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Research article

Evaluation of fast pyrolysis feedstock conversion with a mixing paddle reactor

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ABSTRACT

We have developed a pyrolysis reactor based on a unique auger-paddle configuration with heat transfer material (HTM) and proved to achieve high heating rates and fast pyrolysis. We tested ten different biomass types and obtained bio-oil yields ranging from approximately 40% for thermally treated wood, to approximately 57% for crop residues (corn stover) and 67% yield for woody feedstocks (tulip poplar). These results, as well as the solid char yields, are similar to those obtained for the same feedstock using a circulating fluidized bed. Tests conducted without HTM resulted in lower bio-oil yields (ranging from 8 to 18% decrease in yield) and higher char yields with similar changes in magnitude, which is indicative of slow pyrolysis. In addition, a comprehensive study and analysis of the material residence time and mixing characteristics of the novel auger-paddle system is presented. These results demonstrate that an auger-paddle configuration is capable of achieving the high heating rates required for fast pyrolysis.

1. Introduction

Pyrolysis is a thermal degradation process that occurs in the absence of oxygen. It is a promising route for creating a liquid fuel that can be upgraded to transportation fuels or used directly as a fuel [1]. Of specific interest, biomass pyrolysis has been heavily investigated for the generation of bio-oil for upgrading to fuels with a significantly reduced or neutral carbon footprint. Balat et al. divided pyrolysis into three categories: conventional pyrolysis, fast pyrolysis, and flash pyrolysis [2] based upon their reaction temperature, heating rate, solid residence time and particle size. Conventional pyrolysis is generally applied to relatively large particles (5–50 mm) because conduction heat transfer limits the heating rates to < 1 K/s. Fast pyrolysis is typically applied to small particles (< 1 mm) for which heating rates of 10–200 K/s can be achieved. The residence time of fast pyrolysis reactions are usually in the range of 0.5–10 s. Flash pyrolysis is typically applied to particles that are smaller than 0.2 mm at heating rates > 1000 K/s and residence times < 0.5 s [2].

Several recent reviews have investigated various production technologies for pyrolysis including ablative (coil, mill, plate, vortex, etc.), circulating fluidized bed, entrained flow, fluidized bed, moving bed (vacuum, transported, stirred, horizontal, etc.), rotary hearth, microwave, and rotating cone [3–6]. Regardless of the technology, however, perhaps the most important factor for the conversion reactor is the heat transfer rate stemming from the reactor itself (reactor wall in ablative pyrolysis, gas or wall contact in transport bed or entrained flow), or from use of a heat transfer medium (HTM) such as the bed material in a fluidized bed.

According to Briens et al. [7], and Butler et al. [5], the only current technologies that can be commercially applied for bio-oil production are the bubbling fluidized bed (BFBs) and circulating fluidized beds (CFBs), although auger reactors also have high market attraction because of their simplicity, robustness, and their long established history as effective conversion reactors [5,7]. Particularly the Lurgi-Ruhrgas twin-screw mixer has been extensively investigated in the past for thermal treatment (focusing on coal degassing), and has been demonstrated at a capacity of at least 50 ton/day for pyrolysis [5,6]. In addition, McGee and Miao recently detailed the application of auger feeders in fast pyrolysis systems and difficulties in continuous feed of biomass systems [8,9]. It was found that the established and simple characterization tests, such as bulk density, particle size, and angle of repose did not correlate well with established auger correlations and must be proven empirically. Mixing paddle reactors offer additional advantages over standard mixing auger reactors because they provide greater control of the radial and axial mixing patterns. This increased control offers opportunities to decrease the amount of HTM required to maximize liquid production, while still maintaining the simplicity, robustness and market attractiveness of auger-based reactors. For these

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reasons, this work publishes the fast pyrolysis performance of several feedstocks in a custom auger-paddle reactor.

Specifically for thermal treatment of materials, augers have been heavily studied in disposal and recycling of waste materials, degassing of coals, and gasification. Chun et al. studied the pyrolysis gasification of sewer sludge in a pilot screw reactor [10]. Many studies have been done on the recycling/disposal of automotive waste and shredded tires in pilot conversion units ranging from 100 g/h to 8 kg/h [11–15], and larger commercial units, such as that studied by Day et al. at 200 kg/h [16]. In study of the larger unit, Day et al. concluded that although the auger reactor is a good method of resource recovery and waste disposal, and is energetically self-sustaining, further development is required and there is vast room for improvement. Other studies have found similar results from medium density fiberboard scraps and aseptic packaging [17,18]. The range of studies that have been conducted using auger reactors demonstrates that such systems are robust for a wide variety of materials and processing conditions.

Many researchers have shown that auger reactors operating without using HTM can liquid achieve yields that are comparable those obtained by fluidizied beds [19–29]. However, the liquid composition can be significantly affected from primary and secondary reactions arising from low particle heating rates and vapor-phase residence times.

In order to increase the heating rate of the biomass particles within auger reactors to avoid such secondary charring/cracking reactions or long particle/vapor residence times, some development has been done to include a heat transfer medium (HTM). Through this addition, biomass particles are not only heated through contact with the hot reactor wall, but mostly through contact with the preheated HTM. Several HTM have been investigated including silica sand and quartz [30,31], steel shot [30,32], and various catalysts (clay minerals such as bentonite and sepiolite, and oxides of alkali metals such as calcium oxide) referenced above. Henrich et al. used a twin screw auger (40 mm diameter screws, 1.5 m total length) with various heat transfer media to process hardwood, softwood, wheat bran, and straw [30,31]. Average yields of 66.5%, 69.1%, 60.0%, and 51.4% were achieved for the respective feedstock with feeds of approximately 10 kg/h raw biomass and 1150 kg/h heat transfer media. Brown and Brown also found that auger-type reactors are well suited for bio-oil production, and achieved yields of 73% in a surface-response analysis of their 1 kg/h twin auger system (25.4 mm diameter screws, 0.56 m total length) with an HTM feed rate of 18 kg/h and 63 RPM [32]. They report that the addition of a HTM reduces the solid residence time by > 95%, and achieves 25% more liquid yield compared to other auger studies that use external heating [32]. Both studies used short solid residence times (ranging in 5–15 s) to demonstrate that HTM used within twin screw auger reactors exhibits sufficient heat transfer to perform fast pyrolysis, and produce yields comparable to those of fluid bed reactors.

The present study undertakes the development of a single-shaft auger-type reactor with cuts in the flighting and additional paddles to optimize the mixing between the feedstock and the HTM, in order to reduce the motor power requirement and the wear on moving parts. Here we show that this reactor design produces bio-oil with similar properties and yields as other leading technologies, such as bubbling fluidized bed (BFB) and circulating fluidized bed (CFBs) systems, while potentially reducing capital and operation costs. Other objectives of this study are to determine: (1) residence times as functions of rotation frequency of the reactor shaft; and (2) the quality of mixing, or rather heat transfer, in this configuration.

We tested ten distinctly different feedstock materials with this system at a reaction temperature of 500 °C to evaluate the pyrolysis yields in comparison to other literature. It is shown that the unit produces quantitatively similar liquid yields when compared to other studies, as well as good qualitative representation of yields obtained from varying feedstock in other reactor systems.

2. Materials and methods

In this work we show the reactor configuration and parameters that determine residence time and mixing (heat transfer) rates. Results for ten biomass feedstock that were tested within the mixing auger reactor system are presented to evaluate conversion performance and pyrolysis characteristics. The feedstocks include switchgrass, corn stover, hybrid poplar, clean loblolly pine, sorted construction and demolition (C&D) wood waste, thermally treated loblolly pine, miscanthus, tulip poplar, piñion juniper, and a blended feedstock consisting of clean loblolly pine, tulip poplar, and switchgrass. These feedstocks were tested in a pilot scale reactor described later in this section and compared to results obtained from a circulating fluidized bed reactor.

2.1. Biomass collection and preparation

Ten biomass feedstocks were screened for conversion in this study. Ten biomass samples (approximately 5–10 kg) were prepared at the Idaho National Laboratory as representative samples from larger biomass piles. The samples were ground using a knife mill equipped with a 2 mm screen (Thomas Wiley Laboratory Mill Model 4, 1 hp; Thomas Scientific, NJ).

2.2. Mixing paddle reactor system

The fast pyrolysis system consists of four main parts: (1) the HTM dosing system (2) the biomass dosing system (3) the heating zone for the HTM (4) fast pyrolysis reactor zone similar to the HTM heater. The current system is semi-continuous and is shown schematically in Fig. 1, but is easily adaptable to continuous operation; the cartoon in the figure is not drawn to-scale. The solid bio-char stream exits the system into a sealed container (not drawn). The gas stream (condensable bio-oil and non-condensable gases) flows through a heated transfer line and through a condenser (described further below) that collects the liquid product into a sealed tank (not drawn). After the condenser, the cold non-condensable gases pass through a cold water bath to capture any remaining bio-oil (not drawn). The system is kept inert with a sweep stream of nitrogen. The nitrogen flow rate is adjusted so that the residence time of the gases in the transfer line does not exceed 2 s.

An important aspect of any similar system is the consistent and continuous flow of both HTM and feedstock. The HTM feed system consisted of a bin that flood-feeds a standard 2.54 cm diameter regular screw auger flight with a pitch of 2.54 cm. A pneumatic agitator was placed inside the feed bin to avoid bridging. This agitation was essential for the smooth and continuous operation of the system as it ensures rather constant mass flow rates. A similar agitation configuration was used for the feedstock. The shaft of the dosing augers reduces in diameter from the flood fed bin area to the main delivery shaft to allow for a flood fed mouth and avoid material plugging (depicted in Fig. 1). The shaft has a diameter of approximately 1.6 cm under the feed bin that decreases to 1.27 cm after the material feed bin. The feed bin can accommodate approximately 3.5 L of material and is sealed after material charging. The feed rate is controlled with a motor equipped with a variable frequency drive. The shaft has packing gland seals with graphite packing on both ends of the auger housing to prevent air from entering the system. The biomass is metered into the system in an identical manner. The pyrolysis reactor acts to: (i) heat the HTM, (ii) mix the HTM with biomass, and (iii) react the biomass using fast pyrolysis conditions.

Heating of the mixing paddle reactor was accomplished by 12, 1-inch-wide heating bands of 250 W each down the length of the system (approximately 45 cm length), with attached thermocouples that are inserted inside the reactor and touching the moving material without touching the auger paddles. Fig. 1 also shows a cartoon of the heating-control configuration. Each thermocouple measures the material temperature at the respective location and controls the operation of the

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