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Fast pyrolysis of wheat straw in a dual concentric rotary cylinder reactor with ceramic balls as recirculated heat carrier

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ABSTRACT

Fast pyrolysis of wheat straw in an original dual concentric rotary cylinder (DCRC) reactor with ceramic balls as recirculated heat carriers was studied to access the performance of this unit and explore the product yields and and characteristics in response to temperature. In addition, the performance of the novel bio-oil recovery mode (NBRM) was evaluated and compared with the spray quenching mode. Detailed composition of the bio-oils obtained under optimal conditions by using the NBRM was also analyzed. The DCRC reactor along with the novel bio-oil recovery procedure was successfully scaled up to a 25 kg/h pilot plant and showed good performance. The bio-oil yield was elevated by 21.4% when raising temperature from 400 to 500 °C with the peak value of 47.6 wt%. The prevailing components of pyrolysis gas are CO_2 and CO, both of which account for at least 75 vol%, with the lower heating values increasing from 6.2 MJ/m^3 at 400 °C to 13.6 MJ/m^3 at 700 °C. Compared to the spray quenching way, the bio-oil yields were always elevated at different temperatures when using the NBRM and the increase rate showed an unceasing increase from 2.8% at 400 °C to 9.6% at 700 °C, which confirmed the better performance of NBRM in response to more pyrolysis vapors generated at higher temperatures. The obtained results provided valuable insights into the fundamentals of biomass pyrolysis in the DCRC reactor, as well as the scale-up and technology breakthrough of the originally developed unit.

1. Introduction

Agricultural waste is an important carbon-containing renewable biomass that has drawn the attention of scholars worldwide. Compared with fossil fuels, it has many advantages such as renewability, carbon neutrality and extensive and abundant availability [1,2]. In recent years, many efforts have been dedicated to converting it into high-value bio-based fuels, chemicals and materials [3–5]. As expected, a large number of crops are harvested while producing a considerable amount of residues. Although some of the residues are crushed and used as animal food or directly returned to the fields to increase the organic matter content in the soil, enhance soil microbial activity and improve soil fertility, unfortunately, there is still a considerable amount of waste discarded or used as low-quality fuels, causing air pollution and deterioration of the ecological environment. The use of these residues for energy production would be advantageous to increase the overall crop value while at the same time relieving the inflationary pressure on food prices.

In this scenario, fast pyrolysis with having high feedstock adaptability and versatile product application is regarded as one of the most promising and feasible technologies [6], because it offers an effective and practical means for the conversion of low-grade agricultural waste into the main liquid product bio-oil as well as by-products pyrolysis gas and biochar which could be delivered to their potential terminal sites, respectively. Bio-oils can be used to produce biofuels and chemicals via various biorefinery routes [7–9]. Furthermore, solid biochar can be transported to the fields for soil improvement and carbon sequestration [10] and also used for the preparation of activated carbon or adsorbent via physical or chemical activation processing [11], while pyrolysis gases could be burned to supply the energy needed for biomass pyrolysis or for power or heat production [12].

Regarding the rapid pyrolysis, the heating method of biomass particles largely determines the final distribution of pyrolysis products, which is a key link of this technology. At present, a variety of biomass particle rapid heating methods have been developed at home and abroad, including reactor wall heating, gas heat carrier heating, solid heat carrier heating, and the above-mentioned combination, etc. Based on these heating methods, different types of reactors such as fluidized bed, rotary cone, ablative reactor, and screw or screw reactors, have been developed to meet the needs of fast heat transfer [13], which have

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been widely used in laboratory scale, pilot scale, and even demonstration or industrial devices. In this study, a dual concentric rotary cylinder (DCRC) reactor based on solid heat carrier heating has been ingeniously designed for fast pyrolysis of biomass. The heated ceramic balls transfer heat to the biomass particles through heat conduction, convection, and radiation to cause their thermal decomposition. Another advantage is that it does not require fluidizing gases, which can greatly reduce the energy consumed by the rapid quenching and condensation of pyrolysis vapors, and on the other hand helps to increase the liquid collection efficiency. Furthermore, the ceramic balls have the characteristics of good fluidity, excellent heat storage, high hardness, high temperature resistance, corrosion resistance and wear resistance, etc. and can be recycled and reused. The heat carrier waste heat is easily recovered and the byproduct gas has a high calorific value due to the incorporation of no fluidizing gas. Although this reactor shows many advantages over other reactors, very limited information is available regarding its use for rapid pyrolysis of biomass.

In order to maximize the production of bio-oil, the produced pyrolysis vapors should be quenched and condensed very quickly to reduce their secondary reactions as much as possible. Currently, the commonly used pyrolysis vapor quenching methods are spray direct contact condensation, heat-exchanger-type indirect contact condensation and a combination of both [14], which are considered as conventional condensation ways. For the most frequently used spray columns, the good quenching effect of pyrolysis vapors requires sufficient gas-liquid contact areas. In fact the spray medium atomization droplets are difficult to fully and effectively contact with pyrolysis vapors and some fine bio-oil droplets could be entrained away by pyrolysis gases, resulting in poor vapor condensation effect and thereby reducing the bio-oil yield. As for the heat-exchanger-type condenser, due to the use of indirect heat transfer method, the good condensation effect of pyrolysis vapors is difficult to guarantee. Moreover, the generated bio-oils easily coalesce with the solid particles in pyrolysis vapors and adhere to the surface of heat exchange walls, resulting in the deterioration of heat transfer and even clogging the pipe. Some heavy condensates adhering to the surface of heat transfer walls are difficult to remove. These factors will bring out a decline in bio-oil production. In this study, a novel bio-oil recovery mode (NBRM) has been developed on the basis of the advantages and drawbacks of the conventional condensation methods, which integrates the technical advantages of the spray columns and sieve tray towers and greatly enhances the efficient direct contact and heat transfer effect between pyrolysis vapors and cooling media, which is beneficial for increasing bio-oil production.

The purpose of this work was to study fast pyrolysis of WS in an original DCRC reactor with ceramic balls as recirculated heat carriers to access the performance of this unit and explore the product yields and characteristics in response to temperature. In addition, the performance of the novel bio-oil recovery mode was evaluated and compared with the conventional spray quenching method. Detailed composition of the bio-oils obtained under optimal conditions by using the NBRM was also analyzed. The research findings would provide valuable insights into the fundamentals of biomass pyrolysis in the DCRC reactor, as well as the scale-up and technology breakthrough of the originally developed unit.

2. Material and methods

2.1. Materials

Wheat straw (WS) as typical crop waste in China was collected from Zibo, central region of Shandong province (China). After harvesting wheat plants, WS was first air-dried and then smashed by SF–250 hammer mill and sieved into a particle size below 1.0 mm. The samples were characterized by proximate (STA 449 TGA) and ultimate analysis (Euro EA 3000), heating values measurement (IKA C2000). The obtained characteristic data are listed in Table 1. The ceramic balls with a diameter of 2–3 mm were used as recirculated heat carriers to provide the required heat for biomass rapid pyrolysis. Their detailed characteristics have been described in the literature [15].

2.2. Experimental set-up

The dual concentric rotary cylinder pyrolysis pilot plant was originally developed with a reactor capacity of 25 kg/h, whose process flowchart was presented in Fig. 1, respectively. It was mainly inclusive of a DCRC pyrolysis reactor, a plough type scraper quantitative feeder, two cyclone separators, a novel bio-oil recovery system, and a bucket elevator, etc.

The original DCRC reactor was the core of the whole pyrolysis pilot unit, whose main design dimensions were as follows: the total length of 890 mm, the length of 500 mm and external diameter of 400 mm for the outer cylinder, the length of 500 mm and external diameter of 245 mm for the inner cylinder. The reactor inlet pipe with an internal diameter of 100 mm had a flange joint, and the internal diameters of the pyrolysis vapors, chars and ceramic balls outlet pipes were 80 mm, 150 mm and 150 mm, respectively. The working principle of the DCRC reactor was depicted in Fig. 2. As the 316L stainless steel showed good corrosion resistance and high temperature resistance, it was used for constructing the reactor. Biomass particles and heat carriers (i.e. preheated ceramic balls) were first conveyed into the inner cylinder from the open end and moved by a continuous helical blade and several stirring blades welded on the cylinder. When the pyrolytic reactants and heat carriers moved close to the dead end, they were discharged from the inner cylinder to the outer cylinder through 6 openings evenly distributed on the circumference of the inner cylinder wall. The generated chars and ceramic balls were separated through the outer cylinder. The chars fell into the collector beneath the reactor through the sieves on the outer cylinder while ceramic balls were moved to the heat carrier outlet by the continuous helical blade.

The plough type scraper quantitative feeder mainly consisted of a plough type scraper, a cylindrical vessel and a horizontal screw, which had good feedstock adaptability and achieves the feed continuity, uniformity and stability. The specific structure and main dimensions of the feeder were shown in Fig. 3 (a). Driven by the adjustable-speed motor, the plough type scraper and the anti-blocking cone fixed on the drive shaft rotated at a predetermined speed, giving rise to the materials in the cylindrical container to move up and down and thus avoiding the occurrence of material bridging and accumulation. The materials were uniformly and continuously introduced into the center feed port by the scraper and then rapidly conveyed into the pyrolysis reactor by the horizontal screw.

Two highly efficient diffusion cyclones were employed to retain the fine solid particles entrained from pyrolysis vapors leaving the pyrolysis reactor. The cyclone was equipped with a conical reflective screen, which, on the one hand, could avoid clogging the separator due to the agglomeration of solid particles, on the other hand, could prevent the separated solid dust particles from being rolled up and brought out by the pyrolysis vapors.

The novel bio-oil recovery system originally developed by our research group was mainly composed of a jet/sieve-plate combined condensing tower and a vortex condenser, whose schematic diagram was depicted in Fig. 3(b). The jet/sieve-plate combined condensing tower was the core of the bio-oil recovery system, consisting essentially of a conical nozzle, a mixed-flow tube and eight layer sieve plates.

2.3. Experimental procedure

The fast pyrolysis runs of wheat straw were conducted between 400 and 700 °C in the DCRC pyrolysis development unit, in which the heat carrier-to-biomass ratio was a critical parameter. If this ratio value was too small, it was difficult to guarantee the fully uniform mixing and efficient mutual contact between feeding particles and ceramic balls for