11/07

Basics of Low Emissions Biomass Combustion

Tony Nekut

Overview

Clean combustion of biomass can be achieved using modern systems control techniques similar to those which have been developed in recent years to reduce automobile emissions. In a basic steady combustion process, biomass, in the form of firewood, wood chips or grass/wood pellets is radiantly heated in a combustion chamber whose temperature is on the order of 1000 $^{\circ}C$. The heating causes fuel pyrolysis, the release of volatile gases which burn when turbulently mixed with air injected into the combustion chamber. Following pyrolysis, the residual solid carbon in the fuel, called char, burns more slowly. Exhaust gases from proper combustion of biomass consist almost entirely of water, carbon dioxide, and the atmospheric nitrogen in the combustion air which passes almost inertly through the system. Although this process is well understood, most biomass fueled heating appliances do not approach this level of complete combustion and release smoke containing many environmentally harmful compounds. If biomass heating is to become more widely adopted, it is essential that low emission appliances become the norm.

Chemistry

Roughly speaking, all biomass has the same elemental composition: carbon (C), hydrogen (H), and oxygen (O). The average chemical formula for dry woody biomass, $C_6H_{9.4}O_4$, suffices for an approximate analysis of the combustion process: $\text{wood} + 6.4O_2 = 6CO_2 + 4.7H_2O$. It follows that one pound of dry biomass requires about 6 pounds (lb) of air to supply enough oxygen for combustion. This mass of air consists of about 1.4 lb of oxygen and 4.6 lb of nitrogen.

Energetics

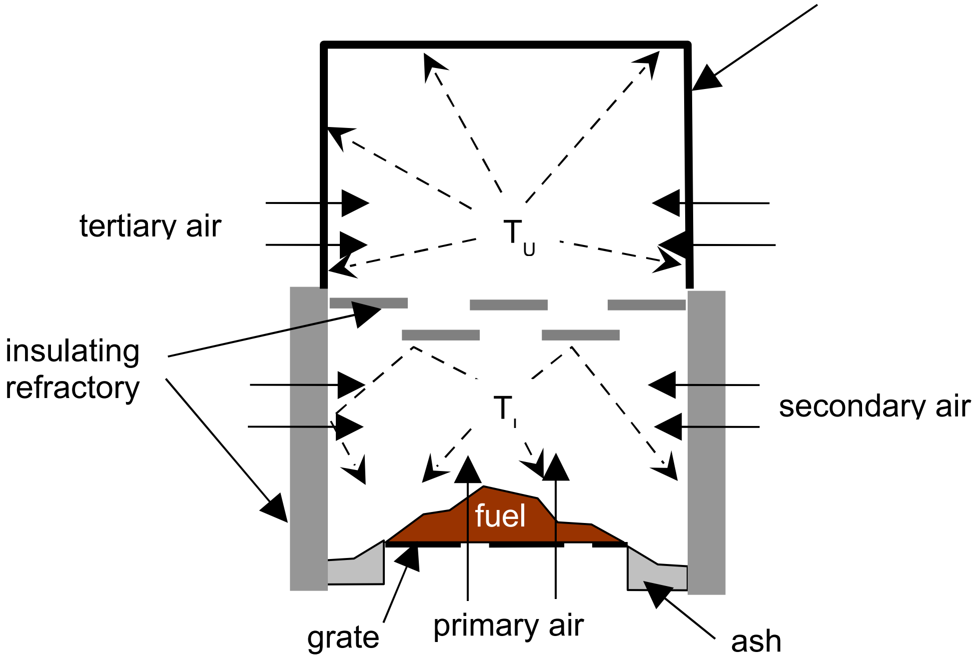
Moisture content is the main factor determining the heating value of a pound of biomass. The average specific heating value of any species of dry wood is about 8600 BTU/lb. Water lowers the specific heating value by replacing part of the fuel mass with water which must then be vaporized and is carried off as steam in the exhaust gases (unless the combustor is designed to recover heat by condensing this exhaust steam). For example, if a fuel sample is 50% biomass and 50% water by weight, it has a heating value of about 4300 BTU/lb if all of the heat content in the exhaust gases are recovered. Peak theoretical gas temperatures can be calculated by energy balance given the fuel heating value, the heat capacities of the combustion product gases, and the heat of vaporization of water (under the assumption of zero heat loss from the combustion chamber).

Heat capacities are very roughly 0.3 BTU/lb°F for N_2, O_2, and CO_2, and 0.6 BTU/lb°F for H_2O. The heat of vaporization of water is 970 BTU/lb. It follows that $8700(1-mc) = \Delta T[(0.3)(7)(1-mc) + 0.6mc] + 970mc$ where mc is the fuel moisture content, ΔT is the °F gas temperature rise, and 7 is the total mass of the exhaust gases per lb of fuel. When mc=0.5, ΔT = 2800 °F = 1500 °C. In principle, there is enough heating value in 70% mc fuel to raise combustion temperatures to 1000 °C. While it is indeed possible to cleanly burn high mc fuel, there are two practical reasons to prefer drier fuel. Most importantly, wet fuel requires a larger combustion system to handle the increased volume of wet fuel required to deliver a specified heating load. Secondarily, unless exhaust gases are cooled below 100 °C, the heat of vaporization of the exhaust steam is lost, reducing efficiency. Both factors require more expensive equipment to efficiently burn high mc fuel.

Dynamics

Chemical reaction kinetics are an important factor in achieving clean, complete combustion of biomass. There must be sufficient time to complete combustion before the reacting gases flow out of the combustion zone and cool. There are two ways to accelerate the combustion process: raise the temperature and increase the turbulent mixing of the reacting gases. Temperatures can be increased by using low moisture fuel or by limiting heat loss from the combustion chamber to the heat transported by the exiting reaction product gases. (Excessive temperatures must be avoided, however, to limit production of NOx emissions. For this reason, it is desirable to maintain combustion chamber temperatures in the neighborhood of 1000 °C.) Turbulence can be improved by injecting combustion air as high velocity, high pressure jets or by directly stirring the reacting gases.

Generic Biomass Combustor



The figure shows some features of a typical biomass combustor design. Fuel on the grate is pyrolysed by the radiant heating from the burning gases and insulating walls of the lower combustion chamber. Primary air flowing through the fuel bed supplies oxygen to the burn solid char. Secondary airflow causes turbulent mixing and supplies oxygen to burn the volatile pyrolytic gases. T_L, the temperature in the lower chamber, determines the rate at which radiant heat is delivered to the fuel (dashed arrows) and consequently, the rate of pyrolysis and the primary and secondary air flow rates required to maintain T_L. Increasing airflow to the lower combustion chamber increases T_L to the point where combustion does not complete in the lower chamber; T_L decreases with further increases in airflow. If wall heat losses in the lower combustion chamber are small and T_L is less than the maximum achievable gas temperature, combustion is completed in the upper chamber. Once the gases move beyond the baffle separating the lower and upper chambers, heat is transferred to the upper chamber walls as combustion completes. Tertiary airflow is added as needed to complete combustion.

Computer models which account for gas dynamics, reaction kinetics, and heat transfer are valuable aids when designing combustion systems.

Process control

Combustion can be optimized by dynamically adjusting the flow of air and fuel to maintain proper combustion chamber temperatures and exhaust gas composition. This is typically implemented using a variety of sensors interfaced to a microprocessor which controls the motors in the fuel feed and blower systems. Low emissions can be automatically maintained despite changes in heat load demand and fuel moisture content. System startup and shutdown can also be automatically managed by the control system.

Low cost designs

Biomass combustion systems are more expensive that equivalently rated natural gas or fuel oil fired systems for several reasons. Automatic feeding of solid fuels is intrinsically more difficult than liquid or gaseous fuels and because the energy density of biomass is low (e.g. about 1-2x10^5 BTU/ft^3 for biomass vs. 10^6 BTU/ ft^3 for fuel oil) larger volumes of biomass must be handled. Another reason relates to the technical difficulties involved in achieving clean startup and shutdown of a biomass combustor. For this reason, most biomass combustors are not completely shut down, but rather are operated in a low output setback mode when there is reduced heat demand. Achieving a high setback ratio (full rated output/setback output) is also a challenging design problem and requires more sophisticated controls than a combustor which is always operated at maximum output. Finally, biomass fuel characteristics (mainly moisture content) are generally a lot more variable than those of fuel oil or natural gas. This requires a higher degree of adaptability for the biomass combustion system.

The high capital cost of biomass systems presents an obstacle to the adoption of this technology, particularly for small commercial or residential applications. Although biomass fuel is relatively inexpensive, it may still take several years to achieve payback on the initial equipment investment.

There are a number of ways to reduce the cost of a biomass system. Pelletized fuel, although more expensive than cordwood or wood chips, is manufactured to have consistent properties (size and moisture content). Pellets can be cleanly burned in relatively simple combustors and are particularly popular for residential room heating. Small pellet stoves require periodic manual filling of an attached fuel hopper.

Batch burn systems with heat storage are a relatively low cost option for central heating. Consider a system with a capacity of one million BTU per firing. This is sufficient to heat a small home for one day. For each firing, about 150 lbs. of woodchips are manually shoveled into a hopper attached to the combustor. The combustor, which is designed to burn this fuel charge in less than a day, is ignited. Rapid ignition can be achieved using, for example, electrical resistance heating. Combustion heat is transferred to a volume of water equivalent to a cube 8 feet on a side (about 500 ft^3) and raises its temperature from 150 to 200 °F. An open (vented) heat storage tank can be constructed inexpensively using conventional building materials. The combustor can also be relatively inexpensive yet clean burning because there is no need to operate in a low output setback mode.

Fuel supply

At present, wood chips are the cheapest form of biomass fuel and can be bought in truckload quantities for $30-40/ton. (Wood chips are often available for less or even free from tree service contractors although these chips often have a wide distribution of sizes.) This is equivalent to fuel oil for 50¢/gal assuming 6000BTU/lb heating value for wood chips. Similarly, wood pellets at $200/ton and 9000BTU/lb are equivalent to $1.70/gal fuel oil and firewood at $150/cord and 25 million BTU/cord is equivalent to 90¢/gal fuel oil. Many people enjoy cutting, splitting and seasoning their own firewood; this fuel is often available for free if the required labor is not counted.

The form of biomass fuel chosen depends on fuel availability and the desired level of convenience, automation and initial capital expense. If biomass heating becomes more popular and demand for these fuels increases, prices will likely increase. As long as biomass prices remain competitive with fossil fuel prices, utilization of biomass heating will probably increase.

Emissions

This table compares emission standards and emission performance of several wood chip systems sold in Europe. The only current US emissions standard for wood burning appliances is the Phase II standard for woodstoves. The sulfur oxides (SOx) column has question marks in places because the sulfur content of wood is typically very low and therefore emission standards and measurements often do not include SOx.

CO	NOx	TOC	SOx	particulates	
8.4	0.12	1.7	0.025	1.2	EPA AP-42 Phase II woodstove standard
1.2	0.4	0.1	??	0.15	Austrian standard
0.4	0.3	0.005	??	0.03	VETO 43kW Chipmatic (Finnish mfr.)
0.4	0.3	0.01	??	0.01	KWB 41kW Multifire (Austrian mfr.)
0.04	0.09	0.01	0.0006	0.008	EPA AP-42 residential natural gas fired boiler
0.05	0.22	0.02	1.5S	0.02	EPA AP-42 residential #2 oil fired boiler (S=wt. percent sulfur)

Conclusions

Use of locally produced biomass for local space heating is one of the most straightforward ways to reduce fossil fuel consumption and greenhouse gas emissions. Although biomass heating is already widely used in Europe, thanks in large measure to government sponsored incentive programs, it is not yet clear if this form of renewable energy will gain popularity in the US; other biomass technologies, such as cellulosic ethanol for transportation fuel, have received more attention. In my opinion, biomass space heating is well suited to the situation in our area and could benefit the local economy. Every barrel of oil and cubic foot of natural gas not burned for space heating can be put to better use, if used at all.