Ignition behavior of single biomass and coal particles
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Abstract
This work concentrates on single particle ignition behavior of solid fuels. Particles of pine shells and wheat straw were sieved down to two size ranges; specifically, 80-90 μm and 224-250 μm. Pulverized bituminous coal particles in the size range 80-90 μm were also examined for comparison purposes. The tests were performed in an optical flat-flame McKenna burner able to produce a confined laminar flow of specific (composition and temperature) combustion products. The ignition behavior of the individual particles was examined for three mean gas temperatures (1500, 1650 and 1700 K) in the ignition zone with the aid of a CMOS high speed camera. The results revealed that (i) the ignition of the pine shell particles occurred mostly homogeneously regardless of the gas temperature and size range; (ii) the wheat straw particles ignited mostly heterogeneously regardless of the gas temperature and size range; (iii) the ignition of the coal particles occurred in the gas-phase regardless of the operating conditions; (iv) the ignition delay time for the three solid fuels generally decreased with the increase in gas temperature, and increased with the particle diameter; and (v) the biomass fuel particles presented higher ignition delay times than the coal particles regardless of the ignition mode.

Introduction
Co-firing and carbon capture storage are becoming more common in existing coal-fired power plants to reduce the carbon footprint of electricity generation [1-3]. In the former case, retrofitting may introduce modifications to the fluid dynamics in the near burner region; in latter case, recycling of CO₂ changes the oxidizer composition. In both cases flame stabilization becomes a critical issue, where particle ignition plays a key role, in particular in coal and biomass firing.

The definition of ignition depends on the type of diagnostics used. For instance, Howard and Essenhigh [4] defined the ignition event based on the percentage of loss of carbon and volatiles during the early instants of burning, whereas Wall and co-workers [5] defined the event based on the particle luminosity and size.

Most earlier studies have focused on the ignition of particles considerably larger than those associated with pulverized coal combustion (typically < 150 μm) [6-11]. More recent studies on coal and biomass ignition under conventional and oxy-fuel combustion have been performed in drop tube furnaces [12-16] and entrained flow reactors [17-19].
Drop tube furnaces enable constant high temperatures along the furnace, high heating rates, and experiments under active or quiescent gas flow conditions. Entrained flow reactors, such as the Hencken and McKenna burners, enable high temperatures and ultra-high heating rates, and have the advantage of allowing easy optical access.

Riaza et al. [15] have concluded that anthracite and semi-anthracite coals tend to ignite heterogeneously. Shaddix and Molina [18] observed that for the case of bituminous coal, the ignition is characterized by the formation of a high-temperature soot cloud around the particle, whereas for sub-bituminous coal the soot cloud becomes dimmer. Khatami et al. [13] observed that low rank lignite coals typically fragmented and ignited heterogeneously. Zou et al. [16] studied oxy-steam ignition of dispersed coal streams, and concluded that the steam gasification and steam shift reaction are beneficial in reducing the ignition delay times of the volatiles mixture in \( \text{O}_2/\text{H}_2\text{O} \) atmospheres. Yuan et al. [19] have also studied diluted coal streams, in an entrained flow reactor, and observed a transition from heterogeneous to hetero-homogeneous ignition with the increase of the gas temperature. Interestingly, these authors correlated characteristic heating and devolatilization times with the ignition mode. Riaza et al. [12] studied the combustion behavior of four types of biomass in quiescent gas conditions, observing that all fuels tended to ignite homogeneously. In general, ignition occurred earlier in \( \text{O}_2/\text{N}_2 \) atmospheres than in \( \text{O}_2/\text{CO}_2 \) atmospheres, and the ignition delay time was shortened when the \( \text{O}_2 \) concentration was increased for both atmospheres.

In this work, the ignition behavior of two biomass fuels are studied for two size ranges and three mean gas temperatures (1500, 1650 and 1700 K) in the ignition zone. For comparison purposes, the ignition behavior of particles of pulverized coal was also examined for one of the size ranges and the same three gas temperatures. The tests were performed in an optical flat-flame McKenna burner able to produce a confined laminar flow of specific (composition and temperature) combustion products. The particle injection system included a vibrating syringe and an air ejector capable to feed the particles to the McKenna burner. The ignition behavior of the individual particles was observed with the aid of a CMOS high speed camera.

Materials and Methods

Experimental setup

Figure 1 shows the experimental setup used in this study. The present McKenna flat flame burner supports premixed flames on a bronze sintered matrix of 60 mm diameter, which is embedded with copper tubes that provide cooling through the circulation of water. This particular burner is fitted with a hole of I.D. 1.55 mm in the center for the injection of solid
particles. A high-grade fused quartz tube of I.D. 70 mm, 500 mm height, and 2 mm thickness was used to avoid entrainment of the ambient air and provide optical access.

The particle feeding system was designed to enable the injection of particles within a broad size range, making therefore possible the utilization of biomass and coal particles. The system consisted of a 10 mL syringe, filled with particles, from which they fall to the feeding tube. The syringe and needle were subjected to mechanical vibration from a decompensated electrical motor. By generating this periodic oscillatory movement, a uniform particle feeding was guaranteed, particle clogging in the needle was avoided, and particles dispersion was accomplished.

A CMOS high-speed Phantom V4.2 camera was used to record the ignition of the particles. The camera was fitted with 2× magnifying lens, and AF Micro Nikkor f/2.8 60 mm lenses. The diaphragm aperture of the camera was set to 8, the exposure time to 20 μs, and the extreme dynamic range to half the exposure time in order to avoid pixel saturation. The frame rate was set to 3600 fps, yielding a resolution of 304×512 pixels. The camera was positioned with its optical axis perpendicular to the axis of the burner and focused to view the ignition zone at the burner axis. A 50 W light source placed behind a diffuser enabled to observe the particles before ignition occurred.

In this work, it was considered that ignition occurred when 15% of the maximum luminosity intensity was reached for either volatile homogeneous flame ignition, or direct surface oxidation heterogeneous ignition. Determination of the ignition mode was evaluated by direct visual observation of the recorded images, whilst ignition delay time was measured by image post processing. Ignition was considered to take place in the gas-phase when a bright area, wider than the particle, and surrounding it, was discernible from the dark particle in the center. Heterogeneous ignition occurred when the

![Schematic of the experimental set-up.](image)

**Figure 1.** Schematic of the experimental set-up.

To characterize the ignition zone, located above the flat flame, mean gas temperatures were measured using fine wire 75 μm R-type thermocouples and mean major gas species concentration were measured with the aid of a water-cooled stainless steel probe and conventional gas analyzers.
particle surface became bright, whether it was the whole particle, or just spots on its surface. A Matlab® routine was developed to calculate the ignition delay time. The code read the data from the .tif files, stored it in matrices, eliminated the background noise, and identified the point in which the pixel value was closest to 15% of the maximum luminosity intensity. Ignition delay time was calculated using the calibrated image height, and by estimating a mean particle velocity for each condition. For each experimental condition, a minimum of 20 single particles were chosen to perceive the ignition mode and to calculate the ignition delay time.

**Test conditions**

Table 1 presents the properties of the three solid fuels used in this study. Particles of pine shells and wheat straw were sieved down to two size ranges (80-90 μm and 224-250 μm), while the pulverized coal particles were sieved down to one size range (80-90 μm). Sieving was performed on a dry basis using an electromagnetic laboratory sieve shaker from Fritsch.

Table 2 shows the burner operating conditions used in this study. The fuel and oxidizer flow rates were varied to yield the same excess air coefficient regardless of the burner thermal input. The transport air flow rate was kept constant for all tests. O₂ concentration was approximately constant along the ignition zone.

![Table 1](image1.png)

**Table 1. Properties of the solid fuels.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Pine shells</th>
<th>Wheat straw</th>
<th>Bituminous coal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proximate analysis (wt%, as received)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moisture</td>
<td>13.9</td>
<td>8.9</td>
<td>1.6</td>
</tr>
<tr>
<td>Volatile matter</td>
<td>58.9</td>
<td>64.9</td>
<td>37.6</td>
</tr>
<tr>
<td>Fixed carbon</td>
<td>25.9</td>
<td>11.5</td>
<td>58.8</td>
</tr>
<tr>
<td>Ash</td>
<td>1.3</td>
<td>14.7</td>
<td>2.0</td>
</tr>
<tr>
<td>Ultimate analysis (wt%, as received)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon</td>
<td>47.8</td>
<td>39.4</td>
<td>76.9</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>4.3</td>
<td>5.2</td>
<td>5.1</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>0.3</td>
<td>0.5</td>
<td>1.6</td>
</tr>
<tr>
<td>Sulfur</td>
<td>&lt; 0.02</td>
<td>&lt; 0.02</td>
<td>0.7</td>
</tr>
<tr>
<td>Oxygen</td>
<td>32.4</td>
<td>31.3</td>
<td>12.1</td>
</tr>
<tr>
<td>Low heating value (MJ/kg)</td>
<td>17.1</td>
<td>18.8</td>
<td>32.7</td>
</tr>
</tbody>
</table>

![Table 2](image2.png)

**Table 2. Operating conditions.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal input (kW)</td>
<td>0.6</td>
<td>1.0</td>
<td>1.7</td>
</tr>
<tr>
<td>Methane flow rate (dm³/min)</td>
<td>1.1</td>
<td>1.9</td>
<td>3.0</td>
</tr>
<tr>
<td>Transport air flow rate (dm³/min)</td>
<td></td>
<td>0.14</td>
<td></td>
</tr>
<tr>
<td>Primary air flow rate (dm³/min)</td>
<td>15.5</td>
<td>25.1</td>
<td>40.5</td>
</tr>
<tr>
<td>Excess air coefficient (λ)</td>
<td></td>
<td>1.4</td>
<td></td>
</tr>
<tr>
<td>Mean gas temperature in the ignition zone (K)</td>
<td>1500</td>
<td>1650</td>
<td>1700</td>
</tr>
<tr>
<td>Mean O₂ concentration in the ignition zone (dry vol%)</td>
<td></td>
<td>7.6</td>
<td></td>
</tr>
</tbody>
</table>

Figure 2 shows the temperature profiles along the burner axis for tests 1 to 3. It is seen that the gas temperatures are approximately constant in the ignition zone for all cases, with increasing mean values as the thermal input increases (see Table 2).
Results and Discussion

Ignition mode

Ignition of coal and biomass particles may occur homogeneously (gas-phase), heterogeneously (solid-gas), or through a combination of both. In brief, homogeneous ignition occurs when particles generate volatiles that ignite before the solid residue, while heterogeneous ignition happens when the particle ignites by direct oxygen attack on the solid surface before the flammability limit is achieved in the gas phase [13].

Figure 3 shows selected images from high-speed cinematography of typical ignition events. Fig. 3a shows the homogeneous ignition of a pine shell particle in the size range 224-250 μm under the test 1 condition, where it is seen a volatile cloud surrounding uniformly the particle. Fig. 3b shows the heterogeneous ignition of a wheat straw particle in the size range 224-250 μm under the test 2 condition, where it is visible a bright trail of volatiles downstream of the particle.

Table 3 shows the ignition modes observed in this study for all test conditions. In the case of the pine shell particles, ignition occurred mostly homogeneously regardless of the gas temperature in the ignition zone and size range. The flame fronts formed upon ignition were uniform around the particles surface, with a tendency to develop upstream of the particles for higher gas temperatures in the ignition zone. The pine shell particles originated flame fronts with the largest average diameters of the three solid fuels (see Fig. 3a). During the experiments with the pine shell particles, flame fronts of two different sizes were discernible. The wider flame fronts were dimmer, while the smaller size flame fronts, more often observed, burned with higher intensity. Under the test 3 condition, the smaller pine shell particles ignited heterogeneously due to their faster heating up. Heterogeneous ignition through hot spots occurred for a reduced number of particles in the size range 224-250 μm. Particle fragmentation was never observed in the case of the pine shell particles.
Figure 3. Selected images from high-speed cinematography of typical ignition events. a) Homogeneous ignition of a 224-250 μm pine shell particle under the test 1 condition; b) heterogeneous ignition of a 224-250 μm wheat straw particle under the test 2 condition; c) homogeneous ignition of a 80-90 μm coal particle under the test 3 condition.

Table 3 reveals that the wheat straw particles ignited mostly heterogeneously regardless of the gas temperature in the ignition zone and size range. The 80-90 μm straw particles showed a growing tendency to ignite through hot spots as the mean gas temperature in the ignition zone was increased. Under the test 1 condition, only ~ 35% of the particles ignited through hot spots, whereas for the test 3 condition all particles showed this type of ignition. The larger size straw particles only undergo ignition by means of discrete spots under the tests 1 and 2 conditions, as illustrated in Fig. 3b. Homogeneous ignition was observed only for the larger size straw particles under the test 3 condition, with the formation of wide and very dim flame front around the particle.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Size range (μm)</th>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pine shells</td>
<td>80-90</td>
<td>GI (96%)</td>
<td>GI (100%)</td>
<td>GI (100%)</td>
</tr>
<tr>
<td></td>
<td>224-250</td>
<td>(90%)</td>
<td>(100%)</td>
<td>(95%)</td>
</tr>
<tr>
<td>Wheat straw</td>
<td>80-90</td>
<td>HI (100%)</td>
<td>HI (100%)</td>
<td>HI (100%)</td>
</tr>
<tr>
<td></td>
<td>224-250</td>
<td>(100%)</td>
<td>(100%)</td>
<td>(87%)</td>
</tr>
<tr>
<td>Bituminous coal</td>
<td>80-90</td>
<td>GI (100%)</td>
<td>GI (93%)</td>
<td>GI (100%)</td>
</tr>
</tbody>
</table>

\(^{\text{1}}\) GI - homogeneous ignition; HI – heterogeneous ignition.
\(^{\text{2}}\) Percentage of particles that ignited homogeneously or heterogeneously.

Despite the high amount of volatiles of the straw particles, which would suggest a tendency for homogeneous ignition, heterogeneous ignition predominantly occurred (see Table 3) owing to a combination of two factors. Firstly, the very high heating
rates enable the particles to rapidly reach high temperatures, and thereby to ignite by direct oxygen attack on their solid surfaces, before extensive devolatilization takes place. Secondly, the shape of the particles induces the heterogeneous ignition through hot spots (typically two discrete spots on the particle surface), which promotes the ignition process in the solid phase before the flammability limit is achieved in the gas phase. The occurrence of fragmentation was always insignificant in the case of the wheat straw particles.

Table 3 reveals that the ignition of the bituminous coal particles occurred in the gas-phase regardless of the test condition. It was observed that the flames became brighter with the increase in gas temperature in the ignition zone, which suggests the presence of soot, in agreement with previous studies [19]. For the test 1 condition, volatiles burned mostly uniformly around the particles surface. For the test 2 condition, the formation of a volatile trail downstream of the particle was observed, and, for the test 3 condition, nearly all particles presented this type of trails, as seen in Fig. 3c. This results most probably from the fact that bituminous coal particles, when heated, swell up and expel volatiles in jets or trails, as discussed by Riaza et al. [13] that have also observed the formation of such phenomena. It should be pointed out that, in these cases, a lift-off of the volatile flame from the particle vicinity was observed earlier, promoting a faster transition to solid phase heterogeneous combustion. Following the homogeneous ignition, particle fragmentation occurred for half of the particles under the test 2 condition, with the resulting fragments igniting heterogeneously at the same instant. This phenomenon was, however, marginal for the remaining cases. Finally, it should be noted that the bituminous coal ignition presented brighter and notoriously smaller flame fronts than the pine shells ignition for the same test condition.

**Ignition delay times**

Figures 4 and 5 show the measured ignition delay times for pine shells and wheat straw particles, respectively. Data for coal is represented in both figures to facilitate comparisons. The ignition delay time showed a general tendency to decrease with the increase of the gas temperature, and to increase with the particle diameter. Overall, the biomass particles present higher ignition delay times than the coal particles regardless of the ignition mode. This can be attributed to the fuel thermal properties (e.g., specific heat and effective thermal conductivity), fuel composition (e.g., volatile content and composition) and particle diameter and morphology.
For the pine shell particles, the ignition delay time decreases with an increase in the mean temperature in the ignition zone and increases with the particle diameter. It is interesting to note that for the smaller particles, under the test 3 condition, the change in the ignition mode indicates that the characteristic devolatilization time may have surpassed the characteristic heating time [19].

The straw particles ignited heterogeneously, with exception of the larger particles under the test 3 condition, which suggests that the characteristic heating time is typically lower than the characteristic devolatilization time. For the larger particles, under the test 3 condition, the homogeneous nature of the ignition suggests that the devolatilization becomes the governing parameter.

It is interesting to note that, under test 3 condition, both biomass fuels present a very similar behavior, i.e., smaller particles ignite heterogeneously and larger particles ignite homogeneously, being the ignition delay times similar. This indicates that, at high heating rates, the biomass composition becomes less important, and the intra-particle effects on the particle heating become dominant on the ignition mode and ignition delay time.

Figure 4. Ignition delay times for pine shells and coal particles. Vertical bars represent 98% confidence statistical error. Solid symbols denote homogeneous ignition and the open symbols denote heterogeneous ignition.

Conclusions
The main conclusions of this work are as follows.
1. The ignition of the pine shell particles occurred mostly homogeneously regardless of the gas temperature and size range. Heterogeneous ignition was observed only
for the smaller pine shell particles for the highest gas temperature.

2. The wheat straw particles ignited mostly heterogeneously regardless of the gas temperature and size range. Homogeneous ignition was observed only for the larger size straw particles for the highest gas temperature.

3. The ignition of the bituminous coal particles occurred in the gas-phase regardless of the operating conditions. The coal ignition event was accompanied by brighter and notoriously smaller flame fronts than the pine shells ignition, for the same test condition.

4. The ignition delay time for the three solid fuels generally decreased with the increase in gas temperature, and increased with the particle diameter. The biomass fuel particles presented higher ignition delay times than the coal particles, regardless of the ignition mode.

Acknowledgements

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References

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