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Short communication

Novel treatment of a biomass tar model compound via microwave-metal discharges

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HIGHLIGHTS

- Microwave-metal discharge process was optimized by using tungsten as electrodes.
- The toluene destruction efficiencies were studied at different gas flow rates.
- MW-m discharge can effectively destruct toluene with an efficiency of over 90%.
- The generated coke can be in-situ eliminated by steam reforming to produce syngas.
- This work can offer important reference for tar removal in biomass gasification.

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ABSTRACT

Electrical discharges triggered by microwave-metal interactions are important phenomena in microwave heating processes with the generation of plasma. In this study, microwave-metal (MW-m) discharge was developed for tar destruction. Toluene was used as a tar model compound. Uniform tungsten electrodes was adopted and optimized to provide a fast-ignition, relatively-stable and sustainable discharge process. The conversions of toluene were investigated at different gas flow rates and preliminary tests were conducted to in-situ eliminate the generation of solid carbon. Microwave-tungsten discharge can effectively destruct toluene into useful gases (H_2, C_2H_2 and CH_4) and solid carbon, with a high conversion efficiency of more than 90%. The generated solid carbon can be effectively eliminated by introducing water steam into the discharge reaction to achieve a comparable toluene conversion efficiency of 92.3% and a production of syngas (H_2 to CO ratio is around 1.6). This work can offer important reference for developing a new technology for tar cracking in a biomass gasification process.

1. Introduction

Owing to the steady depletion of fossil fuels and the aggravation of the global greenhouse effect, the use of biomass as alternative fuel has received considerable attentions both from the perspective of the sustainable development of energy and the reduction of CO_2 emission. Pyrolysis and gasification are regarded as the most promising techniques to convert biomass into biofuels [1–4]. However, besides the useful biofuels, the undesirable byproducts, especially the tar in the bio-gas is the most troublesome contaminant, as upon cooling and condensing it can cause fouling, clogging and corrosion problems in downstream equipments [2,5–9]. Therefore, efficient removal of tar is crucial in biomass gasification processes.

Generally, the removal or destruction of tar is implemented after a gasifier through a wet scrubber or thermochemical conversion methods, i.e. thermal or catalytic cracking [10]. Wet scrubber is unattractive since it causes secondary pollution and a waste of the chemical energy contained in tar [11]. The main challenge for thermal cracking is high energy consumption since a high reaction temperature, usually well over 1000 °C is required [3]. Although catalytic cracking can lower the reaction temperature, the cost and lifetime of the catalysts limit its commercial application since catalysts have high affinity for sulfur and chlorine, and may become poisoned, or else fouled by coke [4,12–15]. Accordingly, the development of a novel cracking technology which is energy efficient, economically feasible and potential to be enlarged for industrial purpose is eagerly desired.

Plasma can significantly promote chemical reactions because of the unique properties of the reacting atmosphere it creates (i.e. free radicals, ions, excited molecules and high temperature) [1,16]. Hence, its benefits on tar cracking can be anticipated to be important. Basic study on low temperature pulsed plasma [17,18], gliding arc plasma [19–21] and microwave plasma

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[22,23] for tar destruction has been conducted. As a novel method, microwave-metal discharges -which are initiated when microwave radiates on the metals with sharp tips, edges or submicroscopic irregularities- also lead to the formation of plasmas as well as distributed local hot spots. Our previous research has proved that microwave-metal discharges can significantly promote chemical reaction process and affect the composition of products largely with the major merits of fast ignition, compact design and high efficiency [24–29].

In this paper, a novel catalytic cracking method based on microwave-metal discharge was specifically developed for the destruction of tars. Toluene which has been reported as the most representative component of tar was selected as model compound. Compared with our previous work [24,27,28], a great effort has been made to optimize the discharge processes to provide a stable and wide three-dimensional plasma region. Experiments were carried out to investigate the toluene conversion at different flow rates (also means retention time). The possible reaction pathways involved in the plasma conversion of toluene and the yield of solid carbon (also referred as coke or carbon deposition [12–15], herein uniformly termed as solid carbon) have been deduced through the analysis of gas and liquid products. In addition, preliminary tests were also conducted to eliminate the generation of solid carbon by introducing steam into the plasma reaction.

2. Experiments

2.1. Experimental setup

The experimental system for toluene cracking was schematically shown in Fig. 1.

In order to generate tar vapor, a certain amount of toluene was firstly added in a washing bottle which was immerged in a water bath at a certain location. Argon was used as a carrier gas to sweep the toluene into the reactor and a mass flow meter (MFC, Flowmethod FL-802) was adopted to control the argon flow rate precisely. Accordingly, the tar sample gas consisted of high-purity argon gas containing a certain amount of toluene. In order to guarantee there was no toluene vapor condensed in the connecting pipes, two heating bands were used to preheat the gas pipes before and after the reactor precisely to 200 °C. For each experiment, the washing bottle before and after experiments were weighted to calculate the toluene input.

With regard to the microwave discharge cracking system, a modified commercial household microwave oven (Midea ModelM3-L233C) was used as the microwave device. The microwave oven has a frequency of 2450 MHz and an adjustable output power of 0–900 W. A customized quartz cup that was made of high-purity quartz glass was used as the container. High-purity quartz sand was used as multifunctional filler in the reactor in order to prevent possible damage to the quartz reactor and conserve the discharge heat. Both the quartz cup and quartz sands are transparent to microwave radiation. A flange was used to seal the reactor as shown in Fig. 1.

The gas flow leaving the discharge reactor passed through four successive absorption bottles that were placed in an iced water bath to collect the unreacted toluene and generated hydrocarbons by referring to the publication of Zhu et al. [19]. The first three washing bottle contains hexane and the fourth one empty to collect entrained droplets. The gaseous products were finally collected in a gas bag and then determined by gas chromatography (GC, PerkinElmer Clarus 500). The liquid solvent was test by the GC–MS (7890A/5975C, Agilent Technologies, USA) device equipped with a DB-WAX chromatographic column and flame ionization detector (FID).

2.2. Assessment methods

The destruction efficiency of toluene in the reactor is defined as follows:

$$\eta_d(\%) = \frac{\text{moles of toluene input} - \text{moles of toluene effluent}}{\text{moles of toluene input}} \times 100 \quad (1)$$

The yield (Y) of the products can be calculated:

$$Y_{C_xH_y}(\%) = \frac{x \times \text{moles of CxHy produced}}{7 \times \text{moles of toluene input}} \times 100 \quad (2)$$

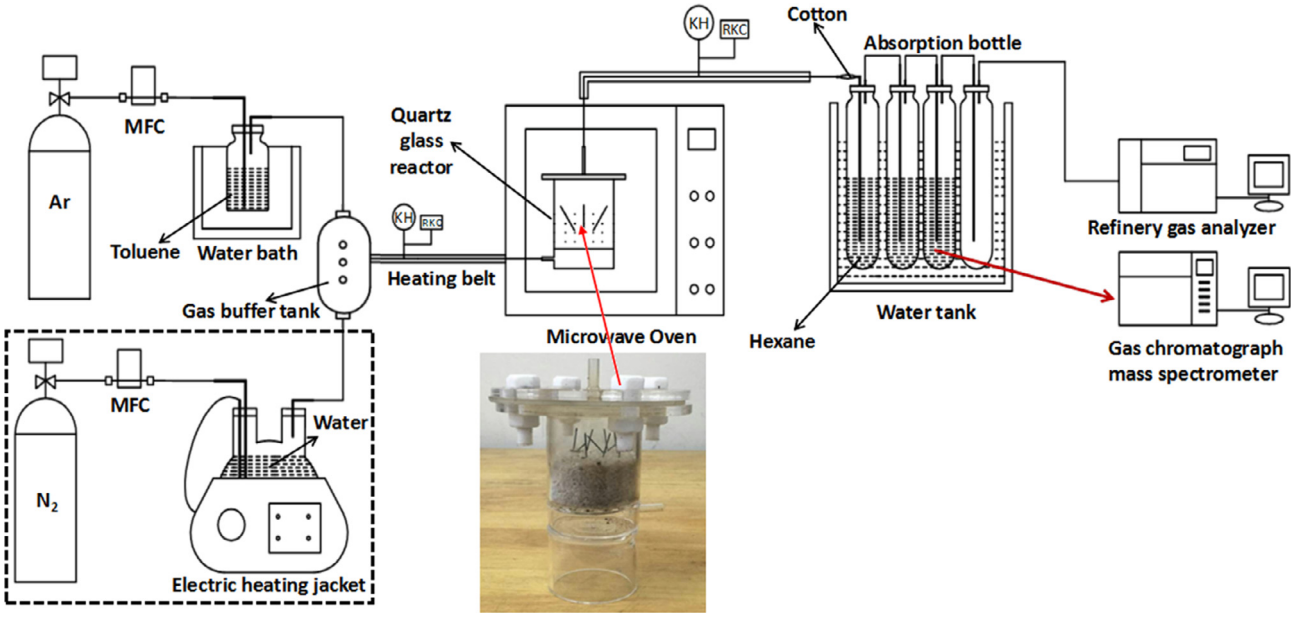

Fig. 1. Schematic diagram of tar removal apparatus.