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Pyrolysis of whole wood chips and rods in a novel ablative reactor

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HIGHLIGHTS

- A novel lab-scale ablative pyrolysis reactor was designed and constructed.
- Wood chips and a rod were directly converted into bio-oil via ablative pyrolysis.
- Bio-oil yield from ablative pyrolysis of wood chips (20 mm) was 60 wt.%.
- Results from ablative reactor were similar to those from a fluidized bed reactor.

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ABSTRACT

The ability to carry out pyrolysis of entire wood chips and rods instead of small particles would be of great value for mobile pyrolysis units, because of the large possible savings in grinding costs (7–9% of total process costs). With this goal in mind, we designed and constructed a novel lab-scale ablative reactor for fast pyrolysis of entire wood chips and even wood rods, converting those directly into a high yield of bio-oil for the first time. The bio-oil yield from fast pyrolysis of wood chips (10 × 20 mm) was as high as 60 wt.%, similar to that from wood crumbles (2 × 2 mm). Additionally, the yield and composition of bio-oil from ablative pyrolysis were in the same range as those obtained from a fluidized bed reactor using <1 mm particles, with the small differences (slightly lower yield and HHV, and higher water content) attributed to the longer vapor residence times in the ablative reactor, which promote secondary reactions. We modeled the heat transfer characteristics of this semi-batch system, and comparison with experimental measurements confirmed that radiation from the hot components does not significantly decompose the wood prior to direct contact with the hot metallic surface in ablative pyrolysis. The findings of this work have the potential to lead to new developments for small-scale, mobile pyrolysis units for the disposal of forest residues.

1. Introduction

Lignocellulosic biomass is an abundant renewable energy resource. The use of biomass for energy leads to carbon neutral processes, and the chemicals and fuels derived from it have a tremendous potential to reduce the problems caused by our dependence on fossil fuels [1]. Fast pyrolysis is a promising technology to convert lignocellulosic biomass into liquid fuels or chemicals, and it has been in development for over 30 years. In this process, biomass is heated up to 400–600 °C at a very high heating rate (~500 °C/s) in the absence of oxygen, whereby it decomposes into organic vapors, solid char, and permanent gases [2,3]. The organic vapors are rapidly cooled down and condensed to a liquid product, known as bio-oil, which is the main product of fast pyrolysis. Depending on the feedstock, the yield of bio-oil can exceed 70 wt.% on dry basis [2,3]. Bio-oil can either be combusted in boilers, engines, and turbines to generate heat or power, or be upgraded to produce transportation fuels and commodity chemicals [2–5].

Fast pyrolysis has been extensively studied for different feedstocks, including agricultural, woody, and algal biomass [6–9]. Our previous study using Py-GC/MS-FID indicated that fast pyrolysis is a promising way to dispose beetle-killed trees by converting them into high-value chemicals and fuels [10,11]. Once these trees are dead, they may fall without previous warning, representing a threat to public safety, and are also undesirable for the solid wood panel manufacturing industry. To date, about 42 million acres of forests have been attacked by bark beetles in the western United States, and they are typically located far from the urban industrial

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areas [12]. Therefore, using a mobile pyrolysis unit to convert beetle-killed trees near the harvesting point could significantly reduce the transportation costs that are a key barrier to widespread utilization of this vast resource, since bio-oil has 6–8 times higher energy density than the green wood chips [13,14].

The reactor is the key component of the mobile pyrolysis system. Reactors for fast pyrolysis of biomass include the bubbling fluidized bed reactor, circulating fluidized bed reactor, free-fall reactor, auger reactor, and ablative reactor. For most pyrolysis reactor configurations, the biomass feedstock needs to be ground into small particles of around 2 mm or less, because the process requires minimizing heat transfer resistances throughout the particle [15]. Kumar estimated that the costs of biomass chipping and grinding were about 7–9% of the overall production costs [16]. Forest Concepts also studied the effects of final wood particle size on the total comminution energy cost for the optimized Crumbler® machine, and found out that the comminution energy cost increases from nearly zero to up to $4.50 per US ton as the wood particle size is reduced from 12 mm to 1–2 mm [17]. Fortunately, the ablative pyrolysis reactor provides an opportunity to use large pieces of wood instead of only small particles as feedstock, saving on grinding costs. In ablative pyrolysis, biomass undergoes melting and/or sublimation reactions as it directly contacts a hot solid surface. There is a steep temperature gradient at the biomass surface, leading to the formation of a thin superficial layer of reacting solid [18,19]. The reacting layer moves at constant velocity towards the heart of the cold biomass. Therefore, the reactive process in the ablative reactor takes place only at the superficial layer rather than the entire biomass particle, and reaction rates are not limited by the heat transfer through the entire particle. For this reason, in principle there is no upper limit to the biomass particle size that can be processed. These characteristics have been speculated in the past, but there were no experimental data to back up the claim that fast pyrolysis of large pieces of wood is possible. The major drawback of the ablative pyrolysis reactor is that it is mechanically driven and therefore more complex than other types of reactors. In addition, ablative pyrolysis is surface area controlled, so scaling up is difficult. However, for using an ablative pyrolysis reactor as a mobile unit, the scale-up issue is less of a concern.

To date, only a few ablative pyrolysis reactors have been developed. The first pioneering experiments with ablative pyrolysis were reported by Diebold [20], who used an electrically heated wire to cut pieces of wood. These experiments demonstrated that biomass could be rapidly pyrolyzed via ablation, producing a thin layer of liquid that vaporizes. Lédé et al. did a fundamental study on the ablation heat transfer with specific application to wood pyrolysis [19,21–23]. However, their experimental setup did not allow for overall product recovery for analytical study and mass balance calculation. Reed and Cowdery [24] designed and constructed a "pyrolysis mill" based on the principles of a conventional grain mill. Liquid bio-oil yield of up to 48.6% (dry basis) was obtained. However, the particle size of their feedstock, pine sawdust, was only as high as 14 mesh (1.4 mm). The major problem of this system was the slow escape of the pyrolysis vapors from the reactor, lowering the yield of bio-oil. Later, Peacocke et al. [25] designed an ablative reactor system with four rotating blades scraping a continuous feed of pine wood, and up to 67.7% of bio-oil yield on dry feed was reported. One limiting factor of this setup was the difficult removal of the char formed on the reactor surface. The char built up below the rotating blades can quickly prevent the incoming particles from being ablated. The particle size of the pine wood feedstock was 4.75–6.25 mm, which was the largest particle size reported for tests in this system. Aston University has claimed that whole wood chips up to 50 mm can be processed in their ablative reactor, but no experimental data or details on the reactor design are available [26]. Recently, Paulsen et al. [27] designed a micro ablative pyrolysis apparatus in order to develop a robust wood particle pyrolysis model that accounts for both transport and pyrolysis decomposition kinetics at high temperatures and high heating rates. In the reactor, pyrolysis of 1 mm thick wood particle was conducted by direct ablation with a heated surface, and the subsequent changes of wood composition were characterized by the spatiotemporally resolved diffuse reflectance *in situ* spectroscopy. However, bio-oil was not collected or analyzed in their work.

Thus, we herein designed and constructed a prototype lab-scale ablative reactor to convert entire wood chips and wood rods into high yield of bio-oil in a single step. The goal is to experimentally verify if high yields of bio-oil can be obtained from large particles via ablative pyrolysis. To the best of our knowledge, our work is the first to report bio-oil production from fast pyrolysis of entire wood chips and wood rods. The results from the ablative reactor were compared to those obtained using a lab-scale fluidized bed reactor. In addition, the effect of pre-heating in this semi-batch reactor prior to ablative pyrolysis of wood chips was evaluated using both modeling work and experimental measurements.

2. Ablative pyrolysis reactor and its operation

As shown in Fig. 1, the ablative reactor is composed of a chamber, which contains a spinning bowl where the wood chips can be placed, and a hot plate at the top that can move down and apply pressure against wood chips. Fast pyrolysis initiates as the hot plate contacts the wood chips, and a high flow rate of inert gas rapidly sweeps the generated vapors out of the chamber for condensation.

2.1. Reactor description

The ablative pyrolysis reactor designed and constructed in the present work is shown in Fig. 1. This is a semi-batch system with a capacity of 500 g wood chips per run. The reactor chamber is made of A240 304L stainless steel with an internal diameter of 0.30 m and an internal height of 0.42 m. This chamber can be split into an upper chamber and lower chamber, which are connected with flanges. A static seal is created by a graphite gasket placed between the two flanges faces. The wood chip bowl made of A240 304L stainless steel has an internal diameter of 0.21 m and a height of 0.09 m. In order to make the generated pyrolysis vapors escape from the wood chip bowl quickly, 0.05×0.01 m rectangular slots were made on the shell of the bowl. To prevent wood chips from dropping out of the bowl from the slots, a 1 mm thick perforated T304 liner with 1.6 mm holes on a 3.2 mm 60° triangular pitch was installed inside the shell. The wood chip bowl is driven by a 3 HP SEW-EURODRIVE gear motor, providing a rotation speed up to 160 rpm. The lower chamber contains a gas inlet and a gas outlet. To minimize the vapor residence time, the product vapors escaped out of the chamber through a perforated tube that was bent around the circumference of the bowl and connected to the gas outlet. The upper plate is driven by a piston connected to a hydraulic system, capable of moving vertically and applying a maximum pressure of 1.5 bar against the wood chips. The lower and upper drive shafts housing on the reactor chamber contain graphalloy bushings to prevent leakages and ingress of air. Three 1 kW Chromalox CIR cartridge heaters were inserted in the upper plate, and are capable of generating a heat flux of up to 105 W/m^2 and heating the plate up to 700 °C. Furthermore, two band heaters (Chromalox HBT 120) were used to heat the reactor wall to a minimum temperature of 300 °C, minimizing the condensation of pyrolysis vapors on the inner reactor wall. Each of the band heaters has a power of 2 kW. The temperatures of upper plate and reactor