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Combustion characteristics of premixed propane/hydrogen/air in the micro-planar combustor with different channel-heights

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HIGHLIGHTS

- Combustion characteristics of premixed propane/air with hydrogen addition are studied.
- Blowout limit can be greatly extended due to the improving of flame stability.
- Hydrogen-enriched fuel can reduce the minimum flammable channel-height of propane.
- Working performance of 2 mm channel-height micro-combustor is better than 3 mm case.

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ABSTRACT

In order to improve the working performance and fuel adaptability of the micro-combustor, micro-planar combustors with different channel-heights are fabricated, and the three-dimensional calculation model is also built so as to study the basic characteristics of the blended propane/hydrogen combustion process. It is found that the hydrogen-addition method can overcome the shortcomings of propane flame instability under micro-scale conditions. When a small amount of hydrogen is added, the flame location could be fixed due to the stimulation of the important free radical like OH, thus obviously bringing the increase of mixture flammability range. The hydrogen-enriched fuel can further reduce the minimum flammable channel-height of propane. When the hydrogen addition ratio reaches 20%, a stable combustion will be achieved even in 1.5 mm channel-height micro-combustor. Regardless of the 2.0 mm or 2.5 mm channel-height combustor, the effect of hydrogen addition will be better, and the flame location moves upstream gradually with the increase of hydrogen fraction. From the view of chemical energy utilization, the 2.0 mm height combustor will be more suitable in the blended-fuel combustion mode, which is owing to the significant growth of the radiant energy output from the external wall.

1. Introduction

The micro-power systems based on hydrocarbon fuel combustion have aroused great interest to researchers in recent years, which are benefited from a series of advantages such as large power density, long power supply time and small volume [1,2]. As the key component of the various micro-power devices, the working performance of micro-combustor is critical to the overall efficiency and power density of each system. Compared with the conventional scale combustion, the micro-combustion process has some obvious different characteristics. The large surface-to-volume ratio leads to a sharp increase of heat losses when the combustor is miniaturized, and free radicals in the flame propagation process will be easy to inactivate due to the wall collision, which can cause the unstable combustion and quenching phenomena. At the same time, the scale effect will also bring about the problem of the short residence time of the mixture, thus increasing the incompleteness of combustion [3].

In the past 10 years, researchers have carried out a lot of studies on the enhancement of micro-scale combustion processes. They mainly focused on micro-scale excess enthalpy combustion [4–7], catalytic combustion [8,9], porous medium combustion [10–12], the special structure design for the purpose of flame stabilization [13–17], as well as liquid fuel combustion [18,19]. Recently, enlightened by the study of natural gas engine hydrogen-enriched combustion, some scholars have also tried to blending-combustion mode under the condition of micro-scale. One obvious advantage of this research method is that it will not bring about the complexity of the combustor structure. So far,

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the most common blending scheme is methane with hydrogen addition, which mainly adopted in the catalytic combustion field. Zhang et al. [20] pointed out that methane/air mixture cannot be ignited in a quartz glass tubular burner with an inner diameter of 2 mm, even with catalytic combustion. But hydrogen could help methane/air mixture achieve a stable combustion. Chen et al. [21] pointed out that the minimum hydrogen mole fraction should be larger than 3.2%, when catalytic combustion happened in a micro-planar combustor with the channel-height of 0.8 mm. Zarvandi et al. [22] showed a comparison of the combustion characteristics of pure methane and hydrogen addition methane in a micro-stepped tube. The calculated results showed that hydrogen incorporation can stimulate the formation of important components, and flame stability was affected by heat dissipation. Some few scholars have also carried out research on the blending of propane and hydrogen. Norton and Vlachos [23] realized the self-ignition of propane/air mixtures with the assistance of hydrogen addition in a catalytic micro-burner. It was concluded that the minimum hydrogen composition for self-ignition of propane/air mixture compositions will be relatively constant, and is irrespective of propane composition. Seshadri and Kaisare [24] simulated the hydrogen-assisted propane ignition in Pt catalyzed micro-channel, they also found that the self-ignition property of hydrogen can be used to provide the ignition energy required for propane. Besides, the method of CO addition has been adopted to improve the combustion characteristic of hydrogen. Jiang et al. [25] pointed out that the region with high radiation power appears far away from the emitter inlet with the increase of CO addition in a micro cylindrical combustor. Ichikawa et al. [26] studied the flame structure and radiation characteristics of a $CO/H_2/CO_2$/air turbulent premixed flame at high pressures, and presented that the $CO/H_2/CO_2$/air flame has a larger total radiation than CH_4/air.

It can be seen from the above that there are few schemes for the blended fuels under micro-scale condition and the related methods are mainly focused on simulation. As for alkanes fuel with hydrogen addition in micro-combustion, researches tend to concern more about the stability of the mixture. However, in respect of energy output characteristics and combustor scale-limit, some further investigation needed to be done.

Compared to the cylindrical combustor, the planar-combustor is more suitable for the modular assembled [27]. The results about a variety of fuels in micro planar-combustion process show that alkanes have certain advantage in the chemical energy utilization than hydrogen, despite the deficiency in flame stability [28]. Therefore, in this paper, experiment and simulation method are adopted to further analyze the effect of hydrogen addition on flame stability and flammability range in the straight-channel micro-planar combustor. Moreover, the working performance and combustion limit of propane with hydrogen addition are systematically investigated by changing the channel-height, hoping to provide a reference for the scale-limit reduction of other micro-combustors.

2. Experimental device and simulation method

2.1. Experimental set up

As shown in Fig. 1, the testing platform consists of gas supply system, mixing chamber, temperature measurement system and micro-combustor and other components. In the experiment, fuel and air are decompressed by the pressure reducing-valves, and the mass flow meters are used to regulate the required flow rate. Then they will flow into the mixer for pre-mixing, and finally arrive at the micro-combustor and get ignited. The purities of propane and hydrogen are 99% and 99.5%, whose absolute pressures are 0.18 MPa and 0.26 MPa decompressed by the pressure relief valves, respectively. The gases used above are controlled by mass flow meters (model: DSN-2000B; 0.5% accuracy of measurement). Temperature of the combustor external wall is monitored by a high-precision infrared thermal imager (Thermovision™ A40). The maximum temperature can be measured up to 2000 °C. Measurement error can be controlled within ±2% of the reading. A macro digital camera (model: Nikon S8200) is used for taking combustor appearance photo during the experiment. Experiments are carried out in a windless and dark environment, and the room temperature is maintained at about 20 °C, so as to avoid sunlight radiation and other disturbing factors.

The structure of straight-channel micro-planar combustor has been, so far, widely used in micro-thermophotovoltaic system, micro-thermoelectric device and other micro-power generators. The improvements of micro-combustor inner structure by various researchers are also on the basis of this straight-channel micro-combustor. From this point of view, the researches on this kind of combustor could be more promising and meaningful. Therefore, this type combustor has been adopted in this paper, as shown in Fig. 2. The length (x direction), width (y direction) and wall thickness are 24 mm, 11 mm and 0.5 mm, respectively. And different height micro-combustor are tested and calculated, such as 2.5 mm, 2 mm and 1.5 mm. The combustors are made of stainless steel, whose maximum heat-resistant temperature exceeds 1600 K. The surface emissivity of the external wall is 0.88, which is tested by the Fourier Transform Infrared Spectrometer.

2.2. Calculation model construction and verification

In order to better reveal the combustion process of hydrogen addition to propane, we also use the method of numerical simulation in the study and the relevant calculation model has been established. The hexahedron structure is adopted in the straight-channel combustor geometry meshing, and the grid independence check is made for different computational problems. Finally, the mesh size is chosen as 0.1 mm in three directions (the corresponding mesh density is 924,000). According to our previous studies about hydrogen [29] and methane simulation [30], the above size is accurate enough to all three gas fuels and blended-mixture when using this kind of micro-combustor.

A detailed gas-phase chemical reaction mechanism model of propane/air is used, which consists of 28-species and 73-reaction mechanism [31]. The basic governing equations include the continuity equation, momentum conservation equation, chemical component transport equation and energy conservation equation, which can be seen in our previous work [30]. The finite volume and the implicit solution method of under-relaxation are adopted for the above equations. Fluent (Ansys 15.0) is selected as the software for the calculation and analysis tool. Each equation is discretized using the second order upwind scheme. The SIMPLE algorithm is used as the coupling method of pressure and velocity. According to our previous simulation experience, the convergence criterion is that the monitored mean temperature of the external wall varies less than 1 K within 5000 steps.

For the mixture gas, the flow is considered to be steady, laminar, and incompressible, and the density follows the ideal gas law [32]. The specific heat of the mixture is calculated according to the composition-dependent mixing-law [22], which can be got through the mass fraction average of pure species heat capacities. Also, the thermal conductivity and viscosity are determined through the mass-weighted-mixing law [33,34]. Moreover, the mass diffusivity and thermal diffusion coefficient of the mixture are calculated according to the kinetic theory, which needs the inputs of characteristic length and energy parameter of each species originating from the database of GRI-Mech 3.0 [35]. When it comes to each component, the specific heat is calculated by the