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Combustion characteristics and performance evaluation of premixed methane/air with hydrogen addition in a micro-planar combustor

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HIGHLIGHTS

- Hydrogen addition has a dramatic function on flame stabilizing of methane combustion.
- The reaction rate of methane will be apparently raised by burned hydrogen.
- The effects on the growth of wall temperature and radiant energy are investigated.
- Hydrogen addition ratio should exceed 10% so as to ensure a good operation effect.

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ABSTRACT

Combustion performance of premixed methane/air with hydrogen addition in a micro-planar combustor is numerically investigated, aiming to extend the application of various fuels in a micro-thermophotovoltaic system. The simulation results show that hydrogen addition has significant effect on raising methane reaction rate and flame stability. With the increase of hydrogen mass fraction, the location of the flame shifts toward the combustor inlet gradually, and the temperature gets a steady growth. For the micro-combustor with a channel height of 3 mm, it is found that the flame of pure methane is far away from inlet, which does not meet the basic working requirement of the micro-thermophotovoltaic system. However, the combustor wall temperature will be significantly improved when a small amount of hydrogen is added into the mixture, which is mainly due to the extension of flammability range. Along with the increase of H_2 addition ratio, both the total radiant energy and the proportion of usable radiant energy to total input chemical energy increase dramatically, which brings a significant improving of electricity output and system efficiency.

1. Introduction

With the development of micro-electro-mechanical systems (MEMS), great attention has been paid to the design of its energy supply system. Recently, several combustion-based micro-power generators have aroused the research interest of scholars around the world, which have the advantages of high energy density, small volume as well as long working time (Ju and Maruta, 2011; Chia and Feng, 2007; Chou et al., 2011). Apart from serving as electric source for MEMS such as micro-pumps and micro-robots, the micro-power generators can also provide adequate electricity or power for portable electronics, wireless communication equipments, vehicles, and military devices (Chia and Feng, 2007). However, due to the very short history, the technology is still far away from mature. So, it is essential to further improve the performance of these micro-power devices.

The micro-thermophotovoltaic (MTPV) system is one of the typical micro-power generators, which consists of three major components: micro-combustor, PV cells and optical filter. Due to its high energy density, no moving parts and convenient to fabricate, it is superior to other portable power generation systems (Chou et al., 2011). During operation, firstly, the chemical energy from hydrocarbon fuel is released during the combustion process. The outer wall of combustor can reach a high-temperature state and emits photons. Then, the short-wave radiation will transmit the filter, and arrive at the surface of PV cells. Finally, free electron can be generated due to photoelectric effect. Therefore, the output power density and energy conversion efficiency of the MTPV system are directly influenced by the micro-combustion process and the outer wall temperature.

For this reason, various research works on the structure optimization of micro-combustor have been carried out in the

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past decade. Yang et al. (2007) tested a micro-cylindrical combustor with backward facing step, and found that the step is very useful in controlling flame position and widening the operational range of mixture flow rate. Pan et al. (2010) presented a design concept of modular TPV power generator based on the sub-millimeter planar combustor. The combustion characteristics of premixed hydrogen–oxygen were investigated through both experimental and computational methods. Yang et al. (2011, 2012) also conducted similar studies about premixed hydrogen–air in the micro-planar micro-combustor. The SiC porous media foam was employed in the combustion channel to enhance heat transfer between the hot gas and the wall (Yang et al., 2011). A micro-combustor with a percolated platinum tube was proposed by Li et al. (2013), which served as catalyst, emitter, and flame stabilizer to overcome the critical heat loss and improve the flame instability. Wan et al. (2012) developed a micro-combustor with a bluff body which can extend the blow-off limit by 3–5 times. Besides, several kinds of micro-heat-recirculating combustors for the MTPV system were reported by Park et al. (2011, 2012), Yang et al. (2014) and Jiang et al. (2013a, 2013b), which all have positive effects on improving the temperature of emitters. In addition, studies of flames propagating in micro-channels were also reported (e.g. Veeraragavan and Cadou (2011), Kurdyumov and Jimenez (2014)), which would provide some promotional effects on the improving of working performance of micro-combustor.

For the MTPV system, the scholars prefer to choose hydrogen as the fuel of the combustion process. This is typically attributed to the higher heating value and ignition propensity of hydrogen. Li et al. (2009) pointed out that the blowout phenomenon occurs when the velocity of premixed methane and air exceed 1 m/s, while the blowout limit of hydrogen case can reach 8 m/s in the same combustion channel. Similar problem of propane combustion in a single channel micro-combustor was also found by Federici and Vlachos (2008), and they employed a heat recirculation combustor to increase the blowout limit of propane air mixture. In the study of conventional scale combustion, it was found that the combustion of hydrocarbon fuel could be greatly improved by adding a small amount of hydrogen into the mixture, so a great deal of research on this subject have been conducted (Khalil and Gupta, 2013; Wang et al., 2009; Sabia et al., 2007; Titova et al., 2014; Cuoci et al., 2013). When it comes to micro-scale combustion, Norton and Vlachos (2005) realized the self-ignition of propane/air mixtures with the assistance of hydrogen addition in a catalytic micro-burner. Yan et al. (2014) studied the hydrogen assisted catalytic combustion of methane on platinum, and concluded that hydrogen addition has a great influence on lowering the methane ignition temperature and shortening the ignition time. Seshadri and Kaisare (2010) also investigated the self-ignition property of hydrogen, in which two different modes of hydrogen-assisted propane ignition were compared. A novel catalytic micro-reactor which combined the concept of catalyst segmentation and cavities was designed by Li et al. (2012), and the enhancement effects on $H_2/CO/CH_4$ multi-fuel combustion were analyzed through numerical simulation. Zarvandi et al. (2012) conducted a study of CH_4/air combustion with hydrogen addition in a micro-stepped tube, and found that adding hydrogen could intensify the production of some crucial species which are very vital for establishing a stable combustion. Tacchina et al. (2010) investigated the combustion performance of CH_4/H_2/air mixtures using different catalysts, and concluded that the presence of H_2 in the fuel will improve the conversion of CH_4 due to an increase in the production of OH radicals.

At the condition of micro-scale, the blending fuel combustion process may present very different characteristic compared with conventional scale combustion, which is subjected to the problems of short residence time and large heat loss. In contrast, the research on blending fuel combustion in micro-combustor is very limited, and most of the studies mainly focus on the aspect of catalytic combustion. However, very few related research for the micro-thermophotovoltaic system using blending fuel has been reported. In this paper, the combustion process of premixed methane/air with hydrogen addition in a micro-planar combustor for the MTPV system is studied by a simulation method. The positive effects of hydrogen addition on the growth of wall temperature distribution and radiant energy output are also discussed, so as to give a reference for further improvement of the system working performance.

2. Construction and verification of a computational model

2.1. Geometric model and grid generation

In this work, a micro-planar combustor is designed, as shown in Fig. 1. The dimensions of the micro-combustor are 18 mm in length, 9 mm in width and 4 mm in height. The wall thickness is 0.5 mm, so the height of straight combustion channel is 3 mm. During the operation process, premixed fuel (methane and hydrogen) and air flow into the straight parallel channel through a rectangle inlet which is located at one end of the combustor. The burned gas will be expelled out from an outlet at the other end of combustor. The material of 316 stainless steel is chosen as combustor wall, which can withstand a temperature of 2000 °C and has a large emissivity at high-temperature state.

A 3D uniform grid is developed to predict the combustion and the heat transport in the micro-combustor. Half of the combustor space is employed as computational domain to save the calculation time. Centerline gas temperature profiles at three different mesh densities have been checked so as to determine the grid size, as seen in Fig. 2. After comparison, the mesh with 0.1 mm density in all three directions and 324,000 total cells number is finally chosen.

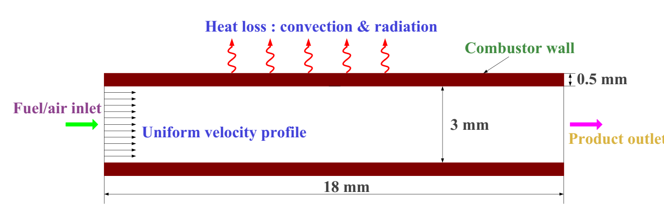

Fig. 1. Schematic diagram of micro-planar combustor.

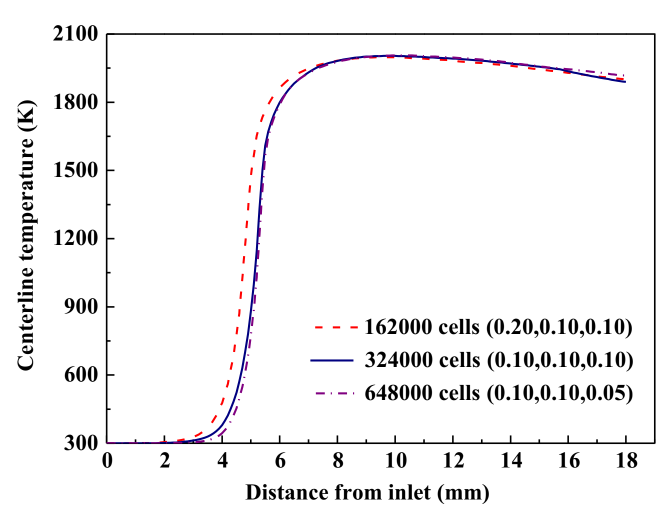

Fig. 2. Centerline temperature profiles of combustor at different mesh densities (10% hydrogen addition, inlet velocity: 2 m/s).