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Effect of fuel properties on biomass combustion: Part I. Experiments—fuel type, equivalence ratio and particle size

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Abstract

Moving bed combustion is commonly used for energy conversion of biomass. Conditions on the moving bed can be conveniently represented by a time dependent fixed bed. The present work experimentally investigates the combustion of four biomass materials having different fuel properties in a fixed bed under fuel-rich conditions. Temperature, gas composition and mass loss curves identified two distinct periods as the combustion progresses in the bed: the ignition propagation and char oxidation. The effects of bulk density, particle size and air flow rate on the combustion characteristics during the two periods are interpreted by using the ignition front speed, burning rate, percentage of mass loss, equivalence ratio and temperature gradient. Different channelling of air was observed for small miscanthus pellets and large wood particles due to the fast propagation of the ignition front around a channel. The elemental ash composition was also analysed, which explained the sintered agglomerates of miscanthus ashes in terms of alkali index.

Keywords: Biomass combustion; Fuel type; Particle size; Fixed bed; Mathematical modelling

1. Introduction

Biomass refers to organic materials that stem from plants. It stores energy from sunlight by photosynthesis in bonds of carbon, hydrogen and oxygen molecules. It is characterised into four main types: woody plants, herbaceous plants/grasses, aquatic plants and manures [1]. Biomass is presently estimated to contribute of the order 10–14% of the world's energy supply. The sources of biomass are specially grown energy crops, agricultural wastes, forestry residues and the organic fraction of municipal wastes. Its energy is converted to heat, power or chemical feedstock mainly by thermo-chemical conversion.

Combustion is a widely used technology for energy conversion of biomass. Most biomass consumed at the present time is burned in fixed or moving beds. A fixed bed has two basic configurations depending on the flow direction of air and fuel: co-current and counter-current, while a moving bed on a grate is counter-current. However, the fixed bed has an analogy with the moving bed since the time elapsed in a fixed bed can be transformed into the location on the grate in the moving bed corresponding to the fuel residence time. Thus, the combustion characteristics and process rates in the fixed bed can be applied to the moving bed. This study is for a counter-current bed which is more commonly applied.

Combustion of solid fuel in a fixed bed involves complicated heat and mass transfer along with various chemical reactions. Conductive, convective and radiative heat transfer takes place (a) between solid phases and (b) between solid and gas within the bed, and (c) between the bed, the walls and the flame above the bed. The composition changes include drying, pyrolysis and char gasification of the solid fuel, and the reactions of volatile gases with air. Once the fuel is ignited by an external heat source (usually by radiation from above the bed), the ignition front propagates into the bed. The heat generated by gaseous reactions and char oxidation at the ignition front transfers downwards to dry and heat up the fresh particles below. Since the heterogeneous char oxidation is relatively slow and oxygen is consumed first by the volatile gases from the particles, carbonised particles remain above the ignition front. Therefore, the drying, pyrolysis, char oxidation

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and ash zones appear sequentially from the bottom to the top of the bed during the ignition propagation, although these processes occur simultaneously for large fuel particles. Once the ignition front reaches the bed bottom, only the oxidation of the remaining char takes place.

Two process rates are often used to quantify the progress of combustion in fixed beds. The ignition front speed, which is also referred as flame front speed or reaction front velocity, is based on the temperature history within the bed. The burning rate is a mass loss rate of the bed per unit area and unit time.

The fuel properties and process conditions affect the combustion characteristics, altering the heat generation, heat transfer and reaction rates in a complicated manner [2–8]. The air flow rate is the key process parameter that determines the amount of oxygen available and convective heat transfer. The process rates are classified into three successive regimes depending on the air flow rate: Oxygen-limited, reaction-limited and extinction by convection regimes [2]. When the air flow rate is small, the propagation of the ignition front is controlled by the amount of oxygen and the process rates are linearly proportional to the air flow rate. In the reaction-limited regime, the process rates are limited by the reaction rate of the fuel. As the air supply increases further, the convective cooling of particles around the ignition front slows down the process and finally causes extinction of the flame. Gort [3] also presented similar classification: partial gasification, complete gasification and combustion regimes.

Biomass has a wide range of variety in physical properties, which significantly change the process rates and detailed phenomena. More fundamental studies are required to understand the combustion characteristics of different biomass materials. One important aspect in the fuel properties is pelletisation that is used because many raw biomass materials, especially grass, straw and sawdust, have a very low bulk density (usually less than 150 kg/m^3), which require high cost for storage, transportation and handling. Pelletisation significantly densifies biomass to over 600 kg/m^3, which is essential for biomass to compete with other sources of energy.

The ash composition is a major concern in biomass combustion. The high presence of alkali metals in biomass may cause slagging, fouling and ash agglomeration. The primary sources of these problems are: the reaction of alkali with silica to form alkali silicates that melt or soften at low temperatures (can be lower than 700 °C, depending on the composition), and the reaction of alkali with sulphur to form alkali sulphates on heat transfer surfaces [9]. Investigating the elemental composition of ash is important in order to identify possible operational problems in the actual application.

This paper is the first part of work that presents the combustion characteristics of biomass samples observed by experiments. The second part investigates the effect of various biomass properties by mathematical modelling in order to identify the controlling factors [10].

Combustion tests of two woody chips, one herbaceous and one refuse-derived pellets in a batch type fixed bed reactor are presented for different air flow rates and particle sizes. The ignition propagation and char oxidation periods are described using the measurements of temperature, gas concentration and mass loss histories, and quantified into key process rates and parameters. Then, the effects of bulk density, particle size and channelling on the combustion characteristics are discussed. Elemental ash compositions are also analysed to elucidate the behaviour of different bottom ashes.

2. Experimental

2.1. Biomass samples

The materials selected for the tests are three pure biomass samples (willow, miscanthus and pine) and one sample from a segregated waste having a large fraction of cellulosic materials. Table 1 lists the results of standard analyses and particle types of these samples. All the samples are fairly dry with less than 8% moisture content. The combustible components in the three pure biomass samples have similar elemental composition and ratio of volatile matter to fixed carbon content. The main differences between the samples lie in the ash content, particle size and density. The two woody samples have a low ash content, while the values for the other samples are over 10%. Willow samples were chopped to a length of about 35 mm. Miscanthus samples were pelletised with a diameter of 4 mm. Pine samples were cut into cubes with four different sizes (5, 10, 20 and 35 cm) in order to investigate the effect of particle size. Refuse-derived fuel (RDF) was prepared by pelletising municipal solid waste after pre-processing (shredding, digestion, segregation and screening). The non-organic combustible fraction in RDF is mainly plastic materials which represents one third by weight. This increases the volatile matter and

Table 1
Properties of biomass samples

Samples		Willow	Miscanthus	Pine	RDF
Proximate analysis (%wt)	Moisture	7.2	6.1	5.5	1.9
	Volatile matter	78.1	67.9	81.2	69.9
	Fixed carbon	13.7	13.1	12.1	9.8
	Ash	1.0	12.9	1.2	18.7
Ultimate analysis (%wt)	C	45.9	39.9	49.8	44.3
	H	6.6	6.3	8.1	6.3
	O (by difference)	39.3	34.8	38.3	28.8
Gross calorific value (MJ/kg)		17.8	15.4	18.3	22.3
Particle type		Length: 35 mm	Pellet: ϕ4 mm	Cube: 5, 10, 20 and 35 mm	Pellet: ϕ7 mm