FSA1051

Gasification, Producer Gas and Syngas

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What Is Gasification?

Gasification involves turning organic fuels (such as biomass resources) into gaseous compounds (producer gas or syngas) by supplying less oxygen than is needed for complete combustion of the fuel. Gasification occurs at temperatures between 1112° and 2732° F and produces a low- to medium-energy gas depending upon the process type and operating conditions. Gasification of biomass resources is already being used to produce bioenergy and bioproducts for use in dual-mode engines to produce power (e.g., for irrigation) and to produce heat, steam and electricity. Studies are underway to develop biomass gasification technologies to economically produce hydrogen, organic chemicals and ethanol for use as transportation fuel in cars and trucks and to extend its use as a source of electricity.

What Is the Gasification Mechanism?

During gasification, the fuel (e.g., biomass resources) is heated to a high temperature, which results in the production of volatile compounds (gases) and solid residues (char). The quantity and composition of the volatile compounds depend on the reactor temperature and type, the characteristics of the fuel and the degree to which various chemical reactions occur within the process. The primary reactions that occur in the presence of oxygen result in the conversion of the fuel to carbon monoxide and carbon dioxide. These reactions are very fast and release heat, which provides the energy needed to sustain other gasification reactions. Gasification of solid materials (char) occurs at high temperatures (> 1112° F) and produces gases, tars and ash. Generally, these reactions are carried out in the presence of reactive agents such as oxygen, steam and hydrogen added to the reactor to aid in the chemical conversion of char to volatile compounds. These reactions dominate the gasification process and dictate the final composition of the producer gas or syngas. Their occurrence and extent depend on the operating conditions of the gasifier. Secondary reactions, which occur at temperatures greater than 1112° F and under appropriate pressure conditions, involve the decomposition of the tars to produce carbon and gases.

Gasification, which is incomplete combustion of carbonaceous fuels, can be represented with the following sub-stoichiometric equation:

Biomass + Limited Air → Carbon Monoxide + Hydrogen + Methane + Carbon Dioxide + Water Vapor + Nitrogen

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What Are the Differences Between Producer Gas and Syngas?

Producer gas is the mixture of gases produced by the gasification of organic material such as biomass at relatively low temperatures (1292º to 1832º F). Producer gas is composed of carbon monoxide (CO), hydrogen (H_2), carbon dioxide (CO_2) and typically a range of hydrocarbons such as methane (CH_4) with nitrogen from the air. Producer gas can be burned as a fuel gas such as in a boiler for heat or in an internal combustion gas engine for electricity generation or combined heat and power (CHP). The composition of the gas can be modified by manipulation of gasification parameters.

Syngas (synthesis gas) is a mixture of carbon monoxide (CO) and hydrogen (H_2), which is the product of high temperature steam or oxygen gasification of organic material such as biomass. Following clean-up to remove any impurities such as tars, syngas can be used to produce organic molecules such as synthetic natural gas (SNG-methane (CH_4)) or liquid biofuels such as synthetic diesel (via Fischer-Tropsch synthesis).

How Much Air Is Required for the Gasification Process?

For complete combustion, 1.0 pound of bone-dry (0 percent moisture content) biomass needs about 4.58 pounds of air. This is referred to as the stoichiometric air. For gasification reactions, the usual practice is to provide a fraction of the stoichiometric air, which is referred to as an equivalence ratio (ER). With dry biomass, best results are normally achieved at ERs of about 0.25, with a "typical" range of perhaps 0.20 to 0.33. Therefore, for normal gasification, 1.0 pound of biomass needs about 1.15 pounds of air.

What Are the Gasification Reactors?

Several biomass gasification reactor designs have been developed and evaluated and can be generally classified into two broad categories; namely, fixed bed and fluidized bed. Fixed bed reactors are those in which the fuels move either countercurrent or concurrent to the flow of gasification medium (steam, air or oxygen) as the fuel is converted to fuel gas. They are relatively simple to operate and generally experience minimum erosion of the reactor body. There are three basic fixed bed designs – updraft, downdraft and cross-draft gasifiers.

In an updraft fixed bed gasifier (Figure 1), the flows of the fuel and gases are countercurrent to each other. The reactive agent is injected at the bottom of the reactor and ascends to the top while the fuel is introduced at the top and descends to the bottom through zones of progressively increasing temperatures (drying, pyrolysis, gasification and oxidation). Heat from the gasification and oxidation zones rises upward to provide energy for the pyrolysis and drying zones. Gases, tar and other volatile compounds are dispersed at the top of the reactor while ash is removed at the bottom. The syngas typically contains high levels of tar, which must be removed or further converted to syngas for use in applications other than direct heating. Updraft gasifiers are widely used to gasify biomass resources and generally use steam as the reactive agent, but slagging can be severe if high ash fuels are used. They are unsuitable for use with fluffy, low-density fuels.

Downdraft fixed bed gasifiers (Figure 2) are similar to updraft gasifiers, except that the locations of the zones are reversed and, as such, the pyrolysis products are allowed to pass through the high temperature oxidation zone where they undergo further decomposition. The fuel is introduced at the top, and the reactive agent is introduced through a set of nozzles on the side of the reactor. Moisture evaporated from the biomass fuel serves as a reactive agent. The syngas leaves the gasifier from the bottom and contains substantially less tar than from updraft gasifiers, which reduces the need for cleaning and is, therefore, more suitable for a wider variety of applications.

Cross-draft fixed bed gasifiers exhibit many of the operating characteristics of downdraft gasifiers. Air or air/steam mixtures are introduced into the side of the gasifier near the bottom, while the syngas is drawn off on the opposite side. The oxidation and drying zones are concentrated around the sides of the unit. Cross-draft gasifiers respond rapidly to load changes, are relatively simple to construct and produce syngas suitable for a number of applications. However, they are sensitive to changes in the fuel composition and moisture content.

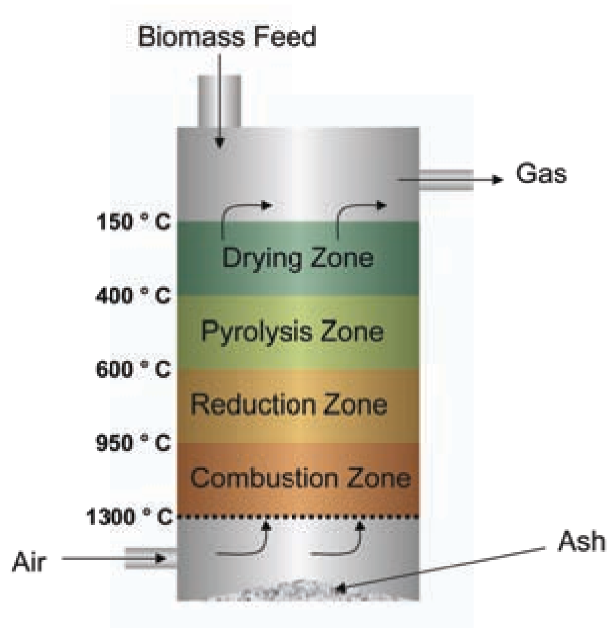

Figure 1. Updraft fixed bed gasifier (Source: G. Foley and G. Barnard. 1985. Biomass Gasification in Developing Countries. Earthscan, London, UK)

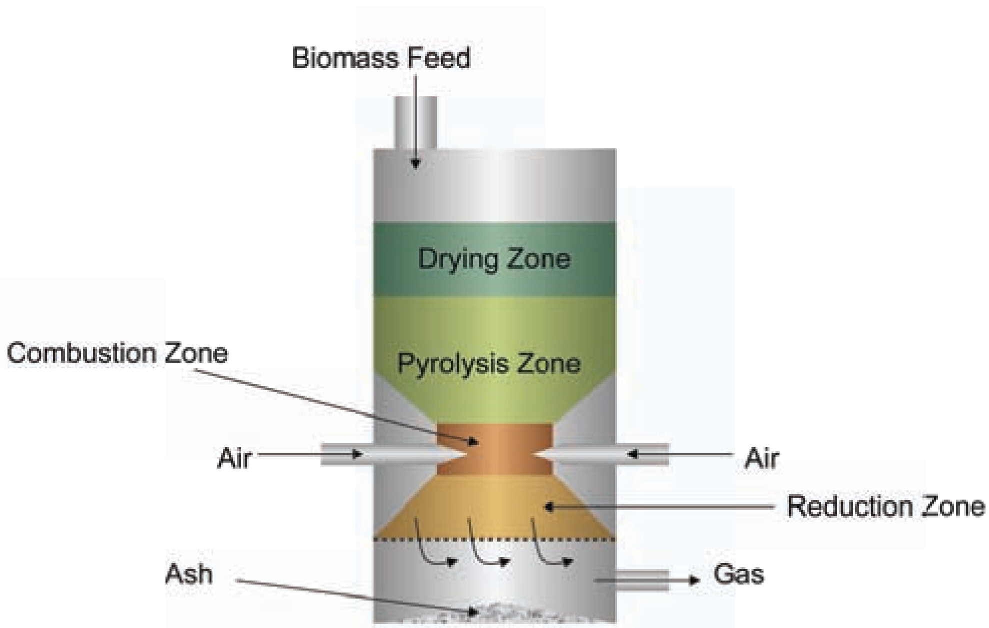

Figure 2. Downdraft fixed bed gasifier (Source: G. Foley and G. Barnard. 1985. Biomass Gasification in Developing Countries. Earthscan, London, UK)

A fluidized bed gasifier has a bed made of an inert material (such as sand, ash or char) that acts as a heat transfer medium. In this design, the bed is initially heated and the fuel introduced when the temperature has reached the appropriate level. The bed material transfers heat to the fuel and blows the reactive agent through a distributor plate at a controlled rate. Unlike fixed bed reactors, fluidized bed gasifiers have no distinct reaction zones and drying, pyrolysis and gasification occur simultaneously during mixing. Compared to other gasifiers, fluidized bed gasifiers have strong gas-to-solids contact, excellent heat transfer characteristics, better temperature control, large heat storage capacity, a good degree of turbulence and high volumetric capacity. But they operate at pressures slightly above atmospheric levels (which requires that leaks be prevented), and they respond slowly to load changes. Due to their complicated and expensive control systems, fluidized bed gasifiers appear to be commercially viable at larger

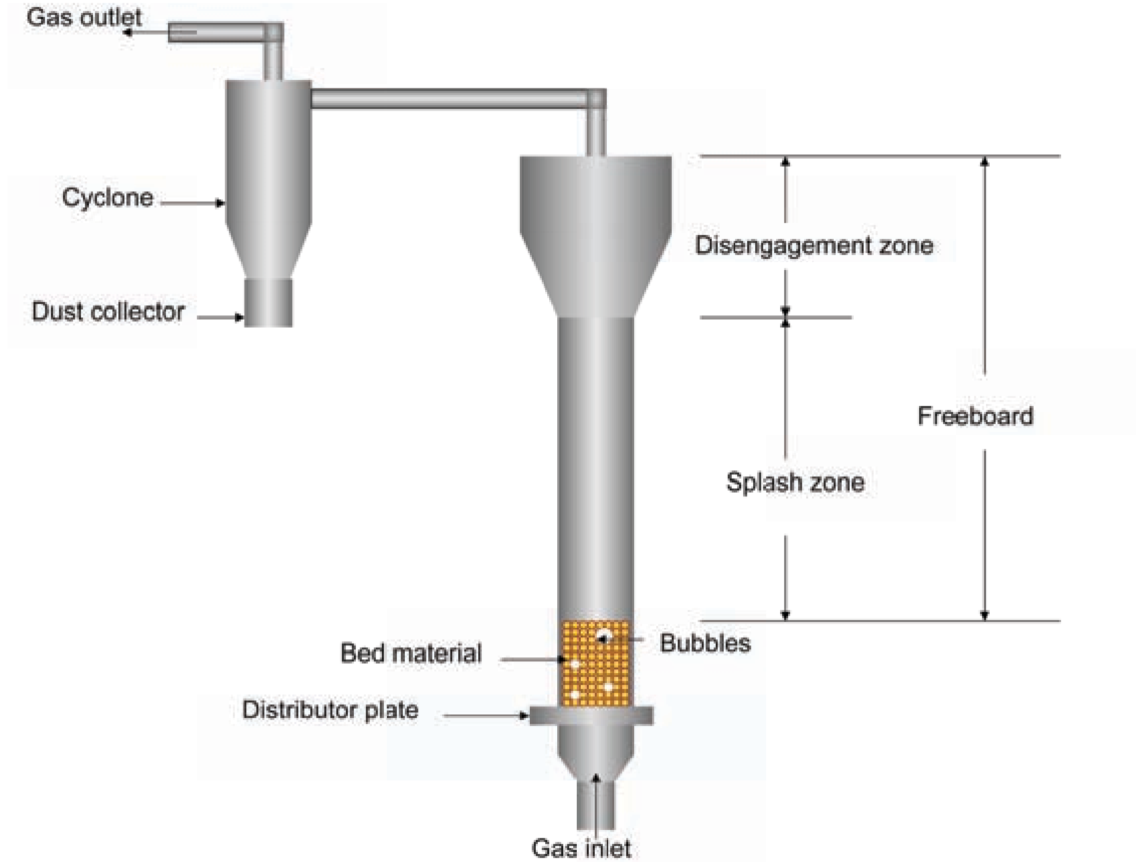

Figure 3. Bubbling fluidized bed gasifier (Source: D. Gelbart. 1986. Gas Fluidization Technology, John Wiley and Sons, New York)

sizes (> 30 MW thermal output). Fluidized bed reactors are classified by their configuration and the velocity of the reactive agent and consist of bubbling, circulating and spouted fluidized beds.

In bubbling fluidized bed gasifiers (Figure 3), fuel is fed into the reactor and gases are introduced at a flow rate that maintains pressure at a level sufficient to keep the fuel particles in suspension. The introduced gases pass through the reactor bed in the form of bubbles that rise and grow in size until they reach the surface of the bed, where they burst. The pressure must be maintained across the bed. Bubbling fluidized bed reactors are categorized as either single or dual fluidized beds. Single fluidized bubbling bed gasifiers have only one bed where the fuel and the reactive agent enter and from which the syngas and char exit. This design results in lower cost and less maintenance relative to multi-bed designs, and the syngas is ready for utilization. However, the energy content of the syngas is lower than achieved in dual-bed designs, inorganic materials in the fuel cannot be separated and pyrolysis occurs at the bottom of the gasifier leading to nonuniform temperature distribution. Dual- or multi-bed bubbling gasifiers have more than one bed. The first bed is usually used to burn some of the char to produce the energy for the second bed, where pyrolysis occurs. Dual-bed systems produce syngas with higher energy content due to the combustion of the char in a separate chamber, which prevents the combustion gas from diluting the pyrolysis gas. Additionally, inorganic materials in the fuel can be separated and the heat of pyrolysis reactions is evenly distributed, allowing pyrolysis to occur at a relatively uniform temperature. Higher construction costs and greater maintenance are the disadvantages of a dual system.

A circulating fluidized bed gasifier (also called a fast fluidized bed gasifier) is a modified bubbling bed gasifier in which the solids leaving the reactor vessel are returned through an external collection system. Compared to other gasifiers, circulating fluidized bed gasifiers have a higher processing capacity, better gas-solid contact and the ability to handle cohesive solids that might otherwise be difficult to fluidize in bubbling fluidized beds. Despite these advantages, circulating fluidized beds are still less commonly used because their height significantly increases their cost. A spouted fluidized bed gasifier has a bed of coarse particles partly filling the vessel and a relatively large control opening at the base where gas is injected. With a sufficient flow of gas, particles in the gas can be made to rise as a fountain in the center of the bed and to develop a circling motion on the bed. Additional air added to the base can produce a spouted bed. This type of gasifier has often been used to gasify coal.

What Is the Gasification Medium?

The simplest gasification process uses air as the reactive agent, which converts the excess char into a low energy syngas (142-209 Btu/ft^3) consisting mainly of hydrogen and carbon monoxide diluted with nitrogen from the air. The producer gas is suitable for boiler and engine applications but cannot be transported through pipelines due to its low Btu content. Gasification of char in the presence of steam produces a gas consisting mainly of carbon monoxide, carbon dioxide, hydrogen and methane. Steam can be added from an external source, or it can be obtained from the evaporation of the water in the fuel. Under conditions of low temperatures, low heat rates and high pressure, secondary reactions involving tars occur, but these reactions are not as prevalent under conditions of low pressure, high temperature and high heat rates. Gasification in the presence of steam produces a higher energy syngas relative to using air as the reactive agent.

The use of oxygen rather than air as the reactive agent reduces the amount of nitrogen supplied to the gasification reactions, which creates a medium energy syngas (approximately 321-563 Btu/ft^3) that is much lower in nitrogen and higher in methane, hydrogen and carbon monoxide relative to systems using air. Medium energy syngas can be used for a wide variety of applications and can be transported through a pipeline (due to its relatively low tar content). A drawback to the use of oxygen as a reactive agent is the need for a nearby source of oxygen, which may increase capital and operating costs.

Hydrogen can be used as a reactive agent in gasification, but its use requires high pressure and stringent operating conditions, as well as an external source of hydrogen. Air, steam, oxygen and hydrogen can be used as gasifying agents as shown in Figure 4.

What Are the Factors Affecting Gasification?

A number of factors affect gasification reactions including the temperature, pressure and height of the reactor bed; the fluidization velocity; the equivalence ratio; the air-to-steam ratio; and the characteristics of the fuel.

Increasing the temperature increases the formation of combustible gases, decreases the yield of char and liquids and leads to more complete conversion of the fuel. Hydrocarbon gases (especially methane and ethylene) increase with temperature while the yields of higher hydrocarbons (C_3-C_8: organic chemicals having 3 to 8 carbons) decrease at temperatures above 1202° F. The energy content of the syngas increases steadily up to 1292° F then decreases at higher temperatures.

The rate of char gasification and yields of methane increase with increasing pressure, and the impacts are most significant at high temperatures (1652°-1742° F).

For a given reactor temperature, higher fuel bed heights increase the time fuels are available for reactions to occur (residence time), which increases total syngas yields and increases the concentrations of hydrogen, carbon monoxide, carbon dioxide, methane and ethylene in the syngas.

Fluidization velocity (fluidization is the processing technique employing a suspension of a small solid particle in a vertically rising stream of fluid – usually gas – so that fluid and solid come into intimate contact) affects the mixing of particles within the reactor. Higher velocities increase the temperature of the fuel bed and lead to the production of lower energy syngas.

The equivalence ratio (actual fuel-to-air ratio divided by the stoichiometric fuel-to-air ratio) affects the temperature of the fuel bed. High ratios increase the rate of syngas production, and low ratios result in the production of lower syngas yields and energy

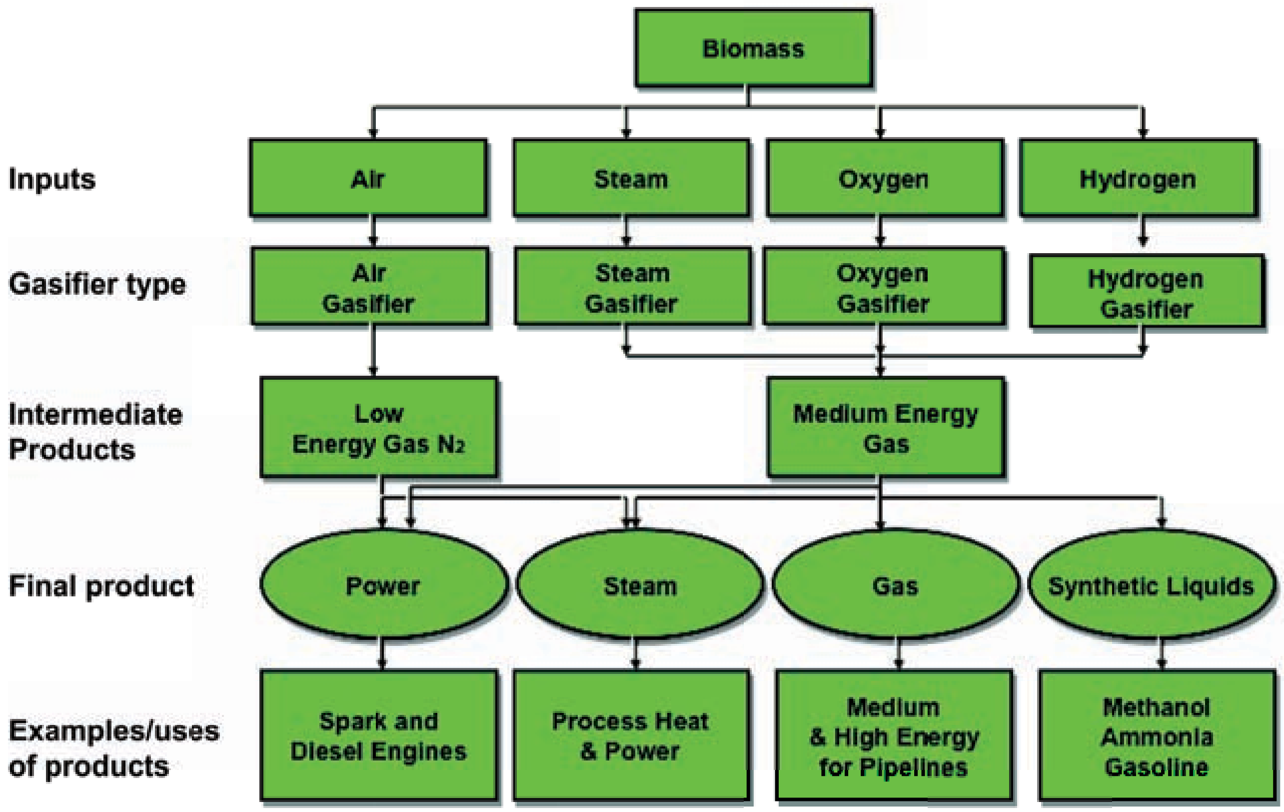

Figure 4. Gasification processes and their products.

content and more tar. Increases in the steam-to-air ratio increases the energy content of the syngas.

What Are the Limitations of the Gasification Process?

Although gasification processes are highly developed, there are still several limitations, particularly with respect to biomass gasification, including the moisture content and size of the fuel particles, the fuel feeding system, the ash deformation temperature, particle mixing and segregation and entrainment (elutriation).

Fuel moisture content differs by fuel type. Fuels with high moisture content lower the reactor temperatures due to the amount of energy needed to dry the fuel, which results in the production of lower energy syngas and lower yields of syngas. The speed at which fuel particles heat up (i.e., the heat rate) decreases as particle size increases, resulting in the production of more char and less tar.

The type of fuel-feeding mechanism required is determined by the size, shape, density, moisture content and composition of the fuel. Mechanisms developed to accommodate the wide variety of biomass fuels include direct feeding in which the feeding mechanism is isolated from the reactor to prevent the back-flow of tar and combustible gases, and over-the-bed feeders, which are usually less troublesome because there is no direct contact between the hot fuel bed material and the feeder. However, the use of over-the-bed feeders is restricted to fuels of higher density and/or larger sized particles and, because of particle emissions, results in the production of a dirty syngas, which must be cleaned before use.

At lower operating temperatures, some minerals in the fuel can cause agglomeration. The temperature at which agglomeration occurs (the ash deformation temperature) depends on the fuel type and its mineral composition. Effective mixing of fuel particles of various sizes is needed to maintain uniform temperature within the reactor.

How Much Energy Can Be Produced by Gasification?

- 1 acre of wheat land produces about 3,000 pounds of wheat straw.
- 1 pound of wheat straw contains about 7,750 Btu.
- 1 pound of straw could produce 23.9 ft^3 of gas with average calorific value of 125 Btu/ft^3.
- 1 acre of wheat land could produce 71,700 ft^3 of producer gas.
- 1 acre of wheat land could produce 8.9 MMBtu.
- 1 acre of wheat straw could replace 410 pounds of propane.

What Types of Biomass Can Be Gasified?

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 to 40 percent 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 is very fuel specific, and it is tailored around a fuel rather than the other way around.

What Are the Applications of Gasification Technology?

- **Production of heat and power**
  Power generation can be accomplished via gasification of biomass, followed by a combustion engine, combustion turbine, steam turbine or fuel cell. These systems can produce both heat and power (CHP – Combined Heat and Power) and can achieve system efficiencies in the range of 30 to 40 percent.

- **Production of hydrogen**
  Hydrogen is currently produced in large quantities via steam reforming of hydrocarbons over a Ni catalyst at 1472º F. This process produces a syngas that must be further processed to produce high-purity hydrogen. The syngas conditioning required for steam reforming is similar to that required for a biomass gasification-derived syngas; however, tars and particulates are not as much of a concern.

- **Production of methanol**
  Commercial methanol synthesis involves reacting CO, H_2 and steam over a copper-zinc oxide catalyst in the presence of a small amount of CO_2 at a temperature of about 500º F and a pressure of about 70 bar (1015 psi). To best use the raw product syngas in methanol synthesis, it is essential to maintain H_2/CO of at least 2 and CO_2/CO ratio of about 0.6 to prevent catalyst deactivation and to keep the catalyst in an active reduced state.

- **Production of gasoline or diesel**
  Gasoline and diesel (synthetic fuels) can be produced from syngas via a process named Fischer-Tropsch (FT). The FT synthesis involves the catalytic reaction of H_2 and CO to form hydrocarbon chains of various lengths (CH_4, C_2H_6, C_3H_8, etc.). Gasifier-produced gases with H_2/CO ratio around 0.5 to 0.7 are recommended as a feed to the FT process when using iron as a catalyst.

- **Production of ethanol**
  Anaerobic bacteria are able to grow on syngas components, thus forming acetate and ethanol. The bacterial conversion has the advantages of high selectivity, no thermal equilibrium and fewer problems with catalyst poisoning. The bacterial culture has to be able to convert CO_2, CO and H_2 into ethanol. The technology has been proven in a pilot plant in Arkansas, where ethanol has been produced from diverse feedstocks for several years. The reaction time from biomass to distilled ethanol has been proven to be short (7-8 minutes) compared to fermentation of sugars, which often lasts one to two days.

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Printed by University of Arkansas Cooperative Extension Service Printing Services.

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FSA1051-PD-5-09N