Biomass and Bioenergy 109 (2018) 54–60

Contents lists available at ScienceDirect

Biomass and Bioenergy

journal homepage: www.elsevier.com/locate/biombioe

Research paper

Studies on combustion behaviours of single biomass particles using a visualization method

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A R T I C L E I N F O

Keywords:
Single biomass particle
Combustion
Visual drop-tube furnace
Luminous intensity
Flame imaging

A B S T R A C T

Combustion behaviours of single particles (125–150 μm) of eucalyptus, pine and olive residue were investigated by means of a transparent visual drop-tube furnace, electrically heated to 1073 K, and a high-speed camera coupling with a long distance microscope. All three types of biomass samples were found to have two evident combustion phases, i.e., volatile combustion in an envelope flame and subsequent char combustion with high luminance. Yet, due to differences in chemical compositions and properties, their combustion behaviours were also seen somewhat discrepant. The volatile flame of the olive residue was fainter than that of pine and eucalyptus due to its high ash mass fraction. During the char combustion phase, fragmentation took place for most pine particles but only for a few particles of olive residue and eucalyptus. For all three types of biomass samples, the flame size and the average luminous intensity profiles were deduced from the captured combustion video images whilst the combustion burnout times of the volatile matter and char were also calculated and estimated. There were two peak values clearly shown on the profiles of both the flame size and the average luminous intensity during the volatile combustion process of pine and eucalyptus particles, which, according to literature, could not be observed by optical pyrometry. The observed peaks correspond to the devolatilisation of hemicellulose and cellulose. The ratio between the estimated char burnout time and volatile combustion time increases quadratically with the fixed carbon to volatile matter mass ratio, confirming char combustion is much slower than volatile combustion.

1. Introduction

In recent decades, nations around the world have attached more importance to renewable energy resources such as biomass, taking them as a crucial part of the energy mix. In addition to various woody feedstock, biomass fuels also include all kinds of agricultural and forestry wastes, such as straw, sawdust, rice husks, peanut shells, bagasse, and animal waste as well as organic municipal solid waste. They are mainly composed of carbon, hydrogen, oxygen, nitrogen and other elements. Usually with high volatile matter mass fraction, high carbon reactivity, and low nitrogen, sulphur and ash mass fractions, biomass has a very short production/replantation cycle of a few years and hence is an ideal carbon-neutral replacement fuel for coal. However, biomass differs from coal in many aspects in terms of fuel properties and hence combustion behaviours. In addition, some properties such as moisture, volatile matter, ash and alkali metal mass fractions can significantly affect biomass combustion processes in terms of flame stability and combustion efficiency, and cause various operational problems such as fouling, slagging and corrosion of heat exchange tubes within the pulverized-fuel combustion boilers [1]. To understand the underlying causes of these problems, a profound understanding of the combustion characteristics and combustion kinetics of various biomass fuels is crucial.

Due to the prominent status in power generation, pulverized coal combustion has been the research focus for past several decades. Numerous scientific publications have been assembled detailing the ignition and combustion behaviours of individual coal particles [2–11]. The commonly used techniques include thermogravimetric analysis (TGA) [9], optical pyrometry [2–10], high-speed cinematography [2–6,9], modelling [7,11] and sometimes in conjunction with morphological examinations [2,5,9]. Over recent years, a number of studies on biomass particle ignition and combustion characteristics have

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https://doi.org/10.1016/j.biombioe.2017.12.008
Received 26 August 2016; Received in revised form 4 September 2017; Accepted 12 December 2017

sprung up, using the similar experimental setup and techniques to the coal particles [10,12–25].

Toptas et al. [13] investigated the combustion behaviour of different kinds of torrefied biomass (lignocellulosic and animal wastes) and their blends with lignite via a non-isothermal TGA method in air. It was found that the ignition and burnout temperatures were reduced by blending biomass into the coal. Liu et al. [14] evaluated the combustion performance of one herbaceous biomass (corncob), one woody biomass (hardwood) and one bituminous coal using TGA and differential thermal gravity (DTG) analysis. The investigation focused on the influence of heating rates, blending ratios and sample kinds on the combustion behaviours and kinetics. Wei et al. [15] also investigated the combustion behaviours of anthracite coal/spent coffee grounds under oxy-fuel conditions by TGA and DTG analysis.

Levendis et al. [10] developed a three-colour ratio pyrometer to measure the surface temperatures and high-temperature combustion rates of burning carbonaceous particles. They also compared the features and performance of this instrument to those of a two-colour ratio pyrometer reported earlier [26]. The three-colour ratio pyrometer was also used in their other investigations on the ignition and combustion characteristics of coal particles [2–5]. Riaza et al. [12] investigated the combustion behaviours of four kinds of pulverized biomass samples (sugarcane bagasse, pine sawdust, torrefied pine sawdust and olive residue) in a drop-tube furnace, at 1400 K, under both air and oxygen-enriched combustion conditions using the three-colour pyrometry method. The obtained temperature-time profiles of the burning particles were used to deduce the char combustion temperatures.

Comparing to the conventional TGA and optical pyrometry, high-speed cinematography offers a temporal and spatial means for the visualization and non-intrusive measurement of a high dynamic process such as particle combustion, and consequently the quantitative characterisation of the burning particle, including particle size, shape, ignition, etc. Riaza et al. [12] used a high-speed video camera, at a frame rate of 1 or 2 kHz, fitted with an infinity model K2 long-distance microscope lens to provide high-magnification images of the combustion events. The behaviours of the four types of biomass samples were found to be similar with two phases: the initial volatile flames and the consequential char combustion. Mason et al. [22] used a FujiFilm Finepix HS10 camera for video recording, with a frame rate of 120 Hz, and evaluated the ignition delay, volatile burning time and char burnout time based on the images captured. Carlsson et al. [23] captured the behaviour of biomass particles (European spruce and American hardwood) during pyrolytic reactions by means of high-speed imaging and image processing to track the contour of the biomass particles. Gao et al. [24] proposed a novel instrumentation system, incorporating a colour CCD camera and multi-wavelength laser sources, to achieve the on-line continuous measurement of particle size and shape distributions. In contrast to the single-laser technique, this system was statistically more representative and more reliable. Qian et al. [25] presented the on-line continuous measurement of mean particle velocity, concentration and particle size distribution of pulverized fuel using multi-channel electrostatic sensing and digital imaging techniques. However, most of the previous studies using high-speed cinematography focus on the measurement of particle size, shape, ignition delay, combustion duration time etc. and few, if any, have investigated the luminous intensity of the flame, which may bring new knowledge on the understanding of the biomass particle combustion process. In addition, as recently pointed out by Wang et al. [27], a proper image enhancement technique is essential to the understanding of combustion flames recorded by a high-speed camera.

In present work, high-speed cinematography was used as the main methodology to study the biomass combustion behaviours of both volatile matter and char residue. From the obtained images, the profiles of equivalent flame diameter and average luminous intensity were deduced by means of image processing, which represents a new attempt to derive some of the biomass combustion characteristics as few have done it so far. The combustion durations of volatile matter and char residue were also calculated and analysed.

2. Biomass fuel characteristics and experimental methods

2.1. Physical and chemical properties of the biomass fuel particles

Three different types of biomass fuels were studied: pine pellets, olive residue and eucalyptus pellets. Pine pellets were made from 100% pine sawdust by-product from saw-mills with the timber coming from various sustainable UK forests. The Olive residue with a particle size of less than 1 mm was the olive oil by-product. It was a bio-fuel of choice for co-firing in some UK power stations, due to its low cost and the high security of supply. Eucalyptus pellets were obtained from a UK power station which was co-firing the pellets with coal. All the biomass fuels were further ground to less than 212 μm using a Retsch planetary ball mill (PM 100) and sieved to different size ranges. The size cut of 125–150 μm was selected for the experiments on the consideration of problem-free and stable feeding. Proximate analysis of the biomass fuels was carried out according to the European Standards (ISO 18122:2015, ISO 18123:2015, ISO 18134-2:2015); in particular, the volatile matter mass fraction was determined at 1173 K and the ash mass fraction at 823 K. The elemental compositions (C, H, N, S) of the fuel samples were determined using a Thermo Flash EA 1112 Series, whereas the high heating values of the biomass fuels were calculated using the correlation developed by Friedl et al. [28]. Table 1 shows the proximate and ultimate analysis as well as the high heating values of the tested biomass fuels.

2.2. Experimental setup

2.2.1. Visual drop-tube furnace (V-DTF)

A visual drop-tube furnace was used for the combustion experiments with the schematic of the experimental setup shown in Fig. 1. The furnace was a lab-scale entrained-flow reactor fitted with a 1400 mm long quartz-tube, of which 1000 mm was electrically heated, with an inner diameter of 50 mm. There was a slotted side window (30 mm × 560 mm), positioned at the mid-section of the furnace, through which the high-speed cinematography could be conducted. A water-cooled feeding probe (internal diameter of 5 mm and length of 760 mm) and a water-cooled collection probe (internal diameter of 15 mm and length of 610 mm), both made of 316 stainless steel, were

Table 1
Proximate and ultimate analysis of the biomass fuels.[a]

Biomass		Eucalyptus[b]	Olive residue[b]	Pine[b]
Proximate analysis	M_{ar}	5.9	6.2	4.4
(mass fraction%, db or ar)	VM_{db}	88.3	71.5	83.8
FC determined by difference	FC_{db}	8.7	16.1	15.6
	Ash_{db}	3.0	12.4	0.6
Ultimate analysis	C	48.7	45.9	48.0
(mass fraction%, db)	H	5.7	5.7	5.9
O determined by difference	O	42.4	33.9	45.3
	N	0.2	2.1	0.2
	S	nd	nd	nd
HHV(MJ kg^{-1} db)		20.7	18.4	20.0

[a] 'FC' = fixed carbon, 'M' = 'Moisture, 'VM' = Volatile Matter, 'ar' = as received, 'db' = dry basis, 'nd' = not detected. Proximate Analysis – according to the European Standards for solid biofuels (ISO 18122:2015, ISO 18123:2015, ISO 18134-2:2015).

[b] This work was performed on substrates of unknown provenance, for which the chain of custody is not known. The species are known but the cultivars cannot be specified and while the authors believe that this work exemplifies the difference between the species - there is a reasonable concern that there may be substrate factors and handling chain factors that could influence the results obtained.