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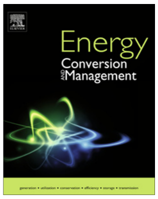

Effect of particle size on the burnout and emissions of particulate matter from the combustion of pulverized agricultural residues in a drop tube furnace

Vera Branco, Mário Costa *

IDMEC, Mechanical Engineering Department, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal

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ABSTRACT

Milling and grinding biomass fuels for pulverized combustion in industrial furnaces can be very expensive. This study aims to evaluate the effect of the particle size on the burnout and emissions of particulate matter from the combustion of agricultural residues (wheat straw and rice husk) in a drop tube furnace. Initially, both agricultural residues were crushed and sieved below 1 mm and the resulting particle size distributions formed one size class here named <1000 μm. In addition to this wide size class, three narrow particle size classes were prepared for each residue; namely, size classes 100–200 μm, 400–600 μm and 800–1000 μm. Subsequently, all size classes of both agricultural residues were burnt in a drop tube furnace at 1100 °C. The data reported include profiles of temperature, particle burnout and particulate matter concentration and size distribution measured along the drop tube furnace. The main conclusions from this study are: (i) for both agricultural residues the size class 100–200 μm presents the highest burnout values, followed by the size classes 400–600 μm and 800–1000 μm; (ii) the burnout values for the rice husk are higher than those for the wheat straw, and the total particulate matter emissions are rather similar for both agricultural residues, regardless of the size class; (iii) during the last stages of the combustion of the wheat straw occur particle fragmentation and the size classes 400–600 μm and 800–1000 μm are those that most contribute to this phenomenon, but particle fragmentation was not observed during the combustion of the rice husk; (iv) the wheat straw size classes 100–200 μm, 400–600 μm and <1000 μm present a bimodal particulate matter size distribution, while the class size 800–1000 μm presents a unimodal one, but the rice husk size classes show all a unimodal particulate matter size distribution.

1. Introduction

The initial particle size of the solid fuels has an important impact on their combustion, affecting phenomena such as ignition, flame stability, pollutants formation and particle burnout. The impact of the initial particle size in these aspects has received much attention in the context of pulverized coal combustion. Abbas et al. [1] evaluated the influence of the coal particle size on the formation of NO in a laboratory pulverized coal-fired furnace and concluded that both small (mean particle size of 25 μm) and large (mean particle size of 121 μm) particle sizes produced flames with lower NO emissions than medium particle size (mean particle size of 46 μm). Sung et al. [2] also examined the influence of the coal particle size on the NO_x emissions from a laboratory pulverized coal-fired furnace with air staging and found that the effectiveness of the air staging on the NO reduction for flames with mean particle sizes of 52 μm and 73 μm is almost twice that for flames with mean particle sizes of 102 μm and 107 μm. Moreover, these authors observed a reduction rate in the burnout performance of 1.7% for flames with fine particles and 0.7% for flames with coarse particles. Steer et al. [3] examined how the process of grinding alters the physical properties, plus the surface chemistry, of coals and their chars formed in a drop tube furnace (DTF) and found that in many cases the larger particle size coals (<1000 μm) gave improved combustion burnout compared to smaller sizes (<106 μm). Ninomiya et al. [4] investigated the effect of the pulverized coal particle size on the particulate matter (PM) emissions in a DTF and concluded that PM emissions increase with a decrease in the coal particle size, and that for coal particle sizes below 63 μm a bimodal mode distribution of PM was formed, in

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* Corresponding author at: Mechanical Engineering Department, Instituto Superior Técnico, Av. Rovisco Pais, 1049-001 Lisboa, Portugal.

E-mail address: mcosta@ist.utl.pt (M. Costa).

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contrast with the single mode distribution of PM formed for the size fractions 63–125 μm and 125–250 μm. Very recently, Saha et al. [5] studied the impact of the particle size on the mild combustion characteristics of pulverized brown coal in a laboratory furnace and found that devolatilisation starts earlier for smaller particles (53–125 μm) and is completed at the end of the recirculation vortex, while for larger particles (250–355 μm) the devolatilisation happened after the recirculation vortex, and that the NO emission for the larger particles are 15% higher than that for the smaller particles.

In contrast with pulverized coal studies, much less attention appears to have been devoted to the impact of the particle size on the combustion characteristics of biomass fuels, which is rather surprising since their milling and grinding for pulverized firing or co-firing with pulverized coal in industrial equipment [6–8] can be very expensive. Moreover, the very few studies available in the literature concentrated either in just one wide range or in just one narrow range of biomass particle sizes. Jiménez and Ballester [9] studied the particle formation and emission in the combustion of four (orujillo, eucalyptus, oak and chestnut tree) pulverized biomass fuels in an entrained flow reactor, but selecting only the particles in the size class 250–300 μm (300–400 μm for the orujillo). The authors observed that the PM emissions presented a bimodal distribution in all cases examined, attributing the origin of the larger particles to char fragmentation and coalescence of the mineral matter contained in the fuels, and the finer particles to condensable mineral species. It can be anticipated with reasonable justification that the initial biomass particle size may affect these findings. Luo et al. [10] examined the influence of the pine sawdust particle size on the combustion performance in a cyclone furnace and concluded that smaller particle size enhances combustion, but that biomass with particle size above 250 mm is not suitable for combustion in the furnace they used. In the context of the influence of the biomass particle size on combustion, the work of Ninduangdee and Kuprianov [11] conducted in a conical fluidized-bed combustor fired with palm kernel shell must be mentioned. These authors observed that the CO and hydrocarbon emissions can be effectively controlled by decreasing the biomass particle size (down to mean particle sizes of 1.5 mm), whereas the NO emissions can be mitigated using coarser biomass particles (mean particle sizes of 10.5 mm).

Given the dearth of literature on the effect of the particle size on the combustion characteristics of biomass fuels, this work will help redress this problem. In this context, this study aims to evaluate the effect of the particle size on the burnout and emissions of PM from the combustion of agricultural residues (wheat straw and rice husk) in a DTF. To this end, four particle size classes were established for each residue; specifically, 100–200 μm, 400–600 μm, 800–1000 μm and <1000 μm. Subsequently, all size classes of both agricultural residues were burnt in the DTF at 1100 °C. The data reported include profiles of temperature, particle burnout and PM concentration and size distribution measured along the DTF. It should be noted that in recent studies [12,13], we examined the impact of the torrefaction on the particle fragmentation of pine shells, olive stones and wheat straw during combustion in the same DTF. In these earlier works we used a single wide particle size distribution for each solid fuel, which hindered the data analysis. The narrow size fractions used in this study allowed for a clear analysis of the dependence of burnout and PM emissions on particle size.

2. Materials and methods

This section is divided in three sub-sections. Section 2.1 describes the DTF and auxiliary equipment, Section 2.2 presents the experimental methods and respective uncertainties, and Section 2.3 gives details of the agricultural residues and specifies the DTF operating conditions used in this study.

2.1. Drop tube furnace

Fig. 1 shows a photograph and a schematic of the DTF and auxiliary equipment used in this study, which is described in greater detail elsewhere [14]. In brief, the combustion chamber is a cylindrical electrically heated ceramic tube, with a total length of 1.3 m and an inner diameter of 38 mm. The furnace wall temperatures are continuously monitored by eight type-K thermocouples uniformly distributed along the combustion chamber. A water-cooled injector, placed at the top of the DTF, is used to feed the solid fuels and the air to the combustion chamber. A twin-screw volumetric feeder transfers the pulverized solid fuels to an ejector system from which the particles are air-transported to the water-cooled injector.

2.2. Experimental methods

Local mean temperature measurements along the axis of the combustion chamber were obtained using 76 μm diameter fine wire platinum/platinum:13% rhodium (type-R) thermocouples. The hot junction was installed and supported on 350 μm wires of the same material located in a twin-bore alumina sheath with an external diameter of 5 mm. The uncertainty due to radiation heat transfer was estimated to be less than 10% by considering the heat transfer by convection and radiation between the thermocouple bead and the surroundings [15].

Particle sampling for burnout calculations along the combustion chamber axis was performed with the aid of a 1.5 m long, water-cooled, nitrogen-quenched, stainless steel probe [14]. On leaving the probe, the solid samples were collected in a Tecora total filter holder equipped with a quartz microfiber filter. Subsequently, the collected solid samples were placed in an oven at approximately 105 °C to dehydrate. Complete dehydration was ascertained by repeated drying and weighting of the sample until the measured mass became constant. The solid samples were subsequently analyzed (ash content). Particle burnout data were obtained from the following equation:

$$\psi\ (\%) = \frac{1 - \omega_f/\omega_x}{1 - \omega_f} \times 100 \qquad (1)$$

where ψ is the particle burnout, ω_f is the ash weight fraction in the input biomass fuel, and ω_x is the ash weight fraction in the collected sample.

Uncertainties in particle burnout calculations based on the use of ash as a tracer are connected to ash volatility at high heating rates and temperatures and ash solubility in water [15]. It was estimated that the uncertainties in burnout calculations using ash as a tracer in the present work were negligible.

PM concentrations and size distributions were made with the aid of two low pressure impactors, namely, a three-stage low pressure impactor (LPI, TCR Tecora), and a 13-stages Dekati low-pressure cascade impactor (DLPI, Dekati Ltd). In both cases, PM was sampled isokinetically from the centreline of the combustion chamber using the water-cooled, nitrogen-quenched, stainless steel probe referred to above. In the case of the LPI, PM sampling was performed at three axial positions of the DTF (x = 700, 900 and 1100 mm from the top of the DTF), while in the case of the DLPI, PM sampling was performed only at x = 1100 mm.

The LPI used allowed collecting three PM cut sizes during the same measurement: PM with diameters above 10 μm (PM10), PM with diameters between 2.5 μm and 10 μm (PM2.5–10), and PM

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