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Flow characteristics of biomass particles in a horizontal stirred bed reactor: Part I. Experimental measurements of residence time distribution

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ABSTRACT

The horizontal stirred bed reactor (HSBR) is a prevalent biomass pyrolysis reactor due to its effective seal, excellent control of temperature and residence time, and capacity to handle a wide range of particle diameters. This paper focused on the effects of various parameters on residence time distribution (RTD) and particle flow behavior in the HSBR. The RTD of biomass particles in a custom-built HSBR was measured using the impulse response method. The effects of operational parameters (including flow rate and agitator rotation rate), material flow properties (characterized by the angle of repose), and design parameters (including the number of blades and blade angle) on solid hold-up, mean residence time (MRT) and relative variance of residence time were investigated. The solid hold-up was affected by the rotation rate, flow rate, blade number, blade angles and material flow properties. The flow rate and material flow properties had a significant influence on the MRT while the effect of the other three parameters on the MRT was minimal. The relative variance was primarily influenced by the flow rate, rotation rate, blade number and material flow properties. The effect of the flow properties on the relative variance was irregular. The inter-particle mixing mainly resulted from agitator stirring. Hence, the inter-particle mixing was enhanced with the increase of the rotation rate and blade number. As such, it is essential to further examine the effect of material flow properties on inter-particle mixing using a modeling approach.

1. Introduction

With the continuous consumption of fossil energy worldwide, the development and utilization of renewable biomass energy are increasingly important for the alleviation of an energy crisis and the establishment of a sustainable energy consumption structure [1]. Among the available technologies, biomass pyrolysis is gaining popularity due to its high efficiency and cleanness. Pyrolysis of biomass is a process by which a biomass feedstock is thermally degraded and then converted into solid (bio-char), liquid (bio-oil) and gaseous products in the absence of air/oxygen [2]. Bio-oil which can be readily stored and transported is a renewable liquid fuel and can also be used for the production of chemicals [3]. Bio-char is useful for the production of various chemical products such as activated carbon and carbon electrodes.

Stirred bed reactors are a common device used for a variety of physical and chemical processes in the chemical, biochemical and mineral industries [4]. Batch and continuous stirred reactors are generally used in both laboratory scale and commercial scale biomass pyrolysis plants [5–11]. Stirring of biomass particles and hot air in pyrolysis reactors greatly accelerates the heat transfer process. It can also help the process attain better energy saving and temperature homogeneity, which could restrain incomplete pyrolysis caused by inhomogeneous temperature [5]. Based on the arrangement of agitators, stirred bed reactors can be divided into horizontal stirred bed reactors (HSBR) and vertical stirred bed reactors (VSBR). The narrow residence time distribution (RTD) of the HSBR [12] has an advantage over the VSBR for the control of the reaction time in the biomass pyrolysis process.

As a fixed bed reactor, the HSBR shows a significant advantage over fluid bed reactors and transport bed reactors because it can cope with a wide range of particle sizes, especially large size solid particles [13]. However, in rotary kilns, which are widely used in the biomass pyrolysis process, though the solid motion is similar to that in the HSBR, an effective kiln seal is difficult to obtain and a relatively high particulate carryover to the gas stream is difficult to prevent [14]. Dalai et al. [6] designed and built an 'internally stirred horizontal kiln' (ISHK) in their research on activation of Canadian coals. The ISHK had almost the same structure as the HSBR. They claimed that the ISHK could 'avoid dusting problems which are normally encountered when handling finely divided solids in a rotary kiln'. The HSBR is also expected to have a better seal than the rotary kiln due to its structural differences.

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Therefore, the HSBR is the most suitable reactor type for biomass pyrolysis because sizes of biomass particles significantly vary.

The HSBR is widely used in continuous processes involving gas–solid reaction (including pyrolysis [6], catalyzed polymerization [15] and powder mixing [16,17]). However, the operation of the HSBR with particles of a wide range in sizes gives rise to difficulties in particle flow modeling [18–20]. Since the inception of the RTD concept [21], the measurement of RTD has become one of the main approaches to studying particle flow behavior in a reactor [22]. The behavior of particle flow in a reactor includes bulk flow and inter-particle mixing behavior. Both the thermophysical properties of the particles and inter-particle mixing behavior greatly affect heat transfer. Also the RTD of particles is critical to the conversion rate of reactions [23]. Hence, an understanding of the effect of the various parameters (including structure parameters of the reactor, operational parameters and particle properties) on the RTD and the particle flow behavior is vital for the optimization and design modeling of the HSBR.

The impulse response test is a common method used for most experimental measurements of particle RTD in reactors [15,16,22,24,25]. Jones and Bridgwater [26] and Laurent et al. [27] investigated powder mixing using positron emission particle tracking (PEPT). This approach allows the motion of a single particle to be followed and thereby provides a deeper understanding of particle flow patterns in reactors [28]. Portillo et al. [17] applied PEPT in the measurements of particle RTD in a horizontal stirred bed mixer. An impulse response experiment was carried out by the same research group in their earlier work [29]. The trend between impeller rotation rate and residence time obtained by PEPT was reported to be similar to the results by the impulse response method [17].

Previous research focused on the effect of flow rate [16,17,20], agitator speed [16,17,20,29], blade angle [16] and slope angle of the mixer on the particle RTD [29]. To date, there have been only a few attempts to comprehensively investigate the influencing parameters of RTD and particle flow behavior in the HSBR. In particular, only a few efforts have been made to investigate the effect of flow properties of granular materials. The particle sizes investigated in the majority of the current research on the HSBR were below 1 mm. Investigations of particles larger than 10 mm are rarely reported [30]. The particle sizes tested in this paper ranged from 4 to 40 mm. The triboelectric forces within particles with such large sizes were relatively less important [29]. In contrast, coulomb forces significantly affected the flow of particles with small sizes in most researches on continuous horizontal stirrers [17,29].

In this paper, the measurements of the RTD of biomass particles were conducted in an HSBR for biomass pyrolysis. The effect of different parameters on the RTD of biomass particles in the HSBR was extensively investigated. The first aspect was operational parameters including feedstock flow rate and rotation rate of the agitator. The second aspect was the flow properties of the particles, characterized by the angle of repose of particles. Four categories of biomass particle materials with different flow properties were employed for these experiments. The third aspect was design parameters including blade number and blade angle, taking into consideration the particle motion that was primarily driven by the agitator. Based on the measurements of the RTD, the effect of the parameters on particle flow and inter-particle mixing behavior was further discussed.

2. Material and methods

2.1. HSBR setup

Fig. 1 shows a schematic diagram of the HSBR for biomass pyrolysis. The HSBR used in this paper was constructed of a stainless steel cylinder (1200 mm length; 500 mm diameter; flanged at both ends). The agitator consisted of a shaft fitted with blades. The axis of the agitator was located 40 mm below the central axis of the cylinder to keep the blades away from the burner flame. In a typical pyrolysis process, raw biomass materials are fed into the front end of the reactor by a screw feeder. The biomass is then mildly stirred by the horizontally installed agitator while moving slowly towards the reactor outlet where the solid product (bio-char) is discharged. The burner was designed to maintain a high-temperature inert atmosphere for the pyrolysis of biomass. In this paper, to measure the RTD in the HSBR, the burner was shut off in order to prevent biomass particles from decomposing. An overflow weir (250 mm height) controlled the depth of the bed. The agitator was driven by an electric motor. The rotation rate was smoothly adjustable from 0 to 33 rpm using a frequency conversion power supply.

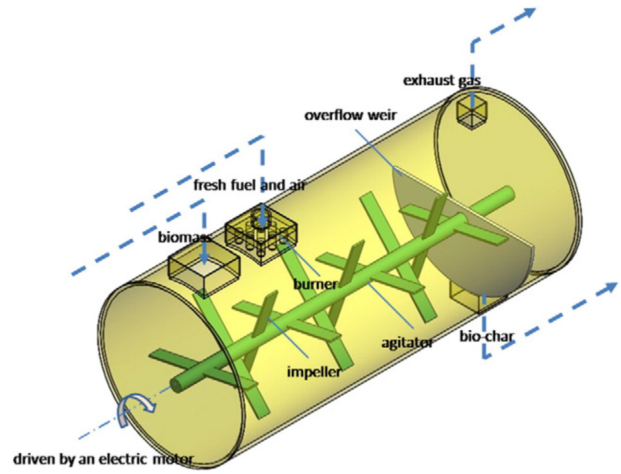

Fig. 1. Schematic diagram of the HSBR for biomass pyrolysis.

Fig. 2 shows the test pattern of agitators with blades. The straight rectangular blades on the shaft were 160 mm in length and 40 mm in width. Agitators with varying blade angles ($\gamma = 0$, 15 and 30°) were used to study the effect of blade angles on the RTD and particle flow behavior in the HSBR. An agitator fitted with 10 pairs of blades was used to investigate the effect of flow rate, rotation rate, flow properties (characterized by repose angle) and blade angle. An agitator fitted with 6 blades, with a blade angle of 0°, was used for comparison. The angle between the neighboring pairs of blades was 60° (Fig. 1).

2.2. Materials

Table 1 lists the main physical properties of the four kinds of materials. The angles of repose characterizing the flow properties of the particles were determined by pouring particles from a discharge port onto a plane surface. The angle of repose was the angle between the sloping side of the cone formed by the particles and the horizontal plane [31]. A high angle of repose indicated poor flow characteristics.

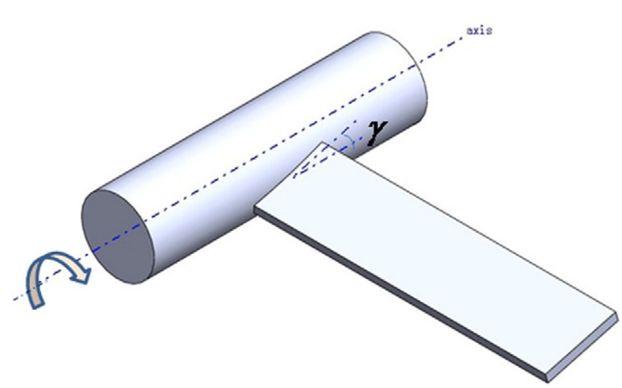

Fig. 2. Patterns of agitators (γ is the blade angle).