relatively high heat contents and can be burned in combustors, but they may plug char filters and may form soot during combustion. Therefore, the first element of a hot gas cleanup system will probably be a catalytic reformer or thermal tar cracker. A catalytic tar reformer will operate at temperatures comparable to gasifier temperature, about 825°C; a thermal cracker will typically operate at 870-980°C. After the tar reformer/cracker, the product gas will be partially cooled to minimize the amount of alkali vapors, typically to 350-650°C. The product will then pass through a filter to remove solids. Much of the alkali will also be removed. For certain applications the gas may still contain too much alkali. For example, gas turbine limits for alkali are about 25 ppb in the turbine combustor exit gas. To ensure that the product gas meets alkali specifications, an alkali getter bed may be added after the filter. Typical bed materials are emaltheite or hectorite.

Alternatively, the gasifier can be operated at low pressure and the cleaned product gas compressed to the pressure required for gas turbine application or fuels synthesis applications. In this case a tar reformer will probably be used to minimize the amount of tar that must be handled during quenching. The product gas exiting the tar reformer will be conditioned to provide a suitable compressor feed. Gas characteristics to be considered for compressor use include the amount of condensable or soluble tar and the water vapor content. The water and tar content must be low enough to ensure no condensation during compression. Also, soluble tars that will affect lubrication oil properties must be eliminated. Lastly, the gas inlet temperature must be suitable for compressor materials of construction. Normally, the temperature should be held below about 90°C. Usually a combination of heat exchange (to reduce the gas from tar reformer exit temperature to residual tar dew point) and wet scrubbing are used. The water vapor content will be at saturation at scrubber exit temperature and pressure.

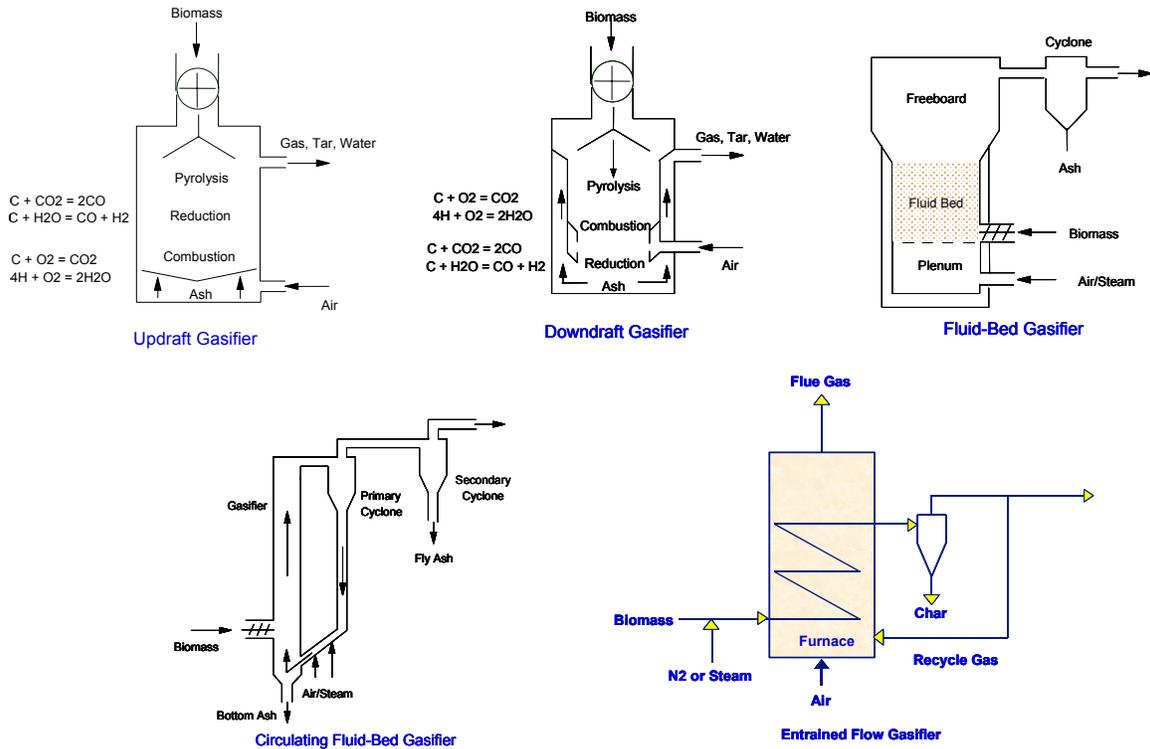
Gasifier Type

The other major variable is reactor type. Four primary types of biomass gasification reactor systems have been developed: fixed-bed reactors, bubbling fluid-bed reactors, circulating fluid-bed reactors, and entrained-flow reactors. Simple schematics of the various gasifiers are shown in Figure 1.

Fixed Bed

Fixed-bed gasifiers can be classified primarily as updraft and downdraft. Updraft gasifiers represent the oldest and simplest gasifiers. The updraft gasifier is a counterflow reactor in which fuel is introduced into the top by means of a lockhopper or rotary valve and flows downward through the reactor to a grate where ash is removed. The gasifying medium, air or oxygen and possibly steam, is introduced below the grate and flows upward through the reactor. At the bottom of the reactor (combustion zone) char burns to form carbon dioxide (CO₂) and steam (H₂O), which then flow upward through the bed countercurrently to the downflowing solids. The exothermic combustion reactions supply the energy to drive gasification, pyrolysis and drying. The maximum temperature in the combustion zone is typically higher than 1,200°C. In the reduction zone CO₂ and H₂O are partially reduced to carbon monoxide (CO) and hydrogen (H₂) through reaction with carbon in the char at temperatures of 800-1,200°C. In the pyrolysis zone these gases contact dry biomass in the temperature range of 400-800° C and devolatilize the biomass to produce pyrolysis products and residual char. Above this zone the gases and pyrolytic vapors dry the wet biomass. Typical product exit temperatures are 80-100°C. A wide range of tars and oils, which can condense in product lines, are produced in the pyrolysis zone. For this reason updraft gasifiers are usually operated in a close-coupled mode to a furnace or boiler to produce steam or hot water. Certain feeds with low-melting ash may have slagging on the combustion grate. In addition, feed particle size needs to be controlled to maintain a uniform bed.

Figure 1: Gasifier Types



In downdraft gasification the air and product both flow in the same direction as the solid bed. Downdraft gasifiers are specifically designed to minimize tar and oil production. The fuel and pyrolytic gases/vapors move co-currently downward through the bed. The pyrolysis products pass through a hot char (about 15% of the original feed) combustion zone, where they are contacted with air and the tars are thermally cracked and partially oxidized. Typical tar conversion is greater than 99%, and is a function of temperature, combustion efficiency and channeling. The combustion zone temperature is typically 800-1,200°C. The hot char in the reduction zone reduces CO₂ and H₂O, to CO and H₂. The exit gas temperature is typically around 700°C. Downdraft gasifiers have the same general constraints on feed properties as updraft gasifiers. The feed needs to have a fairly uniform particle size distribution with few fines to maintain bed physical properties and minimize channeling. The feed needs to have low ash with a high fusion temperature to prevent slagging. In addition, the feed moisture content needs to be less than about 20% to maintain the high temperatures required for tar cracking. A variation on the downdraft gasifier is the crossflow gasifier, in which air is introduced tangentially at the bottom of the gasifier. The operating principle of the crossflow gasifier is the same as for the downdraft gasifier.

Bubbling Fluid Bed

In a gas-solid fluidized bed a stream of gas passes upward through a bed of free-flowing granular materials in which the gas velocity is strong enough that the solid particles are widely separated and circulate freely throughout the bed. During overall circulation of the bed, transient streams of gas flow upward in channels containing few solids, and clumps or masses of solids flow downward (Perry and Chilton 1973). The fluidized bed looks like a boiling liquid and has the physical properties of a fluid. In fluidized-bed gasification of biomass the gas is air, oxygen, or steam, and the bed is usually sand, limestone, dolomite, or alumina. The gas acts as the fluidizing medium, and if air/oxygen is used, is the oxidant for biomass partial oxidation. A fluidized-bed gasifier is a vessel with dimensions such that the superficial velocity of the gas maintains the bed in a fluidized condition at the bottom of the vessel, with a change in cross-sectional area above the bed that lowers the superficial gas velocity below fluidization velocity to maintain bed inventory and act as a disengaging zone. To obtain the total desired gas-phase residence time for complete devolatilization, the larger cross-sectional-area zone (usually referred to as the freeboard) is extended. A cyclone is used to either return fines to the bed or to remove ash-rich fines from the system. A gas distribution manifold or series of sparge tubes are used to fluidize the bed (Hansen 1992). Biomass is introduced

either through a feed chute to the top of the bed or through an auger into the bed. In-bed introduction provides residence time for fines that would otherwise be entrained in the fluidizing gas and not converted in the bed.

The bed is usually preheated using an external burner fired by natural gas, propane or fuel oil. The hot flue gas from the external burner is used to heat the fluidized bed to the fuel ignition temperature. For biomass this temperature is around 540°C. Supplemental firing can be used to heat the freeboard gas to normal gasification temperature. At this point biomass is slowly introduced into the bed to raise the bed temperature to the desired operating range, normally 790-870°C. Bed temperature is governed by the desire to obtain complete devolatilization versus the need to maintain the bed temperature below the ash-fusion temperature of the biomass ash. As biomass is introduced into the bed, most of the organics pyrolytically vaporize and are partially combusted in the bed. The exothermic combustion provides the heat to maintain the bed at temperature and to volatilize additional biomass. Fluidized-bed gasifiers have the advantage of extremely good mixing and high heat transfer, resulting in very uniform bed conditions. Gasification is very efficient, and 95%-99% carbon conversion is typical. Bubbling fluidized-bed gasifiers are normally designed for complete ash carryover, necessitating the addition of cyclones for particulate control.

Circulating Fluid Bed

If the gas flow of a bubbling fluid bed is increased, the gas bubbles become larger, forming large voids in the bed and entraining substantial amounts of solids. This type of bed is referred to as a turbulent fluid bed (Babcock and Wilcox 1992). In a circulating fluid bed the turbulent bed solids are collected, separated from the gas, and returned to the bed, forming a solids circulation loop. A circulating fluid bed can be differentiated from a bubbling fluid bed in that there is no distinct separation between the dense solids zone and the dilute solids zone. Circulating fluid-bed densities are about 560 kg/m³ compared to a bubbling-bed density of 720 kg/m³ (Babcock and Wilcox 1992). To achieve the lower bed density, gas rates are increased from the 1.5-3.7 m/s of bubbling beds to about 9.1 m/s. The residence time of the solids in a circulating fluid bed is determined by the solids circulation rate, the attrition of the solids, and the collection efficiency of the solids separation device. Typical gas compositions for fluid and circulating fluid bed gasifiers are shown in Table 2.

Table 2: Gas composition for fluid bed and circulating fluid bed gasifiers

Gasifier	FERCO	Carbona	Princeton Model	IGT
Type	Indirect CFB	Air FB	Indirect FB	PFB
Agent	steam	air	steam	O₂/steam
Bed Material	olivine	sand	none	alumina
Feed	wood chips	wood pellets	black liquor	wood chips
Gas Composition				
H₂	26.2	21.70	29.4	19.1
CO	38.2	23.8	39.2	11.1
CO₂	15.1	9.4	13.1	28.9
N₂	2	41.6	0.2	27.8
CH₄	14.9	0.08	13.0	11.2
C₂+	4	0.6	4.4	2.0
GCV, MJ/Nm³	16.3	5.4	17.2	9.2

Entrained-flow

In entrained-flow gasifiers, pulverized feed is fed dry or in a slurry continuously into a pneumatic-flow reactor along with a relatively large amount of oxygen or steam. For oxidative heating the high temperatures caused by added oxygen almost completely destroy oils and tars. The high temperature (typically 1,300-1,400°C) also means that the ash is typically removed as a liquid slag. These gasifiers have been developed for coal, and only very limited testing with biomass has been performed. Shell, Chevron Texaco, and Koppers-Totzek have developed entrained-flow reactors for coal. There are a number of reasons for the lack of application of these coal reactors to biomass, but the high cost of feed preparation to reduce moisture content to low levels and reduce the particle size, along with low heat content, is the primary concern (Larson and Katofsky 1992). Refractory life is also a concern for biomass feeds with high potassium content (Higman and van der Burgt 2003). Indirectly heated entrained-flow gasifiers have been developed for biomass by a number of companies, including Brightstar Environmental and Pearson Technologies.

System Applications

Biomass gasifiers can be used for many process applications, including process heat production, combined heat and power, stand-alone electricity production, and chemicals production. Technologies being commercialized today are primarily for thermal applications and electricity production. Development of commercial technologies for chemical synthesis is much further into the future.

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