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Electro-spraying and catalytic combustion characteristics of ethanol in meso-scale combustors with steel and platinum meshes

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ABSTRACT

An experimental study on electro-spraying and catalytic combustion of ethanol at meso-scale is carried out. The electro-spraying process of ethanol is visualized and four typical spraying modes are identified. Based on droplet size measurements by a Phase Doppler Anemometer, the spraying at the cone-jet or multi-jet mode is suitable for meso-scale combustion. Two meso-combustors without and with the platinum catalyst, denoted as combustor A and combustor B, respectively, are designed to conduct the comparative experiments. The flame temperature at the cone-jet mode is higher than those at other modes when equivalence ratio $\varphi = 1.0$, and for the combustor with catalyst, fuel-lean conditions are favorable for stable combustion. It is also found that the carbon monoxide mole fraction in the exhaust decreases by at least 25% due to the catalytic effect. At the cone-jet electro-spraying mode, the combustion efficiencies of ethanol reach the highest value for both combustor A and combustor B due to smaller droplet size and more uniform droplet size distribution. Under the same conditions, combustion efficiency of ethanol can be improved by 4.5% for combustor B, which proves that the platinum catalyst can accelerate the decomposition of ethanol.

1. Introduction

The development of Micro-Electro-Mechanical Systems (MEMS) technology has spurred interest in research and development of micro power generation devices and systems [1]. Compared to power systems using conventional electrochemical batteries, micro power generation apparatuses utilizing combustion energy are considered to be promising in practical systems of relatively small size such as MEMS due to the much higher energy densities involved in liquid hydrocarbon fuels [2]. Hence, in the last two decades, micro- and meso-scale combustion as a component of micro-power generator has been investigated intensively as innovative energy conversion systems [3–5]. A micro-combustor with stable flame is an important component in a micro-power generator [6]. However, it is difficult to keep the flame stable inside the micro-combustor, due to the limitations imposed by inadequate residence time and high heat loss rate associated with the increase in surface to volume ratio, which leads to thermal quenching. Many studies have been conducted on improving the performance and stability of the meso-scale combustors. Several methods have been used, including changing the internal structure of the burner to enhance mixing of fuel and air and prolong the residence time [7–10], enhancing the thermal management to reduce heat loss and preheat reactant [11] and implementing catalytic combustion to reduce the reaction activation energy [12,13]. Most of the existing studies mainly focused on gaseous fuels, while researches on stable combustion of liquid fuels in the micro-combustor are still scarce.

It is desirable to develop a micro-combustor with liquid hydrocarbon fuel, which has relatively high energy density, about two orders higher than that of a lithium ion battery [14,15]. Different from gaseous fuels, fine evaporation is a prerequisite for liquid fuel combustion. Porous media and film combustion [8,16] were used to increase surface area and prolong residence time. Several studies have been conducted on micro-combustors with liquid hydrocarbon fuels [17–21]. Sirignano et al. [22] presented a miniature liquid film combustor with a stable flame inside or outside of the glass tube which was 10 mm in inner diameter and 40 mm in length. Sadasivuni and Agrawal [23] developed a meso-scale combustion system of 30 mm in length and 17 mm in diameter with kerosene fuel injected with a flow-blurring injector. Inside the micro- or meso-combustor, the liquid fuel should evaporate rapidly to generate the fuel vapor, mix with the oxidizer, and burn quickly to establish a stable flame. The electrospray technique enables us to generate a quasi-monodispersed fine spray [24,25]. Deng et al.

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[26] developed a micro-combustor of less than 10 mm with micro-fabricated multiplex electrospray sources and a catalyst, which is more expensive than structural materials, such as stainless steel or quartz glass. Gan et al. [20] developed a meso-scale combustor using electrospray technique for liquid fuel combustion, where liquid fuel dispersed into droplets thus the evaporation rate increased greatly, and the electrospray characteristics were studied.

Despite of the good performance of the electrospray combustor, there are still potentials for improvement in combustion efficiency and the reduction of the carbon monoxide (CO) emission. Investigations have been performed to reveal the effects of combustor fabrications, operating conditions and catalyst or type of support on combustion characteristics [27–29]. Catalysis is an effective way to enhance combustion. The catalytic combustion of liquid fuel with electrospray atomization has not been broadly investigated and only a few studies were conducted focusing on the fuel of JP-8 [26,30]. For energy conversion involving ethanol, most reports have been focused on the integrated reforming process. The combustion of ethanol in catalytic combustors has not been investigated. Being renewable and environmental-friendly, ethanol especially bio-ethanol is playing a more important role in alternative fuels than ever before and its application in MEMS power system is very attractive. Combined with the advantages of electrospray technique, the combustion performance of ethanol in catalytic combustors is expected to be improved greatly. However, there is still a lack of information on the catalytic combustion characteristics of ethanol with electrospray technique.

Thus, the main objective of the present work is to experimentally investigate the electrospray and catalytic combustion characteristics of ethanol. The atomization performance of the electrospray in different modes is firstly examined by Phase Doppler Anemometer (PDA) analysis, and the appropriate conditions (such as the flow rate of the fuel and the voltage applied) for combustion are determined. Then, two meso-combustors with and without the platinum (Pt) catalyst, respectively, are designed to conducted the comparative experiments. The flame temperature, CO emissions and combustion efficiency of the two combustors are subsequently discussed.

2. Experimental system

Fig. 1(a) shows a schematic of the catalytic combustor used in the present study. It consists of three quartz glass tubes with an inner diameter of 12 mm and an outer diameter of 16 mm. Total length of the combustor is 80 mm. A stainless-steel capillary is used as a nozzle, and a stainless-steel ring with thickness of 5 mm is used as a ring electrode. The distance from the nozzle outlet to the ring is 1.1 mm. Positive voltage on the nozzle (V_c) and the ring electrode (V_r) are supplied by two DC power sources respectively. A steel mesh is placed at 16 mm downstream from the nozzle outlet and set as a ground electrode to collect the charged droplets. A catalytic Pt mesh is installed on the right-hand side of the steel mesh and the two meshes are pasted tightly, and the Pt mesh is used as a flame holder. The Pt catalyst is chosen due to its high temperature resistance and high combustion activity. The Pt mesh (Danjie Company, Shanghai, China) has a diameter of 16 mm and a thickness of 0.1 mm, and the hole density on the mesh is 80/cm^2. The Pt mesh inside the tube (with the diameter of 12 mm) is exposed in the combustion area. Another combustor without the catalytic Pt mesh is also designed for the comparative experiments. Their configurations are the same except for the Pt mesh. In the present study, the combustor without and with Pt mesh are denoted as combustor A and combustor B, respectively. For the two combustors, electric spark ignition is used during the experimental process. A stable flame is observed near the steel mesh or the Pt mesh. The measuring point of the exhaust gas is in the middle of the combustor outlet.

Fig. 1(b) shows a schematic of the experimental set-up. The fuel is supplied into the combustor by a syringe pump (KDS100, KD SCIENTIFIC, USA). The nozzle and the ring electrode are connected to the positive electrode of two DC power sources (71030P, GENVOLT, UK) respectively. The mesh is connected to the ground electrode of a DC power source. The air flow is controlled by a mass flow rate controller (Brooks, 5850E, USA). The flame temperature is measured by a S-thermocouple. The data is transferred to the computer by a data acquisition instrument (Agilent 34970A, USA). The components of the exhaust gas are analyzed by a gas chromatograph (Kexiao GC1690, China). The thermal conductivity detector (TCD) is used with hydrogen as the carrier gas, and the pressure of the carrier gas is set to be 0.1 MPa to control the retention time of the combustion products accurately. All spray and flame images are taken by a Digital Single Lens Reflex (Canon EOS 5D Mark III, Japan) and the camera settings of the imaging technique are listed in Table 1. The uncertainties of the flow rate, the flame temperature, and the voltage are less than 1%, 0.7% and 1% respectively. In flame temperature calculations, the radiation heat loss has been taken into account. All the experimental uncertainties are shown in Table 2.

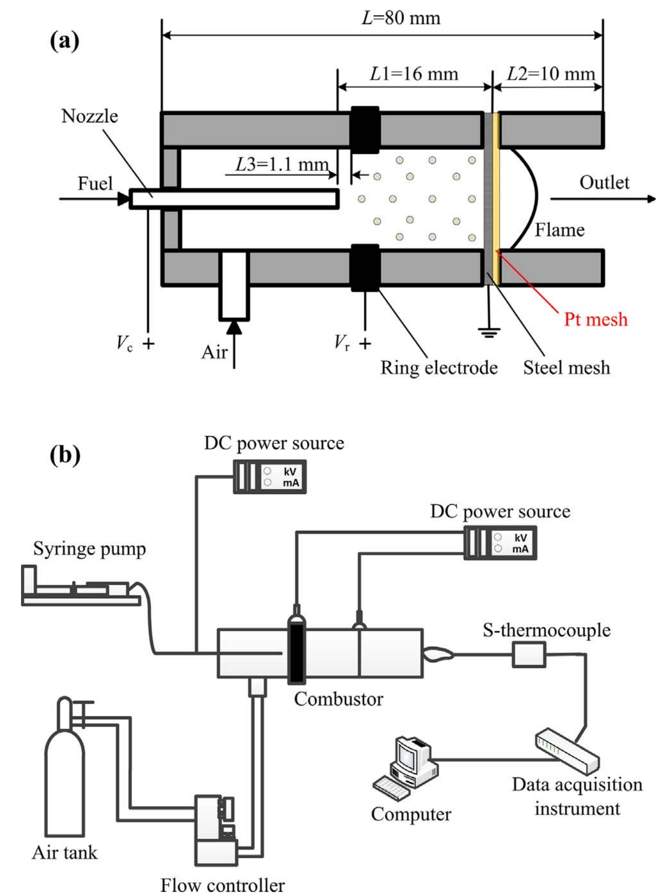

Fig. 1. Schematic of (a) the electro-spray combustor and (b) the experiment set-up.

The droplet size is measured by a PDA (Particle Dynamics Analysis, Dantec, Denmark) with uncertainty of ± 0.5 µm. Fig. 2 shows the distribution of measurement points during the PDA measurement process. 17 measurement points are set on the same plane which is perpendicular to the axis of the combustor. The sample number at every

Table 1
Camera properties.

Optical arrangement	Spray test	Combustion test
Camera	Canon EOS 5D Mark III	Canon EOS 5D Mark III
Frame rate	6 fps	6 fps
Exposure time	2.5 ms	5 ms
Resolution	5760 × 3840	5760 × 3840