



Onset and propagation of smouldering in pine bark controlled by addition of inert solids

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ABSTRACT

We investigated the smouldering onset and propagation in a biomass (pine bark) bed to mitigate or control the process. By the addition of sand, the bed porosity has been modified. Sand of different average particle size, in different arrangements and proportions (from 30 to 70%) has been used, modifying the bed porosity (between 0.44 and 0.67). Experiments have been carried out in a flow reactor, with controlled O₂ content in the feed. The packed bed was large enough to allow the development of a reaction front, as expected in large scale applications. Pressure drop measurements revealed as a useful indication to monitor the smouldering onset and the front evolution. The process appears always controlled by the flux of O₂, as expected for smouldering. Properly tuning the bed porosity with inert solids, allows to control the self-heating propagation, in view of its exploitation for low temperature heat production with simultaneous controlled conversion. The addition of sand supports a well-defined reaction front. The inert solid preserves the bed texture when the biomass is progressively consumed and allows to evenly distribute O₂ to the biomass, thus regulating the heat dissipation and keeping the smouldering front confined.

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1. Introduction

Smouldering can be an effective process to recover energy from renewable sources because it is a mild, self-sustaining process, frequently occurring spontaneously (with a large loss of useful carbon, according to [4], possibly leading to a wider acceptance than incineration. In addition, it would provide heat at a lower temperature, leading to more efficient energy use.

Smouldering is a heterogeneous oxidation reaction that takes place on the surface of a solid fuel. The reaction is limited by the rate of oxygen that can diffuse towards the fuel surface [1,2], resulting in low temperature and slow reactions rates compared to flaming combustion. Drying, pyrolysis and oxidation steps [3–5], are involved during smouldering and hence, compared to pyrolysis [6], smouldering is more complex. The literature describes smouldering as a self-sustaining phenomenon occurring when oxidation reactions generate enough heat to overcome heat losses and, consequently, it is able to sustain the propagation of the reaction [7]. It is well established that, for most materials and typical conditions, the two limiting factors in smouldering propagation are the

oxidizer flux to, and the heat losses from, the reaction zone [3].

Smouldering occurs in an aggregate medium, formed by particulates, grains, fibres forming a porous matrix. A large surface per unit volume is required to enhance heterogenous reactions while permeability allows the oxygen transportation to the reaction zone [8]. Typically, the aggregates provide a considerable thermal insulation (due to their low thermal conductivity) that reduces the heat losses. Smouldering relies on a complex heat transfer dynamic. Prior to the self-heating ignition, the dominant heat transfer mechanism can be either conduction or convection. Conduction mainly occurs by direct contact between the fuel matter and a hot surface, and particles contacts. Convection takes place through a hot gas flow. After the smouldering onset, heat transfer by convection gains a dominant role since heat carried by the gas flow supports the smouldering process [9]. Radiation can also contribute to the heat transfer but, to our knowledge, never investigated. Its influence would be limited to a few millimeters [10]. Despite that, radiation can effectively convey the energy released by smouldering reactions, facilitating the self-sustaining nature of the process, while materials that shrink or move away from a heat source do not support smouldering [11]. Smouldering combustion can propagate in two distinctive modes, namely forward and backward (or reverse), depending on the relative direction to the oxidizer flow. Forward propagation, the mode applied in this study, is

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considered the most energy efficient mode for smouldering propagation, where the O₂ flows towards the reaction front and the heat of reaction released acts pre-heating the material facing the reaction front [3,12]. For this reason, in the forward smouldering, the process is much closer to stoichiometric burning conditions than reverse smouldering, with the maximum char production as reported in Ref. [1].

Among the materials that typically undergoes smouldering, biomass is the most studied. Other investigations have been carried out on coal, RDF, sewage sludge and different types of wood [13–17]. Biomass is a solid fuel of natural origin consisting of an organic porous matrix, with possibly very high moisture and some mineral contents [18]. Once the biomass is heated up, it dries and, successively, goes through its pyrolysis [6], and eventually oxidation, depending on the availability of oxygen. However, if oxygen is present, biomass self-heating may occur and support gas-phase homogeneous combustion (flaming) or heterogeneous combustion (smouldering) [3].

In case of biomass, smouldering can be considered a process to be profitably exploited, if controllable. Indeed, the smouldering combustion process has been recently suggested as a new method in the treatment of biosolids [19] and liquid organic contaminants, such as tars. Smouldering has been also mentioned as an alternative disposal option and environmental remediation [20]. Energy production from the exothermic reaction such as oxidations, using high moisture content fuel (as biomasses), could be one of the main advantages of smouldering process, as well as the recovery of energy from condensable emissions, which may be used to enhance the efficiency of this technology [21].

In the wood industry, bark is a controversial waste, because of its composition and mechanical properties. In the present work, 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 usage as a construction material is limited. Due to the large availability of pine bark on a global scale, there is an increasing interest in its use [22–25]. Transportation, storage and use of biomass require a good knowledge of its spontaneous reactivity [26]. A burning rate higher than coal has been reported [27], likely explaining the onset of fires (even explosions) during storage, milling or conveying [26]. This can be even more critical for bark, where the higher ash content may bear catalytically active inorganic species. The ash layer produced can thermally insulate the core, still remaining permeable to allow O₂ to reach the surface where the smouldering occurs [28].

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, and bed porosity [29]. Chen et al. [30] investigated the role of other parameters on the self-sustained propagation of smouldering, in critical conditions, such as the moisture content, inorganic content, bulk density and the heat of smouldering combustion, but most experimental investigations are limited to TGA analysis and mg samples [26,27], neglecting the role of the bed porosity in supporting (or limiting) the smouldering progress. Small sample investigations severely simplify the crucial role of oxygen and heat transport across the bed. The permeability has been observed to affect the strength of smouldering, since it controls the flow of the oxidant (i.e. air/O₂) across the biomass particles [31–33].

The present study aims at investigating the spontaneous smouldering of the pine bark (taken as a reference biomass) and its propagation front, using laboratory-scale tests at a scale ranging from 10 to 100 g, in an oxidizing atmosphere, both flowing and stagnant. Since smouldering is strongly affected by bed porosity structure and permeability we increased the investigation scale. It

is expected that smouldering is largely affected by mass- and heat transfer rates within the bed, which change dramatically with sample size; if the sample is too small, heat- and mass transfer resistances may be overlooked, being much smaller. The sample size used in this study is large enough (tens of grams) to account for the effects of heat and mass-transport. Data collected are currently under elaboration to build a representative model for successive scale-up considerations and description of smouldering phenomena in typical biomass storage scales. Furthermore, the evolution of the smouldering front in its propagation is another key aspect. It can be controlled acting on the bed texture that, in turn, affects the porosity and permeability of a typical biomass solid phase, before and after the action of smouldering. For this purpose, in this work the packed bed porosity of the biomass sample has been manipulated by mixing the biomass with different amounts of inert solids (sand), characterized by different average particle size, as well as by changing the degree of packing for each sample. Ultimately, the characterization of the smouldering reaction evolution under these conditions gave important information to design and develop continuous processes in which smouldering combustion could be applied as a thermal decomposition stage, at low temperature, simultaneously allowing for energy recovery in biomass and solid waste disposal treatments.

2. Materials and Methods

2.1. Materials

The material used as reference biomass was a commercial pine bark (PB) whose composition is typically characterized by a high carbon and a higher ash content compared to the pine wood core [28,34–37]. The commercial pine bark, initially provided in the form of chips (average particle size of a few cm), was preliminary milled and sieved to collect samples with sufficiently narrow particle size range, around 200 μm. Other chemical-physical properties of PB, including elemental and proximate analysis, as well as the thermal properties obtained from DSC and TGA experiments, have already been reported in our previous work [35] and partially summarized in Table 1.

Pine bark shows chemical-physical properties comparable to analogous woody biomasses [29,34,38]: the moisture content of about 11% w/w, evaluated through the standard procedure of drying out the pine bark at 105 °C until constant weight settles (UNE-EN 14774–2:2010), reflects typical values reported in the literature [39]. The volatile matter percentage is also consistent with those ones mentioned in previous works [36], in the order of 60% w/w. This value was calculated according to standard UNE-EN 15148:2010 where a sample without contact with ambient air is heated to 900 °C for 7 min. The percentage of volatile matter is thus calculated from the mass loss of the test sample minus the mass loss due to moisture. Volatile matter is likely very important in determining the self-heating ignition of a biomass because it is supposed that their emission, during the first stages of smouldering, lead to secondary combustion mechanisms; heat released by combustion increases the local temperature and consequently supports the smouldering front. Finally, ash content and fixed carbon were determined by calculation from the mass of residue

Table 1
Proximate analysis of the pine bark used.

Parameter	[wt. %]
Moisture	11.3
Volatile matter	58.8
Fixed carbon	26.4
Ashes	3.5

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