Experimental and numerical study on methane/air combustion in a micro Swiss-roll combustor

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1 Introduction

With the progress of re1search and development in MEMS, much smaller and higher energy density electrical power sources are required. One possible solution for this might be the development of micro-combustors[1][2] because hydrocarbon energy densities are approximately 100 times higher than the state-of-the-art lithium-ion batteries. One of obstacles to develop a micro combustor is the difficulty of flame stabilization due to increased heat loss by a large surface-to-volume ratio. To overcome this difficulty, a very promising thermal management manner is to employ heat loss to preheating incoming cold reactants. Lloyd and Weinberg[3][4] Proposed and investigated a Swiss-roll-type reactor. In present study, a micro plate Swiss-roll combustor with a groove is fabricated, and experimentally and numerically investigated.

2 Methods of approach

2-1 Experimental setup and combustor model

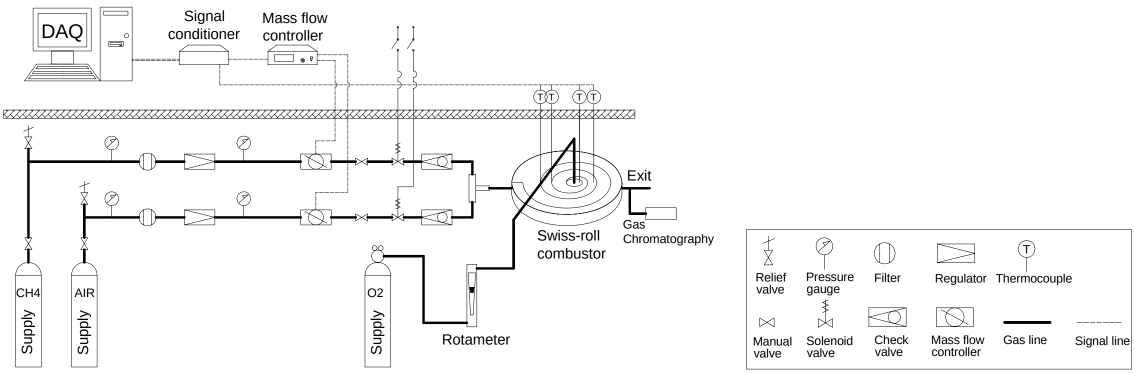

Figure 1. schematic of the experimental setup

The schematic diagram of the experimental setup is shown in Fig. 1. In this study, gas flow rates and outer wall temperature were measured. Major species in the exhaust gas were measured using gas chromatograph(GC-9A). To achieve safe and reliable methane/air combustion in a micro combustor, firstly, methane and oxygen is combusted to heat up its body. Secondly, when surface temperature reaches about 1000K, oxygen valve is turned off and air valve is opened. Then methane/air flame is established in the center room.

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A micro Swiss-roll combustor with an outer diameter of 55mm is fabricated, as shown in Figure 2. Width of inlet channel is 0.6mm, smaller than the quenching distance of a methane flame (2.1 mm) at room temperature and pressure. Width of exhaust channel and thickness of wall between channels are 1mm. A little larger room with diameter of 5mm is designed in the combustor's center. An air groove is cut in the combustor to reduce radial heat loss and heat capacity. Width of the groove is 2mm. In this combustor, both ends of gas channel are sealed to prevent gas flow over the middle wall.

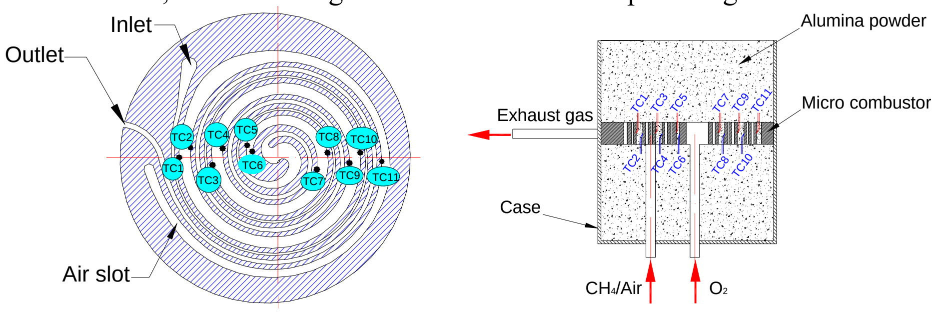


Figure 2. Micro combustor Model

2-2 Numerical approach

To understand flow and combustion characteristics in the combustor, two-dimensional numerical simulations are performed in it. In simulations, laminar transport equations, reduced methane/air reaction mechanism[5] with 35 reversible elementary reactions and 17 species are used. Convective and radiative heat transfer between gas and solid wall is also considered. For convenience of comparison, the simulated combustor has the same mass flux at inlet as that of the experimental counterpart. But the simulated combustor does not have a groove.

3 Results and discussion

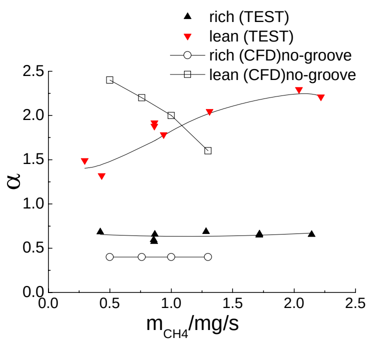


Figure 3. Flammable limits

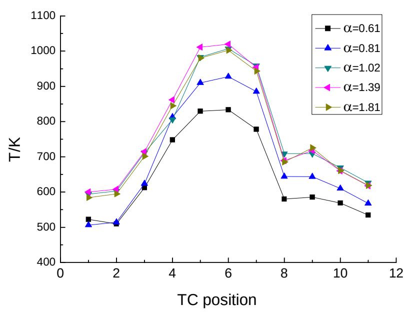


Figure 4. measured surface temperature distributions at various α at $\dot{m}_{CH4}$=0.85mg/s,

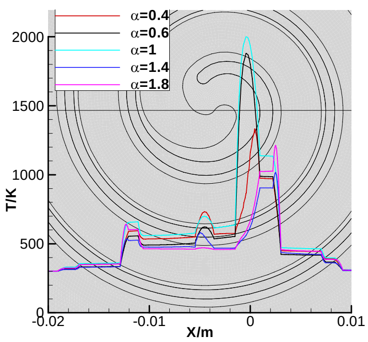
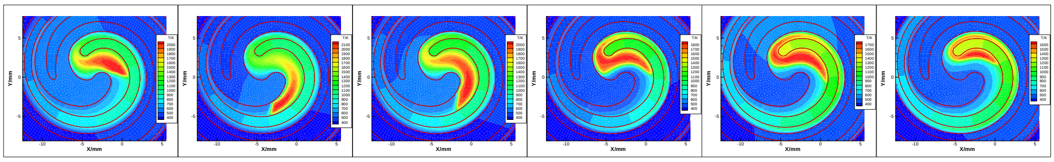


Figure 5. Simulated temperature distribution in the combustor at $\dot{m}_{CH4}$ =0.76mg/s

Premixed methane/air flame was stabilized in the center room. Figure 3 shows flammable limits obtained in experiments and simulation. In experiment's limits, the minimum rich limit is about 0.7 and the maximum lean limit almost reaches 2.2. While in simulation's limits, the maximum lean limit is 2.4 and the minimum rich limit is 0.4. Slope of simulated rich curve is opposite to that of rich curve in experiments. It is due to the numerical model is two-dimensional and there is no heat loss from its both ends. Another reason may be that the model used in simulation has no air groove and its heat capacity is larger than that of the test combustor. Additionally, since there is an air groove in the latter, its minimum methane flow rate allowed for steady operation is even up to 0.5mg/s, corresponding to 3.7W.

Surface temperature distributions on combustor's outside wall are plotted in Figure 5. Abscissa represents thermocouples' positions. It shows that surface temperature reaches a peak value in combustor's center and then declines along the radial. There is a large temperature gradient on the outside wall. When α equals 1.39, surface temperature gradient is up to 29.86K/mm. Figure 5 shows temperature distributions along the straight line in the simulated combustor. It indicates that flame position and the flame temperature both change with variations of α. The simulated highest wall temperature agrees with the measured surface temperature.



(a) α=0.4 (b)α=0.6 (c)α=1 (d)α=1.4 (e)α=1.6 (f)α=1.8

Figure 6. Temperature fileds in the combustor at different air excess coefficients when methane flow rate equals 108.7mg/s, which is corresponding to 0.76mg/s in experiment.

Figure 6 clearly indicates that unburned mixtures are heated up by hot combustion products. In these figures, flame front is an inclined curve, which is tilted from heating wall toward combustor's center. It is due to combustion products preheated unburned gas in vicinity of the heating wall and increases its enthalpy. Figure 6 also shows flame movement with variations of α. Flame is stabilized in a position where temperature gradient is the largest. With increasing α, flame is blown downstream, from a position far from combustor's center, see Figure 6(a), to a position in combustor's center, see Figure 6(d). It is because at this time, inlet gas velocity is low and flame is located where flame speed equals gas velocity. But the flame is also a straight line. Furthermore, if there is more air flow, slope of the flame became larger and the flame would be blowed toward combustor's central room and become a curved surface. Part of incoming air participates in combustion and the rest would flow away without taking part in combustion, as shown in Figure 6(e). When ER equals 1.8, unreacted air would take away more combustion heat, which reduces area of combustion zone and combustion temperature. This will lead to that flame can not be stabilized in the combustor. Eventually, flame would be extinguished.

From the above analysis, it can be concluded that a micro Swiss-roll combustor can steadily work in a larger range of α. Main reason is that unreacted cold gas is heated by hot exhausts and its enthalpy is improved. In addition, concave structure in central room stabilizes flame departing from normal flammable limits and makes it not easily be blowed out.

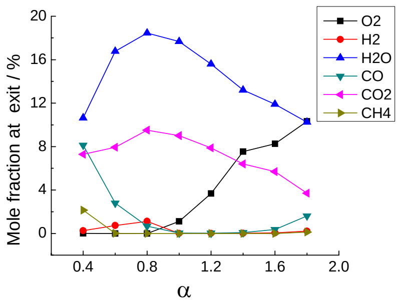


Figure 7. Simulated species mole fraction at combustor exit when methane flow rate equals 0.76mg/s

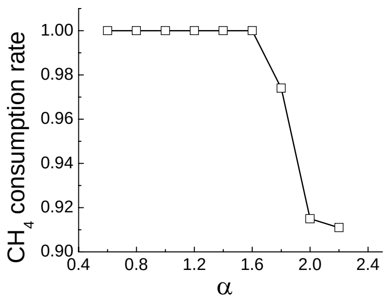
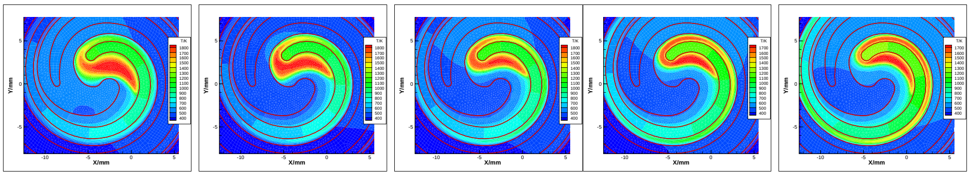


Figure 8. Simulated methane consumption rate at different air excess coefficients when methane flow rate equals 0.76mg/s

Figure 7 shows that when α equals 1, methane is completely oxidized and exhausts are mainly composed of water vapor and CO2. If α is lower than 1, methane is oxidized into H2 and CO. While α is larger than 1, mole fraction of O2 in products is increasing. However, if α is larger than 1, flame is blew downstream and part of incoming CH4 flows away without participating reaction. According to mole fraction of CH4 at exit, methane consumption rate can be calculated, as shown in Figure 8. When α is larger than 0.8 and lower than 1.6, all incoming methane takes part in combustion.



(a) u_{in} = 0.55m/s (b) u_{in} =0.83m/s (c) u_{in} =1.1m/s (d) u_{in} =1.4m/s (e) u_{in} =2.1m/s

Figure 9. Temperature fields in the combustor at different inlet velocities when air excess coefficient equals 1.4

Figure 9 shows that when inlet velocity is 0.55m/s, methan/air flame is located at entrance of the center room and methane completely reacts with air. With increasing inlet velocity, flame is blown into the center room and part of methane participates in combustion. The rest of methane flows away directly without combusting. Additionally, area of high-temperature reaction zone dwindles and it eventually is blown off until quenching.

4 Conclusion

(1)An air groove in a micro-combustor can significantly reduce its thermal loss and extend its flammable limits. In addition, an air groove can also reduce a combustor's heat capacity and make it steadily work at a lower methane flow rate.
(2)An air groove can increase radial temperature gradient on a combustor's outside wall. Wiht a groove, the combustor's center has much higher surface temperature than that on the combustor's edge.
(3)In a micro Swiss-roll combustor, hot exhausts have a strong preheating effect on incoming cold gas. On one hand, it makes premixed flame inclined, and therefore the flame becomes unvertical to flow direction. It is due to preheated gases is more easily ignited than that unpreheated. On the other hand, it makes flame position in the combustor vary with flow veloctiy, air excess coefficient and heat loss to the environment.

References

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