Applied Thermal Engineering 117 (2017) 1–7

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Experimental study on premixed methane-air catalytic combustion in rectangular micro channel

Jianfeng Pan *, Rui Zhang, Qingbo Lu, Zhengqian Zha, Stephen Bani

School of Energy and Power Engineering, Jiangsu University, Zhenjiang 212013, PR China

HIGHLIGHTS

- The catalytic combustion of pre-mixed methane-air was studied experimentally.
- Flammability limits in catalytic and non-catalytic micro channel were obtained.
- The effects of equivalence ratio and channel height on combustion were analyzed.
- The temperature of outer wall increases with the increase of inlet velocity.
- The addition of catalyst in the channel can improve methane conversion.

ARTICLE INFO

Article history:
Received 8 October 2016
Revised 25 January 2017
Accepted 4 February 2017
Available online 7 February 2017

Keywords:
Rectangular micro channel
Micro combustion
Catalyst
Flammability limit
Experimental study

ABSTRACT

The catalytic combustion process of pre-mixed methane-air in a rectangular micro channel was studied experimentally. Infrared thermal imager and flue gas analyzer were used to measure the temperature distribution of the outer wall and main components of exhaust gas respectively. Flammability limits of premixed methane-air in catalytic and non-catalytic micro channel were obtained by changing flow rates of methane, and the effects of equivalence ratio, inlet velocity and channel height on combustion characteristics were analyzed. Results showed that the flammability limits improved significantly when platinum was added into the micro channel. The highest centerline temperature of the outer wall was obtained at an equivalent ratio of 0.9 at the same inlet velocity with or without catalyst in the micro channel. Addition of catalyst in the channel not only gave a uniform temperature distribution on the outer wall of the channel but also improved methane conversion. With the increase of inlet velocity, the centerline temperature of the outer wall increased and the highest points of the temperature shifted to downstream of the channel gradually. Combustion intensity in the channel increased with the increase of channel height at the same inlet velocity.

1. Introduction

From the developmental history of modern society and the evolution of power machinery, the development of industrialization cannot leave the guarantee of stable and continuous power generating facilities. At present, all kinds of micro devices are driven by traditional chemical batteries. Although traditional chemical batteries are simple and reliable, and the technology is mature, its low energy density and longer charging time limits its development. Micro Electro Mechanical System (MEMS) with hydrocarbon fuel has the advantages of high energy density, small size, light weight and low cost and it has wide application prospect. Thus, power MEMS based on combustion has more potential than the conventional chemical batteries. Research works have been carried out by many research institutes from all over the world [1–3]. The core component of power MEMS is the micro combustor, which has a very small combustion space and very short residence time of fuel and oxidizer. Because the characteristic size of micro combustor is close to or less than the quenching diameter or quenching distance, there is a sharp increase in combustion instability [4]. In addition, with the reduction in the size of the combustor, the larger ratio of surface to volume leads to greater heat loss through the wall [5]. Therefore, it is hard to guarantee the complete combustion of fuels, and the blow off limits and ranges of stable combustion are reduced greatly [6], so it is an urgent problem to improve the stability and sufficiency of combustion in the micro combustor.

Many measures have been taken to improve the stability of combustion in micro combustors by scholars from different countries [7–9]. Including the use of special structure design by Wan

* Corresponding author.
E-mail address: mike@ujs.edu.cn (J. Pan).

http://dx.doi.org/10.1016/j.applthermaleng.2017.02.008
1359-4311/

et al. [10], Jiaqiang et al. [11], and Yang et al. [12,13], adding porous media in the combustion chamber by Pan et al. [14] and Yang et al. [15], and using bluff body to improve the stability of combustion by Bagheri et al. [16]. Besides, catalytic combustion is also an effective and simple method to guarantee stable combustion [17–20]. The reason lies in that, the reduction in the size of combustor will result in insufficient and unstable combustion. But the ratio of surface-to-volume will increase, and the relative increase in the surface area of inner face can provide a favorable condition for the surface catalytic reaction. However, the internal combustion process will become complex because of the existence of surface reaction. Numerical simulation and experimental research have been used to research the combustion characteristics of different fuels and oxidizers in micro combustors. Chen et al. [21] performed numerical simulations to analyze the reactions of hydrogen/air inside a catalytic micro-tube with detailed heterogeneous and homogeneous chemistries. They studied the characteristics of heterogeneous and homogeneous interaction in terms of flow velocity, tube diameter and wall thermal conductivity. Benedetto et al. [22] conducted two-dimensional CFD simulations to investigate the catalytic micro-combustor and the non-catalytic micro-combustor. Their numerical results showed that the catalyst coated micro combustor can be operated at high inlet gas velocities and input high powers. Kamada et al. [23] investigated the combustion and ignition characteristics of natural gas components in a micro flow reactor with a controlled temperature profile experimentally and computationally. Their results indicated a significant effect of n-butane addition in the blends on combustion and ignition characteristics of the blended fuels. Davis et al. [24] studied the contributions of homogeneous and heterogeneous reactions to high-temperature catalytic methane oxidation over three different gauze catalysts (Pt, Pt-10%Rh, and Ni) using laser-induced fluorescence (LIF) spectroscopy. They found that Pt is the most active oxidation catalyst among the three catalysts and with the highest catalytic activity. Maruta et al. [25] computationally studied the extinction limits of methane-air mixtures in a micro scale tube reactor coated with Pt catalyst. They found that the exhaust-gas recirculation rather than lean mixtures are preferable for minimizing flame temperatures in catalytic micro combustors. To enrich the basic research data for micro combustion, and obtain the impact of relevant factors on combustion process, the flammability ranges of premixed methane-air in micro channel were tested in this paper, and the effect of some vital parameters on the stable combustion characteristics were researched, such as equivalence ratio, inlet velocity and the channel height.

2. Experimental setup and method

Schematic diagram of the experimental set-up is shown in Fig. 1. The whole experimental system includes a fuel and oxidizer supply system, a control system and an observation and recording system. The fuel and oxidizer were released by high pressure gas cylinders into the premixed chamber through the flow control system for sufficient mixing, and eventually ignited in the micro channel. The observation and recording system includes an infrared thermal imager, a gas analyzer and other auxiliary equipment.

The structure of rectangular micro channel used in the experiment is shown in Fig. 2. It was made of 316L stainless steel, and three kinds of channel height were designed. The internal sizes of the micro channel are 20 mm × 10 mm × 3 mm, 20 mm × 10 mm × 2.5 mm and 20 mm × 10 mm × 2 mm respectively. The catalyst is platinum, and the size of the catalytic surface is 20 mm × 10 mm. The fuel and oxidizer for the experiment were methane and air respectively. Methane has a purity of more than 99.9% and the outlet pressure for both fuel and oxidizer was 0.15 MPa. The ambient temperature is 293 K and the environmental relative humidity is within 76%. The inlet velocity and equivalence ratio of methane and air were set by the mass flow controller, which is produced by MKS Company of America and it can be used in many situations to measure and control the gas flow rate, especially when the situation required a high repeatability. Its accuracy is up to ±1% and has a response time less than 1 s. The model of the infrared thermal imager is Thermovision A40, and its minimum focal length is 4 mm. It can detect the temperature change between −40 to 2000 °C and its measurement accuracy is ±2%. In the experiment, the VARIO PLUS flue gas analyzer was used, and its measurement accuracy was up to ±0.2%, which can be used to analyze the exhaust gas for a long time continuously.

3. Results and discussions

3.1. Analysis of flammability limits

In order to analyze the flammability limits of the micro channel and the ranges of stable combustion, keeps the flow rate of methane constant at first, then increasing the flow rate of air, the flame will stabilize in the channel, and this equivalence ratio is the flammability limits under fuel rich condition. After the flame has stabilized in the channel, increase the flow rate of air gradually until the flame is blown out of the channel, and this equivalence ratio is the flammability limits under oxygen rich condition. Then, changing the flow rate of methane and repeating the above experimental process, the flammability limits and ranges of stable combustion in the micro channel under different methane flow rates are obtained. The height of the micro channel is 3 mm, and the methane flow rate is increased from 50 sccm to 160 sccm. Fig. 3 is the flammability limits of catalytic and non-catalytic micro channel under different flow rates of methane. It can be seen that with the increase of the flow rate of methane, the flammability limits under fuel rich conditions increase at first and then decrease. When the flow rate of methane is over 80 sccm, the drop slope of flammability limits under fuel rich conditions increases gradually with the increase of the flow rate of methane for the two kinds of micro channels. The flammability limits under oxygen rich conditions decrease linearly with the increase of the flow rate of methane, but the reduction of the flammability limits under oxygen rich conditions in the catalytic micro channel is less than that of the non-catalytic micro channel. For the two kinds of micro channels, with the increase of the flow rate of methane, the ranges of stable combustion all decrease gradually under oxygen rich conditions, but its range in catalytic channel is significantly larger than that of the non-catalytic channel. For instance, when the flow rate of methane is 100 sccm, the equivalence ratio of flammability limits in catalytic micro channel are 0.68 and 1.12, which is larger than that of non-catalytic micro channel, in which the flammability limits are 0.71 and 1.08. Thus, we can draw a conclusion that the addition of catalyst in micro channel can improve the stability of combustion greatly. When the flow rate of methane is low, the flammability limits under fuel lean conditions in the catalytic channel are lower than that of the non-catalytic channel, which indicates that the effect of the catalyst is not obvious under the fuel lean and low flow rate conditions. With the increase of the flow rate of methane, the flammability limits under fuel lean conditions in catalytic channel are significantly higher than that of the non-catalytic channel, which indicates that when the flow rate of methane is high, the addition of catalyst in micro channel can strengthen the combustion reaction, and improve the stability of combustion for methane-air in micro channel.

Fig. 4 is the infrared photos of the outer wall at the equivalence ratio of 1 and inlet velocity of 0.5 m/s, Fig. 4(a) and (b) are catalytic