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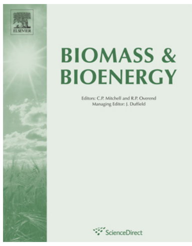

Torrefaction of pine in a bench-scale screw conveyor reactor

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ABSTRACT

Numerous works are reported in the literature regarding the torrefaction of biomass in batch processes. However, in industrial applications, continuous reactors and processes may by more interesting as this allows for the integration of continuous mass and heat flows. To shed light on the operation of continuous torrefaction processes, this work presents the findings of continuous, bench-scale (2.5 kg h^{-1}) torrefaction experiments using pine wood particles as a feed material in a screw conveyor reactor. The shifts in product mass yields were in line with theoretical expectations for changes in reactor temperature and reactor residence times whereas the degree of filling within the screw reactor and the flow of the nitrogen purge gas were found to be negligible. The process allowed for the measurement of the particle surface temperatures throughout the length of the reactor and significant temperature differences where measured between the wall of the reactor and the reactor screw. The proximate composition and the higher heating value of the torrefied biomass were found to be correlated to the ratio of the mass of dry biomass feed to the mass of the torrefied biomass produced. Important observations regarding the operability of such a process, also relevant to larger-scale processes, include the need to prevent the occurrence of torrefaction vapour condensation (which leaves the torrefaction reactor in the form of a saturated vapour) in the presence of fine, solid particles as this leads to rapid particle agglomeration and process blockage.

1. Introduction

The interest in using screw conveyor reactors for torrefaction lies in their perceived ability to process feedstocks with a wide range of bulk-handling properties. Improved feed flexibility allows the processing of cheaper, less homogeneous feedstocks, thereby potentially increasing the overall profitability of a torrefaction process. The mechanical force applied by the rotating screw ensures a relatively narrow residence time distribution for the solid material within the reactor [1]. Indirect heating may be employed when using screw conveyor reactors resulting in product gases and vapours that are undiluted by a heating medium and this may open up new possibilities for downstream processing.

This work documents the performance of a continuous, bench-scale torrefaction process based on screw conveyor reactor technology. While batch and moving bed reactor

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systems are more frequently described in academic literature, results from continuous, screw conveyor reactors are relatively scarce [2] with the exceptions of some recent publications (Shang et al. [3]; Ohliger et al. [4]). The experimental setup used in this work is unique in that temperature readings are taken from the surface of the rotating screw throughout the length of the reactor. The steady-state temperatures measured at the screw surface, which is in direct contact with the surface of the biomass particles, provides a better estimate of the thermal conditions experienced by the particles.

2. Materials and methods

2.1. Materials

Commercially-available pine (Bemap Houtmeel BV, The Netherlands) with a maximum particle size of 6 mm was used in these experiments. These pine particles are produced from mixed pine forestry residues collected in the Betuwe region of the Netherlands. The pine material is therefore a mixture of different pine species, of which Scots pine (*Pinus sylvestris*) was the predominant species. The material was visually uniform in appearance and free from bark and foliage. The biomass was received already air-dried and was stored indoors prior to use. The properties of the pine (as received) are listed in Table 1.

The comparative grindability of the torrefied biomass has been determined as described in the analytical methods. In an attempt to compare these results to coal, this analysis was also repeated on a typical South African coal which is frequently used in large, pulverized-coal power plants. The grindability of this coal, in terms of the Hardgrove grindability index (HGI), was externally determined to be 59 according to ASTM D-409 [5].

Table 1 – Properties of pine chips used in torrefaction experiments.

Mass fractions retained by sieve size	
4 mm	0.186
2 mm	0.660
1 mm	0.125
0.5 mm	0.019
0.25 mm	0.005
0.075 mm	0.003
undersize	0.002
Proximate analysis mass fractions	
Moisture content (wet basis)	0.119
Fixed carbon (dry basis)[a]	0.162
Ash (dry basis)	0.0015
Volatiles (dry basis)	0.836
Elemental analysis mass fractions (dry basis)	
C	0.4879
H	0.0598
O[a]	0.4502
N	0.0007
S	0.0000
Calorimetric analysis (MJ kg^{-1}, dry basis)	
Higher Heating Value	20.37

[a] calculated by difference.

2.2. Analytical methods

Proximate analyses were performed in a muffle furnace (AAF 11/3, Carbolite) according to ASTM D1762-84 [6]. Analyses were performed in triplicate. Torrefied biomass samples were stored in air-tight containers before analyses.

The elemental mass fractions of the dried pine and torrefied biomass were determined in triplicate in an elemental analyser (FLASH 2000 Organic Elemental Analyser, Thermo Scientific) according to ASTM D5373-02 [7]. This allowed the quantification of the carbon, hydrogen, nitrogen and sulphur content (by mass) of the material while the oxygen content was calculated by difference. The samples (3 mg) were dried overnight (378 K) before analysis and 2,5-bis(5-tert-butylbenzoxazol-2-yl)thiophene (BBOT) was used as a standard reference.

Higher heating values of pine and torrefied biomass were quantified in triplicate by bomb calorimetry (6200 Isoperibol Calorimeter, Parr) according to ASTM D5865-04 [8]. The samples (0.5 g) were dried overnight at (378 K) and benzoic acid was used as a standard reference.

All sieving of material was performed in a set of standard sieves (VWR International) in combination with a sieve shaker (AS200, Retsch GmbH). The particle size distribution of the pine material was determined according to ASTM C136-01 [9].

The grindabilities of pine, coal and torrefied biomass were determined by milling 100 cm^3 of sample material (pre-sieved to a 0.5 mm–1.0 mm size range) in a ball mill (PM 400, Retsch GmbH) under controlled conditions (mill frequency: 4.167 Hz, milling time: 300 s). Particle size analysis of the milled material was performed using standard sieves (VWR International) and a sieve shaker (AS 200, Retsch GmbH). The key indicator of grindability was taken as the mass fraction of material passing through a 75 μm sieve. This is similar to the approach used in Hardgrove grindability index standard, ASTM D409 [5].

The non-condensable gases produced during torrefaction were analysed by gas chromatography (490 micro-GC, Varian) in two columns (10 m CP-MolSieve 5A with backflush and 10 m CP PoraPlot Q). No liquid product characterization was undertaken in this work due to the significant dilution that occurred during the recovery of this stream.

2.3. Torrefaction process

Experiments were performed in a turn-key installation (Biomass Technology Group, The Netherlands) which included all peripheral control and data capturing devices. A simplified process flow diagram of the experimental setup is given in Fig. 1. The pine particles are transported from an agitated feed drum to a system of pneumatically-actuated ball valves by a feed conveyor. The ball valves ensure that the reactor remains hermetically sealed. Nitrogen is introduced into the system at four points near the reactor inlet and outlet valves to purge any oxygen from the process and also to sweep the product gases and vapours from the reactor inlet and outlet to the vapour condensation system. The nitrogen flow rates are measured by rotameters and manipulated by adjusting needle valves. The torrefaction reactor is split in two, identical screw reactor sections, operating in series.