Full Length Article

Production and analysis of fuels and chemicals obtained from rice husk pyrolysis with concentrated solar radiation

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A B S T R A C T

Solar energy is the greatest source of renewable energy which can be applied for biomass thermochemical conversion processes. In this study, pyrolysis of rice husk was performed at different temperatures obtained from concentrated solar radiation. The solar pyrolysis of rice husk mainly produced bio-oils (20.6–43.13 wt%), followed by bio-char and pyrolysis gases. The pyrolysis gas was observed to increase with temperature from 14 wt% at 500 °C to its maximum yield of 25.48 wt% at 800 °C. The highest bio-char yield was found to be 43 wt% at 500 °C. As observed by the FTIR spectrometer, functional groups of the raw rice husk changed with pyrolysis temperature. SEM images showed large glass-like holes in the chars produced at 500 °C while EDS analysis revealed highest silica concentrations of 12.3% at 700 °C. Acids, alcohols and phenols as well as trace amounts of ester and aldehydes were the GC–MS identified bio-oil compounds. Solar pyrolysis of rice husk could be a promising and energy-saving technology for fuel and chemical production.

1. Introduction

Fossil derived fuels have become a limited resource and emissions of greenhouse gases are impacting the environment and climate [1–3]. Considerable research has been performed to look for alternative fuels and energy sources which can reduce dependency on fossil fuels and CO_2 emissions [4–6]. Biomass, being a renewable and carbon neutral source of energy, is widely and readily available in almost all parts of the world. It is a natural resource which can be converted into gaseous, liquid and solid fuels the properties and yields of which depend on the thermal, biological or physical conversion mechanisms [7–9].

The large quantities of residue and leftovers from maize, wheat and rice, which constitute world's top three agricultural by-products, can be sought as a strategic source of renewable energy [9]. After the harvest season, open field burning or decaying of the residues in the field is the common disposal practice in many countries, creating health and environmental concerns [10].

Rice husk, which accounts for 20–25% of the total paddy weight, has an annual global capacity of 700.7 million tonnes [11]. It is produced in the first step of milling when the husk is separated from the grain and ends up as a leftover in the open air in most countries [12]. Rice husk contains lignin (up to 10%), cellulose (20–35%), hemicellulose (15–30%) and some other materials. Generally, it is characterised by high ash content and low bulk density [13].

Rice husk can be converted to different types of fuels using thermochemical processes. Direct combustion, pyrolysis, gasification and liquefaction are among the available thermochemical conversion routes which are considered as critical biomass utilization alternatives, offering economic benefits through the production of high value fuel gasses, liquids and/or chars [14]. Pyrolysis of biomass is one of the most efficient technologies for bio-char, bio-oil and bio-gas production [15]. It involves moisture evaporation at around 100 °C, followed by biomass cracking and devolatilisation when the temperature reaches around 300 °C, releasing pyrolysis gases such as CO_2, CO, H_2, and light weight hydrocarbons as well as tars [16].

Many studies have investigated rice husk pyrolysis in reactors heated by products of pyrolysis. Some of the recent studies on traditional rice husk pyrolysis can be seen in the literatures [17,18,2,19]. Li et al. [2] used rice husk pyrolysis products, mainly bio-oil, as raw material to produce synthesis gas (H_2 and CO). The rice husk fed to quartz tube reactor at a rate of 0.29 g/min, was pyrolysed at temperatures ranging from 500 to 800 °C. H_2 and CO produced from the pyrolysis of the bio-oil were found to reach 56 and 18%, respectively, 37% and 36% from the volatiles, respectively. Pyrolysis temperatures ranging from 400 to 800 °C and feeding rate of 1.3 g/min were used to generate raw pyrolysis volatiles with different bio-oil to syngas ratios [19]. Maximum gas, bio-oil and bio-char yields were found to be 45%, 38% and 43% respectively. The maximum uncondensable pyrolysis gases, containing

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mainly CO, H_2, CO_2 and CH_4 were obtained at 800 °C. Bio-oil and bio-char yields were investigated from fast pyrolysis experiments of rice husk conducted in a fix-bed induction heating system at 400 to 800 °C and 200 °C/min [17]. The oil yield was observed to increase from 10 to 37% over the entire range of the pyrolysis temperatures while the bio-char was found to decrease with temperature from 84.22 to 30.7%. Characterisation of bio-char, bio-oil and gas produced from the pyrolysis of rice husk at various temperatures (350 to 600 °C) and feeding rate of 2 g/min were performed by Yu et al. [18]. Maximum gas yield (78 wt%) was obtained at 600 °C while the maximum yields of char (45 wt%) and liquids (47 wt%) were obtained at 350 and 500 °C, respectively.

The above conventional pyrolysis processes require partial combustion and use of the pyrolysis products to maintain the pyrolysis temperature, which compromises the quality and amount of the pyrolysis products. Solar energy if coupled with pyrolysis has vast potential to overcome these shortcoming, as it can provide the required heat to carry out the pyrolysis and enable full recovery of the pyrolysis products [20,21]. Australia receives an average of 58×10^{21} Joules of solar energy in a year which positions the country as one of the best solar energy receivers in the world [22]. Integrating solar technology for biomass pyrolysis in Australia has substantial advantages and can bring significant contribution for the future development of the solar energy technology. Rice husk as well as other lignocellulosic biomass materials can be processed using integrated solar pyrolysis method, however its behaviors under the solar pyrolysis conditions has never been investigated to this date. In this study, rice husk was selected as the feedstock because it is an abundant agricultural waste. In addition, the higher ash content of rice husk than most of the other lignocellulosic materials, was an additional important parameter for selection of this feedstock for solar pyrolysis. Although high ash content biomass was studied previously by Weldekidan et al. [23], however, the biomass used was chicken litter, which is primarily lipid and protein based biomass feedstock. In the current work, the high ash lignocellulosic feedstock was selected with a focus to pyrolyse rice husk at different temperatures and evaluate the different pyrolysis products obtained from the solar pyrolysis. The aim of this work was to investigate properties of pyrolysis gases, bio-char (including the contained ash) and bio-oils through rice husk pyrolysis induced by concentrated solar radiation at different temperatures.

2. Materials and methods

2.1. Materials

Sample rice husk from Carlingford Produce, Sydney, Australia was dried in a vacuum oven for 2 h at 70 °C and 80 kPa then ground and sieved by a 280 μm sieve. ASTM D7582 test method was applied to determine the proximate analysis of the sample while the ultimate analysis was determined with CHNS analyser using Vario MICRO cube elemental analyser (Elementar Analysensysteme GmbH, Germany) with PC based data system Windows™ and electronic miro balance.

It contained 25.32% ash, 14.14% fixed carbon, 54.51% volatile matters and the moisture content was found to be 6.03%. The elemental analysis of the rice husk showed 34.33% C, 4.98% H, 0.38% N, 0.19% S and on ash free basis the O (by difference) was 60.12%.

2.2. Solar pyrolysis reactor

The solar pyrolysis system, with design reported in a previous study [24], was employed to pyrolyse the sample. The system contains 1.8 m aperture diameter parabolic dish coated with an 88% aluminum reflective material. The reactor, which was silica glass tube with 35 cm length and 13 mm in dimeter was loaded with 100 mg of sample and placed at the focal region of the dish which is at 0.655 m from the bottom edge of the dish. Samples were positioned in the middle of the

Table 1
Optical characteristics of dish.

Parameters	Dimensions
Aperture diameter	1.8 m
Surface reflectivity	88%
Focal length	0.655 m
Reactor tube diameter	13 mm
Power per ray	0.25641 W
Generated heat per area	70 kW/m^2
Sun ray count	12,636
Highest temperature	1060 °C

reactor and held in place by glass wool. The parabolic dish has maximum heat flux concentrating capacity of 70 kW/m^2 for one sun (1000 W/m^2), which generates the pyrolysis temperatures. Table 1 is the optical characteristics of the parabolic dish obtained from SolTrace [25] simulations.

Based on the heat flux distribution, theoretical calculation of the highest temperature *(T)* on a blackbody is given by Eq. (1) [26,24]:

$$Q = \sigma T^4 \tag{1}$$

Where Q is the radiated flux per square meter (70 kW/m^2) and σ is the Stefan-Boltzmann constant. Accordingly, the concentrated radiation in this case would result in a corresponding highest temperature of 1060 °C.

The parabolic dish was calibrated for its maximum temperature using K-type thermocouple with USB serial interface, PicoLog software and stick-road which was bolted to the surface of the dish. The dish was first set to its maximum performance position, then corresponding length and position of the shadow of the stick-road, which lie on the dish surface, was marked for reference. To control the temperature during the pyrolysis process, the dish was tracked for the shadow of the stick-road to lie on the reference mark always. When the target temperature was reached, for instance 500 °C, the dish could be rotated to its offset position easily then sample temperature instantly started to drop to ambient value. To maintain constant heating rate, all the experiments were conducted at the same radiation levels, 700–720 W/m^2. Fig. 1 shows variation of the temperature with time during the pyrolysis experiment.

Semi rigid nylon tube (1/4″ outer diameter) was connected to the reactor inlet to pass argon gas (at a flow rate of 85 mL/min) to purge the reactor and as a carrier gas for the pyrolysis gases. Another nylon tube was connected to the reactor outlet to collect the gases in a Tdlar® gas bag for further analysis by the GC machine. Fig. 2 shows schematic of the experimental set-up. Samples were heated up to the maximum temperatures of 500, 600, 700 and 800 °C at a heating rate of 160 ± 6 °C/min. These temperatures were selected as most of the pyrolysis products can sufficiently be produced in this range of
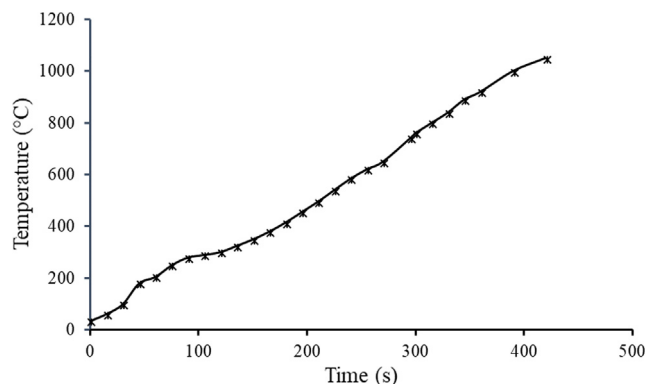

Fig. 1. Temperature variation of the reactor as a function of time (relative error was 5%).