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Experimental study of destruction of acetone in exhaust gas using microwave-induced metal discharge

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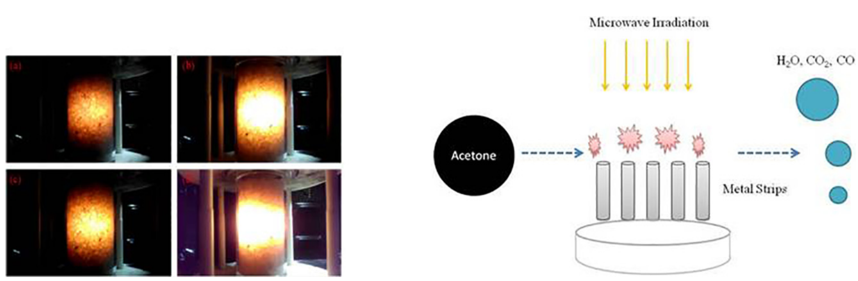
HIGHLIGHTS

- Microwave metal discharge was first investigated for removal of gaseous acetone.
- The discharge phenomena showed high performance in directly destructing acetone.
- Various factors influenced the discharge and acetone destruction efficiency.
- High temperature, plasma and luminous effects associated with discharge took effects.
- Microwave-induced discharge likely used as a universal technology to remove VOCs.

GRAPHICAL ABSTRACT



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ABSTRACT

Volatile organic compounds (VOCs) are air pollutants that pose a major concern, and novel treatment technologies must be continuously explored and developed. In this study, microwave-induced metal discharge was applied to investigate the destruction of acetone as a representative model VOC compound. Results revealed that metal discharge intensity largely depended on microwave output power and the number of metal strips. Microwave metal discharge exerted the distinct combined effects of intense heat, strong light, and plasma. In the case of MW without metal discharge, the decrease in acetone at 200 ppm was remarkably limited (approximately 5.5% (mol/mol)). By contrast, in the case of microwave-induced metal discharge, a considerably high destruction efficiency of up to 65% (mol/mol) was obtained at low concentrations. This finding highlights the potential of microwave-induced discharge for VOC removal. Initial assessment indicated that energy consumption can be acceptable.

1. Introduction

Volatile organic compounds (VOCs) have been widely used in various industries. Various industrial processes produce exhaust gases containing VOCs (Chen et al., 2017; Eliott et al., 2013; Gironi and Piemonte, 2011). These VOCs are well-known air pollutant precursors that are hazardous to human health and the environment (Altinkaya, 2009; Asili and De Visscher, 2014; Cao et al., 2016). The long-term exposure of humans to VOCs, such as ketones and aldehydes, may cause eye and nose irritation, potential carcinogenicity, and neurotoxicity (Bari and Kindzierski, 2018; Jasiński et al., 2009; Tahmasebi et al., 2014). In addition, interactions between VOCs and nitrogen oxides in the atmosphere can form ozone via photochemical oxidation under

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sunlight irradiation (Carabineiro and Thompson, 2007); the produced ozone may oxidize VOCs, SO_2, and NOx, thereby causing air pollution, smog, and haze weather (Chandrasekaran et al., 2012; Cometto-Muñiz et al., 2007; Jiang et al., 2018; Mizeraczyk et al., 2008). Therefore, VOC emissions must be controlled at an acceptable level, and effective methods for VOC removal must be developed.

The conventional strategies for removing VOCs from exhaust gas include recovery and destruction methods. Physical treatment processes, such as adsorption (Yi and Wan, 2017), absorption (Huang et al., 2016), membrane separation (Chen et al., 2014), and condensation (Peng et al., 2016), are typically used to recover VOCs in cases of high concentrations and valuable recovery costs. By contrast, chemical treatment processes, such as thermal oxidation (Choi and Yi, 2000), catalytic oxidation (Wu et al., 2015), ultraviolet (UV) oxidation (Akmirza et al., 2017), plasma (Karatum and Deshusses, 2016), and biological methods (Priya and Philip, 2015) are destructive processes. However, these VOC treatment technologies are generally limited by intensive energy consumption, high energy cost (particularly when VOCs exist at ppm level in indoor air), dependence on expensive catalysts, or low removal efficiency. New, green, and effective methods must be established for VOC abatement to satisfy the increasing societal demands.

Microwave heating is a comparatively novel technology that has been applied in many fields, such as food processing, drying, pyrolysis, and environmental engineering (Amann et al., 2014; Araszkiewicz et al., 2007; Carabineiro and Thompson, 2007; Cogliano et al., 2005; Li et al., 2012; Piumetti et al., 2015; Tahmasebi et al., 2014; Zhao et al., 2014; Zhou et al., 2006). This method offers the advantages of high heating rates, short processing times, and selective and volumetric heating. In addition, no direct contact is required. Microwave heating is time-saving and energy-efficient. In several cases, microwave heating can trigger heating, plasma discharge, and photochemical effect (Dehdashti et al., 2011; Falciglia et al., 2015; Lin et al., 2014). These advantages benefit chemical reaction processes of VOCs (Barba et al., 2012; Mamaghani et al., 2017; Wang et al., 2013).

A unique discharge phenomenon occurs during microwave heating in the presence of metals or their alloys with sharp edges, tips, or submicroscopic irregularities, which are exposed to microwave irradiation (MW). This discharge phenomenon can generate strong heat effects and light, which in turn promote chemical reactions (Wang et al., 2012; Wang et al., 2016). Thus, this discharge phenomenon and its accompanying effects can be explored in microwave-assisted pyrolysis (Hussain et al., 2010; Sun et al., 2011a; Sun et al., 2011b), pollutant removal (Man and Shahidan, 2007; Mizeraczyk et al., 2008; Ozkan et al., 2007), material synthesis (Jones et al., 2002; Olaya et al., 2009), and metal sintering (Hojati-Talemi et al., 2010).

The destruction of VOCs through microwave-induced metal discharge approaches has rarely been reported. This study investigated for the first time the feasibility of using microwave-induced metal discharge to remove VOCs. As one of the most abundant compounds in the world, low-concentration acetone was selected as the model compound for experimental investigations (Mellouki et al., 2015). Paper clips were selected as dielectric substrates for inducing discharge in the microwave field. The factors affecting metal discharge were comprehensively analyzed. The destruction efficiencies of the compound were examined. The factors influencing destruction efficiency, including microwave output power, discharge metal number, air flow rate, and initial acetone concentration, were also investigated.

2. Experimental

2.1. Materials

The main experimental materials included the VOC model compound, a discharge induction medium, and a fixed-bed packing material. As mentioned, analytic-grade acetone was used as the model compound, as it is one of the most representative organic compounds, is commonly found in various exhaust gas sources and in ambient air, and is associated with severe incidents of photochemical smog formation.

Paper clips were selected as the metallic medium for inducing discharge in the microwave fields; their shapes and properties are shown in Table 1. Paper clips were selected for three crucial reasons. 1) The main components of paper clips include Fe and Ni. In our previous experiments, long and thin metal strips, including Fe and Ni, were effectively excited discharge under MW (Wang et al., 2012). 2) The paper clips featured the same shape, a diameter of 1 mm, a length of 3 cm, and a weight of 0.47 g. The differences in the weight of the paper clips did not exceed 2%. 3) Paper clips are easily available and inexpensive.

High-purity quartz sand (>99%), which is a poor MW absorber that guarantees good exposure of metals to electromagnetic radiation, was used as a packed-bed material to protect the quartz reactor. The diameter of the quartz sand particles raged from 3 mm to 4 mm.

2.2. Experimental setup

Fig. 1 shows the experimental setup adopted for VOC destruction. The system consisted of the acetone supply system, an air pump, a microwave device, a self-made reactor, and gas analysis and spectral analysis systems.

Gas flow rate was controlled within 100–500 mL/min by a mass flow meter. Gas was pumped by an air pump (China Whaisp HP-01) with inlet and outlet conduit joints at a constant flow rate of 1500 mL/min.

A commercial household microwave oven (M3-L233C, Midea Corp., Foshan, Guangdong, China) was reconstructed and applied for the treatment. The microwave device featured an input power of 1200 W and a frequency of 2450 MHz. The output power of the microwave oven can be adjusted from 0 W to 900 W at intervals of 10%, 30%, 50%, 80%, and 100% of the maximum power, and irradiation time can be set freely.

A self-made quartz glass container with a wall thickness of 2 mm, a height of 80 mm, and an internal diameter of 55 mm was selected as the reactor. The container displayed excellent wave-transparent properties, and it can withstand high temperatures of up to 1450 °C. A set of polytetrafluoroethylene (PTFE) flange was used to seal the reactor to ensure tightness. The reactor was connected to a Tedlar gas bag and an air pump by using PTFE tubes.

2.3. Procedure

Sample gas preparation: The sample gas was prepared by mixing acetone with air in Tedlar bags. In a typical experiment, a 10 L Tedlar gas bag was filled with a specific volume of air by using an air pump that was precisely controlled by the mass flow meter. Subsequently, a specific amount of acetone liquid was injected into the bag. Then, the Tedlar gas bag was left at room temperature for 3 h to allow complete vaporization of acetone liquid. Acetone concentration was tested by gas chromatography (GC). All experimental results indicated that steady acetone concentrations were obtained in the Tedlar gas bags under various conditions.

Acetone destruction: Paper clips were inserted in silica sands, which were placed in the reactor in advance and at the same amounts in each experiment. Then, the reactor was sealed and placed at a fixed position in the microwave cavity. Afterward, the sample acetone gas was pumped, whereas MW was applied. The outlet gas was collected using a 1 L Tedlar bag at 10 s after the discharge started, and collection time lasted for 5 min. The collected gas samples were analyzed by GC, and discharge phenomena were analyzed with a spectrometer.

2.4. Analysis methods

2.4.1. GC analysis

The collected gas samples were analyzed by using a gas chromatograph (7890A, Agilent Technologies Co., Santa Clara, CA, USA) with a