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On the particle sizing of torrefied biomass for co-firing with pulverized coal

Aidin Panahi [a], Mahmut Tarakcioglu [a], Martin Schiemann [b], Michael Delichatsios [a], Yiannis A. Levendis [a,*]

[a] Mechanical and Industrial Engineering Department, Northeastern University, Boston, MA, USA
[b] Ruhr University Bochum, Bochum, Germany

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ABSTRACT

In biomass harvesting and fuel preparation processes, grinding causes a prominent energy consumption penalty, which results in an analogous cost impact. This is due to the fibrous and tenacious nature of biomass. Torrefaction of biomass makes it brittle, as it diminishes its fibrous nature and, hence, it enhances its grindability. Nevertheless, grinding costs are still important and increase with decreasing targeted particle size. Therefore, this study introduces a methodology for assessing the torrefied biomass grind size that is suitable for firing or co-firing with coal in existing pulverized fuel boilers. It examines combustion of biomass of different origins, herbaceous, woody, or crop-related. Biomass was torrefied for 30 min at 275 °C in nitrogen. It was subsequently ground and sieved to various size cuts, which reflect the mean widths rather than the lengths of these typically elongated particles. Subsequently, the particles were burned, one at a time, in a drop tube furnace (DTF) under high temperature and high heating rate conditions. Luminous burnout times were observed pyrometrically and cinematographically for a number of single particles from various size cuts. Such burnout times were then contrasted with those of individual coal particles in the size range of 75–90 µm, i.e., at the upper end of particle sizes burned in coal-fired boilers. Based on this comparison, the nominal sieve size of the examined torrefied biomass particles whose overall observed burnout times matched those of the 75–90 µm coal particles was determined to be 212–300 µm. Hence, to minimize the grinding cost of co-firing such torrefied biomass with coal in existing boilers, its finer pulverization may not be necessary.

1. Introduction

Approximately 30% of the total power produced in the USA in 2016/2017 was harvested from coal according to the Energy Information Administration and the American Coalition for Clean Coal Electricity [1,2]. Similarly to the benefits of co-firing of different coal types, co-firing of coal and biomass can be used to reduce the emission of a number of environmental pollutants [3–5]. In addition, co-firing coal with renewable biomass can greatly reduce the net emissions of carbon to the atmosphere [6–8].

Since biomass is plentiful and naturally grown, it is categorized as a renewable energy source [9,10]. However, its low calorific value, high moisture content, hygroscopic nature and soot emissions during combustion diminish the appeal of biomass as a fuel. Torrefaction is a practical method for improving the properties of biomass [11–17]. Torrefaction is a thermochemical pretreatment process, which can ameliorate the biomass utilization characteristics, including calorific value and resistance to decay by removing moisture and volatiles [17–24]. Therefore, torrefied biomass can be a suitable alternative fuel in existing large-scale pulverized coal boilers because torrefaction brings the properties of biomass closer to those of coal [12,25–28]. Also, due to their fibrous nature, raw biomass particles cannot be readily pulverized down to the same particle sizes as coal [29–33]. Thus, their grindability is an issue. Torrefaction improves grindability [18,34].

To consume biomass in utility boilers burning pulverized coal, grinding of the solid fuel is a necessary and key step [9,35]. The resulting biomass particle size, and even particle shape are important physical properties, which influence the fuel fluidization and combustion parameters of the particles [36–41]. Marinelli et al. [42] reported that grinding to very fine particle sizes increases the cohesive strength of the powder, which impedes fluidization. Grinding to fine sizes is also expensive as it requires a lot of energy. Whereas grinding of torrefied biomass consumes a fraction of the energy requirement for grinding raw biomass [34,43–45], the

* Corresponding author.
E-mail addresses: y.levendis@neu.edu, yal@coe.neu.edu (Y.A. Levendis).

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energy for grinding any solid fuel still increases with decreasing targeted particle size. Hence, the targeted torrefied biomass particle size should be as large as combustion considerations in boilers would allow. Additionally, it is advantageous that the targeted size of biomass particles in pulverized fuel combustion be larger than that of coal particles because of their typically lower bulk density, faster devolatilization rates and higher volatiles to fixed carbon ratios [46–49]. On the other hand, the larger particle sizes of biomass can induce lengthier ignition delays than coal and can generate larger quantities of unburned residues [35,50–54]. Hence, finding the right biomass particle size to co-fire with coal is important in achieving high combustion efficiency, while also minimizing the grinding costs. The particle size selection has been addressed theoretically by Saastamoinen et al. [51] and experimentally by Mock et al. [55]. The former authors concluded that single biomass in the size range of 500 µm burns with the same time duration as a 200 µm coal single particle. The latter authors burned pulverized biomass and sewage sludge and found that particles of 355–425 µm and smaller, when exposed to a hot upwards moving oxidizer gas stream (heated to 1340 K), moved in the direction of the stream and burned completely. To the contrary, larger particles fell to the bottom of the furnace and failed to burn completely.

This research examines the maximum particle size of torrefied biomass for co-firing with coal based on their relative burnout times under identical conditions. Torrefied biomass is chosen since this fuel is more suitable for co-firing with coal in existing boilers [45,56]. Besides examining overall particle burnout times, this work also examines the contributions of the volatile and char combustion phases to the cumulative burnout times. It is also reporting on pyrometrically-measured particle combustion temperatures and ignition delays. Different types of pulverized torrefied biomass fuels in the size cuts of (75–90) µm, (180–212) µm, (212–300) µm, (300–350) µm and (350–500) µm were burned in a DTF operated at a wall temperature of 1400 K which resulted to an axial gas temperature of ∼1350 K, i.e, the same as that used in the prior coal combustion studies [55,57]. Based on combustion observations, a recommendation for the size of torrefied biomass particles that ignite and burn in time-frames that are comparable to those of coal particles in the range of 75–90 µm is given. This coal particle size was selected based on the industry standard of 65–70% of coal particles passing 75 µm (200 mesh) [58].

2. Methods

2.1. Preparation of samples

Pulverized corn straw and rice husk were harvested in Harbin province of China and were provided by Harbin Institute of Technology. Miscanthus originated from an agricultural farm in Germany (Sieverdingbeck-Agrar). Beechwood was from trees grown in the Netherlands. Pulverized miscanthus and beechwood were provided by Ruhr-University Bochum, Germany [59]. Sugarcane bagasse was obtained from a bio-ethanol production plant in Brazil. DDGS (Distiller's Dried Grains with Soluble) was provided by a North American ethanol-producing company. Torrefaction of all samples was carried out in a laboratory-scale muffle furnace in nitrogen. The furnace was charged with small amounts (a few grams) of millimeter-size particles of biomass and, subsequently, they were heated to 275 °C with heating rates in the order of 10 °C/min. Upon reaching the final temperature, each sample was treated at constant conditions for 30 min. All torrefied biomass fuels were air-dried, chopped in a household blender, and size classified by sieving to obtain size cuts of (75–90) µm, (180–212) µm, (212–300) µm, (300–350) µm and (350–500) µm. Optical microscope photographs and scanning electron microscope photographs of each torrefied biomass are shown in Figs. 1 and 2, respectively. Therein, it can be observed that most types of biomass, except DDGS and rice husk, are elongated and, thus, have high length-to-diameter aspect ratios. Therefore, for those biomass types the aforesaid particle size ranges, are nominally based on size classification by sieving. Whereas the mean widths of biomass particles were in the ranges of mesh sizes, their mean lengths in most cases exceeded the mesh sizes. This shows that the traditional sieve classification method, which is intended for spherical or spheroidal particles, does not represent all of the dimensions of all biomass particles because of their elongated shapes. In the previous work in this laboratory, it was observed that the torrefaction process reduced the particle aspect ratios [60] and produced more uniform particle sizes. All coal samples were procured from the Penn-State Coal Bank and burned in this laboratory as described in a prior publication [3]. The proximate analysis and the ultimate analysis of the biomass fuels on a dry basis, are given in Table 1, whereas those of the coals are given in Ref. [53,61]. The proximate and ultimate analysis, as well as the determination of the heating value of the torrefied biomass fuels, were performed at Harbin Institute of Technology, according to GB/T 212-2008, GB/T 30733-2014, GB/T 30733-2014 and to GB/T 213-2008 Chinese standards, see Ref. [60].

2.2. Experimental apparatus

The combustion of free-falling fuel particles took place in a laminar flow, vertical drop tube furnace, operated at a wall temperature, T_{wall}, of 1400 K. The resulting axial gas temperature profile was measured to be approximately constant at $T_{gas} = 1350$ K [62]. The radiation cavity of this furnace (an *ATS* unit) was 25 cm long and it was electrically heated by hanging $MoSi_2$ elements. A vertical 7 cm i.d. transparent quartz tube was fitted in this furnace. Air was introduced into the tube through a water-cooled stainless steel injector, and, also, through a flow straightener placed coaxially to the furnace injector, see Fig. 3. The air flow through the injector was set at 0.5 l/min. To enable single particle combustion, the fuel particles were introduced through a port at the top of the injector by first placing them on the tip of a beveled needle syringe. Gentle taps on the needle allowed single particles to enter the injector and, subsequently, the furnace. Pyrometric observations of those particles were conducted from the top of the furnace injector, viewing downwards the central axis of the furnace, Fig. 3, i.e., along with a particle's path line. Details of the pyrometer optics, electronics, calibration, and performance were given by Levendis et al. [63]. The voltage signals generated by the three detectors were amplified and then were processed by a microcomputer using the *LabView* software.

A high-speed, high-resolution camera was located at one side of the furnace and viewed through slotted side quartz windows to record the particle combustion histories, against a backlight frosted glass position at the diametrically-opposite side of the furnace. An *Edgertronic* self-contained digital high-speed broadband video camera was used, at speeds of 1000 frames per second. The camera was fitted with an *Olympus-Infinity* model K2 long-distance microscope lens to provide high-resolution images of the combustion events. Scanning Electron Microscopy, with a *Hitachi S-4800* instrument, was used to observe the initial biomass particles. The instrument was operated with a 3 kV of accelerating voltage, 10 µA of beam current and 8.5 mm working distance.

3. Results and discussion

3.1. Cinematographic observations

High-speed, high-resolution cinematographic sequences of single torrefied biomass particles burning in air are shown in Fig. 4. The combustion behaviors of the various types of torrefied biomass