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Full Length Article

Characterization of solar fuels obtained from beech wood solar pyrolysis

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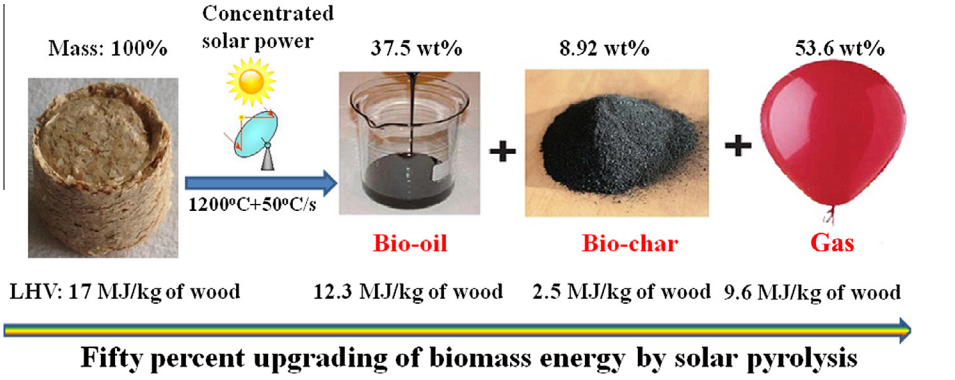
HIGHLIGHTS

- Solar pyrolysis of beech wood was carried out with temperature from 600 to 2000 °C.
- Solar fuels (gas, char and oil) were characterized at different temperatures.
- High temperature favors the tar secondary reaction into H_2 and CO formation.
- The char and oil characterization highly depends on pyrolysis temperature.
- The biomass energy is 38–53% upgraded by the solar pyrolysis process.

GRAPHICAL ABSTRACT



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ABSTRACT

Solar pyrolysis of biomass is a smart way to upgrade biomass and, thus, store intermittent solar energy as solar fuels (gas, bio-char and bio-oil). Distribution and energy content of gas, char and oil depend on experimental conditions. In order to determine these characteristics, experiments have been performed at temperatures of 600, 900, 1200 and 2000 °C, heating rate of 50 °C/s and argon flow rate of 6 NL/min. The gas product was analyzed by micro-GC. The char product was characterized by CHNS, whereas the oil product was subjected to CHNS, Karl-Fischer titration and GC–MS analysis. The LHVs (lower heating values) for gas, char and oil were determined from empirical equations. The gas product yield and LHV significantly increase with temperature, which is mainly due to more H_2 and CO formation by the enhanced secondary tar reactions. The char and oil characteristics highly depend on the temperature. Their high energy contents show that the obtained char and oil can be utilized as valuable solid and liquid fuels. The biomass energy upgrading due to solar processing is discussed. At optimum temperature 900 °C, it ranges from 38% to 53% accounting for the uncertainty of bio-oil water content.

1. Introduction

Currently, more than 80% of the world's overall energy needs are provided by fossil fuels [1]. With the population and economy growth, global energy demand is expected to increase by 37% in 2040. Then, for matching the long term energy demand while limiting CO_2 emissions, more and more renewable sources, such as biomass and solar energy should be utilized. Indeed, they represent only a very small portion of the energy supply now [2]. Biomass contributes only about 9% for the world's energy needs, and solar energy represents less than 1.0% of the primary energy supply in the world [3]. Between 2010 and 2040 significant developments in renewable energy production will be observed in biomass energy (from 45217.44 to 136950.23 PJ) and solar energy (from 184.22 to 55768.18 PJ) [4].

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Nomenclature

Latin letters

HHV	higher heating value, MJ/kg
LHV	lower heating value, MJ/kg
Z	mass fraction (dry basis), wt.%
M	moisture content, wt.%
U	upgrade factor, –
m	mass, kg
Q	energy content, MJ

Greek letter

η	efficiency, –

Subscripts

C	carbon
H	hydrogen
O	oxygen
N	nitrogen
S	sulfur
A	ash
oil	bio-oil product
gas	gas product
char	bio-char product
biomass	biomass feedstock
solar	solar energy

However, there are some drawbacks restricting their usage and development. On the one hand, the low energy density biomass is distributed in a wide range of remote areas. On the other hand, the intermittent solar energy is a diluted and unequally distributed source. One way for breaking these barriers is to combine these two sources. In such a process, the concentrated solar radiation supplies high-temperature process heat for biomass pyrolysis reactions [5]. Then biomass and solar energy can be converted into transportable and dispatchable solar fuels [6]. Solar processes have the potential to produce higher calorific value products with lower CO_2 emission compared with conventional pyrolysis [7]. The biomass energy is upgraded through solar energy providing pyrolysis reaction enthalpy transferred into products.

The concentrated radiation has been tentatively used since a long time to drive the carbonaceous materials pyrolysis. In the 1980s, Beatie et al. [8] obtained a maximum gas yield of 31 mmol/g coal from direct solar pyrolysis at solar flux level of 1 MW/m^2. Antal et al. [9] developed a reactor for achieving flash pyrolysis of biomass: free-falling particles were heated by concentrated solar energy in a transparent tube. They obtained 26% gas yield containing 47.5% CO, 22% H_2, 13% CH_4, 11% CO_2 and 4.3% C_2H_4 with fractions of light hydrocarbons (C_3 and C_4). Tabatabaie-Raissi et al. [10] got 6.6–8.4% char yield from pyrolysis of cellulose under radiation flux density up to 10 MW/m^2 in a TGA. Chan et al. [11] investigated the pyrolysis of pinewood with a solar simulator and found that the char, tar and gas yields were 20–26%, 33–52% and 11–27%, respectively, depending on the flux density. Later, 21–29% char, 25–40% tar and 30–50% gas yields have been reported for radiative pyrolysis of different woods under concentrated lamp radiation (0.08 and 0.13 MW/m^2) [12]. Lédé et al. [13] found an almost stable 62% of liquid yield with various heat flux densities (from 0.3 to 0.8 MW/m^2). Recently, the application of an image furnace (simulating solar radiation) for biomass pyrolysis has been reported [14]. At the same time, the concept of a fix bed reactor heated by a vertical axis solar furnace has been well investigated because of the special interest in the solar pyrolysis of beech wood at CNRS-PROMES [15–17]. Besides, the parabolic-trough solar collector [18] and Fresnel lens [19] were also used to produce bio-oil through pyrolysis.

Solar pyrolysis of carbonaceous materials leads to the formation of gases, bio-oil and bio-char. Gas products can be applied for heat and power production or precursors for chemicals [20]. Bio-oil can be transported and stored for further use in boilers or engines for energy and heat generation [21]. Char can be used as a fuel or adsorbent [22]. The solar pyrolysis bio-oil has already been characterized by some researchers [18,19]. It only shows one part of the energy content from solar pyrolysis products. The solar pyrolysis product characteristics at different temperatures have yet to be reported. The conversion of carbonaceous materials to higher valued solar fuels by solar pyrolysis can be attractive, but at which temperature should the feedstock be handled? Solar gas, bio-char and bio-oil compositions and energy contents (LHV) are presented in this paper. Moreover, the biomass energy upgrade factor, which is a very important indicator for biomass conversion, is determined at different temperatures for the first time.

2. Experimental section

2.1. Biomass feedstock

Beech wood pellets (about 0.3 g), 10 mm in diameter and 5 mm high were used in experiments. The beech wood characteristics are shown in Table 1.

2.2. Solar pyrolysis experiments

2.2.1. Solar experimental setup

Solar pyrolysis experiments were run in a vertical-axis solar furnace shown in Fig. 1. A down-facing parabolic mirror (2 m diameter and 0.85 m focal length) is illuminated by the reflected beam issued from the heliostat. The maximum power and maximum flux density are approximately 1.5 kW and 12,000 kW/m^2, respectively. A shutter placed between the heliostat and the parabola modulates the reflected solar beam, and thus the concentrated radiation. The beech wood pellet set in a graphite crucible is located in a 6L transparent Pyrex balloon reactor swept with an argon flow. A "solar-blind" optical pyrometer (KLEIBER monochromatic operating at 5.2 μm) is used to measure the pellet surface temperature. Based on the measured temperature, the shutter opening controlled by PID controller is adjusted to reach the target heating rate and final temperature. The argon flow in the reactor is

Table 1
The characteristics of beech wood.

Proximate analysis				Ultimate analysis				
Volatile matter %mass, dry	Fixed carbon	Ash	Moisture %mass	C %mass	H	O	N	S
85.3	14.3	0.4	6	50.8	5.9	42.9	0.3	0.02