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Biomass Combustion

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What Is Combustion?

Combustion is a reaction of a fuel with oxygen in air to release heat. This process is used every day in households for heating and cooking and in industries for generating heat or steam. Combustion accounts for 85 percent of our world's energy usage and is vital to our current way of life. Combustion is a complex interaction of physical and chemical processes.

Good fuels for combustion are materials rich in hydrogen and carbon, called hydrocarbons. Such fuels include natural gas, coal, diesel, gasoline, propane, wood, agricultural residues and municipal solid waste. Ideally, all hydrogen and carbon would split off and combine with the oxygen in the air to create water vapor, carbon dioxide and heat. Below is the generalized formula for a combustion reaction:

Fuel + Oxygen ⟶ Carbon Dioxide + Water Vapor + Heat

Since biomass fuels are primarily composed of carbon, hydrogen and oxygen, the main products from burning biomass are carbon dioxide and water. Flame temperatures can exceed 2000°C, depending on the heating value and moisture content of the fuel, the amount of air used to burn the fuel and the construction of the furnace.

Combustion has three requirements – fuel, air and heat. If any of these three are removed, burning stops. When all three are available in the correct proportion, combustion is self-sustaining, because the fuel releases excess heat to initiate further burning.

Complete combustion of biomass requires a certain amount of air. Air consists of 21 percent oxygen and about 79 percent nitrogen. Therefore, the product of a stoichiometric combustion of biomass in air will include carbon dioxide, water vapor and nitrogen. This reaction will generate heat. The stoichiometric equation for the combustion of biomass is given as follows:

Biomass + Air ⟶ Carbon Dioxide + Water Vapor + Nitrogen + Heat

What Is the Combustion Mechanism?

For solid biomass to be converted into useful heat energy, it has to undergo combustion. Although there are many different combustion systems available, the principle of biomass combustion is essentially the same for each. There are three main stages to the combustion process as shown in Figure 1.

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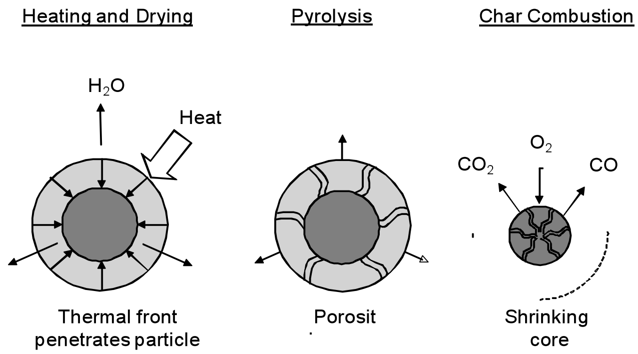

FIGURE 1. Main stages of combustion process

Drying – All biomass contains moisture, and this moisture has to be driven off before combustion can take place. The heat for drying is supplied by radiation from flames and from the stored heat in the body of the combustion unit.

Pyrolysis – When the temperature of the dry biomass reaches between 200ºC and 350ºC, the volatile gases are released. Pyrolysis products include carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4) and high molecular weight compounds (tar) that condense to a liquid if cooled. These gases mix with oxygen from the air and burn producing a yellow flame. This process is self-sustaining as the heat from the burning gases is used to dry the fresh fuel and release further volatile gases. Oxygen has to be provided to sustain this part of the combustion process. Char is the remaining material after all the volatiles have been burned off.

Oxidation – At about 800ºC, the char oxidizes or burns. Again oxygen is required, both at the fire bed for the oxidation of the carbon and, secondly, above the fire bed where it mixes with carbon monoxide to form carbon dioxide that is given off to the atmosphere. Long residence time for fuel in a combustor allows the fuel to be completely consumed. It is worth bearing in mind that all the above stages can occur within a fire at the same time.

Combustion is complete when 100 percent of the energy in the fuel has been extracted. It is important to strive for complete combustion to preserve fuel and improve the cost efficiency of the combustion process. There must be enough air in the combustion chamber for complete combustion to occur. The addition of excess air greatly lowers the formation of carbon monoxide (CO) by allowing CO to react with O_2. More complete combustion will result in less CO in the flue gas.

How Much Air Is Required for the Complete Combustion Process?

Complete combustion will occur when the proper amounts of fuel and air (fuel-to-air ratio) are mixed for the correct amount of time under appropriate conditions of turbulence and temperature. Biomass can be represented chemically as CH_2O. Therefore, to burn 30 pounds of biomass, you need to supply 32 pounds of oxygen, which is accompanied by 105.3 pounds of nitrogen in the air (air is 21 percent oxygen and 79 percent nitrogen). Hence, the required amount of air will be 32 + 105.3 = 137.3 pounds. In other words, we need about 4.58 pounds of air for complete burning of 1.0 pound of bone-dry (0 percent moisture content) biomass. In addition to heat, this reaction will yield 18 pounds of water vapor, 44 pounds of carbon dioxide (greenhouse gas) and 105.3 pounds of nitrogen. In other words, we need about 4.58 pounds of air for complete burning of 1.0 pound of bone-dry (0 percent moisture content) biomass.

Theoretically, stoichiometric combustion provides the perfect fuel-to-air ratio, which lowers losses and extracts all of the energy from the fuel. In reality, stoichiometric combustion is unattainable due to many factors, making 100 percent efficiency impossible. In practice, in order to achieve complete combustion, it is necessary to increase the amount of air to the combustion process to ensure the burning of all of the fuel. The amount of air that must be added to make certain all energy will be retrieved is known as excess air. Typical excess air required for various combustion systems is in the range of 5 to 50 percent, depending on the fuel characteristics and the system configuration.

How Much Heat Could Be Produced From Combustion of Various Fuels?

The amount of heat produced by combustion depends on the type of fuel and the combustion efficiency of the equipment used. The quantity of heat produced by a material's complete combustion at a designated standard temperature and pressure (atmospheric pressure and 25°C) is called the material's Heating Value (HV) or Calorific Value (CV). In the following table is a selection of typical materials and their HV in BTUs per pound. One BTU is the amount of heat energy required to raise the temperature of 1 pound of water 1 degree Fahrenheit.

Fuel	Heating Value$_{dry\ matter}$ (BTU/lb)
Coal	6,450 - 11,080
Diesel	19,260
Ethanol	12,760
Gasoline	20,335
Glycerin	8,160
Methane	23,870
Hybrid poplar	8,183 - 8,491
Wheat straw	6,964 - 8,148
Corn stalks	7,587 - 7,967
Rice hull	6,811 - 8,838

What Are the Combustion Reactors?

Biomass, such as wood, crop residues and animal manure, is burned in various types of combustion reactors. What you are left with is a number of gases, fragments of partially oxidized hydrocarbons and water vapor. Below is a list of some combustion reactors and a brief description of how they work:

Fireplace – A masonry fireplace supplies radiant energy to bring quick comfort to a cold room. However, it is a very inefficient heating device. In addition, air that supports combustion in the fireplace is drawn from the room and must be replaced by cold outside air. The heat radiated to the room may be less than the heat contained in the air that is drawn up in the chimney. Additional heat can be lost if the flue damper is left open after the fire dies out. Fireplaces should be used to take the chill off the room during mild spring and fall weather.

Stoves – There are manufacturers of wood and coal stoves throughout the world. Size, appearance, style, finish, construction, material, weight, durability and ability to burn the fuel efficiently for maximum heat are just some of the characteristics to be evaluated before purchasing a stove. There are two types of stoves, radiant and circulating, and many styles to fit almost any location and furnishings. Most wood and coal stoves transfer heat to the room by radiating heat from the hot surface of the stove.

Radiant heaters produce heat that is most intense at close proximity and diminishes rapidly with distance from the stove. Surfaces in direct line with the stove will be heated. Many people find the comfort of radiant heat hard to beat and enjoy the fact that the family's activities tend to center around the fire.

Circulating stoves are constructed with a metal box spaced about 1 inch from the wall of the firebox. Vents in the top and bottom of the outer box allow natural or fan-forced air currents to carry the heat away from the stove. Circulating stoves can be installed closer to combustible material than radiant stoves, because their outer surface is not as hot. A circulating stove is better suited than a radiant stove for heating a large room.

Furnaces – A central heating system, although more expensive, has several advantages over stoves. Located in the basement or other isolated room, it provides longer, more efficient burn cycles and more uniform temperatures throughout the house. It also keeps the ash and dust out of the living area. Automatic controls make a central heating system safer to operate. Furnaces are available that heat air and distribute it through a duct system.

Wood-Chip and Pellet Furnace – These furnaces, fed from a hopper or by a small auger, are very efficient, and the firing rate can be controlled to match the heating load. Wood-chip furnaces are generally restricted to commercial applications, as chips are not readily available in most areas and must be stored under cover. Outdoor wood-fired furnaces keep the dirt and ash outside the home. The unit is usually located within 200 feet of the house, where fuel can be easily supplied and where the heat can be piped to the home.

Furnaces With Boilers – The furnace of the boiler is where the fuel and air are introduced to combust; fuel/air mixtures are normally introduced into the furnace by using burners, where the flames are formed. The resulting hot gases travel through a series of heat exchangers, where heat is transferred to the water flowing though them. The combustion gases are finally released to the atmosphere via the exhaust section of the boiler. The boiler is an enclosed vessel in which water is heated and circulated, either as hot water, steam or superheated steam for the purpose of heating, powering and/or generating electricity.

Industrial Combustion Systems – Three of the most common types of industrial combustion systems are downdraft combustion, updraft combustion and fluidized bed (Figure 2) combustion systems. Downdraft combustion is where flames are drawn into the combustion chamber and combustion occurs inside the reactor, while updraft combustion is where the combustion occurs outside and above the reactor. In fluidized bed combustion, solid fuels are suspended on upward-blowing jets of air during for the combustion process. This mixes the gas and solids in a turbulent regime. Fluidized bed combustors provide an effective environment for chemical reactions and heat transfer.

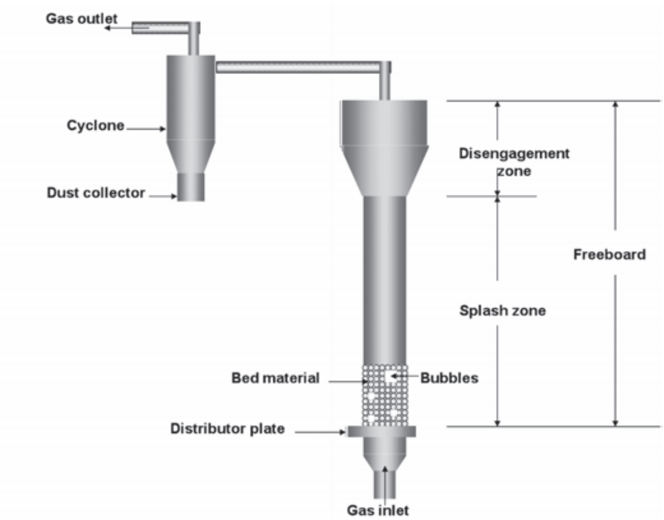

FIGURE 2. Simple fluidized bed combustion system

What Is Combustion Efficiency?

Combustion efficiency is a measure of how well the fuel is being burned. Essentially, it is the percentage of the energy of a fuel that has been used up in the burning process. While complete combustion (100 percent combustion efficiency) is theoretically possible, in reality it is not, mostly due to heat losses. Below is a table of selected combustion processes and their typical combustion efficiencies.

Combustion Processes and Their Combustion Efficiency Ranges

Process	Efficiency
Home fireplace	10%-30%
Space heater	50%-80%
Commercial gas boiler	70%-82%
Residential gas boiler	70%-82%
Oil burner heating system	73%-85%
Induced draft furnace	74%-80%
Boiler with gas burner	75%-85%
Condensing furnace (gas and oil)	85%-93%

What Is Draft?

Draft refers to the flow of gases through the combustion system, beginning with the introduction of air at the inlet of the burner. Once combustion occurs, the heated gas leaves the combustion chamber, passes heat exchangers and exits the exhaust stack. Depending upon the design of the combustion system, draft is natural, meaning combustion air is pulled in by heated gases venting up the stack, or it is mechanical, meaning air is pushed or pulled through the system by a fan. Often, draft relies on a combination of both natural and mechanical means.

The flow of gases in the stack must be carefully controlled to ensure that all the gases of combustion are removed from the combustion zone at the correct rate. Monitoring draft is important, not only to increase combustion efficiency but also to maintain safe conditions. Low draft creates a buildup of highly toxic gases such as carbon monoxide and highly explosive gases such as hydrogen/air mixture. These buildups may take place in the combustion chamber or may even be ventilated indoors creating health risks. Conversely, extremely high draft can cause unwanted turbulences in the system preventing complete combustion. Unwanted high draft tends to damage the combustion chamber and heat exchanger materials.

What Is Combustion Analysis?

Combustion analysis is the monitoring of the gas that escapes after combustion, or flue gas, in order to improve the overall process. It is important to monitor the content of the flue gas for three reasons – environmental concerns, safety and maintenance of machinery and maximum combustion efficiency.

The EPA has set standards for the amount of pollution allowed in the air. They are called the National Ambient Air Quality Standards (NAAQS). Regular testing of the flue gas ensures compliance with the environmental standards required by law.

Combustion analysis can provide information on the concentration of certain toxic gases. Equipment can be shut off or modified if the concentration exceeds a certain amount, since it could be dangerous to those working in close proximity to the equipment or living in the surrounding area. High concentrations of toxic gas can also be an indication that maintenance of the machinery needs to be performed in order to reduce the toxic compounds.

The presence of compounds such as carbon monoxide (CO) indicates that the combustion process could run more efficiently, which would conserve expensive fuel and save money. Using combustion analysis is vital to achieving maximum combustion efficiency.

What Are the Combustion Analysis Factors?

Combustion analysis involves the measurement of flue gas concentrations, temperatures and pressure for boiler tune-up and emissions.

Oxygen, Carbon Monoxide and Carbon Dioxide

When oxygen (O_2) is found in the flue exhaust, it usually means that more air was supplied than needed for complete combustion to occur. When too little oxygen is supplied to the burner, carbon monoxide (CO), a highly toxic gas, forms in the flue gas. Not only improved fuel efficiency but also decreased soot generation will occur when the correct amount of air is supplied to the combustion process.

Temperature and Draft

The stack loss, or chimney loss, of a combustion system is the amount of heat that travels up the stack without doing any useful work. It depends on the amount of air traveling through the burner and the temperatures of inlet and outlet air. There are also some fuel-specific factors that will affect stack loss. Naturally, this is not a true measure of all the losses that will occur in a combustion system, but stack loss is a useful number that shows factors that can be changed when tuning a combustion system.

Nitrogen Oxides, Sulfur Dioxide Hydrocarbons or Volatile Organic Compounds and Soot

Additional byproducts from the combustion process are nitrogen oxides (NO_x), sulfur dioxide (SO_2), hydrocarbons (HCs)/volatile organic compounds (VOCs) and soot. Because of regulatory and efficiency concerns, it is best to minimize the presence of these potentially harmful byproducts. Keeping the air temperature and air flow at the optimum level minimizes these combustion byproducts. Use of a low-sulfur or desulfurized fuel will minimize the amount of SO_2 emissions.

What Combustion Products Pollute the Home?

The major combustion pollutants released indoors from combustion reactors include carbon monoxide, nitrogen dioxide and particles. Unvented kerosene burners generate acid aerosols. Combustion gases and particles can come from chimneys that are improperly installed or maintained and cracked furnaces. Pollutants from fireplaces and woodstoves with no dedicated outdoor air supply can be “back-drafted” from the chimney into living spaces, particularly in weatherized homes.

How Much Heat Can Be Produced From Burning Rice Straw?

The use of agricultural crop residue as a biomass for heating is receiving renewed interest. The figures below provide an approximate analysis of the heating potential of one acre of rice straw: one acre of rice land produces about 3,000 pounds of rice straw.

- One pound of as-received rice straw contains about 5,890 Btu.
- One acre of rice straw produces approximately 17.6 MMBtu.
- Assume that the combustion efficiency is about 50 percent.
- Therefore, one acre of rice straw produces approximately 8.8 MMBtu of usable heat.
- One acre of rice straw can replace about 410 pounds of propane.

Summary

Biomass combustion simply means burning organic materials. Biomass combustion takes place when biomass reacts with the oxygen in air to produce heat. The heat created by the burning of biomass is used in the operation of equipment such as boilers, furnaces, kilns and engines. Along with heat, carbon dioxide and water vapor are created as byproducts of the chemical reaction.

Farmers and other rural homeowners are increasingly looking to biomass heat as an economical alternative to propane or furnace oil. Biomass burning provides a relatively cheap fuel source, reduces reliance on fossil fuels and provides self-sufficiency, even during blackouts. On the other hand, open field burning of biomass (Figure 3) is a major contributor to poor air quality and reduced visibility. Open field burning produces significant amounts of air pollutants that have been linked to numerous health problems. Effective burning of biomass can help reduce our dependence on fossil fuels.

FIGURE 3. Fields of burning biomass

For more information concerning combustion, visit:

- http://www.e-inst.com/combustion/
- https://www.epa.gov/environmental-topics/air-topics
- https://www.epa.gov/clean-air-act-overview
- http://www.engineeringtoolbox.com/fuels-higher-calorific-values-d_169.html

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