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Oxidative pyrolysis of wood chips and of wood pellets in a downdraft continuous fixed bed reactor

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HIGHLIGHTS

- A counter-current oxidation zone was stabilized inside a downdraft reactor.
- Detailed mass balance including char, permanent gases and tar yields.
- The fed air flow rate and the fuel (wood) density were varied.
- Insights acquired on the shape and stability of the oxidation zone.

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ABSTRACT

In air staged gasification and advanced carbonization processes, oxidative pyrolysis occurs in downdraft continuous fixed bed reactors. An oxidation zone separates the virgin fuel from the resulting char and propagates upward. Here, the oxidation zone was stabilized at a fixed elevation in a 20 cm I.D. fixed bed reactor using wood chips or wood pellets. In controlled continuous operating mode, we investigated the impact of air flux and bed bulk density on the behavior of the oxidation zone in terms of wood consumption, and yields of char, gas and tars. An air:wood mass ratio of 0.7 was measured and in our operating conditions, and was not sensitive to air mass flux and bed density. With oxidative pyrolysis, yields of organic condensates were lower than with allothermal pyrolysis, whereas the production of pyrolysis water and permanent gases increased. Finally, the oxidation zone was shown to be flat and horizontal in a wood pellet bed but inclined in a wood chip bed.

1. Introduction

Thermochemical biomass conversion, i.e. combustion, gasification, and pyrolysis, can convert a biomass into useful energy such as heat, electricity, or liquid fuel. Although biomass combustion has clearly reached the commercial development stage, the trajectories of the two other routes are quite different.

Pyrolysis was widely developed for charcoal production, also called carbonization, in the past, but in most cases, the technologies remain simple and robust and not always adapted to the need for efficiency and environmental constraints today [1]. Nevertheless thanks to the awareness of some constructors, but also due to the new interest in charcoal as reducing agent, fertilizer, or active carbon, the technologies have been significantly improved in recent years.

Research and development programs on gasification have been underway for many years; some commercial demonstrations exist, but the technology positioning in the market remain fragile and the success stories still limited [2]. Nevertheless, a wide range of reactors have been developed varying mainly in their feedstocks and applications. Usually, a simple classification is proposed based on the size of the installation: entrained flow, fluidized bed, and fixed bed reactor, for large, medium and small reactors, respectively. Fixed bed reactors are widely acknowledged to be the best solution for low power production because of their greater simplicity and lower production cost.

In many of the above mentioned carbonization and small scale staged gasification processes, biomass pyrolysis occurs in a specific continuous downdraft fixed bed configuration. But in the same way as in any thermochemical conversion processes, pyrolysis plays a major role as it produces char and pyrolysis gases that

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are subsequently converted. Moreover, partial oxidation can be a simple and efficient way to sustain pyrolysis, by providing the energy needed for heating, drying, and endothermic reactions of the conversion, and to allow the process to be autothermal: it is thus referred here as oxidative pyrolysis.

During pyrolysis in continuous downdraft reactors, the biomass and air are fed into the top of the reactor and char and pyrolysis gases are removed from the bottom. We define the oxidation zone as the reactive zone inside the packed bed where major changes in temperature and gas composition take place (Fig. 1). This zone separates the unreacted biomass from the char and is the location of several complex and coupled transformations or reactions. The first to occur is drying. When the temperature increases, oxidative pyrolysis occurs, which can be defined as a combination of biomass oxidation and biomass pyrolysis [3]. Then, oxidation of some light and heavy pyrolysis gases, and of char, provides the energy to the system, and thus allows the propagation of the oxidation zone.

The stabilization of the oxidation zone inside the bed is of particular interest for operators because (i) the top of the bed is maintained at a low temperature, thereby facilitating control of the process and limiting the production and deposition of tar, and (ii) a higher temperature zone is created that favors tar cracking when crossing it.

The upward propagation of the oxidation zone towards the virgin biomass can be controlled by removing char from the bottom of the reactor, which causes a downward movement of the whole bed.

The propagation of an oxidation zone in a porous medium, called smoldering, has been studied in many contexts, including forest fires and tree trunk combustion [4,5], home fires and burning of polymeric foams or tissue [6], propagation of underground fires in coal mines [7] or in oil shale exploitation [8], organic waste incineration [9,10], and also during combustion of cigarettes [11]. These configurations differ in several respects. In particular the two first examples [4–6] refer to natural smoldering, as opposed to forced smoldering [7–11], which describes situations where the air flow is forced to cross the porous media, as in packed bed incineration and oil shale combustion. Moreover, forced smoldering is classified as reverse (counter-current) or forward (co-current) depending upon the relative directions of the air and of the propagation of the oxidation zone in the porous medium. In forward smoldering [7,8,11] the oxidation zone moves in the same direction as the air flow. In reverse smoldering, it propagates in the opposite direction to that of the air mass flux, meaning that air first crosses the unreacted carbonaceous material [9,10,12–14].

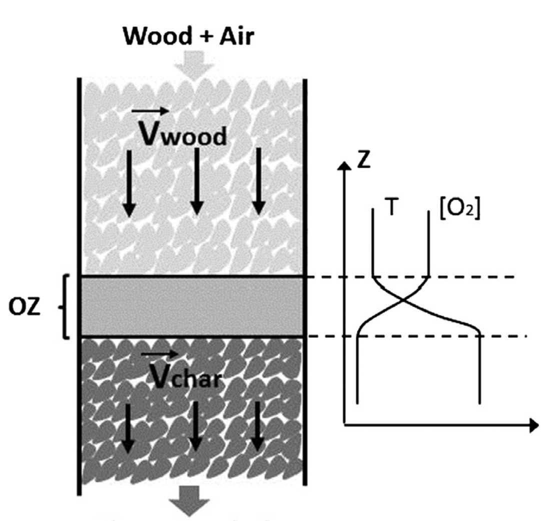

Fig. 1. Oxidative pyrolysis in a continuous downdraft fixed bed reactor.

The oxidative pyrolysis of wood chips in a continuous fixed bed investigated here involves forced reverse smoldering because oxidation zone propagates upwards, in opposite direction to wood and air flows [15].

In smoldering, the oxidation zone can be described by several specific features: - its propagation rate; - its temperature; - its geometry, thickness and shape; - its yield of char, gases, and tar, and the composition of these outputs. These features can be observed experimentally using the appropriate research equipment. Their prediction remains a real challenge for researchers, as they require the elaboration of complex models combining a description of chemical reactions with heat and mass transfer phenomena.

Among these features, the propagation rate of the oxidation zone has been widely investigated in the literature on reverse smoldering [10–15]. It should be noted here that when referring to propagation rate or velocity, the terms "front" or "ignition front" are more commonly used by authors than oxidation zone. The propagation rate, which is controlled by combustion and heat and mass transfers, depends on: - air flow-rate; - fuel properties like size, density, thermal conductivity, moisture, volatile matter, ash, and elemental composition; - and bed properties, such as porosity and density. However, as mentioned by Mahapatra and Dasappa [12], not all of these parameters are independent variables and most are interrelated, so that drawing conclusions about the dependence of each separate parameter on the behavior of the oxidation zone is very difficult.

Nevertheless, there is a consensus in the literature that air mass flux is the parameter that has the most influence on the propagation rate. This point has been checked on more than 10 carbonaceous feedstocks with significantly different properties [13,16]. Regarding the influence of the air mass flux, the propagation rate inside a wood packed bed initially increases as the air mass flux increases until it reaches a peak. A further increase in the air mass flux then results in a decrease of the propagation rate. Three different regimes are usually identified in reverse smoldering applied to the combustion process, which are determined by the main process controlling the propagation of the front: oxygen-limited, reaction limited and quenching by convection [13,16,17].

Air mass flux does not only influence the propagation rate, but also the other features of the oxidation zone. It has been shown that peak temperature in the zone increases with an increase in the air flux until a maximum is reached in the sub-stoichiometric conditions of the combustion regime [13]. An increase of about 100 °C in temperature has been reported when air mass flux fed through a wood downdraft batch gasifier was increased from 0.12 to 0.14 $kg\,m^{-2}\,s^{-1}$ [12]. In these studies, these maximum temperatures match the maximum propagation rates of the oxidation zone.

Regarding geometry, some authors have attempted to measure the thickness of the ignition zone in counter current combustion processes. It has been reported to be in the same order of magnitude as particle size [14,16], and is said not be sensitive to the air flux [14].

The influence of the biomass or bed properties has been more rarely investigated. But the few studies that did showed that front propagation velocity was higher when: - particle size [13,16,17] or water content [10,13,17] or ash content [13] was low; or - when the heating value [13,17] was high. Moreover, ignition front speed was shown to be inversely proportional to bed bulk density [16,18].

From the previous literature on reverse smoldering, the following remarks can be made. First, most of the studies focused on understanding the propagation rate. Other specific features of the oxidation zone received less attention, in particular, the geometry of the oxidation zone and yields and the composition of all the products leaving this zone. Second, very little information is available on the influence of operating parameters and fuel/bed properties on the features of the whole oxidation zone, and more