



Full length article

Effects of potassium and calcium on the early stages of combustion of single biomass particles

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ABSTRACT

The main objective of this work is to evaluate the effects of potassium (K) and calcium (Ca) on the early stages of combustion of single biomass particles. The biomass used was grape pomace, sieved in the size range of 200–250 μm. With the pre-treatments of demineralization and impregnation, a total of 12 different samples were obtained: raw grape pomace, demineralized grape pomace and impregnated grape pomace with 0.1, 0.5, 0.82, 3 and 6 wt% of K, and 0.1, 0.5, 1.08, 3 and 6 wt% of Ca. The tests were performed in an optical flat flame McKenna burner able to produce a confined laminar flow of combustion products, in which single particles were air-injected upward through a central hole. The equivalence ratio and the thermal input of the burner were adjusted to yield two operating conditions in the working zone: condition T1 with a mean temperature of 1575 K and a mean dry O₂ concentration of 5.4 vol%, and condition T2 with a mean temperature of 1775 K and a mean dry O₂ concentration of 5.2 vol%. A CMOS high-speed camera was used to record the early stages of the combustion process, particularly the ignition and the volatiles combustion events. The collected images were processed to calculate the ignition delay time and the volatiles combustion time. The results obtained showed that the demineralization pre-treatment used increased both the ignition delay time and the volatiles combustion time of the single biomass particles. The K impregnation pre-treatment led to a decrease in the ignition delay time as the concentration of K increased, while the Ca impregnation pre-treatment did not have a significant impact on the ignition delay time. Both impregnation pre-treatments decreased the volatiles combustion time as the concentration of K or Ca increased. Finally, the impregnation with K and Ca had a more significant impact on the volatiles combustion time than in the ignition delay time.

1. Introduction

Biomass is a CO₂-neutral energy source and it has been shown to emit much less pollutants during pulverized suspended combustion than coal [1]. However, its diverse composition may be the origin of critical issues in industrial applications. These issues are generally associated with the low heating value, the high content of moisture and ash composition of the biomass [2–4]. A critical fraction of the biomass composition is its ash content that can have a significant impact on the whole combustion process. Potassium (K) and calcium (Ca) are two main alkali and alkaline earth metals present in the ash content and they can exist in biomass as inorganic salts, minerals or be organically bounded [5,6]. In addition to their contribution to the well-known problems of ash deposition and corrosion in boilers and furnaces, which may reduce their conversion efficiency, the K and Ca can also have a catalytic effect on the thermochemical conversion processes of biomass [7].

Most of the studies focusing on ash behaviour during combustion are related to the final stages of combustion [8–10], with little attention being given to the early stages of combustion, namely ignition and volatiles combustion. Previous studies on the catalytic effects of K and Ca on biomass conversion were usually performed using thermogravimetric analysers (TGA) mostly focusing on pyrolysis [11–15] and gasification [16–18]. These studies revealed that K catalyses both pyrolysis and gasification processes, whereas Ca has little or no impact during pyrolysis, but shows catalytic behaviour in gasification processes. Fuentes et al. [13] studied the effect of K and Ca on the biomass combustion stages using TGA. The authors observed that K catalysed both the volatiles release and the char oxidation stages by shifting the DTG characteristic peaks of these stages to lower temperatures, whereas Ca catalysed only the char combustion stage, but to a lesser extent than K.

There have been very few attempts to study the ignition behaviour of single particle biomass fuels [19–23], and studies focusing on the

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effect of the biomass composition on particle ignition are rather scarce. Mason et al. [20] studied the duration of the combustion stages of three biomass fuels (pine, eucalyptus and willow) on a Meker burner, observing a tendency for the ignition delay time to be higher for the solid fuels with higher moisture content. Simões et al. [21] studied the ignition behaviour of five biomass fuels (wheat straw, kiwi branches, vine branches, sycamore branches and pine bark) using an optical flat flame McKenna burner, and concluded that, for temperatures of 1500 and 1650 K, particle shape plays a more important role than the biomass composition on the ignition mode, and that the biomass composition has a higher impact on the ignition delay time for temperatures of 1500 and 1650 K than for temperatures of 1700 and 1800 K. Li et al. [22] studied the ignition behaviour of straw, softwood and torrefied softwood particles in a down-fired reactor and analyzed the effect of the biomass type and the particle size on the ignition delay time and on the volatile release time. Jones et al. [23] studied the effect of K on the combustion stages of static single particles in a Meker burner and of moving particles of biomass in a flat flame burner, simulating conditions typically encountered in pulverized combustion. The results showed a catalytic effect of K through the reduction of the devolatilization and char oxidation times.

This study focuses in the early stages of combustion of grape pomace. This residue is a by-product of the production of distilled wine. Grape pomace can be used for soil amendment or food for specific animals, and when in excess this residue can be used to produced heat locally in the winery (or distillery) using small- to medium-scale boilers, or for electricity production using large-scale grate furnaces in regions with significant production of grape pomace [24]. In a parallel study [25], we examined the impact of K and Ca on the pyrolysis and combustion behaviour of grape pomace at low heating rates, using TGA, in order to understand the processes and reactions involved during devolatilization and char oxidation. With the aim of extending the study to conditions closer to those of practical applications, in this study, raw, demineralized and impregnated grape pomace particles used in [25] were fed, as single particles, inside a confined laminar flow of combustion products produced by a McKenna flat flame burner. This apparatus allows submitting the particles to heating rates of around 10^4 K/s and provides optical access to study the early stages of combustion, namely ignition and volatiles combustion. First, the raw, demineralized and impregnated grape pomace particles were tested under two distinct temperature conditions to evaluate the effect of the presence of K and Ca on the ignition delay time. Subsequently, one of the conditions was chosen to evaluate the effects of the presence of those minerals on the volatiles combustion time. Finally, the ignition delay time variations were compared to the volatiles combustion time variations in order to evaluate the relative importance of the catalytic effects of the K and Ca in both phases.

2. Materials and methods

2.1. Experimental setup

Fig. 1 shows the schematic of the experimental setup. It consists of McKenna flat flame burner, a biomass feeding unit, a gas feeding system, and an image acquisition system. The McKenna flat flame burner consists of a stainless steel cylinder containing a water-cooled bronze porous sintered matrix of 60 mm diameter with a central hole of 1.55 mm internal diameter. The flat flame is created above the sintered matrix by a premixed mixture of primary air flow and methane flow supplied to the burner by the gas feeding system. Two mass flowmeters are used to control the flow rates. Furthermore, to cool the sintered matrix, water is supplied through copper tubes. A high-grade fused quartz with an internal diameter of 70 mm, a height of 500 mm and a thickness of 2 mm, is used in order to confine the combustion products flow, and prevent the entrainment of ambient air while providing optical access.

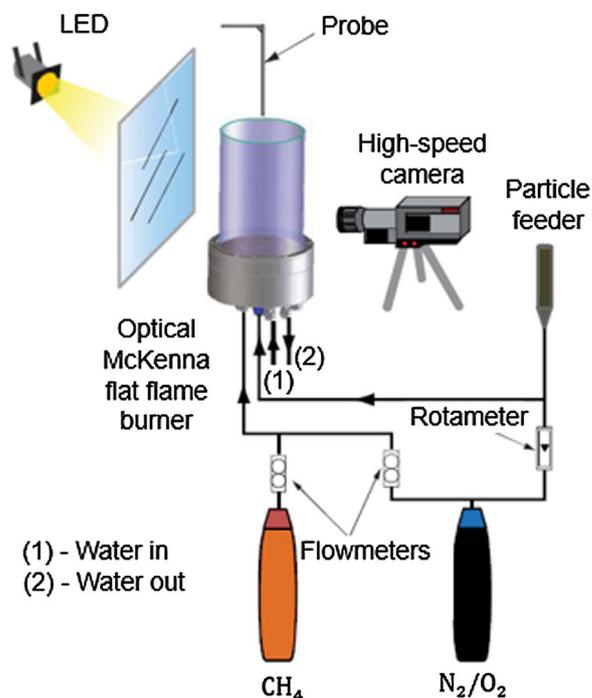


Fig. 1. Schematic of the experimental setup.

The biomass feeding unit includes a 10 mL syringe where the biomass particles are stored, a fine mesh, and a rotameter to regulate the transport air flow. The biomass particles are added to the transport air stream by gravitational force and injected upward through the central hole of the burner. The fine mesh placed inside the syringe ensured a low feeding rate of particles allowing the recording of single particle videos.

The image acquisition system includes a CMOS high-speed camera Optronis CamRecord CR600x2, equipped with a lens AF Micro-Nikkor 60 mm f/2.8D and a teleconverter Kenko TelePlus MC7 AF 2.0X DGX to increase the focal length of the lens used. Additionally, the image acquisition system includes a diffuse LED backlight to enable the camera to record the shadow projection of the particles. In order to align the position of the camera, a target with millimetre marks was used for calibration before and after each experimental session. The axis of the camera was aligned perpendicularly with the axis of the burner so that the camera could record images of the particles since their injection. The frame rate was 2300 fps and the resolution was 200×720 pixels. A detailed description of the experimental setup used can be found elsewhere [21].

2.2. Test conditions

Two different operating conditions were used in this work named here conditions T1 and T2. These conditions were established by varying the thermal input while maintaining constant the excess air coefficient. This made it possible to obtain a mean temperature difference of approximately 200 K along the working zone. Also, during the experiments the transport air flow rate was maintained very low ($0.11 \text{ dm}^3/\text{min}$), which was the lowest flow rate tested that guaranteed single particle feeding. Table 1 lists the burner operating conditions used in this work.

The mean gas temperature measurements were obtained by using $76 \mu\text{m}$ diameter fine wire platinum/platinum: 13% rhodium (type-R) uncoated thermocouples and the mean O_2 concentration measurements were obtained with the aid of a water-cooled probe and a paramagnetic analyser. Each measurement was repeated three times. Fig. 2 shows the mean gas temperature and the mean O_2 concentration profiles for the

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