ABSTRACT

The main goal of this work was to access the ignition behaviour of four solid Turkish fuels, two biomasses, almond shell and olive residue, and two lignites. The biomass samples were sieved into two sizes, 80-90 µm and 224-250 µm, whereas the lignite samples were sieved into 80-90 µm. The experimental tests were performed in an optical flat-flame McKenna burner for six different conditions: three mean gas temperatures in the ignition zone (1460 K, 1560 K e 1660 K) and three mean dry oxygen concentrations (3.5%, 5.2% and 6.5% vol.). The ignition mode and the ignition delay time were evaluated through the analysis of images obtained by a high-speed camera. The available image post-processing script was improved in order to get more accurate ignition delay times, especially for fuels which present weaker flames. The experimental results revealed that: (i) the ignition of all fuels occurred predominantly in the gas phase, except for the lowest size range of both biomasses in the lowest temperature operating condition; (ii) the ignition delay times for all fuels decrease with the increase in the gas temperature, indicating that the particle size and composition become less important as the heating rate increases; (iii) within the studied oxygen concentration range, its variation did not have a significant impact on the ignition mode and delay time; (iv) it was found that fuels with a higher moisture content showed longer ignition delay times; (v) biomass ignition delay times were more affected by the gas temperature than lignites, indicating that particle thermophysical properties, in particular density and specific heat, play a key role.

Keywords: Biomass, lignite, single particle, high-speed imaging; ignition delay time; ignition mode

INTRODUCTION

According to the International Energy Agency [1], the global demand of coal and lignite will continue to increase due to their availability and low cost, mainly in countries like United States, Russia, China, India, Turkey, among others [2]. Co-firing is becoming more common in existing coal-fired power plants to reduce the emissions of greenhouse gases. In order to correctly modify existing furnaces and boilers to burn both biomass and coal, a detailed knowledge about the combustion process, where ignition plays a key role due to flame stabilization, is needed.

Ignition studies normally address the relationship between ignition delay time and ignition mode with changes in, particle size and composition, and combustion atmosphere (temperature and composition). Ignition mode can be identified as gas phase ignition, i.e., homogeneous ignition, when it results from the ignition of the volatile matter in an envelope flame surrounding a devolatilizing char particle; or heterogeneous ignition (which often signifies surface ignition) [3]. The definition of ignition has been an ambiguous subject for the last half century and it depends on the type of diagnostics used. The first studies in ignition [4,5], defined the ignition event based on the percentage loss of carbon and volatiles during the early moments of burning. Still in the last century, Wall et al. [6], relied on optical diagnostics to define the ignition event based on particle luminosity and size. Recently high speed imaging and pyrometry techniques have been widely used to characterize the ignition event (ignition delay time and ignition mode). Recent studies combine one or both techniques and have been performed in drop tube furnaces [7–10] or entrained flow reactors [11–13]. Drop tube furnaces enable constant high temperatures, high heating rates and allow an easier atmosphere control than entrained flow reactors. Entrained flow reactors, such as the Hencken and McKenna burner enable high temperatures and ultra-high heating rates, similar to the ones found at industrial appliances, another advantage is the easier optical access.

In a recent review put together by Khatami and Levendis [7], they report that ignition delay times decrease with decreasing coal rank, it reaches a minimum in the case of bituminous particles and then increases again as the rank decreases from bituminous to lignite. The authors also report the briefest ignition delays for the case of sugarcane bagasse particles. Regarding the ignition mode and process its indicated that all bituminous and some sub-bituminous coal particles experience homogeneous ignition; whereas same size (75–150 µm) anthracite, semi-anthracite and lignite coal particles experience mostly heterogeneous ignition; fragmentation was observed during devolatilization for sub-bituminous and lignite particles; soot content in volatile envelope flames and, thus, luminosity during combustion increases with increasing fuel rank from lignite to bituminous.

This work, within a cooperation with Middle East Technical University, characterizes the ignition behavior of four Turkish fuels, two biomasses and two lignites. Single particles were injected in an optical flat-flame McKenna burner able to produce a confined laminar flow of specific (composition and
temperature) combustion products. Solid fuels were studied under six different test conditions: three mean gas temperatures in the ignition zone (1460 K, 1560 K e 1660 K) and three mean dry oxygen concentrations (3.5%, 5.2% and 6.5% vol.). Ignition mode and ignition delay times were evaluated through the analysis of images obtained with a CMOS high speed camera.

MATERIALS AND METHODS

Figure 1 shows the experimental setup used in this study. The McKenna flat flame burner supports premixed flames on a bronze sintered matrix of 60 mm diameter, which is embedded with copper tubes that provide water cooling. The burner has a center hole of 1.5 mm internal diameter through which particles are injected in the combustion products with the aid of manual vibration and a constant transport air. A high grade fused quartz tube of 70 mm I.D., 500 mm height, and 2 mm thickness was used to confine the laminar flow while providing optical access. All fuels were sent to certified laboratory for composition analysis. Lignites were sieved down to one size range, 80-90 μm which is very similar to the ones used in pulverized coal power plants. Biomasses were sieved to two size ranges, 80-90 μm for comparison purposes and 224-250 μm to study the effect of particle size in ignition.

To characterize the ignition zone located above the flat flame, mean O₂ dry concentrations were measured with the aid of a water-cooled stainless steel probe and conventional gas analyzers; mean gas temperatures were measured using fine wire 75 μm, an estimation of the “true” gas temperature was done according to [15] by [16]. The image acquisition system is composed by a CMOS high-speed camera Optronis CamRecor CR600x2, and a diffuse led backlight. The camera was equipped with two lenses, a 2x tele-converter and a Nikkor 60 mm f/2.8D. The camera was operated with a constant exposure time of 1/15000 s, a frame rate between 2000 and 3500 frames per second with resolutions between 250x452 – 250x600. The camera was positioned with its optical axis perpendicular to the axis of the burner and focused to view the ignition zone. Single particles were traced since they entered the burner until ignition. For larger particles (224-250 μm) the camera was positioned to capture two windows, one on top of the other. In the bottom window the particle position was traced until y position, in the overlying window particle was traced since y position until ignition. For the smaller particles (80-90 μm) because ignition was sooner, one window was enough to observe the particle since it was injected in the burner until ignition. Particle identification was done with the Canny method and edge function of Matlab. Figure 2 shows the steps from a raw image until the calculated centroid.
Ignition delay times were calculated with a Matlab script. For each particle a set of frames was collected, a signal (‘Original’) corresponding to the maximum luminosity of each frame normalized by the maximum luminosity found in that specific set of frames was calculated. A filter was applied to the Original signal, filter steps are shown in the next equations:

\[ \text{Signal}'(j) = w \times \text{Original}(j) + (1 - w) \times \text{Signal}'(j - 1) \]  
\[ \text{Signal}''(j) = \text{Original}(j) - \min(\text{Signal}') \]  
\[ \text{Signal}'''(j) = \text{Signal}''(j) / \max(\text{Signal}') \]  
\[ \text{Signal}''''(j) = w \times \text{Signal}'''(j) + (1 - w) \times \text{Signal}'''(j - 1) \]  
\[ \text{Signal}''''(j) = \text{Signal}'''(j) / \max(\text{Signal}'''') \]

Filter weight is identified by \( w \) and it was kept the same for all particles. Several values have been tested for the parameter \( w \) and 0.4 produced the most suitable results. Equation 1 leads to a noise reduction which allows to identify the medium background noise defined as \( \min(\text{Signal}') \). Equation 2 corresponds to a translation which eliminates the background light of the original signal. Equation 3 modifies the scale of the curve in order to vary between 0 and 1. Equation 4 smooths the noise. Equation 5 normalizes again to re-establish the scale between 0 and 1. The ignition criterion was defined as 5% of maximum light intensity of the filtered signal. For each experimental condition and solid sample fuel, an average of 45 single particles were collected to calculate the average ignition delay time and the associated standard deviation as well as the relative frequency of gas phase ignition.

**RESULTS AND DISCUSSION**

**Solid fuels characterization**

Table 1 shows the results of the proximate, ultimate and heating value analysis, as well as the calculated aspect ratios. It should be noted that the bituminous coal used in [17] is included for comparison purposes. Table 1 shows that biomasses are very similar. Tunçbilek lignite presents a fixed carbon and volatile matter close to the bituminous coal. Soma lignite has a volatile matter close to the bituminous coal, however presents a fixed carbon closer to the biomass values. Both lignites show high ash values and Soma lignite presents the higher moisture content.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Almond Shell</th>
<th>Olive Residue</th>
<th>Soma Lignite</th>
<th>Tunçbilek Lignite</th>
<th>Bituminous Coal [17]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proximate analysis (wt.%)&lt;sup&gt;1&lt;/sup&gt;</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Volatile matter</td>
<td>73,0</td>
<td>70,7</td>
<td>31,4</td>
<td>33,3</td>
<td>37,6</td>
</tr>
<tr>
<td>Fixed carbon</td>
<td>17,6</td>
<td>17,1</td>
<td>26,0</td>
<td>43,9</td>
<td>58,8</td>
</tr>
<tr>
<td>Moisture</td>
<td>8,5</td>
<td>10,1</td>
<td>18,8</td>
<td>6,4</td>
<td>1,6</td>
</tr>
<tr>
<td>Ash</td>
<td>0,9</td>
<td>2,1</td>
<td>23,8</td>
<td>16,4</td>
<td>2,0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ultimate analysis (wt.%)&lt;sup&gt;2&lt;/sup&gt;</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon</td>
<td>47,4</td>
<td>48,3</td>
<td>45,3</td>
<td>57,3</td>
<td>76,9</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>6,3</td>
<td>6,2</td>
<td>3,1</td>
<td>5,3</td>
<td>5,1</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>0,2</td>
<td>0,7</td>
<td>0,6</td>
<td>2,1</td>
<td>1,6</td>
</tr>
<tr>
<td>Sulphur</td>
<td>&lt;0,02</td>
<td>0,1</td>
<td>1,3</td>
<td>1,3</td>
<td>0,7</td>
</tr>
<tr>
<td>Oxygen</td>
<td>46,1</td>
<td>44,7</td>
<td>49,7</td>
<td>34,0</td>
<td>12,1</td>
</tr>
<tr>
<td>LHV [MJ/kg]</td>
<td>16,2</td>
<td>18,6</td>
<td>13,4</td>
<td>24,1</td>
<td>32,7</td>
</tr>
</tbody>
</table>

<sup>1</sup> as received; <sup>2</sup> dry ash free

The aspect ratio was simply calculated as the ratio between the largest length of the particle and the corresponding perpendicular length. Figure 3 reveals that all fuels except AS 224-250 µm maybe considered almost spherical (AR<2). Despite of AS 224-250 µm presenting a relative larger value, the difference is not meaningful.
Figure 3: SEM micrographs of the tested fuels and respective aspect ratios (AR).

Operating conditions

Table 2 presents the operating conditions in which each fuel sample was tested. For the conditions T1 to T3 the burner thermal input was increased keeping the same excess air coefficient. For the operating conditions O1 to O3, both the thermal input and excess air coefficient were varied to yield different oxygen concentrations for the same temperature. Transport air flow rate was kept constant for all tests. Figure 4 shows the average temperature and oxygen dry volume concentration in the ignition zone.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>T1</th>
<th>T2</th>
<th>T3</th>
<th>O1</th>
<th>O2</th>
<th>O3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal input [kW]</td>
<td>0,7</td>
<td>1</td>
<td>2,2</td>
<td>1,1</td>
<td>1,2</td>
<td>2,2</td>
</tr>
<tr>
<td>Excess air coecient λ [-]</td>
<td>1,44</td>
<td></td>
<td></td>
<td>1,18</td>
<td>1,29</td>
<td>1,40</td>
</tr>
<tr>
<td>Transport air [dm³/min]</td>
<td></td>
<td></td>
<td>0,14</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean O₂ [% dry volume]</td>
<td>6,88</td>
<td>3,52</td>
<td>5,16</td>
<td>6,49</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean gas temperature [K]</td>
<td>1460</td>
<td>1560</td>
<td>1660</td>
<td></td>
<td>1680</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4: Average temperature and oxygen dry volume concentration in the ignition zone. Left: Measured gas temperature (open symbols), and corrected gas temperature (solid symbols) for tests T1-T3 following the method described in [15]. Temperature corrections were done by [16]; right: Measured oxygen concentration for tests O1-O3.
**Ignition Process**

Figure 5 a) shows the filtered light intensity for three different particles, that represent typical ignition events. Each event marked in Figure 5 a) is shown in Figure 4 b). Event 1 shows the particles during the heat up phase. Event 2 shows the onset of ignition, event 3 presents the maximum visible light during volatile flame combustion, event 4 shows the last stage of volatile flame combustion and the visible beginning of char oxidation. Event 5 is the established char oxidation.

Signal a) corresponds to a gas phase ignition of a Tunçbilek lignite particle (80-90 µm), the combustion of volatiles in this fuel is very bright with the maximum light intensity been achieved for both volatile combustion and char oxidation. This can be attributed to soot content in volatile flames, a similar behaviour was observed by Levendis and Khatami [7] for bituminous coal particles. When compared with the other two cases, the whole process is faster which is typical of smaller particles. Signal b) and signal c) correspond to two different almond shell (224-250 µm) particles, b) under condition O1 and c) under condition T1. Biomass particles typically present faint volatile flames as can be seen in Figure 4 b) panel b.3. Particle c) undergoes surface ignition with no clear detached volatile flame. Both char and volatile oxidation happen at the particle surface.

![Graph showing filtered light intensity for three particles.](image)

**Figure 5:** a) Filtered light intensity for 3 particles. b) Panel with images corresponding to each event marked in a).

Note that particle c) corresponds to a surface ignition so doesn’t go through events 3 and 4.

**Ignition Modes**

Ignition mode was evaluated by direct visual observation of the recorded images. Ignition was classified as gas phase whenever it was possible to distinguish a bigger and surrounding volatile flame. On the other hand, when visible light came from the surface, ignition was classified as surface ignition.

Figure 5 shows the ignition mode of the studied fuels, except for Soma lignite. Soma lignite experienced fragmentation which made the analysis of the ignition mode impossible. Figure 5 shows that Tunçbilek lignite and olive residue 224-250 µm present gas phase ignition regardless of the operating condition. In the case of smaller biomass particles is noted an increase of the gas phase ignition with the increase of mean gas temperature. The majority of gas phase ignition of biomass particles is consistent with the observations of [17] where the authors suggest that quasi-spherical particles (AR<2) tend to ignite in the gas phase for similar atmosphere conditions.

Smaller biomass particles in the lowest temperature condition (T1) show a significant amount (>50%) of surface ignitions. The transition of ignition modes with the particle size was documented by Howard and Essenhigh [5], the authors defined a critical particle size, for a given set of conditions such that for the particles smaller than that size, the flame does not lift away from the particle, hence volatiles...
and char burn simultaneously on the surface of the particle. Figure 6a) suggest that for almond shell and olive residue the critical size is close to 90 µm. Figure 5b) presents the change of the ignition mode with the operating condition, no major changes were observed and all fuels predominantly experienced gas phase ignition. This behaviour is in line with [17] where for the same oxygen concentration range, its variation did not have a significant impact on the ignition mode.

**Soma Lignite Fragmentation**

Figure 7 presents the relative frequency of primary fragmentation as function of the operating condition. It is possible to observe that at higher temperatures (conditions T3 and O1 to O3) the majority of particles fragmented and typically present a number of fragments lower than 5. For both biomasses and Tunçbilek lignite no fragmentation was observed. Note that despite the occurrence of fragmentation, this did not affect the ignition delay times since if considering only particles which did not experienced fragmentation the maximum difference between the results is 3%.

**Ignition delay time**

Figure 8 shows the ignition delay times as function of the mean gas temperature in the ignition zone for all the studied fuels. Regardless of the fuel, ignition delay times decreases as temperature increases. It is interesting to note that with the increasing in the gas temperature ignition delay times seem to converge, this suggests that as the particle heating rate increases, the differences between composition and size become less important. Larger biomass particles show a higher ignition delay time compared with the smaller particles. It is expected that for the same fuel, composition does not vary
significantly among the size range, also, the aspect ratio of the different size ranges is pretty much the same (see Table 1), this shows again that particle heating rate plays a key role in ignition delay time since smaller particles experience higher heating rates (for the same mean gas temperature). Tunçbilek lignite which presents a composition closer to the bituminous coal (see Table 1), shows the lowest ignition delay times for all the mean gas temperatures. This is consistent with the observations of [17], where for the same temperature and size range bituminous coal presented lower ignition delay times than biomass samples. This behaviour can be attributed to fuel thermal proprieties (e.g. specific heat and thermal conductivity) and composition. As expected, taking into account the compositions and morphologies of biomass fuels no significant differences are seen between ignition delay times of almond shell and olive residue. Soma lignite which has a high moisture content as well as a composition closer to the biomasses presents ignition delay times also closer to the biomasses, being higher than Tunçbilek lignite.

Figure 8: Ignition delay times of all the studied fuels for the operating conditions T1 to T3. Vertical bars represent 98% confidence statistical errors.

Figure 9 shows the ignition delay times of all fuels for the operating conditions O1 to O3. Results denote that ignition delay times does not change significantly and remained approximately constant. Shaddix and Molinna [11,12] reported that ignition delay time decreased with the increase of O2 molar fraction (keeping the same atmosphere temperature). In [12], for a bituminous coal tested in an entrained flow reactor, the authors concluded a decrease of 25% in ignition delay time related to a change of 24% in the O2 concentration. In the same experimental facility [11], for a difference of 9% of O2 concentration the authors reported a decrease of about 7%. Levendis et al. [9,19] in a drop tube reactor, claimed that a major increase of O2 molar fraction in mixtures of O2/N2 had a marginal impact in ignition delay time.

Although an increase in O2 molar fraction leads to an increase in the reactivity of the local fuel-oxidizer mixture, which in turn is expected to decrease the ignition delay times [11,12,20], the results presented here are consistent since the differences in O2 concentrations are not as significant as in previous works.
Figure 9: Ignition delay times of all the studied fuels for the operating conditions O1 to O3. Vertical bars represent 98% confidence statistical error.

Figure 10 shows the results of the smaller particles of the tested fuels and the results of same size range particles taken from [17]. Orange colour represents all the biomasses and Soma lignite, blue colour represents the bituminous coal and Tuncbilek lignite. It is possible to observe that both Tuncbilek lignite and bituminous coal fall around the blue line showing ignition delay times lower than fuels around the orange line, biomasses and Soma lignite.

Figure 10: Ignition delay time as function of mean temperature in the ignition zone. Results of pine bark (PB), wheat straw (WS) and bituminous coal (BC) were taken from [17]. Vertical bars represent 98% confidence statistical error.

Khatami and Levendis [7], reported that ignition delay times decrease as coal rank decreases from bituminous to lignite, also the authors report for biomass (sugarcane bagasse) the lowest ignition delay time. Figure 10 shows an opposite behaviour since biomasses ignition delay times are always higher than Tuncbilek and bituminous coal. However, it should be noted that the moisture content of studied biomass is rather low (~4%), this moisture level is similar to the ones shown by bituminous coal and Tuncbilek lignite, which are the fuel with lowest ignition delay times in Figure 10. This observation indicates that moisture content may play an important role in ignition delay time.

Figure 11 presents the relationship between ignition delay times and moisture (wt. % as received) of all the fuels shown in Figure 10. Figure 11 shows a tendency of increased ignition delay times as moisture content increases, it also shows that bituminous coal and lignites particles are less dependent of gas temperature, this maybe related with particles thermophysical proprieties, such as density and specific heat.
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Figure 11: Ignition delay time as a function of moisture (wt. % as received). Fuels are the same as Figure 10. Results of wheat straw (WS), pine bark (PB) and bituminous coal (BC) were taken from [17]. Vertical bars represent 98% confidence statistical error.

CONCLUSIONS

The main conclusion of the presented work are: (i) both biomasses present similar composition, aspect ratios, Tunçbilek lignite show a typical lignite composition with a morphology similar to a bituminous coal, Soma lignite show similarities with both biomasses and bituminous coal and the highest moisture content; (ii) the ignition of all fuels was predominantly in the gas phase, except for the lowest size range of both biomasses in the lowest temperature operating condition; (iii) the ignition delay times for all fuels decrease with the increase in the gas temperature, indicating that with the increase of the heating rate, particle size and composition become less important; (iv) within the studied oxygen concentration range, its variation did not have a significant impact on the ignition mode and delay time; (v) it was found that fuels with a higher moisture content showed longer ignition delay times, meaning that moisture plays an important role in ignition; (vi) biomass ignition delay times were more affected by the gas temperature than lignite particles, indicating that particle thermophysical properties, in particular density and specific heat play a key role.

REFERENCES


