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Temporally and spectrally resolved images of single burning pulverized wheat straw particles

Wubin Weng[a], Mário Costa[b,*], Zhongshan Li[a], Marcus Aldén[a]

[a] Division of Combustion Physics, Lund University, P. O. Box 118, S 221 00 Lund, Sweden
[b] IDMEC, Mechanical Engineering Department, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal

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ABSTRACT

This work focuses into the combustion behaviour of single wheat straw particles with the aim of providing a quantitative description of the particle burning process from ignition to the early stages of the char oxidation. The single particles, in the size range 224–250 μm, were injected upward into a confined region with hot combustion products, produced by a flat flame McKenna burner, with a mean temperature of 1550 K and a mean dry O_2 concentration of 6.5 vol%. Spectral emission data and temporally resolved images of the single burning particles were obtained with a spectrometer and an ICCD camera, respectively. To obtain spectrally resolved images the camera was equipped with different band-pass filters. Overall, the results demonstrate the ability of the present experimental setup and associated optical diagnostics to gather quantitative information of the combustion process of single pulverized solid fuel particles. The emission spectra from the burning wheat straw particles showed that the emission was mainly originated from CH^*, C_2^*, Na^* and K^* chemiluminescence, and thermal radiation from soot and char burning particles. The ICCD images show that the emission from excited CH, C_2, Na and K is initially detected almost at the same time, the burning of the soot particles initiates soon after the ignition, and the char particles experience ignition after the extinction of the homogeneous combustion. During the volatiles combustion stage, the temporal evolution of the normalized emission intensity of the excited CH, C_2, atomic sodium and atomic potassium is quite similar; during the char oxidation stage, however, the decrease of the emission intensity of the excited atomic sodium and potassium is delayed in relation to the decrease in the emission intensity of CH and C_2 because of the continuous release of atomic sodium and potassium from the burning char particles.

1. Introduction

Despite the great attention that the use of pulverized biomass in combustion processes has attracted in recent years, notably in co-firing with coal, this interest has not promoted a significant increase in the number of fundamental studies on biomass combustion. One reason for this is presumably the conviction that fossil fuels, particularly coal, will remain the main source of power generation in the next decades. Nonetheless, the reduction of the greenhouse gas emissions demands an increasing use of biomass so that it is essential to rapidly reduce the gap between the current superior knowledge on pulverized coal combustion and that on pulverized biomass combustion, recognizing the similarities between the two cases, but identifying and deepening the differences. The perception of these differences is fundamental for the design of new burners for both pure biomass firing and co-firing biomass with coal and thereby to increase the use of biomass in combustion processes.

The study of basic reaction processes such as particle heating, pre-ignition and ignition behavior, devolatilization, combustion of the volatiles and char oxidation is commonly performed in single particle experiments under laminar flow conditions or low levels of turbulence. These experiments allow the use of optical diagnostics to measure particle size and temperature, flame luminosity and chemiluminescent emission from various radicals. On the pulverized coal side, Shaddix and Molina [1] used an intensified charge-coupled device (ICCD) camera to investigate the ignition and devolatilization of single coal particles during oxy-fuel combustion, Levendis and co-workers [2–6] employed three-color pyrometry and high-speed high-resolution cinematography to study the ignition and combustion of single coal particles in O_2/N_2 and O_2/CO_2 atmospheres, Köser et al. [7] used planar high-speed laser-induced fluorescence of OH to examine the ignition and volatile combustion of single coal particles in oxygen-enriched environments, and Bai et al. [8] employed a high-speed video camera and image processing techniques to quantify the combustion behavior of single coal particles in terms of size, shape, surface roughness,

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

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rotation frequency and luminosity. All these studies provided valuable information on the ignition mechanisms, ignition delay time, volatile matter composition and combustion, soot formation and oxidation and char combustion of single coal particles burning in various atmospheres.

On the pulverized biomass side, Riaza et al. [9] used the techniques employed in Refs. [2–6] to study the combustion behavior of single particles of sugarcane bagasse, pine sawdust, torrefied pine sawdust and olive residue, all in the size range 75–150 μm, in air and O_2/CO_2 atmospheres at a gas temperature of 1400 K; authors concluded that the combustion behavior of the four biomass residues evidenced only small differences based on their origin, type and pre-treatment. Mock et al. [10,11] employed high-speed photography to study the burning behavior of single particles of torrefied wood, coffee waste, sewage sludge and torrefied sewage sludge, in size ranges 150–215 μm, 255–300 μm, 355–425 μm and 425–500 μm, in an atmosphere with O_2 concentrations ranging from 10% to 40% at gas temperatures of 1090 and 1340 K; authors observed different burning characteristics for the various single biomass particles, which they attributed to their different chemical and physical properties. Simões et al. [12] also employed high-speed photography to examine the ignition behavior of single particles of wheat straw, kiwi branches, vine branches, sycamore branches and pine bark, in size ranges 80–90 μm, 212–224 μm and 224–250 μm, in a confined laminar flow of combustion products with O_2 concentrations ranging from 3.5% to 6.5% at gas temperatures ranging from 1500 to 1800 K; authors concluded that ignition of the biomass particles generally occurred in the gas-phase, although surface ignition was also observed.

In contrast with the combustion of single coal particles, the existing information for the combustion of single biomass particles does not include data on the temporal evolution of excited species in the flame. Therefore, this work focuses into the combustion behavior of single biomass particles with the aim of providing a quantitative description of the particle burning process from ignition to the early stages of the char oxidation. The single particles were injected upward into a confined region with hot combustion products, produced by a flat flame McKenna burner. Spectral emission data and temporally resolved images of the single burning particles were obtained with a spectrometer and an ICCD camera, respectively. To obtain spectrally resolved images the camera was equipped with different band-pass filters. The manuscript provides new data on particle ignition, volatiles burning, soot formation, alkali species release and early stages of char combustion of single biomass particles.

2. Materials and methods

2.1. Experimental setup and optical diagnostics

Fig. 1a shows a schematic of the experimental setup used. It consists of a biomass feeding unit, a McKenna flat flame burner and an air/methane feeding system. The biomass feeding unit consists of a mass flow controller (to control the transport fluid flow rate), a 10 mL syringe and a vibrating motor. The biomass particles, which are stored in the syringe, are fed (by gravitational force) into a stream of nitrogen (transport fluid) and injected upward through a central hole located in the burner (I.D. 1.55-mm) into the hot combustion products region of the McKenna burner. The vibrating motor avoids the clogging of the biomass particles in the syringe hole and ensures a low feeding rate of particles.

The Mckenna flat flame burner consists of a stainless-steel cylinder enveloping a water-cooled bronze porous sintered matrix of 60-mm diameter. Two mass flow controllers allow the control of the methane and primary air flow rates to the burner. In addition, cooling water is fed to the burner through copper tubes. Above the burner, a high-grade fused quartz of I.D. 70-mm, height of 500-mm, and thickness of 2-mm confines the flow and avoids the entrainment of ambient air, while providing optical access.

Fig. 1b shows a schematic of the optical diagnostics used for the emission spectrum measurements and capture of the images of the single burning particles. The spectral emission data from the single burning particles was obtained with a spectrometer (Andor, SR-750, *f*/9.7) with a 300 lines/mm grating and a 100 μm slit. The temporally resolved images of the single burning particles were obtained with an ICCD camera (Andor, iStar, 1024 × 1024 pixels) with an exposure time of 500 μs. To obtain spectrally resolved images the camera was equipped with different band-pass filters. Additionally, a stereoscope lens was placed in front of the ICCD camera to allow for the simultaneous capture of images of each particle with two filters. The synchronization between the spectrometer or the ICCD camera and each incoming single particle was achieved with the aid of the signal synchronization system shown in Fig. 1b. This synchronization system also allowed for the calculation of the residence time of each particle in the hot combustion products region produced by the McKenna burner. A 532 nm continuous-wave laser (200 mW) was used to generate a laser beam with a diameter of 1-mm. This laser beam was placed very close to the exit of the central hole located in the Mckenna burner through which the particles were injected upward into the hot combustion products region. The scattering signal generated by each single particle crossing the laser beam was collected by a photodiode together with a spherical lens, which triggered the spectrometer or the ICCD camera with a pulse generator (DG535).

2.2. Biomass fuel and test conditions

Table 1 shows the properties of the wheat straw used in this study. The biomass was ground and sieved to a particle size range of 224–250 μm. The McKenna burner was fed with a mixture of CH_4 (1.03 L/min) and air (14.68 L/min). The resulting flat flame, with an equivalence ratio of 0.67, produced a region of hot combustion products, where the particles were injected, with a mean velocity of 0.42 m/s, a mean temperature of 1550 K and a mean dry O_2 concentration of 6.5 vol%. The nitrogen flow rate used to transport the biomass particles was 0.097 L/min.

3. Results and discussion

3.1. Emission spectrum

Fig. 2a shows the emission spectrum of burning pulverized wheat straw particles obtained with the spectrometer, where several emission lines can be recognized. The measured emission lines around 430 nm are identified as the emission from excited CH radicals based on a comparison with the spectral structure of the CH emission from LIFBASE [13]. In addition, the interference from the broad-band emission is negligible in this short wavelength region. Consequently, the measured signal using the 430 nm band-pass filter (BF430) is mainly attributable to the excited CH radicals of the burning wheat straw particles.

Fig. 2b shows typical images of burning pulverized wheat straw particles obtained with the ICCD camera equipped with different filters for particle residence times in the hot combustion products region of 70 and 120 ms. Note that these two residence times correspond to different moments during the combustion process of the particles; specifically: 70 ms corresponds to an instant when only volatiles combustion takes place and 120 ms to an instant when only char oxidation occurs. In this study, particle ignition started with the ignition of the volatiles released from the particles. The subsequent volatiles oxidation forms a spherical flame front around the particles. Since CH^* (BF430) is a good indicator of the reaction zone, its emission signal represents the flame front, as may be seen in Fig. 2b for a residence time of 70 ms. The flame front has a size of around 2 mm, which is almost 10 times larger than the initial particle diameter. For a residence time of 120 ms, the signal at 430 nm is dominated by the thermal radiation from the char oxidation since there is no volatiles flame any longer to originate CH radicals. The