Energy 126 (2017) 42–52

Contents lists available at ScienceDirect

Energy

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

Microwave-induced electrical discharge of metal strips for the degradation of biomass tar

Yuli Zhou, Wenlong Wang*, Jing Sun**, Lunjing Fu, Zhanlong Song, Xiqiang Zhao, Yanpeng Mao

National Engineering Laboratory for Coal-Fired Pollutants Emission Reduction, Shandong Provincial Key Lab of Energy Carbon Reduction and Resource Utilization, Shandong University, Jinan, 250061, China

ARTICLE INFO

Article history:
Received 18 November 2016
Received in revised form
28 February 2017
Accepted 2 March 2017
Available online 3 March 2017

Keywords:
Microwave
Metal discharge
Degradation
Biomass tar

ABSTRACT

Considering the global energy and environment crisis, biomass energy is a major research focus. Gasification is a commonly used biomass energy conversion technology, but it inevitably yields tar as a by-product, accompanied by many hazards. This study investigates the use of microwave metal discharge as an energy-efficient alternative to current technologies for processing and treating tar from biomass gasification. The related special effects and factors affecting metal discharge were also investigated. The experimental and analytical results confirmed that microwave metal discharge could easily degrade toluene, reaching more than 50% degradation in the presence of very few (n = 5) discharge points. Compared with the traditionally employed tar-cracking process, the proposed process has distinct advantages and characteristics, particularly regarding speed and efficiency. In addition, microwave metal discharge achieves an excellent combination of multi-physical effects of light, heat, and plasma. In this study, the thermal and luminous effects associated with the discharge process were successfully studied in isolation, and a feasible mechanism research method was obtained by the appropriate test instruments and characterization parameters. This facilitates study on the mechanism of toluene degradation by microwave metal discharge. In-depth studies of the mechanism are necessary to enable the potential applications of microwave-assisted pyrolysis, pollutant removal, organic synthesis, and material preparation and regeneration.

1. Introduction

The development of modern industry has entailed various challenges including energy shortages, environmental pollution, and mineral exhaustion. These problems require the development and utilization of new and renewable energy resources. The sustainable and environmentally friendly energy resource of biomass has been particularly attractive as a replacement for fossil fuel, because the relative abundance of the resource could to some extent satisfy future energy requirements and ensure a secure fuel supply [1]. Gasification is one of the most widely utilized industrial biomass conversion technologies. However, the produced gas inevitably contains high-molecular-weight organic compounds. These compounds are commonly referred to as “tar”, which can cause fouling, corrosion, and blocking of pipes, heat exchangers, and particle filters, thus reducing the process efficiency [2–6]. In addition, tars are carcinogenic in nature and contain a significant amount of energy that could be transferred to the syngas [6]. The presence of tars and the need for their removal from the produced gas is thus undoubtedly critical to the development of biomass gasification, and extensive related studies have been conducted [1,7,8].

Several reviews address tar formation-avoidant strategies for the production of tar-free syngas [4,6,9–14]. These removal measures can be categorized as primary or secondary. Primary removal means the reduction or limitation of tar in the gasifier, while secondary removal refers to the purification of gaseous products from the gasifier, including methods of physical separation (filtration, condensation, and electrostatic precipitation) and chemical conversion (thermal and catalytic cracking) [6,8]. Each of these methods has advantages, but these are accompanied by varying disadvantages. For example, physical separation is relatively simple, but it only partially captures the liquefied tar via the gas–liquid

* Corresponding author. School of Energy and Power Engineering, Shandong University, Jinan, 250061, China.
** Corresponding author. School of Energy and Power Engineering, Shandong University, Jinan, 250061, China.
E-mail addresses: wwenlong@sdu.edu.cn (W. Wang), sunjing0108@163.com (J. Sun).

http://dx.doi.org/10.1016/j.energy.2017.03.008
0360-5442/

phase transformation. The process also entails several other problems, such as the adhesion of tar to the device interface, the challenge of recycling the tar, and the need to repeatedly clean the device. Chemical conversion has received more attention and deeper investigation than physical separation. However, the need for high temperatures in traditional thermal cracking increases the cost of the process. Therefore, catalytic cracking is considered as the best potential technology for tar removal. In selecting the catalyst, the cost, catalytic activity, and service life of the catalyst must all be considered, as the key factors in determining the feasibility of catalytic gasification processes. Catalysts used at ambient temperature have strict requirements; the many constraints of catalyst cracking have limited the industrial use of the technique, and a pressing need to develop an effective method for tar removal remains.

Microwave irradiation has been rapidly developed since the thermal microwave effect was discovered in the 1940s [15]. Microwave heating is unique in volumetric heating, enabling faster heating and thus accelerated and enhanced chemical reactions through efficient heat transfer [16]. Microwave irradiation thus affords a means to increase the yield of a chemical reaction [17] and to achieve significant heating energy savings, shorter process times, and improved general process yields. Because of these features, microwave irradiation has received considerable attention for employment in diverse technological and scientific applications such as food processing, activated carbon regeneration, sintering of metals and ceramics, plasma processing, solution treatment, polymer processing, preparation of functional materials, pollution control, and pyrolysis [16,18–27]. The technology has the added advantage of being environmentally friendly [17]. Against this background, the application of heating by microwave irradiation to the thermo-catalytic treatment of toluene, as a model tar compound, has been comprehensively investigated [28]. Microwave irradiation technology has demonstrated particular success in tar cracking, with good efficacy and low energy consumption [2].

In a previous study, a unique phenomenon was observed in which metals with sharp edges, tips, or submicroscopic irregularities were subjected to microwave irradiation. This produced an electric spark or electric arc (generally referred to as a discharge) [29,30]. The spark or arcing caused the formation of several local hotspots and substantial pyrolysis, which could significantly affect the chemical composition and reaction of a material [31]. This discharge phenomenon and its special effects have attracted increasing interest and are currently utilized for various purposes such as microwave-assisted pyrolysis [32–36], pollutant removal [37–40], material synthesis [41–45], and metal sintering [45–48].

The objective of the present study was to investigate the performance of microwave metal discharge for biomass tar cracking with respect to the operating conditions. Toluene was used as a model compound for the experimental investigations because it has been reported as the most representative component of biomass tar. Different types of metal pins were considered as dielectric media in the microwave field. The factors affecting the discharge intensity were also investigated, including the irradiation time and some other characteristics of the discharge metal (type/number). Further, by comparing the concentrations of the toluene before and after the reaction, the pyrolysis of the compound with respect to the discharge intensity was examined.

2. Experiments

2.1. Experimental system testing microwave metal discharge in degradation of toluene

Fig. 1 shows a schematic of the employed tar-degradation apparatus, which contains the toluene supply system, microwave device, quartz glass reactor, gas piping system, and gas analysis system.

2.1.1. Experiment setup

The biomass tar cracking experiment was performed on a fixed-bed test system. The major parts of the system were the gas distribution device and microwave irradiation device. The tar sample gas consisted of high-purity nitrogen gas containing toluene at a certain concentration. The flow rate of the gas was controlled by a mass flow meter to within 500–10,000 sccm.

A commercial household microwave oven (Galanz Model G70F20CN1L-DG(B0)) was modified for use as the microwave device with an excitement frequency of 2450 MHz. The microwave device had an adjustable power output of 0–700 W in steps of 10% of the maximum power, and the irradiation time was also easily controlled. A simple self-made transparent quartz glass apparatus was used as the reaction container. Quartz glass can withstand high temperatures reaching 1450 °C, while ordinary glass can only withstand 600 °C. Fig. 2 shows additional details of the experimental apparatus, where 1 is the quartz flange, 2 is the porous plate (pore diameter of 1 mm), and 3 is the lower supporting structure. The diagram on the left shows the details of the quartz flange with its three identical and uniformly distributed circular apertures.

2.1.2. Experimental materials

The major experimental materials were the biomass tar model compound, discharge medium, and fixed-bed packing material. As noted earlier, toluene was used as the model compound because it is the most representative component of biomass tar (13 wt% of tar) [4,49,50].

In contrast to the primitive use of scrap metal with sharp edges or submicroscopic irregularities (Fig. 3(a)), the present experiment utilized uniform metal strips with diameters of 1 mm and lengths of 40 mm (see Fig. 3(b)). This eliminated the effects of differing material morphology. And the corresponding properties of these metal strips were shown in Table 1.

High-purity quartz sand was used as multifunctional filler in the reactor for three crucial reasons: 1) It created a retardant layer preventing possible damage from direct contact between the quartz reactor and the discharge metal. 2) It prevented overheating of the system; quartz sand is often used for heat storage and thermal insulation because of its high specific heat. In the present application, it absorbed excessive heat generated during the discharge process. 3) It absorbed little microwave irradiation, thus guaranteeing the good exposure of the metals to electromagnetic radiation.

2.1.3. Experimental methods

Different factors determined the experimental conditions. Some general steps were nevertheless applied. Firstly, the appropriate experimental conditions were set to test the feasibility of the sample gas preparation system to obtain environments with steady toluene concentrations. The toluene concentration was tested every 5 min until it became stable, as shown in Fig. 4, which indicates one simple testing result in the commissioning of the toluene supply system. From this figure, it is known that toluene stabilization would take a long time, largely because the flow rate of the carrier gas is low and the volumes of the pipes and reactors in the system are relatively large. To ensure the consistency of the inlet toluene concentration in each experiment, the relevant experimental parameters were set to a fixed value in gas distribution. The temperature of liquid toluene in the thermostat water bath was set at 25 °C. The flow rate of nitrogen was $Q_1 = 2000$ mL/min and $Q_2 = 100$ mL/min, Q_1 being the flow rate in the dilution