



## Full Length Article

# Performance of a commercial-scale biomass fast pyrolysis plant for bio-oil production



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## ABSTRACT

A commercial-scale biomass fast pyrolysis plant, based on downdraft circulating fluidized bed technology with biomass throughput of 1–3 T h<sup>-1</sup>, has been developed for bio-oil production and its performance has been investigated. The technological process consists of six parts: a feeding system, a heat carrier system, a reactor system, a cyclone system, a condensation system and a carbon separating system. The plant has four circulation systems: circulation of a heat carrier, quenching materials (bio-oil), cooling water and non-condensable gas. The bio-oil, raw material (rice husks), char and non-condensable gas samples were analyzed using GC–MS, FTIR, and SEM to characterize the physical properties and chemical composition. Results showed that the operation of the plant was stable. At 550 °C, the highest yield of bio-oil obtained was 48.1 wt% with char, and non-condensable gas yields of 26.0 wt% and 25.9 wt%, respectively. GC–MS results revealed that the composition of the bio-oil was complicated and the most abundant compound category was phenolics (14.92%). The char had complex pore structure by SEM analysis, which can be collected as a resources for further comprehensive utilization.

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## 1. Introduction

Bioenergy, derived from biomass [1,2], municipal organic solid waste [3], livestock manure [4], and other biological materials [5–7], has been seen increasingly as a renewable and clean energy source. Among all utilization methods in bioenergy research (such as direct combustion, thermo-chemical conversion and biological conversion technologies) fast pyrolysis—a rapid decomposition of organic materials in the absence of oxygen—has many advantages. It is a relatively simple process, rarely affected by the environmental conditions, has a high energy conversion rate, is CO<sub>2</sub>/GHG neutral without SO<sub>x</sub> emissions [8,9]. A final product, the liquid bio-oil, produced by fast pyrolysis, has numerous advantages of being storable and transportable, as well as having the potential to generate electricity through combustion in a boiler, diesel furnace, engines and gas turbines, and to supply a number of valuable chemicals, such as food flavorings, resins, agri-chemicals, fertilizers, and emissions control agents [10,11].

To produce bio-oil as a renewable fuel replacement and as a source of chemical commodities, a fast pyrolysis reactor has to be

designed and operated to meet the requirements for high yields of liquid fuels. A wide range of reactor configurations have been operated, such as fluid bed reactor, ablative reactor, circulating fluidized bed reactor, entrained flow reactor, rotating cone reactor, transported bed reactor and vacuum moving bed reactor. The capacity of a reactor can vary greatly. For example, a fast pyrolysis fluid bed reactor with the biomass throughput 100 g h<sup>-1</sup> was built in Aston University, UK; and Ensyn technologies had constructed a 400 dry T d<sup>-1</sup> processing capacity reactor [12,13]. In our previous research, a 1–5 kg h<sup>-1</sup> bench-scale fluidized-bed reactor was constructed, which consisted of three main sections: a feeding section, a reactor section, and a product collection section. The total bio-oil, gases, and char yields were 41.5, 43.3, and 15.2%, respectively [14]. However, detail operation status and product characteristics of large scale biomass fast pyrolysis plant are urgently needed in order to promote the commercialization of biomass pyrolysis technology. Meier et al. [12] indicated that the size of the commercial-scale plant was from 5 T d<sup>-1</sup> to 120 T d<sup>-1</sup>. Additionally, Butler et al. [13] mentioned that the size of the commercial-scale plant was from 7.2 T d<sup>-1</sup> to 400 T d<sup>-1</sup>. To our knowledge, little research has been conducted on the detailed structure, operational principles and stability of the commercial-scale pyrolysis plants and on characteristics of bio-oil and char produced by the commercial-scale pyrolysis plant in spite of success in designing pilot-scale pyrolysis plant.

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Thus, in the current work, a commercial-scale biomass fast pyrolysis plant, based on downdraft circulating fluidized bed technology with biomass throughput of  $1\text{--}3\text{ T h}^{-1}$ , was developed and fabricated primarily for bio-oil production.

## 2. Objectives

The objective of this study was to investigate performance of a commercial-scale biomass fast pyrolysis plant. In addition, the physicochemical properties of bio-oil, char and non-condensable gas samples obtained from fast pyrolysis of rice husks were obtained using multiple analytical tests to characterize the physical properties and chemical composition of the samples. This work could provide a valid reference and technical support for biomass fast pyrolysis and bio-oil potential utilization in larger systems and commercial scales.

## 3. Methods

### 3.1. Feedstock preparation

Rice husks, with characteristics of particle size of approximately 80 mesh ( $<0.177\text{ mm}$ ), moisture content around 10%, bulk density about  $340\text{ kg m}^{-3}$ , were collected from Shanxi and Wuhan Provinces.

### 3.2. Pyrolysis system

The schematic diagram of the feeding system and the fast pyrolysis plant is shown in Fig. 1. This fast pyrolysis system with a feedstock throughput of  $1\text{--}3\text{ T h}^{-1}$  was developed by Shanxi Yingjiliang Biomass Company and Shanghai Jiao Tong University, PR China and constructed in Dali county, Shanxi Province, PR China. The pyrolysis system consists of six parts: the feeding system, the heat carrier system, the reactor system, the cyclone system, the condensation system and the carbon separating system.

Referring to Fig. 1, the biomass was pushed into the biomass inlet by the atmospheric pressure because a draft fan creates a negative pressure at the mouth of the feed cyclone. When the biomass was transported into the system by a screw feeder through the pipes, it was heated by the exhaust gas ( $180\text{ }^{\circ}\text{C}$ ) from vertical bed. The biomass cannot be burned because of a lack of oxygen and a temperature lower than its ignition point ( $340\text{ }^{\circ}\text{C}$  for rice husks [15]).

In the reactor, the energy from the preheated carrier-ceramic balls (temperature,  $560\text{ }^{\circ}\text{C}$ ; particle size,  $1.2\text{--}1.6\text{ mm}$ ) was transferred to the biomass. And the energy to preheat the carrier-ceramic balls was from the bio-oil and non-condensable gas combustion in the horizontal bed. The bulk density of ceramic balls is  $1582.7\text{ kg m}^{-3}$  and particle density is  $2278.9\text{ kg m}^{-3}$ . The biomass was pyrolyzed at a temperature of around  $550\text{ }^{\circ}\text{C}$ . At the bottom storage chamber, the heat carrier was separated from the pyrolysis vapor and char. The pyrolysis vapor carried the char to the cyclone system and the heat carrier fell to the bottom of the chamber due to their different density. Then the heat carrier was heated by the combustion of the bio-oil and the non-condensable gas to start the next circulation of the heat carrier for the plant continuous operation. The circulation of the ceramic balls is indicated by the arrow at the left part of Fig. 1(b). The ceramic balls were heated in the vertical bed. And they were stored in the upper storage chamber. Then the heat carriers were transported to the reactor. And then they dropped to the bottom storage chamber. After the ceramic balls were separated from the char, they were transported to the vertical bed. As can be seen from Fig. 1(b), the bottom of the vertical bed was connected to the horizontal bed, where the

combustion of the bio-oil and the non-condensable gas generated a lot of gas at the high temperature. In vertical bed, the balls were moved up by the flow of the gas to the upper storage chamber. The bio-oil was used in the combustion only at startup stage of the system. At normal operation phase, only the non-condensable gas was used to heat the ceramic balls.

The pyrolysis vapor entrained with char particles passed through two series of cyclones, where char was separated from the pyrolysis vapor. The pyrolysis vapor was quenched in the spray column system using liquid bio-oil, which was cooled in a tubular heat exchanger (GLL7–200L, Taizhou Hengtong Heat Exchanger Equipment Co., Ltd.) with an atmospheric temperature water. It was cooled by the air in the cooling tower. The non-condensable gas was recycled for combustion in the horizontal bed through a blower (LSR300WD, 37 kW, Nantong Jiteng Trifoliolate Blower Co., Ltd.) to generate energy to raise the temperature of the heat carrier, which is indicated by arrow at the right part of Fig. 1(b). The heat carrier was located in the upper storage chamber prior to transferring the energy to biomass.

### 3.3. Analysis methods

#### 3.3.1. The proximate and ultimate analysis

The proximate analysis was conducted according to ASTM E 1756-08 for moisture content, ASTM E 1755-01 for ash content and ASTM E872-82 for volatile matter. Ultimate analysis of biomass particles was performed to get the elemental content of carbon, hydrogen, nitrogen, sulfur, and oxygen using an Elemental Analyzer (Model Vario EL III). Other elements were determined by inductively coupled plasma-optical emission spectroscopy (ICP-OES) with the method of ICP general rule JY/T015-1996.

#### 3.3.2. Lignocellulose composition

Lignocellulose composition was tested to find the ratio of the cellulose, hemicellulose, and lignin in accordance with NREL/TP-510-42618 (Determination of Structural Carbohydrates and Lignin in Biomass) with an HPLC, equipped with Bio-rad Aminex HPX-87P column,  $300\text{ mm} \times 7.8\text{ mm}$ , and appropriate guard column. HPLC conditions: injection volume  $50\text{ }\mu\text{l}$ , mobile phase HPLC grade water, column temperature  $80\text{--}85\text{ }^{\circ}\text{C}$ , run time 35 min.

#### 3.3.3. Bulk density

Bulk density of the biomass and char was analyzed in accordance with NY/T1881.6-2010 (Densified biofuel - Test methods - Part 6: Bulk density).

#### 3.3.4. Heating value

The heating value of the rice husks, bio-oil and char was measured by the bomb calorimeter equipment (XRY-1B, Shanghai Changji Geological Instruments Co., Ltd.).

#### 3.3.5. Water content

The water content of the bio-oil was determined using Karl-Fischer titration (KFT 870, Swiss Manthon Instrument Factory) according to ASTM E 203.

#### 3.3.6. Acidity

The pH value of the bio-oil was measured using pH meter (PHS-3C, Shanghai Lei Ci Instrument plant) at room temperature. The instrument was calibrated with liquid calibration standards of pH 4 and 6.86 prior to the measurement.

#### 3.3.7. Density (bio-oil)

The density of the bio-oil was analyzed using a density meter (Anton Paar, DMA 4100 M, ASTM D4502).

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