Powder Technology 302 (2016) 222–235

Contents lists available at ScienceDirect

Powder Technology

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

Effect of particle size, density, and concentration on granular mixing in a double screw pyrolyzer

Breanna L. Marmur *, Theodore J. Heindel

Department of Mechanical Engineering, Iowa State University, Ames, IA 50011, United States

ARTICLE INFO

Article history:
Received 7 March 2016
Received in revised form 29 June 2016
Accepted 14 August 2016
Available online 16 August 2016

Keywords:
Granular materials
Mixing
Multiphase flow
Particulate process
Powder technology
Renewable energy

ABSTRACT

Double screw pyrolyzers can be used to convert cellulosic biomass into bio-oil. Bio-oil can then be converted into synthetic gasoline, diesel, and other transportation fuels, or can be converted into bio-based chemicals for a wide range of purposes. One method of industrial bio-oil production is called fast pyrolysis, the fast thermal decomposition of organic material in the absence of oxygen. One type of pyrolyzer, a double screw pyrolyzer, features two intermeshing screws encased in a reactor which mechanically conveys and mixes the biomass and heat carrier media. The mixing effectiveness of the two materials in the pyrolyzer is directly correlated to the bio-oil yield—the better the mixing, the higher the yields. This study investigates the effects of particle size, density, and concentration on mixing effectiveness in a double screw pyrolyzer. Using glass beads as simulated heat carrier media and various organic particles as biomass, a cold-flow double screw mixer with 360° of optical access and full sampling capabilities was used to collect mixing data. Unique optical visualization and composition analysis paired with statistical methods were used to evaluate the effects of varying the biomass particle size and density, the heat carrier particle size, and the biomass particle concentration. Both qualitative and quantitative analysis indicated that reducing the biomass particle size, for counter-rotating down pumping screw rotation orientations, noticeably increased mixing effectiveness. Increasing the heat carrier media particle size showed both increases and decreases in mixing effectiveness depending on operating condition. For all screw rotation orientations, a change in biomass particle density resulted in little change in mixing effectiveness, while reducing the biomass particle concentration reduced the overall mixing effectiveness.

1. Introduction

Granular mixing processes are very important across many industries including, but not limited to, the pharmaceutical, agricultural, and biotechnology industries [1–3]. These processes often require both a high degree of homogeneity and a high degree of customizability [4]. As granular mixing processes are so widely employed, a thorough understanding of the mixing dynamics is necessary to understand and control the resulting products [5].

Granular mixing has been widely studied since the 1950′s when the science began to gain attention [6]. Considerable experimental research has since been done on a wide variety of mixers, including: bladed mixers [7,8], vertical shakers [9,10], single screw mixers [11–13], and rotating cylinders [14]. Granular mixing processes have also been studied using simulations [10,15,16]. Several literature reviews are available on the subject [1,2,17,18].

Although many studies have investigated granular mixing, most work has focused on mixers with relatively simple geometries. While these studies have done much to improve the theoretical understanding of granular flows, these theoretical understandings are often difficult to apply to broader industrial uses. Moreover, granular mixing processes are often very sensitive to changes in operating conditions, and any solutions provided to deal with specific mixing problems are highly system-sensitive. These sensitivities mean it is necessary to study more complicated mixer geometries and more complicated operating condition interactions if we hope to apply knowledge of granular mixing to industrial processes [19].

One example of a complicated industrial mixer is a double screw pyrolyzer used in the bioenergy industry to produce bio-oil via fast pyrolysis [3,20]. Fast pyrolysis is the thermochemical conversion of biomass into bio-oil in the absence of oxygen [3]. In a double screw pyrolyzer, a biomass material is mixed with a heat carrier media at high temperatures to produce vapors that are collected and condensed into bio-oil [21]. Bio-oil has the potential to be converted and upgraded into transport fuels, such as synthetic gasoline or diesel, to be used as a source of fuel via direct combustion, or to be converted into a wide variety of bio-based chemicals [22,23]. Fast pyrolysis is still, however, a relatively new technology [21] and much of the research that has been done with double screw pyrolyzers has focused on the products [20,24,25] and not on the mixing dynamics of the mixer. Recent work by Kingston and

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* Corresponding author.
E-mail addresses: bmarmur@gmail.com (B.L. Marmur), theindel@iastate.edu (T.J. Heindel).

http://dx.doi.org/10.1016/j.powtec.2016.08.040
0032-5910/

Heindel [26–28] began to correct this by investigating the mixing dynamics within a double screw pyrolyzer to further understand both the mixing dynamics themselves, and the effects of operating conditions on the mixing effectiveness within the double screw mixer.

Kingston and Heindel [26–28] developed measurement techniques to determine the mixing effectiveness of the continuous mixing process inside a double screw mixer. Using both quantitative and qualitative methods, they investigated the interactive effects of screw rotation speed, screw rotation orientation, material injection configuration, dimensionless screw pitch, and dimensionless mixing length on the mixing dynamics and mixing effectiveness. Their results provided a greatly improved understanding of the mixing dynamics within a double screw mixer and offered valuable insights into the optimization of industrial double screw pyrolyzers.

However, the studies performed by Kingston and Heindel featured only one size, type, and concentration of biomass and heat carrier media, whereas in actual fast pyrolysis there is often a wide variability in particle characteristics. Various considerations, such as biomass growth times, ease of planting and harvesting, and media influences on bio-oil yields and composition can influence the availability and profitability of using different biomass and heat carrier media, which may have different particle sizes and densities [3]. Investigating different particles in a double screw pyrolyzer is important because the mixing dynamics of a granular flow can vary considerably based on particle characteristics [2,4,18]. Additionally, many studies have investigated the tendency for granular flows to segregate by varying particle characteristics, such as size [19,29], shape [29,30], and density [9,10, 31]. All studies have shown that changes in these particle characteristics can have a dramatic effect on the mixing dynamics within a granular flow.

Furthermore, as fast pyrolysis is the thermochemical conversion of biomass into bio-oil, it is highly dependent on the heat transfer from the heat carrier media to the biomass media. Increasing the ratio of heat carrier to biomass media, by reducing the biomass concentration in the system, may increase the rate of heat transfer into the biomass material, thus increasing potential bio-oil yields [20,22]. Thus, it is important to also investigate the effect of biomass particle concentration on the mixing effectiveness within a double screw pyrolyzer.

The purpose of this study is to expand upon the work completed by Kingston and Heindel, and to investigate the effect of changing particle size, density, and concentration on mixing effectiveness in a double screw pyrolyzer. Selected operating conditions investigated by Kingston and Heindel [27,32], featuring changes in screw rotation speed, dimensionless screw pitch, and screw rotation orientation, were repeated using different combinations of biomass and heat carrier media. In this study, particle size in the form of a new biomass particle size and a new heat carrier particle size, particle density in the form of three different biomass particle densities, and particle concentration in the form of changing biomass inlet concentrations, were investigated. Qualitative optical visualization methods and quantitative composition analysis, as developed by Kingston and Heindel [28], were used to assess the mixing effectiveness of the double screw mixer. The operating conditions, based on these parameters, which led to the highest degree of granular homogeneity—and thus the optimized mixing effectiveness—were determined.

2. Experimental procedures

The experimental setup and procedures used in this study are very similar to those developed by Kingston and Heindel [28,32]. Only a summary is provided here.

2.1. Experimental setup

The clear, laboratory scale cold-flow double screw pyrolyzer used in these studies is shown in Fig. 1 and will hereafter be referred to as a double screw mixer. The double screw mixer was manufactured using 3D printing technology using a rigid, clear, designer plastic material. This unique manufacturing method allows complete 360° optical access to the internal structure of the screw mixer. The double screw mixer features two intermeshing, noncontact screws with screw diameter D = 2.54 cm. The characteristic length of the mixer is defined as the screw diameter. The effective mixing length, L, is defined from the center of inlet port 2 in Fig. 1 to the beginning of the outlet ports, where L/D = 10.

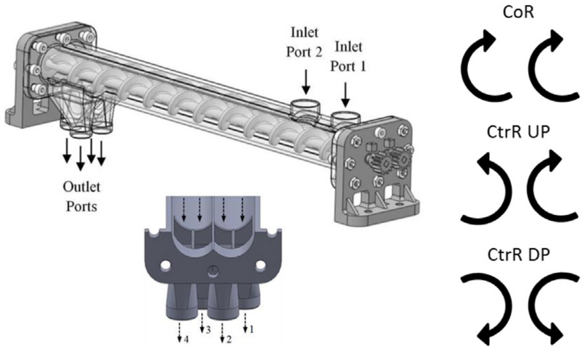

Fig. 1. The cold-flow, laboratory scale pyrolyzer used in these studies (referred to as a double screw mixer) with a cross-sectional view of the unique outlet ports that allows the outlet stream to be divided for sample composition analysis [28]. The double screw mixer can operate at three screw rotation orientations: co-rotating (CoR), counter-rotating up pumping (CtrR UP), and counter-rotating down pumping (CtrR DP).

Two material injection ports are positioned axially two characteristic lengths apart and laterally halfway between the two screws. The biomass and heat carrier media are injected vertically into ports 1 and 2, respectively, which was the preferred injection configuration determined by Kingston and Heindel [27]. The two granular materials are fed into their respective inlet ports by two Tecweigh CR5 volumetric auger feeders. The exit stream of the double screw mixer is divided into four equal sections by a unique outlet port design, located on the bottom of the double screw mixer. These outlet ports, shown in Fig. 1, spatially divide the outlet flow of the pyrolyzer into four separate channels from which four unique samples are collected for composition analysis.

This study varied dimensionless screw pitches (p/D = 0.75, 1.25, and 1.75) and screw rotation speeds (ω = 20, 40, and 60 rpm). Screw rotation orientation was also varied and included a co-rotating (CoR), counter-rotating up pumping (CrtR UP), and counter-rotating down pumping (CrtR DP), as schematically shown in Fig. 1.

2.2. Granular materials

The biomass materials were red oak, corn stover, or cork (to simulate pyrolysis char), while the heat carrier was simulated with glass beads. The properties of the granular materials are shown in Table 1. Six specific material combinations were investigated and are listed in Table 2. All granular materials are shown in Fig. 2.

Virtually any type of biomass can be pyrolyzed to produce bio-oil [3]. Red oak and corn stover where chosen for this study to represent two

Table 1
The properties of the granular materials used in this study.

Granular material properties				
Particle	Abbrv.	Size [μm]	Density [g/cm^3]	Geometry
Red oak	LRO	500–6350	1.47	Board-like, non-uniform size
Red oak	SRO	300–710	1.53	Board-like, uniform sized
Corn stover	CS	300–710	1.37	Needle shaped
Cork	CO	300–710	0.89	Chunk shaped
Glass beads	SGB	300–500	2.50	>90% Spherical
Glass beads	LGB	800–1000	2.50	>60% Spherical