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Experimental investigation on combustion characteristics of premixed propane/air in a micro-planar heat recirculation combustor

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ABSTRACT

With respect to micro-thermophotovoltaic (MTPV) system, achieving a higher wall temperature and wider range of flame stability in micro-combustor is pivotal, which may be the most effective method to improve the work efficiency of the device. On this basis, an improved combustor with heat recirculation is designed and fabricated. Experimental investigation has been conducted to study the effects of equivalence ratio and volume flow rate on combustion characteristics of premixed propane/air. Results show that the radiation efficiencies of external wall in heat recirculation combustor are significantly higher than the corresponding value in straight-channel combustor under the same conditions. In the meanwhile, the maximum blowout limit in heat recirculation combustor can be more than three times as that of straight-channel combustor. Furthermore, the baffle length is a critical parameter of the micro-combustor, which can determine the residence time and reaction zone of the propane/air mixture. Accordingly, studies under different baffle length cases have been adopted to further explore the most suitable length in heat recirculation combustor. By contrast, the 15 mm baffle length is the most advantageous, in which case the radiation efficiency of the external wall is highest.

1. Introduction

Micro-power generation systems based on the hydrocarbon fuel combustion, possessing a series of advantages such as high power density, long working time and small volume [1–3], have become research foci. Many prototypes of micro-power system have been designed for the past decades [4–6]. Some disadvantages may occur due to the small volume of combustion chamber: the reduced residence time of fuel/oxidant mixture, increased heat losses owing to large surface-to-volume ratio [7–9] and poor flame stability [10–13]. Different from other systems, the large heat losses may be advantageous for MTPV system, which is made up of optical filter, micro-combustor as well as PV cells. Therefore, various researches have been carried out on micro-combustor to improve its working performance.

So far, researches on micro-combustor mainly centered on the following aspects: micro-scale excess enthalpy combustion [14–18], porous media combustion [19–26], catalytic combustion [27–30], and the special methods for the purpose of stabilizing combustion [31–39] and so on. Among them, the concept of excess enthalpy combustion was proposed by Weinberg and Lloyd [40,41], also known as heat recirculation combustion. The enthalpy of inlet mixture in heat recirculation micro-combustor can be significantly enhanced because of the heat exchange between high temperature exhaust gases and fresh mixture. Therefore, the combustion reaction speed can be improved. The way of strengthening micro-scale combustion was firstly implemented on the development of mini roll type ("Swiss roll") thermoelectric generator [42]. Then, some studies on the heat recirculation combustor were carried out by scholars from all over the world. For instance, Vijayan and Gupta [43] examined the dynamics of propane/air premixed flame in a meso-scale heat recirculating combustor. Federici and Vlachos [44] compared the stability between a single-pass heat recirculation and a single channel micro-combustor using computational fluid dynamics. It was found that the structure of heat recirculation can extend the blowout limit but has little influence on extinction. Effects of flame holder geometry, material conductivity, equivalence ratio, and inlet Reynolds number on the combustor performance were studied experimentally by Vijayan and Gupta [45]. Taywade et al. [46] observed that the flame stability limits can be extended significantly and the mean wall temperature of the combustor will also be improved in heat recirculation combustor. Jiang et al. [47] analyzed entropy generation in H_2/air premixed flame; it was found that the rate of entropy generation increased with an increase in inlet velocity and equivalence ratio. However, the lower exergy loss can take place due to the usage of heat recuperator.

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Furthermore, micro-combustor with heat recirculation has also been adopted for MTPV system [48–51]. Park et al. [50] experimentally studied the power generation of micro-thermophotovoltaic device using a heat recirculation micro-emitter. Bagheri and Hosseini [51] investigated the effect of two types of heat recirculation combustor on the combustion characteristics through numerical simulation, and found that flame characteristics and stability can be significantly affected by inner heat recirculation reactor, while the emitter efficiency in outer reactor heat recirculation is much higher.

Although previous researches have elaborated the effect of heat recirculation, experimental investigation about micro-planar combustor used for MTPV system is not enough. This kind of micro-combustor have advantages of easy assembly, and also easy for modular piled up, which can ensure high power output and energy conversion efficiency of this micro-power generator system. To this end, we conduct research of excess enthalpy combustion on the basis of straight-channel micro-planar combustor. In this work, a novel micro-planar combustor inserted with symmetric baffles is put forward for this system. Meanwhile, the working characteristics of propane/air premixed combustion in micro-planar combustor with and without heat recirculation have been investigated through the method of experiment, as well as flame stability range of fuel has been studied under different equivalence ratios and the mean temperature of external wall has also been analyzed under different baffle lengths. The conclusions drawn from this paper, surely, will have a guiding role for the optimization work of micro-combustor.

2. Experimental devices

2.1. Design method of heat recirculation combustor

A three-dimensional, micro-planar combustor with two symmetric baffles, namely heat recirculation combustor, is fabricated, as shown in Fig. 1. From the figure, it can be seen that the inside section of the combustor is divided into three zones by two symmetrical baffles. The area between two baffles is inlet zone, and between the upper of two baffles and inner wall is burning zone, while the area between side wall and outside of two baffles are outlet zones. The purpose of inserting two baffles is to enable the cold coming gases to be preheated as the high

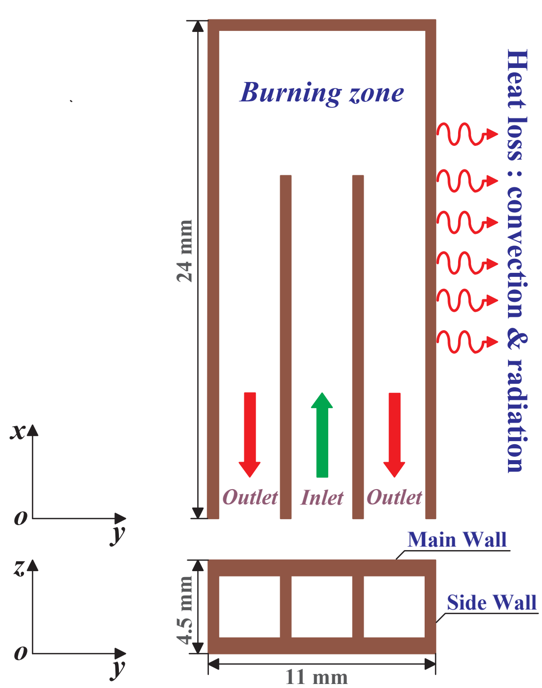

Fig. 1. Design scheme of heat recirculation combustor.

temperature exhaust gases are expelled from the outlet zone, thereby improving the utilization efficiency of the fuel chemical energy. The structure of the combustor is cuboid; the overall sizes are 24 mm in length, 11 mm in width and 4.5 mm height. The main wall thickness is 0.75 mm, while the side wall is 0.5 mm. Due to two symmetrical inserted baffles along gas flow direction, the height and width of the baffle are 3 mm and 0.5 mm, respectively, and the height of the channel is also 3 mm. The material of combustor and baffles are both made of nickel which has a high thermal conductivity. It can not only withstand high temperature but also be hardly oxidized. In order to improve the emissivity of combustor, a method of coating has been conducted on the surface of the combustor. A test using the Fourier Transform Infrared Spectrometer, recorded the emissivity of the combustor surface as 0.88.

2.2. Experimental set up

The experimental set up for this work is illustrated in Fig. 2. Propane is stored in high pressure tank and air is provided by air compressor. In order to guarantee the safety of experimental process, propane (purity: 99.0%) from high tank will be decompressed by reducing valve. At the same time, the flow controllers (model: DSN-2000B; accuracy of measurement: 0.5%) have been used to control the volume flow rate of each gas, then flow into the mixing chamber, finally get burnt in micro-combustor. During the experiment, the external wall temperature is monitored by the high precision infrared thermal imager (thermovision™-A40), which has a large measurement range up to 2000 °C and its maximum measurement error can be controlled below 2%. At the same time, the external wall working condition is examined by the camera of Nikon S8200.

3. Results and discussion

3.1. Basic working performance of heat recirculation

Here, the combustor without heat recirculation is defined as straight-channel combustor. First of all, the experimental photos (taken by Nikon S8200) on external wall of heat recirculation combustor (baffle length $L = 15$ mm) and straight-channel combustor have been studied at two propane volume flow rates (equivalence ratio $\phi = 0.9$), as shown in Fig. 3. From the figure, it can be seen that increasing the flow rate, the high temperature zones of both combustors become bigger. This is due to more fuel and chemical energy released with an increase in inlet velocity. Also, it should be noted that the high temperature zones in heat recirculation micro-combustor are brighter and shift toward downstream for all the two cases as compared to straight-channel combustor. In order to quantitatively analyze the temperature difference about these two combustors, further investigations at different propane flow rates have been carried out.

Fig. 4 compares the experimental results (obtained by infrared thermal imager) for the two combustors. It can be observed from the figure that regardless of the volume flow rate and equivalence ratio, the external wall mean temperature in heat recirculation combustor are higher than that of straight-channel combustor under the same working conditions. For a given equivalence ratio 0.9, the temperature difference between these two kinds of combustors grows with an increase in propane volume flow rate. When the flow rate is 30 mL/min, the external wall mean temperature of the heat recirculation combustor is 829 K, which just exceeds 25 K as compared to the straight-channel combustor. Furthermore, the value of wall temperature difference expands greatly and reaches 88 K as the flow rate is up to 60 mL/min. When the equivalence ratio is 1.0, the mean temperature of external wall in straight-channel combustor at 60 mL/min case has a tendency to shrink compared to 50 mL/min case. The main reason for this phenomenon is that as the propane flow rate increases, the combustion process in micro-combustor becomes unstable, the shape and position of flame starts to fluctuate. Under these circumstances, the propane/air