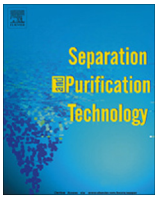
Separation and Purification Technology 124 (2014) 81–88

Contents lists available at ScienceDirect

Separation and Purification Technology

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



Fractional condensation of bio-oil vapors produced from birch bark pyrolysis

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ARTICLE INFO

Article history:
Received 23 May 2013
Received in revised form 29 November 2013
Accepted 7 January 2014
Available online 12 January 2014

Keywords:
Pyrolysis
Bio-oil
Fractional condensation
Birch bark
Electrostatic precipitator

ABSTRACT

The bio-oil vapors produced from the pyrolysis of birch bark have been fractionated using a series of three condensers maintained at different temperatures. The temperatures of the condensers have been optimized in order to separate the water present in the bio-oil vapor stream from the organic phases and, consequently, increase the quality and the stability of the bio-oil. The condenser train consisted of an electrostatic precipitator-cum-condenser (C–ESP) installed between two cyclonic condensers. As a result of the high efficiency of the fractional condensation system, the water content of the fractionated bio-oil was reduced to be less than 1 wt%. The effect of pyrolysis temperature on the fractionated bio-oil yield and characteristics is also reported.

1. Introduction

With rising energy requirements and gradually depleting fossil fuel resources, the interest for the production of fuels from biomass residues and wastes has been increasing. Various thermal processes have been developed to produce useful energy from different kinds of biomass residues. In the recent past, fast pyrolysis has been gaining immense interest because of its ability to achieve high liquid yields of up to 75%, based on the type of biomass, through the rapid thermal decomposition of lignocellulosic biomass in the absence of oxygen. Fast pyrolysis liquid, also called bio-oil, is a complex mixture of oxygenated hydrocarbons. A typical bio-oil has a higher heating value of around 17 MJ/kg, which is about 40% of the heating value of diesel. The relatively low heating value of the bio-oil can be attributed to its high water concentration (typically in the range between 15 and 30 wt%) and to the high oxygen content (35–40 wt%). Apart from their low heating value, bio-oils have other undesirable properties for fuel applications such as low thermal stability, high corrosiveness and high acidity. The upgrading of bio-oils is essential to convert bio-oils into stable liquid fuels [1,2].

The energy density, corrosiveness and the phase stability of the bio-oils could be greatly improved by decreasing the water content of the bio-oils. The distillation of bio-oil is not attractive as some of its components are thermally sensitive, degrade and produce solid residues upon heating to temperatures greater than 100 °C [1]. Recently, fractional condensation of the bio-oil vapors has been receiving increasing attention by researchers to separate bio-oil constituents [3–6]. In the fractional condensation process, the bio-oil vapor stream exiting the fast pyrolysis reactor is passed through a series of condensers maintained at different, gradually decreasing temperatures to enable the collection of liquid fractions of different physical and chemical properties in each condenser.

Westerhof et al. [5] utilized two counter-current spray condensers and an intensive cooler in series to fractionate the bio-oil into heavy and light fractions. The first condenser, maintained between 70 and 90 °C, collected heavy oil fraction, which contains 10–4% water and around 3–2% acetic acid. The heating value of the heavy oil fraction was in the range of 14 and 24 MJ/kg on a wet oil basis. The light oil fraction collected in the second condenser contained around 10% acetic acid.

Pollard et al. [6] developed a five stage bio-oil collection system to enable the recovery of different classes of compounds at each stage of the condenser train. The water content of the first four bio-oil fractions was in between 6.6 and 14.8 wt%. These four oil fractions recovered 85% of the total bio-oil energy. The condensing system used three condensers and two electrostatic precipitators (ESPs). They used one ESP between every two condensers to collect aerosols escaping the preceding condenser. The condensers were designed as shell and tube heat exchangers.

The aim of the present study is to obtain dry bio-oil, i.e. with very low water content, from the pyrolysis of birch bark. Birch bark is pyrolyzed in a bubbling fluidized bed and the resulting bio-oil

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http://dx.doi.org/10.1016/j.seppur.2014.01.003

vapors are fractionated using a three-condenser train to obtain a dry bio-oil. The effect of reactor temperature on the dry bio-oil yield and characteristics will also be investigated.

2. Materials and methods

2.1. Materials

Birch bark was used as the feedstock and pyrolyzed using the ICFAR bubbling bed pyrolysis pilot plant [7,8]. To facilitate the continuous feeding using the ICFAR slug injector [9], the birch bark was ground to a particle size of about 1 mm prior to being fed into the bubbling bed reactor. The bulk density and the higher heating value of the resulting birch bark powder were 200 kg/m3 and 22 MJ/kg, respectively.

Inert silica sand with a Sauter-mean diameter of 180 μm was used as the bed material in the bubbling fluidized bed. The bed mass was 1.5 kg.

Nitrogen was used as the inert fluidization gas. Nitrogen was also the carrier gas for the injection of birch bark powder slugs into the bubbling bed using periodic gas pulsations.

2.2. Bubbling fluidized bed setup

The fluid bed reactor is made of Inconel 600, 0.075 m in diameter, with a 0.65 m long cylindrical section [7]. The reactor is heated by three radiative electric heaters, covering both the dense sand bed and the freeboard sections. The heaters are independently controlled using Watlow PID digital controllers, to set a constant temperature profile along the axis of the reactor. The temperature feedback for the Watlow controllers is provided through the type K thermocouples placed within the bed at the same height as the heaters. The fluidization gas (nitrogen) enters the bed through the perforated distributed plate located at the bottom of the reactor. Before entering the bed, the nitrogen is heated using the 400 W in-line air process heater (Omega AHP-5052).

The ICFAR biomass "slug injector" is used to feed birch bark into the bubbling bed reactor [9]. The birch bark is discharged into the bed, 0.15 m above the gas distributor through an inclined line (45°). As shown in Fig. 1, a hopper filled with birch bark discharges through a pneumatically activated pinch valve. The pinch valve opens periodically (usually every 10 s) for short periods of time (0.7 s), allowing small amounts of birch bark to fall into a horizontal injector tube. During each cycle, the birch bark forms a slug, which is propelled into the reactor by intermittent pulses of nitrogen and a continuous stream of carrier gas (nitrogen). The continuous nitrogen flow prevents any solids settling in the injector tube. A solenoid valve is used to deliver this gas pulse. The pinch valve and the solenoid valve are controlled and synchronized with a programmable logic controller (PLC). The flow rates of the fluidization and carrier nitrogen are metered and controlled with two Omega mass flow meters.

As the birch bark is injected into the reactor, it mixes rapidly with the hot sand, ensuring fast pyrolysis conditions. The produced vapors exit the top of the reactor through a hot filter. The filter uses a stainless steel, 10 μm screen and a ceramic fiber insulation layer that retains all the solids in the reactor to avoid contamination of the produced bio-oil by char and elutriated sand. The product gases and vapors together with the nitrogen gas flow into the condensing system where the bio-oil vapors are rapidly condensed using three condensers connected in series.

2.3. Condensing system

The condensing system consists of two cyclonic condensers (condenser 1 and 3), an electrostatic precipitator-cum-condenser (C–ESP) and a cotton wool filter. As shown in Fig. 2a, the three condensers are connected in series such as the vapor/gas stream flows through condenser 1, then the C–ESP, condenser 3 and, finally, the cotton wool filter. In order to separate the water present in the bio-oil vapors, condenser 1 and C–ESP are maintained at higher temperatures, so that water is primarily condensed in condenser 3. The temperature of the stream leaving each condenser is constantly recorded using a K-type thermocouple placed at each condenser's outlet.

The cyclonic condensers (condenser 1 and 3) are made of a stainless steel pipe, 0.7 m long and 0.05 m in diameter. In the cyclonic condensers, the mixture of vapors and gases enters each condenser and is immediately directed to the condenser wall with a 90° elbow (shown in Fig. 2a). This nearly tangential entry forces

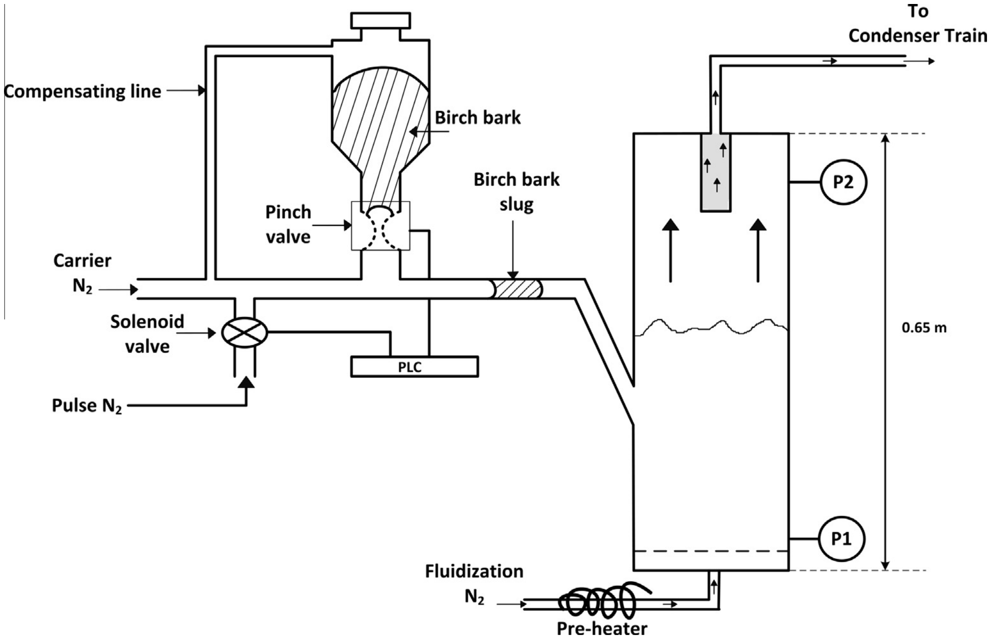

Fig. 1. Schematic of bubbling fluidized bed setup used for the pyrolysis of birch bark.