Energy Conversion and Management 159 (2018) 76–84

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Oil production from microwave-assisted pyrolysis of a low rank American brown coal

Yaning Zhang[a,b], Shiyu Liu[b], Liangliang Fan[b,c], Nan Zhou[b], Muhammad Mubashar Omar[b,d], Peng Peng[b], Erik Anderson[b], Min Addy[b], Yanling Cheng[b], Yuhuan Liu[c], Bingxi Li[a], John Snyder[e], Paul Chen[b], Roger Ruan[b,c,*]

[a] School of Energy Science and Engineering, Harbin Institute of Technology (HIT), 92 West Dazhi Street, Harbin, Heilongjiang 150001, China
[b] Center for Biorefining, and Department of Bioproducts and Biosystems Engineering, University of Minnesota, 1390 Eckles Ave., St. Paul, MN 55108, USA
[c] Ministry of Education Engineering Research Center for Biomass Conversion, Nanchang University, 235 Nanjing Road, Nanchang, Jiangxi 330047, China
[d] Department of Farm Machinery and Power, University of Agriculture, Faisalabad, Pakistan
[e] Minnesga Inc., 2017 Jade Ln., Eagan, MN 55122, USA

ARTICLE INFO

Keywords:
Oil production
Microwave-assisted pyrolysis
Brown coal
Feedstock load
Pyrolysis temperature
Heating time

ABSTRACT

Obtaining energy from brown coal is an everlasting pursuit. This study detailed the oil production from microwave-assisted pyrolysis of a low rank American brown coal. The effects of feedstock load (20, 30, 40, 50, and 60 g), pyrolysis temperature (550, 600, 650, 700, and 750 °C) and heating time (10, 15, 20, 25, and 30 min) on the oil yields and compounds were also investigated. The results showed that the oil yields obtained were 13.17–22.97 wt% of the brown coal on ash free basis, and it increased initially and then decreased with increasing feedstock load, pyrolysis temperature, and heating time. Light oil and heavy oil accounted for 33.49–65.08 wt% and 34.92–61.94 wt% of the oil yields, and the compound weights were 1.21–5.41 wt% and 90.75–98.14 wt%, respectively. The highest oil yield was achieved at the feedstock load of 50 g, pyrolysis temperature of 700 °C and heating time of 20 min, and it was very close to the oil yield at high heating rates of 2000–10,000 °C/s for the electrical heating pyrolysis. The results obtained from this study not only detailed the oil yields and compounds obtained from microwave-assisted pyrolysis of a brown coal but also demonstrated the effects of feedstock load, pyrolysis temperature and heating time on the oil production. The results also indicated that microwave-assisted pyrolysis may be a more suitable technology for obtaining oil from brown coals than electrical heating pyrolysis.

1. Introduction

The oil crisis in the mid 1970 s accelerated the price rise of crude oil and drove the hot pursue of oil alternatives. Among the many oil alternatives, coal to oil became a focus of scientists around the world and received lasting attention during the past forty years. These were mainly due to the reasons that coal had advantages of large reserve, low-cost, high reactivity, etc. [1], and oil from coal required no extra infrastructures other than the existing plants, refineries, pipelines, etc. [2]. Generally, there are three fundamental methods that can be used to produce oil from coal, namely pyrolysis, direct liquefaction and indirect liquefaction [2,3]. Among these three methods, pyrolysis is the most widely studied and used mainly due to its simple process, low cost, and high efficiency [4,5].

Although brown coals may have some disadvantages such as high moisture content (up to more than 50 wt% [6]), high oxygen content (up to 30 wt% on dry basis [7]), and high ash content (up to 29 wt% on dry basis [8]), the large worldwide reserve (about 201 Giga tonnes [9]) makes pyrolysis of brown coal be still attractive for oil production. Especially the reports that the Victorian brown coals had very low ash contents which were less than 2 wt% on dry basis [10–12], greatly promoted the study and utilization of brown coal pyrolysis for oil production.

Pyrolysis of brown coal for oil production has been widely studied and reported. These included the oil yields obtained from pyrolysis of Australian brown coals [10–12], German brown coals [9], and Chinese brown coals [8]. The pyrolysis oils obtained from treated brown coals were also reported, e. g. the acid-washed brown coals [13], oxidized brown coals [14], and Ca brown coals [15]. The pyrolysis parameters that affect oil production were also systematically studied, and these

* Corresponding author at: Distingushed Guest Professor, Nanchang University, and Professor and Director, Center for Biorefining, and Department of Bioproducts and Biosystems Engineering, University of Minnesota, 1390 Eckles Ave., St. Paul, MN 55108, USA.
E-mail address: Ruanx001@umn.edu (R. Ruan).

https://doi.org/10.1016/j.enconman.2018.01.004
Received 23 October 2017; Received in revised form 2 January 2018; Accepted 2 January 2018

Table 1
Proximate analysis and ultimate analysis of the American brown coal.

	Value	Unit
Proximate analysis[a]		
Moisture content	3.85	wt%
Volatile matter	48.67	wt%
Ash content	21.74	wt%
Fixed carbon	25.74	wt%
Ultimate analysis[b]		
C	58.28	wt%
H	4.00	wt%
N	1.11	wt%
S	3.12	wt%
O[c]	10.88	wt%

[a] On as received basis.
[b] On dry basis.
[c] By difference.

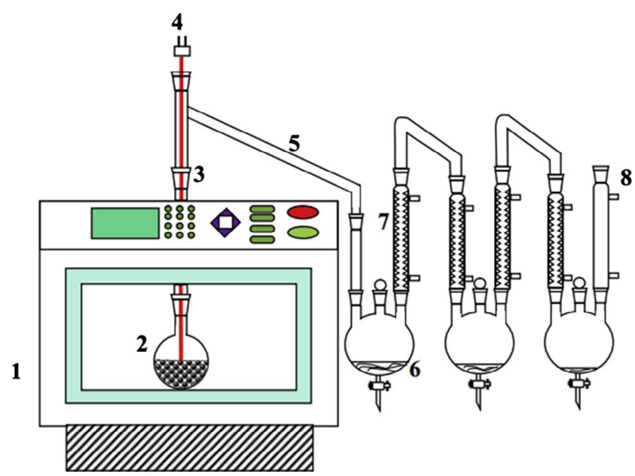

Fig. 1. Schematic diagram of the MAP set-up used. (1) microwave oven; (2) quartz reactor with SiC particles; (3) quartz connector; (4) K-type thermocouple; (5) quartz connector; (6) collection flask; (7) cooling line; (8) gas outlet.

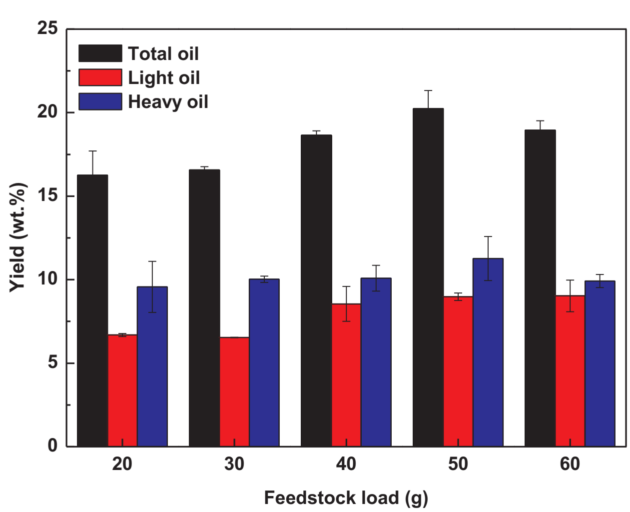

Fig. 2. Oil yields at different feedstock loads.

included pyrolysis temperatures [16–19], heating rates [16,17], residence times [18], pressures [20,21], atmospheres [22,23], catalysts [24,25], reactors [26], and co-pyrolysis [27]. The other issues during the brown coal pyrolysis process were also widely studied, these included alkali and alkaline earth metallic (AAEM) species [16,20,26], functional groups [28], small molecular phase [29], volatile evolution [30], sulphur evolution [29,31], chemical kinetics [32], cross-linking reactions [33], etc. Generally, these studies were mainly focused on the electrical heating pyrolysis.

Microwave-assisted pyrolysis (MAP) is a new pyrolysis technique which has different heating mechanisms as compared with the electrical heating pyrolysis [6,34–36] and it is generally more rapid and efficient than the electrical heating pyrolysis [37–40]. However, limited work has been reported for oil production from microwave-assisted pyrolysis of brown coal which is mainly due to the low microwave absorbability of brown coal [41]. The main objective of this study was therefore to investigate and report the oil production from microwave-assisted pyrolysis of a brown coal. The specific objectives were (a) to detail the oil yields and compounds obtained from microwave-assisted pyrolysis of a low rank American brown coal, and (b) to study the effects of operation parameters such as feedstock load, pyrolysis temperature and heating time on the oil production.

2. Materials and methods

2.1. Materials

A low rank American brown coal was used in this study. The brown coal was obtained from a company located in Greenfields of Beckley, West Virginia, USA. The coal was sieved to less than 0.841 mm through a 20-mesh sieve (Cole-Parmer, Vernon Hills, Illinois, USA). The moisture content, volatile matter, and ash content of the sieved coal were measured according to the standard methods of ASTM D3173-11, ASTM D3175-11, and ASTM D3174-12, respectively. Fixed carbon was calculated by difference. The element contents of C, H, N, and S were measured by Keystone Materials Testing, Inc. (Newton, Iowa, USA). O content was calculated by difference. The proximate analysis and ultimate analysis of the sieved coal are shown in Table 1.

Because the brown coal had low microwave absorbability [3,41], high microwave absorbability material (microwave absorbent) was therefore needed to increase the heating rate and improve the pyrolysis process [42,43]. Silicon carbide is a good microwave absorbent [44–46], and it was used in this study. The SiC was bought from Industrial Supply, Inc. (Twin Falls, Idaho, USA), and it had a particle size of 0.6 mm (30 grit).

2.2. Experimental set-up

Fig. 1 shows the schematic diagram of the MAP (microwave-assisted pyrolysis) set-up used in this study. The MAP set-up is mainly composed of (1) a microwave oven, (2) a 500 mL quartz reactor, (3) a straight quartz connector, (4) a K-type thermocouple, (5) a U quartz connector, (6) three collection flasks, (7) a cooling line, and (8) a gas outlet. The microwave oven is a MAX type microwave oven (CEM Corporation, Matthews, North Carolina, USA), and the power and frequency are 1200 W and 2450 MHz, respectively. The thermocouple is a KHIN-IM60 type K thermocouple (Omega Engineering, Norwalk, Connecticut, USA), and it is connected to a temperature reader (720 True RMS Multilog Multimeter, Extech Instruments, Waltham, Massachusetts, USA). The cooling line is sustained by circulating ~9 °C cold water. To maintain an inert atmosphere for the pyrolysis in the quartz reactor, a vacuum (Model DOA-P104-AA, Gast, Merrimack, New Hampshire, USA) is connected to the gas outlet.

2.3. Experimental procedures

Before the experiment, the quartz connectors, K-type thermocouple,