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Research article

Bio-oil production from fast pyrolysis of rice husk in a commercial-scale plant with a downdraft circulating fluidized bed reactor

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ABSTRACT

Bio-oil, a promising candidate to replace fossil fuels, has received considerable attention for its sustainability, resource diversity and environmental benefits. Industrial production of bio-oil is urgently needed. In this study, a downdraft circulating fluidized bed reactor commercial-scale fast pyrolysis plant with biomass throughput of 1–3 $t\,h^{-1}$ is studied. Rice husk was processed at a fast pyrolysis temperature of 550 °C to evaluate the plant operation status. The system was continuously operated for 80.42 h. The thermal properties of the feedstock (rice husk), dust (separated from feedstock), char and heat carrier were analyzed and the bio-oil properties such as water content, pyrolytic water content, viscosity, density, pH, heating value, solid content and ash content were analyzed and presented. All the tested properties of the bio-oil meets the pyrolysis liquid biofuels standards in ASTM D7544-12 for Grade G biofuels, except for the water content of the bio-oil, which is slightly higher than that of Grade G biofuels. In energy balance analysis, the potential recovered energy of the three main products was 8.0 ± 1.1, 2.1 ± 0.1 and 5.3 ± 0.7 $MJ\,kg^{-1}$ for bio-oil, char and non-condensable gas, respectively, which shows that the largest portion of the energy in biomass was recovered in the bio-oil.

1. Introduction

Global climate change and limited fossil hydrocarbons have driven the efforts to generate clean, compatible, sustainable and renewable energy [1,2]. Bio-oil is the liquid product from biomass fast pyrolysis, which can be used as a fossil fuel replacement and a feedstock to produce chemicals for sustainability, resource diversity and environmental benefits [3]. Fast pyrolysis is a thermal decomposition process in the absence of oxygen or when oxygen content is at a level resulting in incomplete combustion [4,5]. In this thermal conversion process, up to 75% of the biomass energy can be converted to a liquid product, bio-oil [1]. Major efforts have been made to develop new processes for converting renewable biomass to bioenergy or products for several decades with fast pyrolysis technology at the forefront [6,7].

Fast pyrolysis is a well-studied technology which is reaching an early stage of commercialization [8]. Companies such as Biomass Technology Group (BTG), Ensyn Technologies, PYTEC, Dynamotive and Air Liquide (Lurgi Technologies) lead the developments of fast pyrolysis commercialization [9]. The commercial plant sold by BTG was based on a rotating cone reactor [10], with a biomass throughput of 50 $t\,d^{-1}$. The bio-oil was produced from a biomass waste (empty fruit bunch) from palm oil production, which was used to replace diesel in a co-firing plant located in 300 km away from the fast pyrolysis plant. One of the world's largest fast pyrolysis plants was built by Ensyn based on Rapid Thermal Processing (RTP) technology with a biomass feeding rate of 400 $t\,d^{-1}$ on dry basis [11]. Each year 75 million liters of bio-oil were produced from sawmill residuals. Bio-oil was used as an ingredient (resin) or a replacement for fossil fuels. The PYTEC had established a 4 $t\,d^{-1}$ pyrolysis oil from a pilot plant based on a ablative pyrolysis reactor [11], and is currently building a 50 $t\,d^{-1}$ unit. And the liquid from which was used for power generation in an engine [12]. Dynamotive has constructed four installations based on bubbling fluidized bed technology and the largest plant is located at Guleph with a processing capacity of 200 $t\,d^{-1}$ [8]. Researchers at Air Liquide and KIT (Karlsruhe Institute of Technology, German) has developed a pilot plant with a 500 $kg\,h^{-1}$ (dry biomass feed capacity) twin-screw mixing pyrolysis auger reactor. The liquid productivity (organic condensate and aqueous condensate) can achieve up to 55% [13].

Although several commercial-scale fast pyrolyzers for bio-oil production have been operated and reported, most of them were briefly introduced and summarized in some review articles. The exact constituent, work mechanism, technical parameters, operation state and

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product properties were not presented. And as mentioned above, pyrolysis reactors and operation principals vary greatly among those studies. In this research, downdraft circulating fluidized bed technology was employed, which was not reported by other researches. This paper focuses on measuring the operation stability of the commercial-scale fast pyrolyzers from two aspects: mass balance of the plant and physicochemical properties of the bio-oils. The originality also lies in adopting BOX CHAT method to remove the outliers. And a set of eigenvalues, reflecting the operation state and product properties, was obtained. The stability of the commercial scale pyrolysis plant with a downdraft circulating fluidized bed reactor was evaluated and a set of representative bio-oil properties was obtained under a selected condition based on existing literatures and pre-experiment results to provide a reference for the future researches. In addition, thermal properties of the original feedstock, dust, char and heat carrier were carried on comparison and analysis to evaluate the heat transfer characteristics.

2. Experimental

2.1. Feedstock analyses

Rice husk was used as the raw material in this work. It was received from a farm without any pre-treatment. The proximate and ultimate analyses of rice husk are listed in Table 1. The content of carbon, hydrogen, oxygen and nitrogen was tested by an Elemental Analyzer (Model Vario EL III).

2.2. Commercial-scale downdraft circulating fluidized-bed fast pyrolysis system

A continuous downdraft circulating fluidized bed fast pyrolysis system with a feeding capacity of 3 t h^{-1} has been jointly established by Shanxi Yingjiliang Company and Shanghai Jiao Tong University, P. R. China. The schematic diagram of the fast pyrolysis system is shown in Fig. 1. The plant consists of six sub-systems: a feeding system, a heat carrier system, a reactor system, a cyclone system, a condensation and collection system and a char separating system.

Biomass can be fed into the system by a draft fan which creates a negative pressure at the inlet of the feed cyclone. When the feedstock falls to the bottom of the biomass hopper, it is carried by the exhaust gas to the dust removal cyclone, where the fine particles, such as dust and soil, are separated out from the feedstock. During the entrained process, the biomass is preheated and dried by the exhaust gas which is from the vertical bed at a higher temperature. The fine particles are discharged from the cyclone through the dust outlet.

The heat carrier system consists of four components: the horizontal bed, the vertical bed, the upper storage chamber and the bottom storage chamber, which are used to heat the ceramic balls (heat carrier) in circulation to maintain the plant operating continuously. The ceramic balls located in the upper storage chamber are transported to the reactor, where the energy from the ceramic balls is transferred to the biomass. In the fluidized bed reactor, ceramic balls are used as heat carrier with the temperature of 560 °C. The particle size of the heat carrier is between 1.2 and 1.6 mm and particle density is 2278.9 kg m^{-3} and bulk density is 1582.7 kg m^{-3}. The volume of the reactor is 2.17 m^3, which is made of stainless steel. The temperature of the reactor was set at 550 °C controlled by electrical heaters and thermal couples. The biomass is pyrolyzed to produce char and vapor. In the bottom storage chamber, the heat carrier is separated from the char by difference in density. The heat carrier is reheated in the vertical bed by the energy produced from the combustion of bio-oil and non-condensable gases in the horizontal bed. The heat carrier is stored in the upper storage chamber prior to starting the next circulation allowing the plant to operate continuously. The char is separated in the cyclone system and then discharged from the system through the char outlet. The pyrolysis vapor is quenched in the condensation system to form bio-oil, and the non-condensable gases will be recycled for combustion in the horizontal bed to generate heat to raise the temperature of the heat carrier. The bio-oil collection system mainly consists of four parts: spray column, tubular heat exchanger, cooling tower, oil tank and water pool. In the spray column, the quenching media is bio-oil with the flow rate of 110 m^3 h^{-1} at 60 °C. The tubular heat exchanger is used to cool down the quenching media with the flow rate of 260 m^3 h^{-1} at normal temperature. Fig. 2 shows an image of the fast pyrolysis plant. A detailed description of the fast pyrolysis plant can be found in our previous publication [14].

Table 1
Proximate and ultimate analyses of rice husk.

Proximate analysis[a] (wt%)		Elemental analysis[b] (wt%)	
Moisture	9.5 ± 0.1	C	37.86 ± 0.21
Volatile matter	62.7 ± 0.3	H	5.24 ± 0.01
Fixed carbon[c]	15.1	O	35.32 ± 2.15
Ash	12.7 ± 0.1	N	0.68 ± 0.06

[a] As received basis.
[b] Dry basis.
[c] By difference.

2.3. Analytical methods

2.3.1. Thermophysical properties

Thermophysical characteristics of rice husk, dust, char and heat carrier were measured in accordance with GB/T 10298-1988 standard by a KD2 Pro thermal properties analyzer (Decagon Devices, Inc., USA). The analyzer is equipped with dual parallel needle probes (30 mm long, 6 mm interval distance), one working as a heating element and the other working as a temperature sensor. During the testing process, the heating probe will generate a small constant heat pulse and the sensing probe located at a fix distance from the heating probe will receive this signal and send it to the attached handheld microcontroller. Each sample was tested three times at room temperature and the average value along with the standard deviation was recorded.

2.3.2. Heating value

The higher heating value (HHV) was measured by a bomb calorimeter (XRY-1B, Shanghai Changji Geological Instruments Co., Ltd.) in accordance with ASTM D240.

2.3.3. Water content

The water content of bio-oil was measured by Karl-Fischer titration (KFT 870, Swiss Manthon Instrument Factory) in accordance with ASTM E203.

2.3.4. Acidity

The pH value of the bio-oil was tested by a pH meter (PHS-3C, Shanghai Lei Ci Instrument Co., Ltd.). The pH meter was calibrated prior to each measurement.

2.3.5. Density

The density of bio-oil was measured using a density meter (DMA 4100 M, Anton Paar) in accordance with ASTM D4502.

2.3.6. Viscosity

The viscosity of bio-oil was tested by a capillary viscometer (SYD-265C, Shanghai Changji Geological Instruments Co., Ltd.) in accordance with ASTM D445.

2.3.7. GC–MS

The composition of bio-oil was measured using a GC–MS analyzer (AutoSystem XLGC, TurboMass MS), with the DB-5MS capillary column (30 m × 0.25 mm, film thickness 0.25 μm). The injection volume was