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Full Length Article

Experimental investigation on the smouldering of pine bark

A. Ronda [a], M. Della Zassa [b], A. Biasin [b], M.A. Martin-Lara [a], P. Canu [b,*]

[a] Department of Chemical Engineering, University of Granada, 18071 Granada, Spain
[b] Department of Industrial Engineering, University of Padua, 35131 Padova, Italy

HIGHLIGHTS

- Heat dissipation is the key to trigger and support smouldering.
- Air permeation through the biomass bed controls the smouldering.
- Study on tens of grams of biomass.
- The geometry of the biomass bed is crucial.
- Tests under flow, to control the O_2 content and measure emission.

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ABSTRACT

We investigated the pine bark spontaneous reactivity in oxidant atmosphere, and its self-heating development in laboratory tests on samples in the tens of grams range. Smouldering has been triggered and sustained by limiting the biomass heat dissipation. Tests in an oven (uncontrolled ambient composition, imposed ambient temperature) were first carried out to screen the effect of different parameters, including particle size, amount of material, moisture content, material compaction, heating rate, and storage geometry, on the onset and development of smouldering. The thermal ignition of pine bark was observed starting from 190 °C. Experiments carried out in a flow tubular reactor (imposed ambient temperature and composition) were also carried out. The main produced gases analyzed under different ignition conditions, and concentrations of CO, CO_2, H_2 and O_2 were measured and discussed. The flow results indicated that pine bark evolves into smouldering supported by a minimum oxygen concentration, at low enough fluxes to limit the material cooling due to convection. Finally, the ratio CO/CO_2 monitored identifies different oxidation stages during the smouldering process.

1. Introduction

The environmental and strategic issues associated with an energy based on fossil fuels require their substitution with renewable sources in the power generation processes. Among all renewable energy sources, biomass can be the largest contributor to the primary global energy supply. Lignocellulose-based biomass is one of the most abundant biomass resources on earth. It is available in a number of different forms, but wood is the largest family. The wood transformation industry produces several wastes, useful for energy production. Beyond saw-dust, bark is a controversial waste, because of its composition and mechanical properties. Here we focus on pine bark as a common and representative type of bark. It is a lumber transformation by-product. Because of its mechanical structure, pine bark's use as a construction material is limited. Spain is 4th in Europe for forest surface, being 29% of the total surface (5.2 million hectares), dominated by conifers, mainly pine. *Pinus pinaster* is also the tree occupying the most extended area in Europe and Asia, and it is the species with the most extended dissemination in the West of the Iberian Peninsula, where it covers more than 28% of the whole forest surface, and the timber industry is largely (82%) based on pine wood transformation. Others Mediterranean subspecies extend all over Spain and in all the countries located in the Mediterranean area as well [1]. Due to large availability of pine bark on a global scale, there is an increasing interest in its use [2–6]. Transportation, storage and use of biomass require some knowledge of its spontaneous reactivity [7]. A burning rate higher than coal has been reported [8], likely explaining the onset of fires (even explosions) during storage, milling or conveying [7]. That can be even more critical for bark, where the higher ash content may bear catalytically active inorganic species.

* Corresponding author.
E-mail address: paolo.canu@unipd.it (P. Canu).

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Reactivity of a biomass often shows in a subtle form, i.e. the spontaneous smouldering [9]. Smouldering is a slow, low-temperature, flameless combustion, sustained by the heat evolved when oxygen directly reacts on the surface of a condensed-phase fuel (solid or liquid) [10]. Uncontrolled smouldering processes can produce severe damages, mainly when flaming occurs. However, smouldering can be profitably used if carefully controlled. A self-sustaining low temperature combustion could be used to obtain bio-char from biomass plants, to be used as more stable and efficient fuel or in agriculture. Additionally, smouldering has the important advantage of not requiring additional energy because it can be self-sustained by the heat released during biomass oxidation [12]. Recently, the smouldering combustion process has been suggested as a new method potentially useful in the treatment of biosolids [13], and liquid organic contaminants, such as tars, especially as an alternative disposal option or environmental remediation [14].

The smouldering onset and propagation are still poorly understood. It occurs within a solid porous medium which can be a permeable aggregate of particles, grains, or fibers where the fuel is either a combustible component of the porous matrix or a separate substance embedded. The reaction can be self-sustaining in the presence of a sufficient amount of fuel, enough oxygen and limited heat losses. The characterization of smouldering activation is complicated, since the ignition temperature is not a fundamental parameter of the fuel, but it depends on several factors including the sample mass, heating rate of the material, surrounding gas atmosphere, bed porosity, and others [15]. Chen et al. [16] investigated the role of other parameters on the self-sustained propagation of smouldering, in the critical conditions, such as the moisture content, inorganic content, bulk density and the heat of smouldering combustion. The effect of oxygen concentration on biomass smouldering is critical but still poorly investigated [17]. The literature about the role of parameters that certainly affect the smouldering process, including the gaseous atmosphere and produced gases, appears limited [18]. Most experimental investigation are also limited to TGA analysis [7,8], severely simplifying the crucial role of oxygen and heat transport across the bed. The present study aims at investigating the low-temperature ignition of the pine bark and its spontaneous smouldering using laboratory-scale tests at a larger scale (10^1 to 10^2 g), in static or flowing atmosphere. The increase of scale is a need given that the smouldering process is the result of chemical and transport mechanism, where the latter are determined by the geometry. This is a first experimental investigation to explore factors like particle size, amount of material, moisture content, material packing, heating rate, geometry of the storage, air feed flow and oxygen concentration. Flow experiments add information about the gases produced during and after the ignition, under different atmospheres and operating conditions.

2. Materials and methods

2.1. Pine bark

In this work, the material used as reference biomass was a commercial pine bark (PB). Its composition, characterized by high carbon and higher ash content compared to the core wood [19], makes its combustion to differ, because of the special reactivity conferred by inorganics in the ashes. This is also the motivation to focus on bark.

2.2. Characterization of pine bark

The commercial pine bark initially provided in the form of chips (mean size of a few cm) was preliminary milled and sieved in order to collect samples with sufficiently narrow particle size ranges. Specifically, different fractions were collected, with mean particle size <2 mm, between 2 and 4 mm and >4 mm. Pine bark was then physically and chemically characterized: elemental analyses was carried (Fison EA 1108 CHNS) following standard procedures suggested by European technical committees [20]. Composition analysis of pine bark was performed according to TAPPI and Wise methods [21,22]. The determination of the gross calorific value was performed by using a calorimeter pump Phywe LEC-02 model and by following the procedure described in the standard UNE-EN 14918:2011. The proximate analysis was carried out in a thermobalance with an amount of about 50 mg, through a sequence of two steps. A first stage is run in a N_2 atmosphere, from ambient temperature to 800 °C, at a heating rate (HR) of 5 °C/min, to evaluate the moisture and volatile matter. A second stage was under an oxidative atmosphere (air), keeping a constant temperature of 800 °C until total combustion of any organics, to determine the amount of fixed carbon and ashes. Differential scanning calorimetry (DSC) has been carried out to identify the range of temperature where the exothermic reaction should be expected. Test were performed under an oxidative atmosphere (air), from ambient temperature up to 150 °C at HR of 2 °C/min, 1 h isothermal, further heating at the same HR up to a final temperature of 500 °C.

2.3. Experimental set-up

In the present work two experimental techniques have been used to investigate the onset of pine bark smouldering. Specifically, they involved (i) a standard laboratory oven and (ii) a flow tubular reactor. The two experimental configurations are sketched in Fig. 1.

With the former, pine bark samples were loaded in gas-permeable containers and arranged inside an oven (Fig. 1, above). It is known that smouldering phenomena, even those ones triggered by an external heat source, are the result of a thermal balance between the heat provided to the sample, or generated by the biomass combustion, and the amount of heat lost, because of thermal dispersions. Therefore, the oven allowed to keep the ambient around the sample at a fixed temperature, initially controlling the heat transferred to the biomass, and required to activate the onset of smouldering; afterwards, the oven limits the heat losses from the biomass when the sample temperature increased as a result of the smouldering ignition.

We carried out a variety of tests using the oven, specifically analyzing the temperature of a stagnant air atmosphere required to activate the pine bark smouldering. The standard conditions in the oven experiments are: 45 g (approx.) of sample, with a particle size <2 mm and a heating rate of 2 °C/min. Modifications of these conditions to investigate the effect of individual variables are specified in the following. Basically, these tests allowed to study the onset of smouldering under conditions comparable with a large scale biomass storage, assuming to reproduce the thermal inertia of a large amount of biomass by means of the oven. The gas-permeable containers were square or cylindrical in shape, made with an aluminum net having mesh size equal to 0.5 mm. Two thermocouples (TCs) were used to record both sample temperature and gas temperature inside the oven. The gas temperature in the oven was regulated by a third TC, placed below the container, quite close to the oven wall. Note that the oven atmosphere could not be controlled, since it is not gastight. Different thermal policies were applied to heat up the biomass sample, increasing the oven temperature at different heating rates, from room temperature up to 250 °C. When the sample temperature increased above 250 °C, the oven was automatically switched off. The onset of smouldering was conventionally defined as the point where the temperature of the sample overcomes that of the gas atmosphere in the oven.