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Experimental investigation on the combustion characteristics of premixed CH_4/O_2 flame in a micro plate channel

Zhengqian Zha[a], Jianfeng Pan[a]*, Wenming Yang[b], Qingbo Lu[a], Bani Stephen[a], Xia Shao[a]

[a]School of Energy and Power Engineering , Jiangsu University , Zhenjiang 212013, Jiangsu, China;

[b] Department of Mechanical Engineering, National University of Singapore, 119260, Singapore

Abstract:

The combustion characteristics of premixed rich CH_4/O_2 in micro channel was investigated experimentally via the visual micro-scale combustion test bench. The flammability limits, flame behaviors, stability limits and flame propagation speed were researched by changing the combustor sizes and inlet flow rates. The results show that there are three flame behaviors observed in the experiment, respectively external flame at the exit, stable flame in the channel, flame with repetitive extinction and ignition (FREI). Stable combustion zone increases with the increase of CH_4 inlet flow rate. But the stability of the flame at high velocity may not be increased when the inlet flow rate is increased. The flammability limit was greater when the channel height was larger. Meanwhile, the increasing height and the decreasing length of the channel were also beneficial to stability limits in the channel with a certain range of equivalence ratios of 1.25 - 1.80. This experimental study on the combustion characteristics of premixed rich CH_4/O_2 in micro planar channels provides support for micro combustion in the future.

Key words: Micro-scale combustion; Premixed combustion; Combustion characteristics; Flame propagation

1 Introduction

Recent advancement in the fabrication technologies for micro electromechanical systems (MEMS) requires the effort to combine the micro machined electronic and mechanical systems with an on chip micro – power (power MEMS) [1, 2]. Micro-combustors will significantly enhance the functionality of MEMS for many portable devices [3]. One of the most important things in micro-scale combustion is to understand how the flame-combustor structure coupling extends the classical flammability limit and render micro-scale combustion a possibility. The hydraulic diameter of micro-channel is smaller than conventional gaseous fuel quenching distance, which will make the researches on micro-scale combustion a more difficult thing [4-6]. Intensive works have been carried out to investigate the factors on flammability and flame instability phenomena. Earlier researches on combustion in different diameter tubes were conducted by Davy et al. [7]. They believed that the flame could not propagate in a circular tube when the diameter was smaller than a certain critical value, which was defined as flammability limit. Fan et al. [8] examined the flammability limits of premixed CH_4/air in the micro channels and found that the flammability limits decreased with the decline of the channel height. Weigand P et al. [9] proved that flame behaviors were different under different equivalence ratios. A parametric study was performed by Vetlicky B et al. to investigate the effects of equivalence ratio, inlet velocity, inlet fuel distribution, and inlet swirl on combustion stability. It was found that all of these parameters had an effect on the stability characteristics of the combustor. Maruta et al. [11, 12] examined FREI in straight micro tubes and named it Flames with Repetitive Extinction and Ignition. They found that the flame instability in the micro channel was mainly due to the too fast heat loss on

* Corresponding author: Dr. Jianfeng Pan

Address: School of Energy and Power Engineering, Jiangsu University, 301 Xuefu Road, Zhenjiang 212013, China

Phone: +86-15050869595

Fax: +86- 0511-88780210

Email address: mike@ujs.edu.cn

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the wall or the impact of the flame on the inlet. It was found that heat exchange through the structure of micro-combustor could lead to a broadening of the reaction zone in researches. And heat loss to the environment decreased the broadening effect and eventually resulted in flame quenching [13, 14]. Na H et al. [15] pointed out that mixture flow rate had a strong effect on combustion instability. Fig MK et al. [16] proposed an empirical correlation between flame quenching and burning velocity, in that, high flame propagation velocity might lead to combustion instability. As the scale of combustor was reduced to a value comparable to the laminar flame thickness, a heat loss model and a radical quenching analysis proposed seemed more adequate for the prediction of the combustion process inside such a volume [17, 18]. Small scales hindered the experimental approach and enhanced the system dependency of the flame. However, knowledge of premixed flames in micro combustor close to the flammability limits was important in the development of small combustors [19]. In this work, the combustion characteristics of premixed rich CH_4 / O_2 in a micro planar channel were experimentally investigated. To focus on the factors affecting the flame stability, the flame propagation process was recorded to study the flame propagation and combustion characteristics of premixed CH_4 / O_2 using a high speed digital camera.

2 Experimental setup and methods

The experimental setup to investigate the combustion characteristics of premixed CH_4/O_2 flame in the micro channel is shown in Fig. 1. CH_4 and O_2 are passed through their separate pressure reduction valve and the mass flow controller. They then blend in the gas mixer and finally enter the combustor to be ignited. The Mass flow controllers played a role in controlling the flow rates of the reactive gas. Check value was added behind the mass flow controller to prevent gas tempering. A ruler was attached to the edge of the combustor and used to determine the exact position of the flame at any specific time. Supplementary lighting, with cold-light source and high speed digital camera was used to capture images of the flame propagation, which were stored on a personal computer. In the experiment, the high-speed digital shooting frequency was set to 8000 pictures per second, that is, the internal time is 1.25 × 10-4 s between two adjacent pictures.

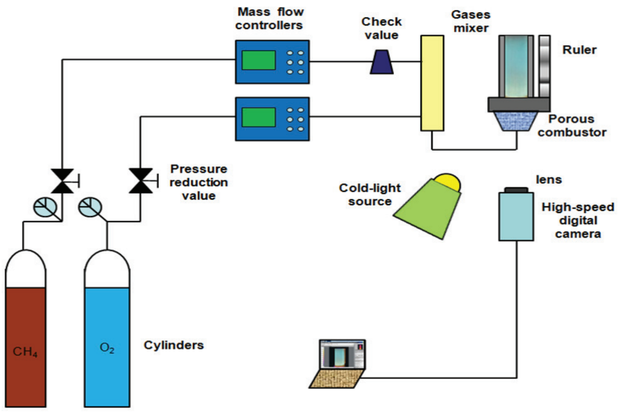

Fig. 1 Schematic of the experimental setup for combustion characteristic of premixed CH_4/O_2 flame in a planar channel.

In the experiment, the micro planer combustor is composed of a piece of quartz glass and a stainless steel groove, as shown in Fig. 2. The main function of quartz glass is to observe the propagation phenomena of flame in the channel. The width of the micro channel is 13 mm, and the wall thickness is 1 mm. In order to ensure the full development of the flame propagation process of FREI, the length of micro combustion channel is designed to 190 mm. However, the length of micro combustion channel was set to 50 mm to make flames easier to be stable. In addition, in order to analyze the influence of the height on the combustion characteristics, the heights of the micro channel were set as 0.6 mm, 0.8 mm, 1.0 mm and 1.2 mm respectively. The maximum value of the Reynolds number in the experiment was 150, which means that the study objects were the premixed CH_4/O_2 laminar flames. The experiments were conducted at the condition that ambient temperature was 20 ℃ and the relative humidity was 45% - 60%.

Fig. 2 Schematic diagram of the micro combustor structure with length 50 mm and height 1.2 mm.

3 Results and discussion

3.1 Combustion characteristics

Combustion characteristics are different for various inlet flow rates and equivalence ratios [20, 21]. Usually, the flame transforms from stable flame into FREI, and finally goes out. The experimental results show that, flammability limit of the mixture is maintained at equivalence ratio of 1.73 ~ 1.77 when the channel height is 1.2 mm. The flame can only enter the channel when the equivalence ratio is below the top curve in Fig. 3. When CH_4 inlet flow rate is smaller than 199 sccm（standard-state cubic centimeter per minute）, the flame remains an unstable state from entering into the channel to extinction. When the CH_4 inlet flow rate is bigger than 199 sccm, the flame is stable when it enters the channel. But with the increasing flow rate of O_2, heat dissipating capacity rises significantly. As a result, the stable flame becomes FREI, being extinguished eventually for excessive amounts of O_2. As the inlet flow rate of CH_4 continues to increase, stable combustion zone becomes larger because the heat produced from the combustion gradually overcomes the adverse influence of heat loss [22]. When the flow rate of CH_4 is greater than 400 sccm, the FREI phenomenon did not occur. The stable flame was extinguished by contacting the entrance surface or blown out at high velocity. Fig. 3 shows that the FREI combustion zone is sandwiched by stable combustion zone and quenching zone, and there is a remarkable negative correlation between FREI combustion zone and stable combustion zone, indicating that FREI is unstable state between stable flame and quenching. In addition, with the increase of CH_4 inlet flow rate, stable combustion zone increases, indicating that increasing the inlet flow rate of CH_4 is beneficial for stable combustion.

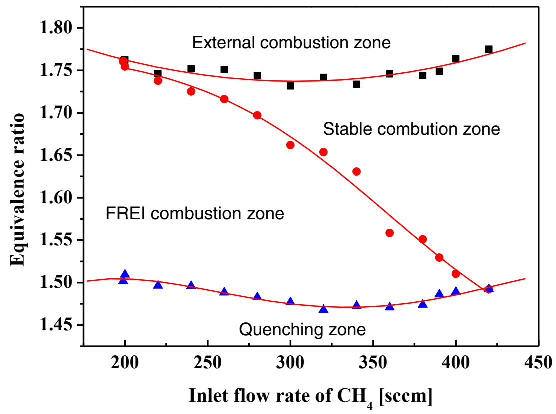

Fig. 3. Partitions of flame behaviors under different inlet flow rates of CH_4.

3.2 The flammability limits of premixed CH_4 / O_2 in micro channel

When the inlet flow rate of CH_4 is constant and the amount of O_2 is too small, there is not enough heat released from combustion to make the flame enter the channel. However if the inlet flow rate of CH_4 is constant and the amount of O_2 is considerably large, the flame may be blown out because of high inlet flow rate. Only in a certain range of equivalence ratio, the reaction can continue spontaneously and the flame can spread in the channel. Fig. 4 shows the relationship between the inlet flow rate of CH_4 and flammability limits under the different channel heights. When equivalence ratio is above the corresponding curve at the same channel height in Fig.4, the flame cannot propagate in the channel. For example, when the channel height is 0.6 mm, flammability limit of the gaseous fuel is from 1.3 to 1.35. Only when the equivalence ratio is less than or equal to the value of the corresponding points on the curve, the flame can propagate in the micro channel. The lower curve location shows the same inlet flow rate of CH_4 mixed with more amount of O_2. As can be seen from Fig. 4, with the increase of inlet flow rate of CH_4, there is a slight upward trend in the flammability limit. That is because, with the increase of total flow rate of the gaseous fuel, more heat generated from combustion will be more conducive to overcome the wall effects, which is one of the major adverse factors. In addition, with the increase of channel height, the flammability limit of the combustion in the channel is also growing. When the channel height is 0.6 mm, the CH_4 / O_2 flammability limit in the micro channel is within 1.3 ~ 1.35. But when the channel height is up to 1.0mm, the equivalence ratio increased to 1.6 ~ 1.7. Even when the channel height is 1.2 mm, the equivalence ratio is expanded to 1.7 ~ 1.8. Because with decreases of micro channel height, the surface-to-volume ratio increase, which leads to wall heat effect and the wall chemical effect more obvious. Too fast heat loss and rapid deactivation of OH radical will lead to the fire not entering the channel [23].

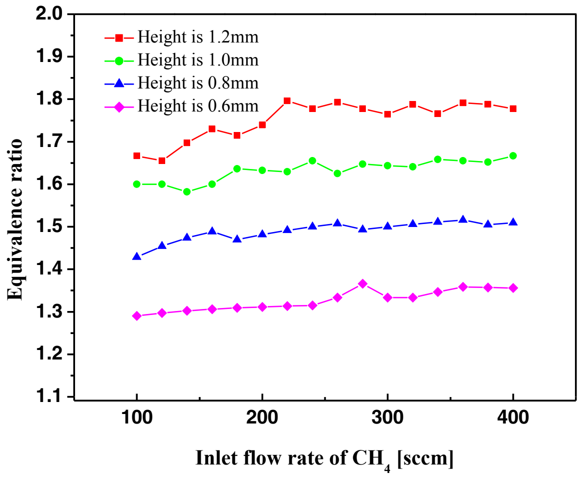

Fig. 4 Flammability limits under different combustor sizes.

3.3 Combustion characteristics of stable flame

Stability problem of the flame has attracted much attention. Fig. 5 shows the relationship between equivalence ratio of stable flame and the inlet flow rate of CH_4 at different lengths and heights of the channels. As can be seen from Fig. 5, the shorter the channel is, the easier it is for the flame to reach the stable state. This is because heat dissipations are more serious in the longer channels. In addition, it is distinct with the changing trend of equivalence ratio with the increase of inlet flow rate in the shorter channel. With the increase of length of combustor, the stable combustion zone decreases. In this regards, the combustion channel with the length of 50 mm is chosen for the study of stable combustion.

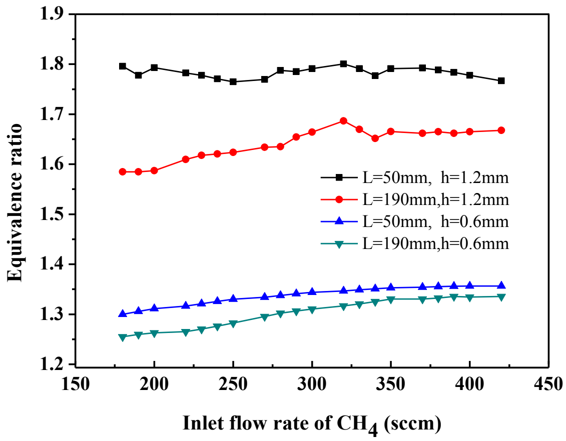

Fig.5 The equivalence ratios under different channels when the flame attains stability.

Fig. 6 shows the relationships among equivalence ratio, speed of gaseous fuel and inlet flow rate of CH_4 when the flame begins with stability. In Fig. 6, with the increase of the channel height, surface-to-volume ratio and the heat loss of the micro-combustor decrease so that it is easier for the flame to become stable. In addition, it can be seen that increasing the flow rate of CH_4 and improving the speed of gaseous fuel at the inlet provide a positive effect on the flame at first, and then they show negative effects. At first, with the increase of the inlet flow rate of CH_4, reaction will produce more heat, which helps the flame to attain stability. But when the inlet flow rate of CH_4 is increased to a considerable value, the beneficial heat effect becomes smaller, and the adverse effect of inlet speed cannot be ignored. Greater inlet speed means shorter reaction time and more heat loss [24], so it is difficult for the flame to attain stability. More obviously, in the 0.6 mm height channel, the inlet velocities are so large that the flame is semi-stable when the inlet flow rate of CH_4 is 380 sccm and the flame transforms into FREI when the inlet flow rate of CH_4 is larger than 380 sccm. In general, the increase of channel height will increase the stability of the flame. And the stability of the flame at high velocity may not be increased when the inlet flow rate is further increased.

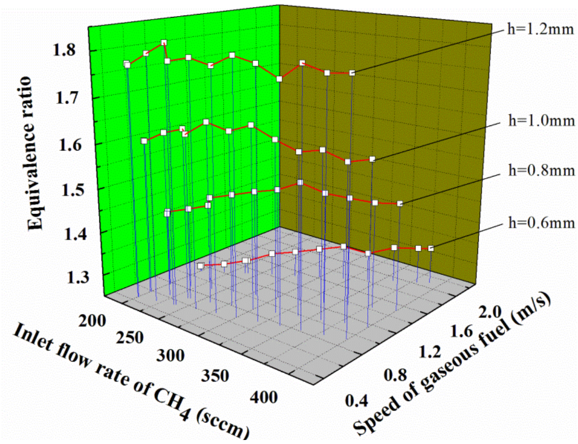

Fig.6 Equivalence ratio under different inlet flow rate and flow velocity.

3.4 Propagation characteristics of FREI

Longer channel is mainly used to study FREI, since large scale facilitates the observation of propagation process. The high-speed digital camera is used to film the flame propagation process. Fig. 7 shows FREI propagation process at the condition that the inlet flow rate of CH_4 is 480 sccm and that the equivalence ratio is 1.88 when the channel height is 0.8 mm. In Fig. 7, a flame front sheet, "U" shape, shallow and narrow, spreads to the upstream from the gas outlet. Gaseous fuel is ignited at the exit, and then the flame propagates in the channel and finally the flame extinct at a certain position. After a period of time, the gaseous fuel will be ignited at the exit again, and then repeat the above processes [25]. This is why the flame is called FREI.

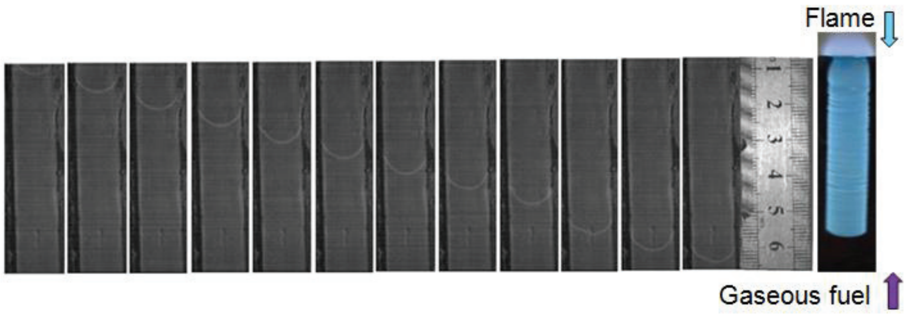

Fig.7 Propagation process of the FREI with the CH_4 inlet flow rate of 480 sccm and the equivalence ratio of 1.88.

When the inlet flow rate of CH_4 is 450 sccm and the equivalence ratio is 1.88, the relationship between the propagation distance and time in the micro channel is shown in Fig. 8. In Fig. 8, curve 1, 2, 3 and 4 respectively represents the four cycles of the flame propagation distance. Four cycles are almost the same. In fact, the whole process in a single cycle can be divided into three parts, ignition at the exit, propagation in the channel and gaseous fuel supplement to the exit. Experimental data showed that the time spent on the first part is less than 5×10^{-3} s. In Fig. 8, the second part from the ignition to extinction time is about 2.4×10^{-2} s, and a complete cycle is 0.062 s or so. The time of the third part is the quotient between the amplitude and the inlet velocity of the gaseous fuel.

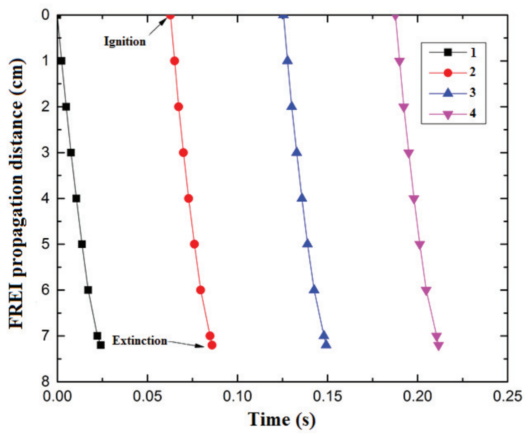

Fig. 8 The trend of FREI propagation distance over time under the channel height of 0.8 mm.

In the range of combustion channel length, the average velocity per cm can be calculated to analyze the flame propagation characteristics. Fig. 9 shows the velocity change trends of FREI at different positions under different equivalence ratios when the inlet flow rate of CH_4 is 630 sccm and the channel height is 0.8 mm. The experimental data shows that, the complete cycles are 0.082 s, 0.078 s and 0.075 s for the equivalence ratio of 1.64, 1.58 and 1.50, respectively. The velocity corresponds to a certain point and is defined as the average velocity of 1 cm in front of the point in Fig. 9. The average flame propagation velocity of the former 1cm is smaller than the later ones, and the flame propagation velocity gradually slows down after 6cm. In the whole process of propagation, the acceleration process is due to the heating effect on the wall from the outer flame at the exit. As the flame propagates downward, the heat dissipation function becomes larger, the heating effect is reduced, the velocity will be flat, then slows down, and finally the flame will turn off. As the equivalence ratio decreases, more O_2 involved in the reaction, the reaction becomes more intense, which leads to a faster flame propagation velocity. And even to the extent that it shortens the time of gaseous fuel supplement to the exit after extinction and increase the frequency. In conclusion, the reduction of equivalence ratio will increase the instability of flame and even result in the extinction.

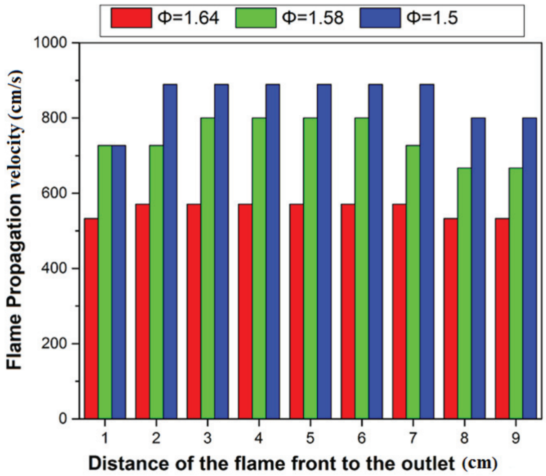

Fig. 9 Speed changes trends of FREI at different positions with the CH_4 inlet flow rate of 630 sccm.

4. Conclusions

In this paper, experimental studies of premixed rich CH_4 / O_2 in the micro channels are conducted to test the flammability limits and flame propagation process. The relationship between inlet flow rate, equivalence ratio of air and flame behaviors are analyzed. The following conclusions were drawn:

(1) For premixed rich CH_4 / O_2 combustion, at the same height of the channel,, an increase in the inlet flow rate of CH_4 leads to increase in the stable combustion zone and the FREI combustion zone decreases.

(2) For premixed rich CH_4 / O_2 in the micro plate channels, the flammability limit was 1.25 when the combustor height was 0.6 mm. However, the flammability limit increased to 1.80 when the combustor height increased to 1.2 mm. As the channel height increases, the flammability limit increases. At the same channel height, flammability limit increases slowly with the increasing inlet flow rate of CH_4.

(3) Under rich fuel conditions, the shorter the channel length, the flame is more stable in the channel. In addition, the flammability limit was 1.30 when the combustor height was 0.6 mm in the 50mm length channel. However, the flammability limit increased to 1.69 when the combustor height increased to 1.2 mm. And as the channel height increases, the flame is more likely to attain a stability state. Experimental results point out that the stability of the flame at high velocity may not be increased when the inlet flow rate is increased.

(4) FREI phenomenon is a kind of unstable state between stability and extinction. Moreover, FREI is similar to a periodic flame, The result shows that, the complete cycles are 0.082 s, 0.078 s and 0.075 s for the equivalence ratio of 1.64, 1.58 and 1.50 when the inlet flow rate of CH_4 is 630 sccm. With the reduction of equivalence ratio, the flame propagation is accelerated, the cycle time becomes shorter, and the flame instability is improved.

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