DIRECT COMBUSTION OF BIOMASS

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Summary

Biomass combustion such as burning fuelwood to provide heat, power, or combined heat and power (CHP) is a link in the energy chain from producing renewable biomass resources to providing sustainable services in the form of heat (or refrigeration), shaft power and electricity. Biomass combustion supplies about 11% of the world’s total primary energy. There are several broad categories of combustion applications: heat for daily living use (stoves); community applications including district heating; industrial use for both process heat and electricity production, combined heat and power (CHP) uses in the pulp and paper, forest industries, and sugarcane processing; finally the production of electricity. Each of these applications will use different biomass materials according to the local availability of

such fuels. Nevertheless the majority of biomass used is a lignocellulosic fiber (wood, straws, stalks, nuts shells, etc.)

The most common application of biomass energy in developing countries is its use as a source of heat for cooking, sometimes called traditional biomass use. Industrial use of biomass combustion takes place in a combustor or furnace with the heat being used to in a manufacturing process, or to raise steam in a boiler which can expand through a steam turbine to generate shaft power in the so called Rankine cycle. Other prime movers that utilize the heat of combustion to provide power include gas turbines, Stirling engines and some direct conversion devices. The produced shaft power or electricity can be used directly to drive a mill or other machine. In combined heat and power (CHP) applications the most common variant is when the electricity is generated first using high grade heat from the combustor and the lower temperature heat is taken from the exhaust of the electricity cycle.

Properly applied biomass combustion, unlike that of fossil fuels is climate neutral with respect to greenhouse gas production. In the case of biomass the combustion process releases carbon dioxide, which was removed from the atmosphere by photosynthesis, and thus maintains an equilibrium level of carbon dioxide, unlike the combustion of fossil fuels which increase the level of carbon dioxide by releasing the carbon that was long ago stored in the earth. Carbon dioxide is the leading greenhouse gas and the use of biomass is as a result neutral with respect to global warming potential.

Biomass as a fuel has a number of special properties and qualities that distinguish it from the other fossil solid and gaseous fossil fuels. This Article discusses the use and impacts of the combustion of biomass, and biofuels (charcoal, biogas, producer gas, and liquid fuels) that are produced from biomass in combustion applications.

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1. Background

Combustion is the process by which more than 90% of the world’s primary energy supply is realized in order to provide heat and energy services such as materials processing including food preparation; space heating, ventilation and cooling; electricity, and transportation. The non-thermal sources of energy in the primary energy mix are hydro and nuclear power, as well as renewable sources. Only about 11% of the fuels used are biomass resources, and the wide range of fuels used in combustion include: coals ranging from anthracite (an almost pure form of carbon) to lignite or brown coal; peat; natural gas; crude and refined oils including liquid petroleum gas (LPG), gasoline, diesel and kerosene. Coal, oil, gas and biomass, at shares respectively 23.3, 35.7, 20.3, and 11.2 %, are the recent major primary energy sources for the world.

Combustion is a process in which the fuel is burnt with the oxygen from the air to release the stored chemical energy as heat in burners, boilers, internal combustion engines and turbines. The scale of combustion devices encompasses a few kW of thermal input such as a single gas ring for cooking, to huge coal fired combustion boilers with inputs of 3 - 5 GW in a single unit serving the electrical needs of almost 1 to 2 million households. There are probably over 1 billion small biomass cook stoves in use rated at less than 5 kW.

In the case of biomass the combustion process releases carbon dioxide, which was removed from the atmosphere by photosynthesis, and thus maintains an equilibrium level of carbon dioxide, unlike the combustion of fossil fuels which increase the level of carbon dioxide by releasing the carbon that was long ago stored in the earth. Carbon dioxide is the leading greenhouse gas and the use of biomass is as a result neutral with respect to global warming potential. There are however, a number of environmental costs of biomass combustion, which require innovation and significant investment for their mitigation. These costs include both direct human health impacts as well as environmental damage to the earth's productive ecosystems.

The damage caused can be very local in the form of health impacts from indoor air pollution produced by cook stoves in household energy provision, or at a scale of several kilometers as in the case of carbon monoxide and much of the particulate material released in combustion. Regional impacts (at the 1000 to 3000 km path length) include acid rain and ground level ozone for which the precursors are sulfur dioxide (SO_2), nitrogen oxides (NO_x), and non-methane hydrocarbons (NMHC), which are sometimes described as volatile organic compounds (VOC). While the production of excess ozone at ground level is hazardous, it is perverse that the reduction of stratospheric ozone by chemical reactions with the products of combustion diffusing into the stratosphere is also hazardous as it allows ultraviolet light to reach the ground. On a global scale the release of greenhouse gases (mainly non-renewable carbon dioxide), methane, nitrous oxide and halogenated materials increases the likelihood of global climate change.

As harvested from the field or forest, the biomass materials are not purely a mix of carbon, hydrogen and oxygen (CH&O), but also contain the elements N, P, K, S, and Cl as well as many trace elements that in the living plant are essential to maintaining metabolism, respiration and growth. These additional chemical elements present challenges to combustion engineering technology in the form of fouling, deposition, slagging and corrosion of the internal burner structure and heat transfer surfaces. The emission of metals and other elements to the air and soil may also have environmental impacts. However, depending on the quality of the combustion process and the investment in emissions controls, the use of biomass fuels can be as clean as natural gas utilization or even dirtier than coal.

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2. Fundamentals of Biomass Combustion

Biomass combustion is not only the oldest form of combustion used by humanity, but it is also one of the most complex combustion systems to manage since it involves the use of solid fuels in a multi-phase reaction system with extensive interaction between the thermal and mass fluxes, processes that have only recently been properly analyzed and used in simulations to design efficient combustion systems.

The key to understanding solid fuel combustion processes is to recognize that only fuel gases burn and release heat, that liquids and the solids do not burn themselves, but actually consume heat in the drying and volatilization processes needed for them to be chemically converted into fuel gases. The main fuel intermediates are the volatile hydrocarbons and energy rich organic molecules, carbon monoxide (CO) and hydrogen (H_2) (Figure 1).

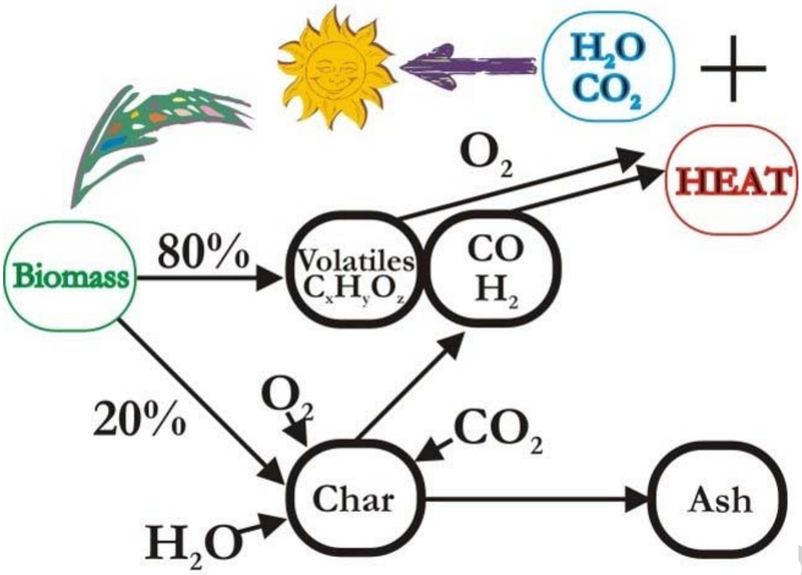

Figure 1. Biomass combustion diagram and carbon cycle closed loop

The process of gas evolution due to heat is called pyrolysis, and progressively converts the biomass into gases, volatile liquids, and a carbon rich solid residue called char. In the pyrolysis stage, the rate of fuel gas evolution is a function of both the temperature and the intensity of the heat flux supplied to the solid surface and the pyrolysis liquids. When the char combustion stage is reached, after all of the volatiles have been removed, the char combustion rate is controlled by the velocity with which oxidizers namely oxygen, carbon dioxide and water vapor can reach the hot char surface to produce the fuel gases, hydrogen and carbon monoxide. The action of the hot char on water vapor and carbon dioxide is to convert the fully oxidized carbon and hydrogen forms back to fuel intermediates. This process of chemical reduction requires energy and is described as an endothermic reaction. The energy comes from the flame in which the carbon monoxide and hydrogen burn with oxygen from the air producing water vapor and carbon dioxide. This reaction is so endothermic that if the rate of heat release to the hot char surface is not sufficient the combustion reaction will come to a halt as the temperature at the surface will fall below 700°C. For this reason simple camp fires glow with only an red-orange color due to the limitation on the rate of diffusion of the gaseous reactants to the surface of the char. If the air flow is forced through the charcoal, the diffusion limitation is overcome and the temperatures become very high with a white incandescent appearance and temperatures greater than 1500°C – sufficient to melt even stainless steels.

There are many different materials that are described as biomass ranging from solid wood, to oils, fats and proteins. While the majority of biomass used is a wood biomass or lignocellulosic, there is an increasing number of industrial and processing residues that have different material properties and combustion characteristics that are being used. However, a general and important biomass characteristic is the very high level of volatile material that is released during the pyrolysis stage. This is reported by the proximate analysis (see below) by the measurement of volatiles, which generally exceed 80% in most biomass materials, whereas many coals have volatile fractions less than 50%. This has a major effect on the technical design of biomass combustors, which as a consequence are

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often very different to traditional coal fired systems. The technical challenges of this highly volatile renewable fuel require attention to the three T's: Temperature, Time and Turbulence, needed to obtain efficient and environmentally satisfactory combustion.

Each of the biomass combustion stages shown in Figure 1has a series of limitations, which limit the overall efficiency of heat generation and the maximum temperature reached. To ensure that combustion is as efficient as possible, it is essential to maximize the three T's simultaneously. The role of turbulence is to ensure full and complete mixing of the fuel gases with oxygen in the process and ensure complete burning without diffusion limitations. Time is required as the processes of drying and pyrolyzing the solids are relatively slow processes, and even the combustion of the fuel gases requires a few seconds to be complete. Finally, maximizing the temperature increases the rate of all of the reactions. The maximizing of all three T's carries with each a practical difficulty – that of using the heat from biomass combustion. The ideal system would fully complete the combustion before trying to transfer the heat to the boiler, stove or whatever application is desired. The highest efficiency combustion systems do have a separate combustion zone from the heat transfer surfaces. The lowest efficiency systems, open fires, lose energy by radiation into space, and by drawing in a large amount of excess air by convection, lose energy in the hot air and smoke, in addition to large unburnt carbon losses due to the resulting low temperatures of combustion.

2.1. Efficiency Constraints in Combustion

The influence of excess air and the moisture content of the biomass fuel on the efficiency of the combustion process is very strong and this is explored through the use of some approximate models derived by Tillman to describe combustion. In a system with a good separation of the combustion chamber from the heat transfer surfaces, a formula for the efficiency of combustion is established:

$$\eta = \text{(Efficiency, \%)} = 96.84 - 0.28\, MC\mathrm{g} - 0.064\, T\mathrm{s} - 0.065\mathrm{EA},$$

where MCg, %- is the moisture in the fuel measured on a total weight basis; i.e., 50% moisture would be a typical green wood as harvested with half dry matter and half water. The large effect of this term is due to the 2.8 MJ kg^{-1} of energy required to produce steam from the water; Ts, ^{o}C –is the stack temperature. While lower values increase the efficiency, they may also cause corrosion in the stack due to condensation of water vapor and acid gases such as CO_2 dissolving in the water. To avoid this condensation, both the stack temperature and the excess air (EA) may be maintained at quite high values. Typical values may be Ts = 150 - 200°C and an EA of 25 to 100%. EA is measured as a percentage of the minimum amount of air required to fully consuming all of the oxygen in combusting the fuel to carbon dioxide and water. A related term is the λ, which is the ratio of the actual air used to the stoichiometric amount of air needed to fully combust the fuel. The equivalence ratio, φ, is defined as the actual fuel to air ratio relative to the stoichiometric fuel to air ratio, and is a reciprocal of λ. For a typical biomass with an HHV of 18.6 GJ t^{-1}, the stoichiometric mass of air is 5.7 t. Practical excess air values when burning high moisture biomass result in about 10 t of air per 1 t of biomass at 70% excess air.

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Very often combustion emissions data are quoted in terms of the flue gas oxygen content $[O_2]$, %. Typical for boilers $[O_2]$ is 12% , for gas turbines -15%. This can be quickly converted to the excess air factor by the equation:

$$\mathrm{EA}=\frac{21}{21-[\mathrm{O}_2]}\times 100$$

The adiabatic temperature of the flame in a furnace or combustor can be calculated as follows:

- Temperature, °C = $420 - 10.1\,MC\mathrm{g} + 1734\varphi + 0.6(A\text{-}25)$
- A,°C is the temperature of the preheated combustion air.

Many boilers have stages of heat recovery after the boiler has produced steam, namely, the economizer and the air preheater (Figure 2). The pressurized boiler feed-water is passed through the economizer, while the air to the boiler is passed through the preheater and heated to temperatures over 200°C.

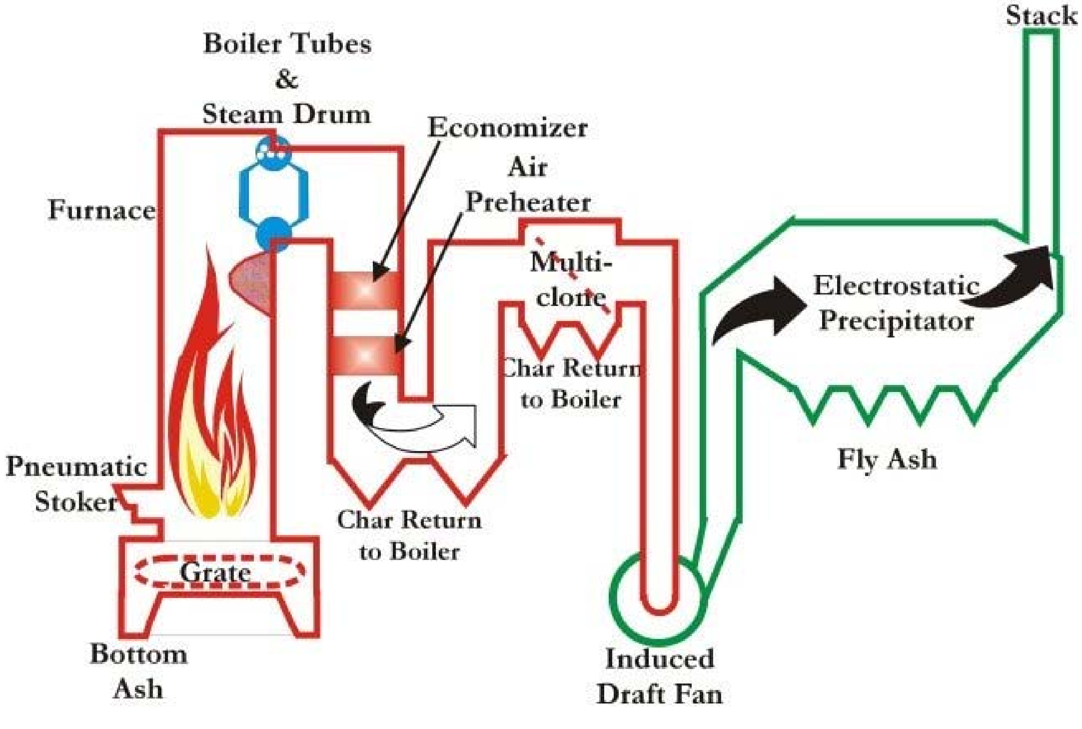

Figure 2. Schematic of a boiler installation

The temperature of the fully burnt combustion gas leaving the furnace is critical to the eventual power cycle efficiency because of the limitations of the second law of thermodynamics, since it defines the maximum conversion efficiency of heat into work, which can be obtained using a Carnot Cycle.

There are several reasons for the practical observed efficiency of power generation being less than the Carnot theory would predict. First, the efficiency of the actual cycle used for energy conversion, for example the Rankine or Brayton cycle, is less than that of the Carnot cycle. Second, not all of the fuel is burnt in the boiler – there are unburnt carbon losses. At very low excess air values, neither the char, nor the non-methane hydrocarbons (NMHC) volatiles can be fully burnt out. The reason being that at very low excess air or oxygen values the rate of the oxidation reactions which are proportional to the available oxygen concentration fall to very low values and the furnace would have to have an infinite volume for the reactions to be completed. In addition to the need to avoid condensation of flue gas in the stack, excess air is also required to reduce the temperature of the flue gases as the materials of construction cannot withstand the theoretical flame temperatures of a stoichiometric air to fuel ratio. These temperatures are well in excess of 3000°C, while a good quality stainless steel can only sustain continuous temperatures of at most 1100°C. Typically the steam turbine and alternator are only 95% efficient, and finally the parasitic loads to provide the induced air flow to the boiler, feed-water pumps and other mechanical services reduce the efficiency.

For example the wood fired McNeil station has a parasitic load of about 5 MW on a 55 MW gross output from the generator, or say 9% of station generation for a net 50 MW out. Wood boilers suffer from the fact that they are usually small (thus higher relative heat losses), burn wet fuel (energy lost in evaporating water) and have very high excess air (to avoid condensation in the stack). Boiler efficiencies as a result are in the range of 65 to 75% for biomass. The McNeil biomass fueled station is representative with a net efficiency of electricity generation of 26 - 28% at 50 MW.

3. The Nature of Biomass Solid Fuels

Biomass properties that affect its utilization for energy, biofuels, and materials include the chemical composition, the polymeric composition, and the physical traits such as density and strength. The traditional biomass used in energy applications has been fuelwood, this is a fiber that is composed of lignin, cellulose and hemicellulose or in shorthand, and wood is a lignocellulosic material resource. Cellulose, hemicellulose and lignin are carbon hydrogen oxygen polymers that serve different structural purposes in the construction of the cell walls of woody plants. Lignocellulosics include trees, most woody plants, the straw and stalks of cereal crops, and are the most important biomass materials and energy resource as they represent much more than half of the above ground biomass produced by photosynthesis. In addition to the lignocellulosic component, there are more complex polymers such as proteins (that can contain sulfur in addition to nitrogen), extractives, and inorganic materials. The inorganic materials range from anions such as chlorine, sulfate, and nitrates, and cations such as potassium, sodium, calcium and magnesium as major constituents and there are also many trace elements including manganese and iron, which are the metallic elements in key enzyme pathways involved in cell wall construction.

The energy content of biomass fuels is reported in two different thermodynamic conventions. The one preferred in the USA is the gross calorific value (GCV) or higher heating value (HHV) and refers to the energy released in combustion when the water vapor resulting from the combustion is condensed thus realizing the latent heat of evaporation. Most European countries and the manufacturers of gas turbines tend to use the lower heating value (LHV) which reports the energy released when the water vapor remains in a

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gaseous state. For pure carbon, which only produces carbon dioxide when burned, the HHV and LHV are the same, while for methane when it is burned there are two molecules of water produced for each molecule of carbon dioxide, and the HHV is 11.1% greater than the LHV.

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Biographical Sketch

Ralph P. Overend, NREL Research Fellow, was trained in physical chemistry, and worked in bioenergy and renewable energy since 1973 as a researcher, research manager, and coordinator of research and development in both Canada and the United States. His nearly 20 years with the National Research Council of Canada, was as manager of the Bioenergy program, and advisor to the Department of Energy Mines and Resources on biomass energy. In addition, he served as coordinator of Canadian renewables R&D for several years. He joined the United States Department of Energy Biomass Power program at the National Renewable Energy Laboratory in 1990, and has worked extensively in the development of long-range plans and strategies for biomass power and biofuels since that time. His major technical activity at the present time is assisting the development of the Vermont Gasification project—a 60 MW thermal indirect gasification system attached to the McNeil station in Burlington, Vermont.

He was the Chairman of the American Chemical Society Cellulose Division 1993-94. He edits the journal, *Biomass and Bioenergy*, and the biomass section of the Journal, *Solar Energy*, in addition to being a member of several editorial boards. He has also served as a United Nations, World Bank, and FAO lecturer/advisor in the USSR, China, Pakistan, and Mexico. He recently completed the biomass component of a renewable energy atlas for the Government of the Philippines.

Significant recognitions for outstanding scientific contributions in biomass and bioenergy include: Fellow of the Chemical Institute of Canada, 1990; Johannes Linneborn Prize, 1996; H.M. Hubbard Award, 1997; R&D 100 Award, 1998; NREL Research Fellow, 2000; the Thomas R. Miles Award, 2001, and the World Renewable Energy Network, Pioneer Award, 2002.

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