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Research Paper

Thermal performance of a meso-scale combustor with electrospray technique using liquid ethanol as fuel

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HIGHLIGHTS

- Thermal performance of a meso-scale combustor is evaluated experimentally.
- The flame is anchored near the steel mesh in the combustor.
- Thermal efficiencies are from 22.0% to 48.8% under different equivalence ratios.
- Heat recirculation zone is found near to the mesh and improve the combustion.

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ABSTRACT

A new meso-scale combustor designed to couple with energy conversion modules is fabricated. The volume of the combustor is of the order of a few cubic centimeters. Liquid ethanol is electrosprayed at a flow rate of 3.50 ml/h. The stable flame is observed to be in a disc shape near the mesh of the combustor when the equivalence ratios varying from 0.9 to 1.7 without external heating and catalyst. The temperatures of flame, combustor outer wall and exhausted gas are measured. Flame temperatures are within the range of 1134–1287 K. Exhausted gas components are detected by a gas chromatograph and the combustion efficiencies of ethanol are calculated, which are from 51.2% to 92.4%. Heat loss from the combustor wall is evaluated and it accounts for 29.2–43.6% of the input energy. The outer wall temperature distributions along the flow direction are obtained and a heat recirculation zone is found at about 10 mm away in the upstream of the mesh, which is beneficial to stable combustion. The mesh in the present combustor is used not only as a collector for gathering charged droplets but also a flame holder. The thermal efficiencies of the combustor are found to vary from 22.0% to 48.8%.

1. Introduction

Micro/meso-combustion has attracted more and more attention with the development of manufacturing technology. Chemical batteries are still the most used power source for electronic products. Though great progresses have been made in battery technology, such as fast recharging, new materials of electrodes, the energy density of batteries is extremely limited compared to liquid fuels [1]. Power sources with high specific energy and small volume are in great need. Micro combustion is a feasible way to fulfill energy conversion in a compact area with high energy density.

A comprehensive review of fundamentals, devices and applications on micro combustion can be seen in [1,2]. Combustion in microscale faces many difficulties due to scaling effects. Surface-to-volume ratio is increased dramatically which results in high heat loss ratio [3]. Short residence times on micro and mesoscale combustors lead to incomplete conversion of fuels [4]. To establish stable combustion in a micro combustor, numerous experimental researches were carried out, and gas fuels were applied for most conditions. Heat recirculation and external heating are common and effective methods to reduce heat losses. Heat recirculation, which means that the enthalpy from burned gas was recirculated to preheat reactants, was widely used in previous studies [5–7]. External heating of combustor can prevent the flame from quenching if the internal diameter is smaller than the quenching diameter [8–10]. The combustor geometry is essential to the mixing of fuel and oxidizer and the extension of residence time. A backward-facing

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step applied in the combustor can significantly improve the performance in many aspects [11–13]. The effect of mixed fuels on combustion was also investigated [14–16]. Different from gas fuels, fine evaporation is a prerequisite for liquid fuel combustion. Porous media and film combustion was used to enlarge surface area and prolong residence time [17–20]. Gan et.al developed a micro combustor using electrospray technique for liquid fuel combustion [21]. Liquid fuel was dispersed into droplets thus the evaporation rate increased greatly, and the electrospray characteristics were studied [22,23]. Based on the previous work about micro combustion and combustors, some energy conversion modules were developed. Contributions in this field can be divided into two categories. The first category is known as direct energy conversion module, for example, a thermoelectric (TEG) or thermophotovoltaic (TPV) generator. Direct energy conversion system is easy to be fabricated and operated. A crucial disadvantage of direct energy conversion system is its particularly low efficiencies which were less than 15% [24–26]. Kang and Veeraragavan [27,28] studied the characteristics of mesoscale combustors with different wall materials and demonstrated a novel approach to increase power conversion potential of a TPV system. Another category involves the modules based on conventional power cycles, such as gas turbines, internal combustion engines and Stirling engines [29–31]. In this method, the challenges are in the balance of the rotary parts, the fabrication technologies and the sealing difficulties. However the comparatively high efficiencies make them a feasible way to be a miniaturized power source for practical use with high energy density.

Micro/meso combustor is a key component of miniaturized power system. The combustor in the present study is designed to couple with an energy conversion module based on conventional cycle. The emphasis falls on the combustion design to burn liquid fuel with electrospray technique in a volume on the order of a few cubic centimeters. Quenching problems should be considered at sub-millimeter dimension [32], thus quenching problems can be ignored in this study. In order to combust liquid fuel in meso-scale, the combustor using electrospray technique is chosen and fabricated. To characterize the performance of the combustor, flame temperatures are measured, the heat losses by radiation and convection are calculated, and combustion efficiency and thermal efficiency are investigated in the present study.

2. Experimental setup

The schematic diagram of the meso-scale combustion system is shown in Fig. 1. The whole system is exposed to the ambient. It consists of two high voltage power sources, an air tank, a mass flow controller, a syringe pump, a meso-combustor, a PC, an IR camera, a gas chromatograph (GC) and several connection tubes. Ethanol is chosen to be the fuel because of its high heat value, low boiling point, fast evaporation rate and it is renewable and environmental friendly. The flow rate of ethanol is controlled by a syringe pump (KDS100, KDScientific, USA) with an accuracy of ±1%. The flow rate of air is accurately adjusted by a mass flow controller (Brooks5850E, Brooks, USA) with an uncertainty of ±1%. The two-dimensional temperature distribution of the outer wall is recorded by an IR camera (PM575, FLIR, USA) with an uncertainty of ±0.1 K. It is noted that the measured surface temperature is strongly depended on the surface emissivity. Other factors, such as the ambient temperature, the air humidity and distance between the camera lens and the tube surface can be accurately measured. The infrared signal will have reflection and refraction on the surface of quartz tube, thus the measurement of IR camera will result in unaccepted errors. To avoid the problem and enhance the accuracy of measurement, the quartz tubes have been painted with black lacquer. The temperature measurements are calibrated by an S-type thermocouple coated on the outer wall surface. The emissivity of the black lacquer is about 0.90–0.93 with temperatures in the range of 1100–1300 K. The variation in terms of temperature readings caused by two different emissivity values is about 3–5 K, depending on the temperature magnitude (the higher the temperature, the larger the variation). Thus the overall uncertainty of IR camera is within ±0.5%. Flame temperatures and exhausted gas temperatures are measured by an S-type thermocouple. Five points on the flame front surface are selected for temperature measurement, which is shown in Fig. 2. The average temperature of the five points is considered as flame temperature. The head diameter of the thermocouple is 0.30 mm, which is much smaller than the diameter of flame, so the influence of thermocouple on the flame can be negligible. In the present study, all flame and gas temperatures are corrected by taking the radiation heat loss of thermal couple into account. And the uncertainty of flame and gas temperature measurements after correction is less than ±0.7%. The main components of the exhaust gas are detected by a gas chromatograph (GC1690, Kexiao, China). All measurements

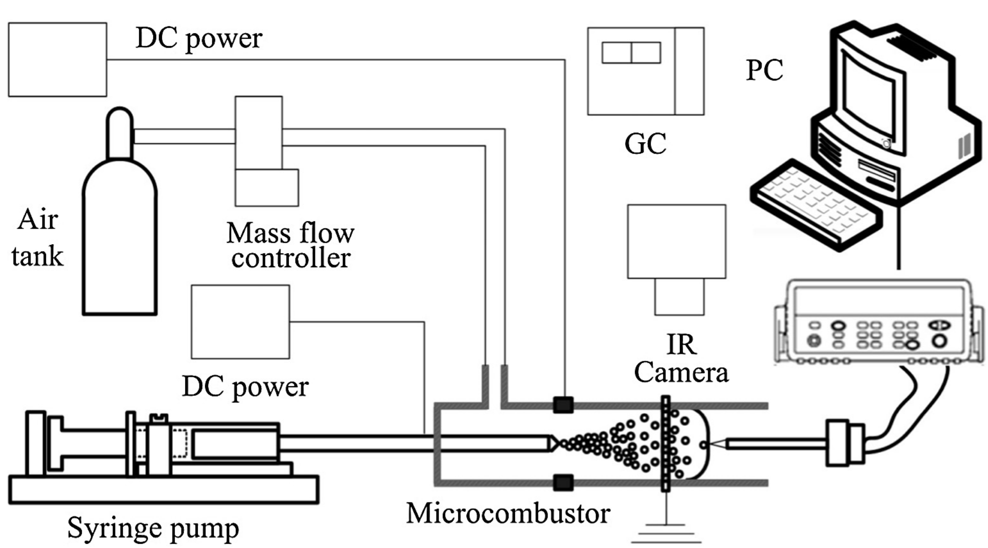

Fig. 1. Schematic diagram of the meso-scale combustion system.