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Ignition behavior of Turkish biomass and lignite fuels at low and high heating rates

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HIGHLIGHTS

- Ignition of Turkish biomass and lignite fuels at low and high heating rates.
- At low heating rate biomass residues ignited homogeneously.
- At low heating rate lignite fuels ignited hetero-homogeneously.
- At low heating rate biomass presented high self-ignition risk and lignites low-risk.
- At high heating rates all solid fuels generally ignited homogeneously.
- At high heating rates ignition delay times decrease with the gas temperature.

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ABSTRACT

The main objective of this work was to investigate the ignition behavior of two Turkish biomass residues (almond shell and olive residue) and two Turkish lignite coals (Tunçbilek and Soma) at low and high heating rates. The low heating rate experiments (20 K/min) were performed in a thermogravimetric analyzer (TGA) coupled with a differential scanning calorimetry (DSC) analyzer, while the high heating rate experiments (10^5 K/s) were conducted in an entrained flow reactor (EFR) coupled with a high-speed imaging system. In the TGA experiments, the biomass and lignite fuels were tested for one particle size range (106–125 μm) in a dry air atmosphere, while in the EFR experiments, the biomass residues were tested for two particle size ranges (80–90 μm and 224–250 μm), and the lignite fuels for one particle size range (80–90 μm). Six different operating conditions were used in the EFR experiments: three mean gas temperatures (1460 K, 1560 K and 1660 K), and three mean dry volume oxygen concentrations (3.5%, 5.2% and 6.5%). The low heating rate results showed that: (i) both biomass residues ignited homogeneously (gas-phase), whereas the lignite coals underwent hetero-homogeneous ignition; (ii) all solid fuels showed similar volatiles ignition temperature (500 K) and particle ignition temperature (660 K); and (iii) the biomass residues presented a high self-ignition risk, in contrast with the low-risk presented by the lignite fuels. The results of the high heating rate experiments revealed that: (i) the solid fuels generally ignited in the gas-phase; (ii) both biomass residues and the Soma lignite presented higher ignition delay times than the Tunçbilek lignite, and the ignition delay times of the fuels with the same particle size converged with the increase of the atmosphere temperature; (iii) the ignition delay times tended to decrease with the increase of the atmosphere temperature; and (iv) the impact of the atmosphere oxygen concentration on the ignition delay times was insignificant.

1. Introduction

The demand of low quality lignite coals in Turkey has a tendency to increase due to the availability and low cost of these fuels [1]. Furthermore, Turkey has endogenous forestry and agricultural resources, being one of the largest grape and olive producer countries in the world [2], and a major exporter of wheat flour and prepared nuts [3]. Nowadays there is a renewed interest in coal/biomass co-firing, with an increasing number of operational co-firing plants [4]. This is due to the economic incentives that arise from the reduction of emissions of gases such as CO_2, SO_2, and NO_x, when co-firing coal with biomass instead of the combustion

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of coal [5,6]. In order to ensure a safe handling of solid fuels, the self-ignition propensity during processing, transportation, storage and conveying needs to be well understood. Flame stability during (co-)firing of coal and/or biomass is an issue to be taken into account when designing a new boiler or retrofitting existing ones, and is largely dependent on the particle ignition behavior. The fuel type and composition, and the surrounding oxidizing atmosphere temperature and composition are some of the parameters that strongly affect the ignition of solid fuels at both low and high heating rates.

Thermogravimetric analysis (TGA) and TGA-DSC (differential scanning calorimetry) based studies are commonly used to investigate the characteristic ignition temperatures [5,7–15], and the self-ignition risk of solid fuels [16–19]. A number of studies have focused on the influence of the fuel type [5,7,10,12–15], heating rate (5–40 K/min) [5,7] and atmosphere composition (air, O_2/N_2 and O_2/CO_2) [9,11,15,20] on the characteristic ignition temperatures. Both TGA and TGA-DSC experiments indicate that the ignition temperature of biomass fuels is typically lower than that of lignite fuels regardless of the biomass or lignite type. The ignition temperature of biomass fuels fall in a range between 470–540 K and that of lignite fuels in a range between 550–630 K [2,5,7–10,17,18,21].

Self-ignition risk assessment of biomass and lignite fuels is vital for their transportation and storage. More recently, a number of authors have assessed the self-ignition risk under low heating rates using TGA [16–19,22]. Since a comprehensive parameter to evaluate the ignition susceptibility of biomass and coal fuels is often needed, Querol Aragón et al. [22] established a TGA based self-ignition risk plot based on the TG characteristic temperature in combustion with pure oxygen and on the activation energy from conventional air combustion, which enables an easy classification of biomass and coal in terms of self-ignition. According with this criterion, biomass fuels and high volatile coals have a high to very high propensity of self-ignition, whereas low volatile coals present a medium- to low-risk of self-ignition [16–19].

The TGA-DSC technique was also used to determine the ignition mode of solid fuels by Chen et al. [21], who examined the effect of the coal rank on the ignition mode. According with Chen et al. [21], ignition can be defined in three distinct modes: homogeneous when only gas-phase reactions occur; heterogeneous for the case of solid-gas-phase reactions; or hetero-homogeneous if both gas-phase and solid-gas-phase reactions are present at the moment of ignition.

Entrained flow reactor (EFR) based studies of the ignition of biomass and coal fuels are typically focused on the analysis of the ignition mode and ignition delay time of single fuel particles [23–28] or dispersed particle jets [29–32]. A number of studies have addressed the effect of parameters such as the fuel type [24,25,27], particle size [25] and atmosphere temperature and composition [23–27] on the ignition delay time and ignition mode.

The ignition mode has been defined in two distinct ways. In most studies, the ignition mode was defined with respect to the type of reaction occurring: homogeneous (gas-gas reaction), heterogeneous (gas-solid reaction) or mixed (both types of reactions). More recently, Simões et al. [25], who captured the total light emitted by single particles, used the definition of gas-phase and surface ignition. As discussed by Howard and Essenhigh [33,34], the volatiles flame (homogeneous reaction) can lift from the particle or can "attach" to its surface. Unless the diagnostics technique allows identifying tracers of homogeneous and heterogeneous reactions, it is not possible to distinguish between reaction modes (homo- or heterogeneous) close to the surface.

The definition of ignition onset has been an ambiguous subject and depends largely on the type of diagnostics method used. A number of authors have applied high-speed imaging techniques to capture either chemiluminescence emission of diluted particle streams [29,31] or visible light signal of single particle ignition [23–25,27,28], and determine the ignition delay time and ignition mode. As a result, it is possible to find in the literature various definitions for the ignition mode and various ignition onset criteria, which are basically setup dependent. For instance, when the total emitted light was captured, the ignition criterion was either based on visual observation [24,27] or based on a given percentage of the maximum intensity collected from each event [25,30]. This value is setup dependent and it is adjusted to provide the best results for all conditions studied.

The ignition mode of different rank coals was reviewed by Khatami and Levendis [35]. Anthracite and semi anthracite undergo homogeneous ignition, whereas bituminous coals undergo homogeneous ignition, and lignite samples experience hetero-homogeneous ignition. As for biomass, Riaza et al. [27] reported homogeneous ignition for several residues, namely pine sawdust, torrefied pine sawdust, sugarcane bagasse and olive residues. Simões et al. [25] reported gas-phase ignition for pine bark, kiwi branches, vine branches and sycamore branches, and surface ignition for wheat straw particles.

Khatami et al. [24] observed that high rank coals tend to present the longest ignition delay times (~30 ms), followed by lignite (~15 ms), bituminous coal (~10 ms), and lastly by sugarcane bagasse (1–2 ms). In addition, Simões et al. [25] showed that different biomass fuels, with the same particle size, present similar ignition delay times for the same test condition (15–20 ms under an atmosphere temperature of 1500 K, and 7–10 ms under 1800 K). These authors also reported ignition delay times for 80–90 μm biomass particles (15–20 ms) lower than those for 224–250 μm biomass particles (20–30 ms). The oxygen concentration in the surrounding mixture also influences the ignition delay time due to changes in the reactivity of the mixture. Previous studies on coal ignition, namely by Molina and Shaddix [28,31] and by Khatami et al. [24], showed that the increase in the oxygen mole fraction from 20% to 80% led to lower ignition delay times under oxy-fuel conditions, whereas under O_2/N_2 mixtures the ignition times were not significantly affected. Furthermore, Simões et al. [25] observed that variations in the oxygen concentration from 3.5% to 7.6% resulted in a slight decrease of the ignition delay times of biomass fuels.

There is still a gap in the literature on what concerns the ignition behavior of Turkish biomass and lignite fuels. Furthermore, TGA and EFR are complimentary techniques that allow studying ignition at distinct heating rates, but have been seldom used in combination, as in the present work. The low heating rate ignition data, obtained from TGA, is relevant to ensure the safe handling of solid fuels during its processing, storage, and transportation. In addition, the EFR allows attaining heating rates that are very close to those encountered in industrial equipment and thus allow studying ignition under realistic conditions. Hence, the main objective of this work is to use both techniques to study comprehensively the ignition behaviors of Turkish biomass and lignite fuels. To this end, the solid fuels were firstly tested using a low heating rate of 20 K/min and a dry air atmosphere in a TGA coupled with a differential scanning calorimetry (DSC) analyzer. The ignition mode, characteristic ignition temperatures and self-ignition risk of the fuel samples were determined by analysis of the TG, DTG and DSC profiles. Subsequently, the ignition mode and ignition delay time of the same solid fuels were evaluated under high heating rates (~10^5 K/s) using an EFR. Here, six different operating