Powder Technology 274 (2015) 205–212

Contents lists available at ScienceDirect

Powder Technology

journal homepage: www.elsevier.com/locate/powtec

Mixing and operability characteristics of mechanically fluidized reactors for the pyrolysis of biomass

Valentina Lago, Charles Greenhalf, Cedric Briens *, Franco Berruti

Institute for Chemicals and Fuels from Alternative Resources (ICFAR), Department of Chemical and Biochemical Engineering, University of Western Ontario, London, ON N6A 5B9, Canada

ARTICLE INFO

Article history:
Received 24 July 2014
Received in revised form 31 October 2014
Accepted 26 November 2014
Available online 29 November 2014

Keywords:
Mixing
Pyrolysis
Aeration
Torque
Power
Mechanically fluidized

ABSTRACT

Mixing characteristics of a novel Mechanically Fluidized Reactor (MFR), a continuous, cylindrical, mechanically mixed reactor developed for biomass pyrolysis in the ICFAR laboratory, have been investigated with the specific objective of selecting the optimal stirrer geometry for fast pyrolysis of biomass. The MFR does not use any fluidization gas and its stirrer provides the required mixing between the injected biomass and the bed material while effectively breaking any possible agglomerate. In addition, good mixing is crucial to achieve effective heat transfer characteristics between the heaters and the bed, and between the bed and the biomass particles.

In conventional fluidized beds, the torque required to mix the bed decreases as the superficial velocity of its fluidization gas increases, becoming constant above a critical superficial velocity which is a function of the stirrer characteristics. For the MFR, a method has been developed to monitor the torque and the power required to mechanically mix a bed of low density particles with the natural bed aeration resulting from the formation of gases and vapors during pyrolysis.

In this study, three different shaped stirrers were first compared at various rotational speeds by artificially aerating the bed with nitrogen at different superficial velocities to simulate the generation of vapors and gases during pyrolysis. Furthermore, different fluidization gases were used in order to simulate the different characteristics of vapors produced during pyrolysis and, specifically, to evaluate the effects of their density and viscosity. The critical aeration rate at which the stirrer torque becomes constant is similar for all the stirrers.

The second part of this study focused on actual wood pyrolysis tests. The reactor was first supplied with nitrogen above the critical aeration rate. Then, the nitrogen was shut off and wood pellets were fed into the reactor. The formation of pyrolysis gases and vapors greatly decreased the power required to mix the bed and this reduction was dependent on the type of stirrer.

The stirrers were ranked in terms of their performance in minimizing the pyrolysis time. The vertical blade stirrer resulted in the smallest pyrolysis time and power consumption. Additionally no segregation of the biomass pellets was observed. Hence, gases and vapors were formed at the optimum location for effective aeration.

The findings of this project have provided a better understanding of the MFR technology when used for the pyrolytic processing of biomass materials.

1. Introduction

Biomass is a renewable energy source that could partially replace fossil sources for the production of chemicals and fuels in the future. Pyrolysis is one of the most attractive processes to convert biomass to valuable products, since it is operated at atmospheric pressure and relatively low temperatures. A series of consecutive and parallel reactions take place in this process leading to liquid, gaseous and solid products.

Fast pyrolysis, performed at high heating rates and low vapor residence times, minimizes secondary reactions and maximizes the liquid yield [1]. In fast pyrolysis, the organic feedstock is rapidly heated up to high temperature in the absence of oxygen, favoring depolymerisation, dehydration, decarboxylation, esterification, condensation, and cyclization in order to generate vapors, as cracking reactions lead to the formation of organic volatiles, and char, mostly due to lignins cross-linking and condensing to three-dimensional, thermally stable aromatic polymers [2]. The vapor residence time is usually controlled between 0.5 and 2 s and the bio-oil is formed upon condensation of the vapors produced during the pyrolysis process. The liquid product is mainly formed by acids, aldehydes, esters, aromatic, phenolic derivatives and other hydrocarbons as well as water [3]. While the non-condensable gases (mainly CO, CO_2 and CH_4), forming the gas product, might be combusted to provide heat for the process, the solid residue, bio-char, may be used either as a fuel or as the feedstock for higher value applications (bio-char, bio-coal, bio-coke, or bio-carbon-based materials, such as catalysts, adsorbents, carbon nanotubes or fillers in polymeric composites [4] and [5]).

---

* Corresponding author.
E-mail addresses: vlago@uwo.ca (V. Lago), cgreenh4@uwo.ca (C. Greenhalf), cbriens@uwo.ca (C. Briens), fberruti@uwo.ca (F. Berruti).

http://dx.doi.org/10.1016/j.powtec.2014.11.038
0032-5910/

The Mechanically Fluidized Reactor (MFR) is a technology developed to perform fast pyrolysis of biomass without fluidizing gas, without limitation on the biomass particle size, while producing a pure char product. Because this technology does not require any fluidization gas, the residence time of the vapors is solely controlled by their production rate. Therefore, the goal of the present study is to develop a technique to track the evolution of pyrolysis gases and vapors and, thus, to determine the reaction time as a function of stirrer geometry and operating conditions. In particular, different stirrer configurations and pyrolysis conditions were compared to minimize the pyrolysis time.

2. Review of relevant literature

Fast pyrolysis is the thermal decomposition of organic material at moderate temperatures and short residence times. These operating conditions favor the production of the condensable product (bio-oil), with a yield of up to 75 wt.% of biomass, which is particularly interesting since it can be stored and transported to produce energy and chemicals [6]. Typical fast pyrolysis yields are 60–75 wt.% of liquid bio-oil, 15–25 wt.% of solid char, and 10–20 wt.% of non-condensable gases [1].

Fluidized bed reactors have been extensively studied for the pyrolysis of biomass, since they are easy to operate and they are characterized by good temperature control and good heat transfer from bed to biomass particles [7]. These reactors, however, require high fluidizing gas flowrates that dilute the pyrolytic vapors. Auger reactors avoid the use of fluidizing gas by mechanically moving the biomass along a hot tubular reactor. However, high heat transfer rates to the biomass particles and very short residence times are difficult to achieve with this kind of technology [6].

The MFR technology presented in this study does not need any fluidizing gas and is able to achieve high heat transfer rates to the biomass particles due to the vigorous mixing, as well as maintain short vapor residence times, depending on their production rate.

In the past, agitation has been used to improve the fluidization of different materials which are difficult to fluidize. Many studies have been focused on the fluidization of fine powders, since channeling and agglomeration often occur with this kind of material.

Kim and Han [8] found out that channeling and agglomeration of a fine powder in a fluidized bed are reduced when mechanical agitation is provided. A slow speed stirrer was used to fluidize powders that could not otherwise have been fluidized and they concluded that the mechanical agitation is necessary only to start fluidization, which could then be maintained solely with the fluidization gas. Furthermore, they observed a decrease in the minimum fluidization velocity as the agitation speed is increased and a decrease in the pressure drop due to reduction of cohesive forces between particles. Park et al. [9] observed that particles classified in the Geldart C group could be fluidized only with mechanical agitation and that the pressure drop in the bed decreased as the agitator speed increased. However, a different behavior was observed at higher agitation speeds, supposedly because of centrifugal forces. Reed and Fenske [10] used agitation in order to enhance heat transfer between the bed and immersed heat exchange surfaces. They noticed that the agitation increased the pressure drop, mostly at low gas flowrates.

Bait et al. [11] showed that, when mixing fine powders, a ribbon-type agitator leads to a better mixing than pitch-blade and straight-blade agitator. Reina et al. [12] studied waste-wood fluidization. They state that fine softwood particles with Geldart group C characteristics are not fluidizable in the absence of agitation. The power consumed by the driver is relatively low and is constant after reaching fluidization. Additionally, they found out that the minimum fluidization velocity decreased as the agitator speed increased.

Some other laboratories tried to improve the fluidization of Geldart group D powders. Puspasari et al. [13] used agitation in order to fluidize crushed oil palm fronds. They found out that mechanical agitation avoids the entanglement between the elongated fibers, so that they can be fluidized. Reyes and Vidal [14] studied a spouted bed reactor. The stirrer reduced the airflow required to reach a pseudo-fluidized regime. Han et al. [15] focused on the observation of polypropylene particles. They claimed that, for constant gas velocity, the pressure drop was independent of the agitator speed, but the fluidization improved with increasing stirrer speed, as bubble size decreased. In a subsequent study [16], the authors found that the pressure drop and the minimum fluidization velocity changed with the agitation speed when using an axial flow impeller, but remained constant with a radial-type impeller. In conventional fluidized beds, the torque required to mix the bed decreases as the superficial velocity of its fluidization gas increases, becoming constant above a critical superficial velocity depending on the stirrer characteristics [17] and [18].

Few studies focused on Geldart group B powders. Leva [19] proved that when the bed is aerated, mechanical agitation becomes feasible. Additionally, at minimum fluidization condition, the particles are barely moving, while with a mechanical stirrer, they are mixed at much faster rate. With some mixer geometries, the pressure drop across the bed is lower when stirred and the pressure drop then decreases with increasing agitation speed. The pressure drop curves do not show any discontinuity at fluidization conditions. Unexpectedly, alumina particles characterized by a higher density and a smaller particle size, resulting in much larger surface area, require much less power than sand. However, the alumina particles have a more regular shape and flow more smoothly than sand. Leva concluded that the surface characteristics of the bed material are very important in influencing the power requirements.

In the present work, the same phenomena have been studied, but with the purpose of investigating the aeration effect of gases and vapors formed during pyrolysis using a mechanically mixed reactor without additional inert gas.

3. Material and methods

The experimental apparatus is shown in Fig. 1. The reactor is a 0.15 m diameter vessel, 0.25 m tall. The reactor is equipped with a hot filter for gases and vapors formed, consisting of a chamber located above the bed of solids with five holes, 0.032 m in diameter covered with 10 μm and 26 μm wire meshes. The bio-vapors exiting the filter are collected using a condensation train, made up of three condensers in series, 0.057 m in diameter and 0.622 m tall, and a cotton filter, 0.089 m in diameter and 0.445 m tall (Fig. 1).

The heat is supplied to the reactor with two band heaters (1.8 kW each), controlled by an On–Off controller. The controller regulates the bed temperature, which is measured by a K type thermocouple placed 5 mm inside the bed and 0.065 m from the bottom. The maximum temperature limit of the controller uses the external wall temperature, which is measured with a K type thermocouple placed between the bottom band heater and the reactor wall, 0.051 m far from the bottom (Fig. 1).

When gas was used, it was introduced through four snubbers placed on the bottom of the reactor, which prevented the glass beads from plugging the sonic nozzles located upstream. The gas flowrate was set with a pressure regulator and a bank of pre-calibrated sonic nozzles (Fig. 1). In this study, nitrogen, argon or helium was injected in the reactor at 550 °C to simulate the range of properties expected for pyrolysis gases and vapors.

The characterization of each stirrer and the pyrolysis runs were performed using a ¾ hp air motor, whose torque can be determined from the air pressure supplied to the motor and the rotation speed of the motor shaft [20] and [21]. Preliminary experiments showed that this motor is much more sensitive to the bed aeration than a standard electric motor. In addition, it is much lighter and compact than DC electric motors. The stirrer speed was monitored thanks to a laser, whose beam interruption by a metal clamp placed on the stirrer was monitored with a photodiode connected to a data acquisition system.