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Combustion of single biomass particles in air and in oxy-fuel conditions

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ARTICLE INFO

Article history:

Received 18 September 2012

Received in revised form

4 March 2014

Accepted 11 March 2014

Available online 3 April 2014

Keywords:

Biomass process residues

Torrefied biomass

Combustion

Ignition

Single particle

Pyrometry

ABSTRACT

The combustion behaviors of four different pulverized biomasses were evaluated in the laboratory. Single particles of sugarcane bagasse, pine sawdust, torrefied pine sawdust and olive residue were burned in a drop-tube furnace, set at 1400 K, in both air and O₂/CO₂ atmospheres containing 21, 30, 35, and 50% oxygen mole fractions. High-speed and high-resolution images of single particles were recorded cinematographically and temperature–time histories were obtained pyrometrically. Combustion of these particles took place in two phases. Initially, volatiles evolved and burned in spherical envelope flames of low-luminosity; then, upon extinction of these flames, char residues ignited and burned in brief periods of time. This behavior was shared by all four biomasses of this study, and only small differences among them were evident based on their origin, type and pre-treatment. Volatile flames of biomass particles were much less sooty than those of previously burned coal particles of analogous size and char combustion durations were briefer. Replacing the background N₂ gas with CO₂, i.e., changing from air to an oxy-fuel atmosphere, at 21% O₂ impaired the intensity of combustion; reduced the combustion temperatures and lengthened the burnout times of the biomass particles. Increasing the oxygen mole fraction in CO₂ to 28–35% restored the combustion intensity of the single biomass particles to that in air.

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1. Introduction

Biomass has higher volatile matter content than coal, but it has less carbon, more oxygen and a lower energy content (heating value). The use of biomass in existing pulverized coal power plants requires only minor modifications as compared to the construction of new biomass-specific fired power plants, making the co-firing of biomass with coal an easier and less costly way for generating power. Co-firing is becoming

more common in coal power plants because replacing part of the coal with biomass results in lower pollutant and greenhouse gas emissions, as compared to firing neat coal [1,2]. Co-firing biomass and coal reduces the emissions of SO₂, NO_x and CO₂. Altogether elimination of such emissions may be achieved in future power plants (termed zero emission power plants) by implementing carbon dioxide capture and storage (CCS) techniques. However, co-firing coal with biomass reduces the power output of a power-plant in proportion to the amount of the latter fuel [3–5].

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<http://dx.doi.org/10.1016/j.biombioe.2014.03.018>

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Oxy-fuel combustion is a promising technology for facilitating CCS. It burns fuel in a mixture of oxygen and recycled flue gases (mainly CO₂) instead of air in conventional combustion. The exhaust flue gases consist mainly of CO₂, approx. 95% on a dry volume basis, and small amounts of excess oxygen, nitrogen and, to a lesser extent, pollutants, such as nitrogen oxides (NO_x) and sulfur oxides (SO_x) (approx. 0.1–0.2% dry volume basis) [6]. The combination of oxy-fuel combustion, as a CCS technology, with biomass [2] could effectively provide a method which would not only avoid further CO₂ emissions but, perhaps even help reduce the atmospheric CO₂. Simpson et al. [7] compared the efficiency of oxy-fuel combustion and post-combustion carbon dioxide separation cycles by thermodynamic analysis. They concluded that the air separation efficiency in oxy-fuel technology must increase sufficiently to offset the additional cost and inefficiency of requiring a CO₂ purification unit on the back end. They proposed that oxy-fuel combustion may be more attractive for systems operating with oxygenated fuels such as biomass. For such systems, the development of near-stoichiometric combustors would not need expensive CO₂ purification units. Moreover, a recent investigation [8] suggested that biomass/coal blend combustion may be a method for controlling the excess heat generated from oxy-combustion of coal in neat oxygen, a proposed “clean” coal technology. They utilized a TGA-DSC technique at 1173 K to burn blends of a lignite coal and two biomasses, at high oxygen partial pressures. They reported that the heat flux from the combustion of lignite increased dramatically when the oxidizing medium was altered from dry air to neat oxygen. However, in the case of co-firing lignite with biomass under neat oxygen, the excess heat flux arising from the combustion of lignite was reduced and the temperature of the combustion chamber was thus controlled. Based on their results, they suggested that co-combustion of coal/biomass blends in enriched oxygen environments may be an alternative method to CO₂ recycling in future oxy-fuel combustion systems.

All biomasses are composed of three main components: cellulose, hemicellulose and lignin. For instance, the sugarcane bagasse sample burned herein contained 41.3% cellulose, 34.3% hemicelluloses and 13.8% lignin. Whereas cellulose and hemicellulose are macromolecules constructed from different sugars, lignin is an aromatic polymer synthesized from phenylpropanoid precursors [9]. Hemicellulose is easily degraded, and its pyrolysis takes place at temperatures in the range of 493–588 K. The pyrolysis of cellulose occurs in the 588–673 K range, whereas that of lignin covers a wider temperature range (423–1176 K) [10].

Torrefaction is a useful pre-treatment for the biomass materials as they are sometimes difficult to fluidize and introduce into furnaces because of their fibrous shapes [11]. The management and milling of torrefied biomass is easier than that of the parent biomass. That is why the torrefaction process is being introduced to industrial practices [12,13]. This process consists of heating the biomass in nitrogen, or in a low oxygen-containing atmosphere, to temperatures up to 573 K. In this process, the biomass dries, and as the temperature increases, certain changes take place in the molecular structure. Light hydrocarbon molecules are released through the decomposition of the reactive hemicellulose fraction [14]. Torrefied fuels are easier to manage, and they contain more

fragile particles as well as a higher energy density than the parent biomass particles [15,16]. During the torrefaction process, the biomass loses typically 30% of its mass, but only 10% of its energy content [17]. The resulting higher energy density of the torrefied fuel reduces the transportation costs.

Biomass pyrolysis has been investigated in numerous studies. Results are highlighted in several reviews, including those in Refs. [3,18–22]. The pyrolytic products are H₂, H₂O, CO, CO₂, CH₄, other light hydrocarbons, tar, ash and char. At temperatures below 773 K, biomass fuels decompose into primary volatiles. At these temperatures, tars are produced by depolymerisation reactions while pyrolytic water is produced by dehydration reactions. The main gaseous products of pyrolysis are CO₂ and CO. At temperatures above 773 K, the primary volatiles are subject to a secondary pyrolysis, during which tars are converted into a variety of gaseous species, especially CO, light hydrocarbons, hydrogen and CO₂. At high heating rates, biomass decomposes expediently generating mostly gas, vapors and char [23]. The char that remains upon termination of the pyrolysis reactions is enriched in carbon [24].

Implementation of optical pyrometry and high-speed cinematography for the study of ignition and combustion of single coal particles and streams of coal particles has been well documented [25–33]. However, there is a scarcity of analogous studies on biomass particle ignition and combustion characteristics. On the other hand, Wornat et al. [34] studied the combustion rates of single particles of two biomass chars (southern pine and switch grass), with nominal sizes in the range of 75–106 μm, in a laminar-flow reactor with 6% and 12% O₂ mole fraction (balance N₂) at 1600 K. *In situ* measurements using a two-color optical pyrometer and a video camera revealed that biomass char particles burned over a wider temperature range (1500–1950 K, ΔT ≈ 450 K) than high volatile bituminous and lignite coal particles (1800–1950 K, i.e., ΔT ≈ 150 K versus 1900–2000 K, i.e., ΔT ≈ 100 K, respectively). Austin et al. [35] conducted an experimental study in a drop-tube furnace, burning 300–1500 μm corncob particles in air using a video camera (50–100 frames per second) and an infrared phototransistor. They determined that the burning times of the volatiles and the ignition delay times increased with the increase of the initial particle density and diameter. Meesri and Moghtaderi [36] burned pine sawdust particles at drop-tube furnace temperatures of 1473 K in air and reported particle temperatures circa 1700 K. They also reported that the char oxidation reactions occurred in Regime II, where chemical reactions and pore diffusion happen concurrently. Arias et al. [37] studied the ignition and combustion characteristics of coal/biomass blends under oxy-fuel conditions. They burned a bituminous coal and bituminous coal/eucalyptus biomass blends (90%–10% or 80%–20%, by weight). Their experiments were performed in an electrically-heated entrained flow reactor (EFR) set to 1273 K. Oxy-fuel combustion of pulverized fuels (75–150 μm) occurred with 21%, 30% and 35% O₂ mole fraction in CO₂, and was compared with results obtained in air. When coal was blended with the biomass, its ignition temperature in air was reduced. However, this effect was less pronounced in the case of oxy-fuel combustion, regardless of O₂ concentration. The effect of blending biomass and coal on burnout effectiveness was negligible. Rianza et al. [2] observed similar results. Borrego et al. [38] obtained chars from different biomasses by

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