Effects of External Heating on Flame Stability in A Micro Porous Combustor Fuelled with Heptane

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1 Introduction

Recent advances in small scale devices promote growth of demanding portable power source with high energy density and long working time. Liquid hydrocarbon has much higher energy density than common batteries, so combustion-based power source with liquid hydrocarbon fuel has a promising future. To overcome difficulties of complete evaporation and mixing within limiting time, many methods were used in previous researches, such as electrospray technology[1], porous medium combustion[2], liquid fuel-film[3] and so on. Heat recirculation is one of promising ways in miniaturized combustion devices, so effects of heating on flame stability in a micro porous combustor were investigated experimentally. Since this part of heat is provided by heating wire instead of heat recirculation in this research, heat amount can be varied easily and similar methods have been used to study the stabilization mechanism of micro diffusion flame[4].

2 Experimental setup

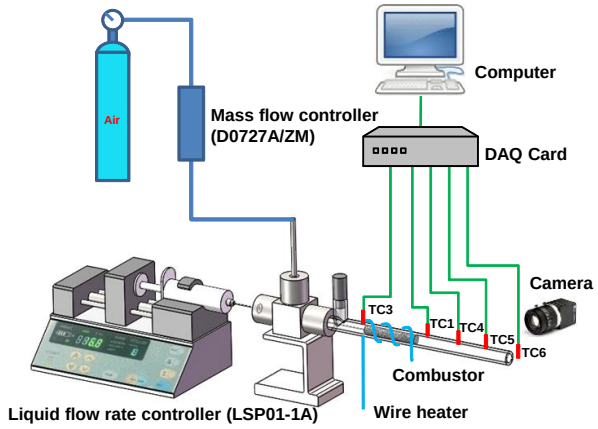

Fig. 1 Schematic of experimental system.

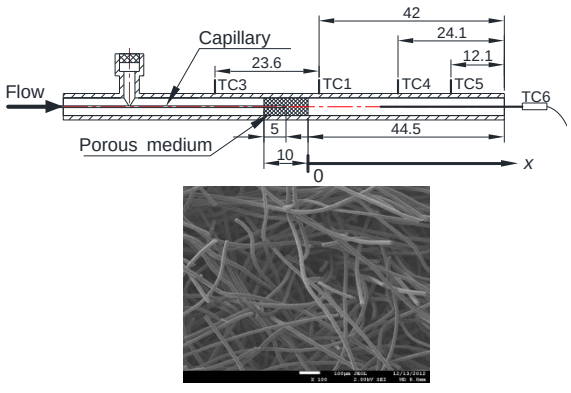

Fig. 2 Structure of combustor (Unit: mm) and SEM photograph of fibrous porous medium.

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Schematic of the experimental system is shown in Fig. 1. A straight quartz tube (I.D. 4mm, O.D. 6mm) is used as micro-scale combustor. Flow rate of compressed air is adjusted by a mass flow controller (D0727A/ZM, 0~0.5SLM). Liquid n-heptane is squeezed into a stainless steel capillary and then injected into the fibrous porous medium with diameter of 4mm and length of 10mm. The flow rate is controlled by a liquid syringe pump (LSP01-1A). Wire heater is placed around outer wall near porous medium and heating power is adjusted by changing voltage. Flame pictures are recorded by a digital camera (JVC, 50-200fps). Temperature of the outer wall, porous medium and exhaust gas is measured by six K-type shielded thermocouples of 0.5mm.

Structure of the combustor is shown in Fig. 2. Right surface of the porous medium is taken as coordinate origin and downstream direction as the positive direction. TC1, TC3, TC4 and T5 are used to measure tube wall temperature, whose positions are shown in Fig. 2. TC2 is located at the capillary outlet to measure porous medium temperature and position of TC6 is x=2.5mm or x=16.5mm.

Electric heating power is expressed by voltage of heating wire (U) for convenience. When the voltage is 3.2V or 6.4V, flame extinguishes after ignition in the combustor. However, when the voltage is between 9.6V and 22.4V, flame is stable and stabilized on the porous medium surface. In these cases, the flame doesn't move into porous medium and there is no flashback, which ensures safety and reduces carbon deposition of fuel. Voltage, heating power, equivalence ratio (ER), air flow rate (Q_a) and heptane flow rate (Q_f) used in this study are listed in Table 1.

Table 1 Experimental conditions

Case No.	Voltage (V)	Heating power (W)	ER	Q_a (L/min)	Q_f (μL/min)	V_{air} (m/s)
C1	9.6	2.6				
C2	12.8	4.6				
C3	16	7.2	1	0.15	17.5	0.20
C4	19.2	10.8				
C5	22.4	14.8				

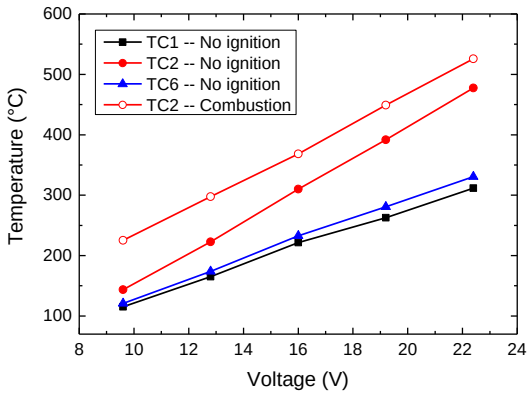


Fig. 3 Preheating temperature of TC1, TC2 and TC6 with various voltages.

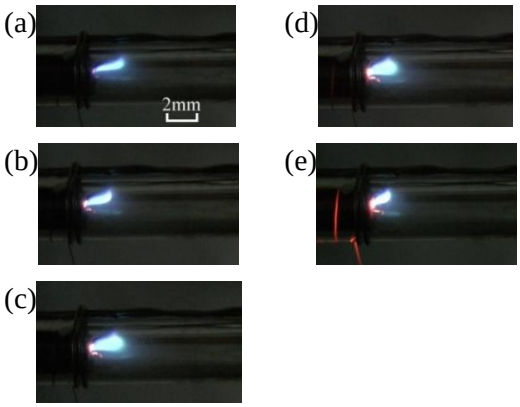


Fig. 4 Flame shapes with various heating power, (a) 9.6V, (b) 12.8V, (c) 16V, (d) 19.2V, (e) 22.4V (Q_a=0.15L/min, Q_f=17.5μL/min)

Obtaining preheating temperature is the premise of analyze combustion characteristics. But it's difficult to calculate convection heat transfer coefficient theoretically because of complex structure of the porous medium. In order to estimate preheating effect, temperature of reactants flowing out of the porous medium is measured by TC6 at x=2.5mm. Fig. 3 shows preheating temperature of combustor wall (TC1), the porous medium (TC2) and unburned gases (TC6) at different heating powers. When voltage increases from 9.6V to 22.4V, TC2 temperature increases from 143.6℃ to 477.6℃, and TC6 temperature is

increased from 120.9 ℃ to 330.7 ℃ accordingly. When mixtures are ignited, flame is stabilized on the surface of the porous medium. At this time, the porous medium is heated by the electric heater and the flame. TC2 temperature with combustion is also shown in Fig. 3. With the heating of flame, TC2 temperature rise varies from 48.1 ℃ to 81.7 ℃ at different heating powers. According to experimental data, the relationship of porous medium temperature (T_2) and temperature of heated reactants in porous medium (T_6) is

$$T_6 = -247.33 + 25.59T_2^{0.5} + 8844.51T_2^{-1}$$

This equation can be used to estimate preheating temperature after measuring TC2 and it will be used later in this study.

Flame shapes with various heating power are shown in Fig. 4. Shape of the flame is non-axisymmetric due to effect of tube wall, assembly error of fuel inlet position and non-uniform diffusion. When U=9.6V, the flame shape is like a sheet. When increasing heating power, flame spreads wider and becomes shorter, and luminous intensity of the porous medium increases, which indicates flame temperature rises.

3 Results and discussion

3.1 Effects of external heating on flame stability

N-heptane flammability limits with heating voltage of 9.6V, 16V and 22.4V is measured to investigate the effect of external heating on flame stability, as "■", "▲" and "●" shown in Fig. 5. With increase of heating power, left boundary of the flammability region is almost kept constant and right boundary is extended. Range of the flammability limits reaches the maximum when U=22.4V. In this case, flame can be stabilized in the tube and heptane flow rate is changed from 10μL/min to 32.5μL/min, inlet air velocity from 0.040m/s to 0.358m/s and inlet equivalence ratio (ER) from 0.343 to 4.285. According to reference[5], flammability limits of heptane vapor in air at 25 ℃ and 1atm is 0.56~3.6. So both lean limit and rich limit of heptane in this combustor are wider than ordinary values. Although small size of combustor is bad for stable combustion, external heating and heat recirculation of porous medium strengthen flame stability and extend flammable limits.

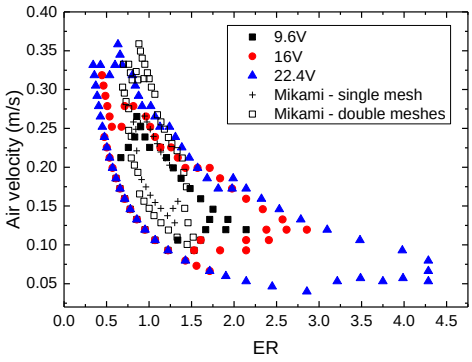


Fig. 5 Comparison of flammability limits between PM combustor and Mikami's combustor[1].

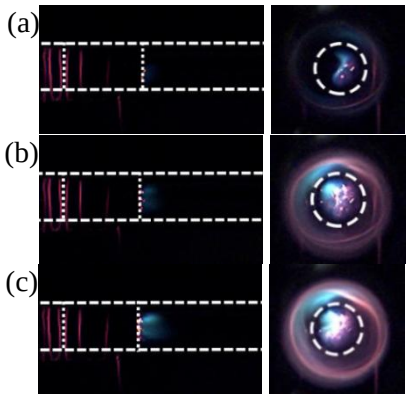


Fig. 6 Q_f=30μL/min and U=22.4V, flame shape with various air flow rates. (a): Q_a =0.06L/min; (b): Q_a=0.09L/min; (c): Q_a =0.12L/min. (Exposure time of left column is15ms, right column is 50ms).

It should be noted that flame is prone to oscillation when Q_f is large and hence the air flow rate range for stable combustion is very small. For example, the maximum air flow rate at which combustion remains stable is 0.13L/min at U=22.4V and Q_f=30μL/min. However, at Q_f=20μL/min, the maximum air flow rate is 0.27L/min. When Q_f is large, the unburned mixture is ultra-rich and flame speed is relatively small. Therefore, the air flow rate range for maintaining stable combustion is small.

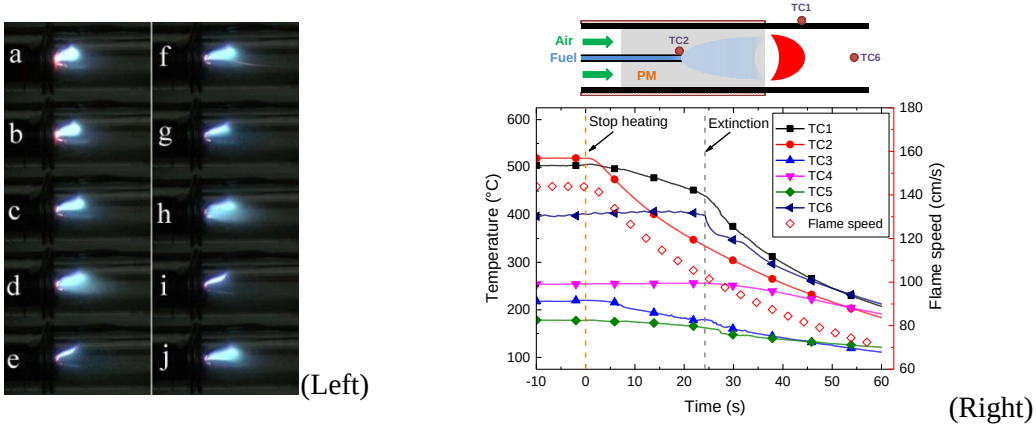
The flammable limits are compared with experimental results of Mikami et al[1]. In their experiment, combustion of electro-sprayed ethanol/n-heptane mixtures inside a meso-scale tube (d=3.5mm) with a single mesh and double meshes was studied. The flame can be stabilized near the mesh without external heating. The measured flammable limits are shown in Fig. 5. Single mesh and double meshes are presented as "＋" and "◇" respectively. As Fig. 5 shows, stable flame can't be obtained when 1.50<ER<4.285 because wall wetting stops electro-spray system. The micro-combustor with external heating and porous medium can still work at these conditions, and there is no accumulation of liquid fuel on the combustor wall. When 1.43<ER<1.5, the flammability limits of our micro-combustor is wider than that of Mikami's combustor. When 0.7<ER<1.178, the lower flammable limit of our micro-combustor is wider and upper limit is lower than that of double-mesh but higher than that of single-mesh. The distance for fuel atomization, evaporation and mixing in Mikami double-mesh combustor is 8mm and liquid fuel is far from flame. The distance in our micro-combustor and Mikami single-mesh combustor is 5mm, so flame stability of the former is better than that of the latter at large flow rate and small ER.

The flame shapes at different air flow rates at Q_f=30μL/min and U=22.4V are shown in Fig. 6. The white dash line indicates position of the tube wall. When Q_a is small, the flame is weak. As seen from side view in right column, the flame isn't evenly spread on the surface of porous medium. If increasing Q_a, the flame covers whole surface of the porous medium and its length increases. However, excessive Q_a will cause flame to oscillate and extinction.

3.2 Effects of external heating on flame extinction

In order to investigate operating state of micro combustor without external heating, stopping heating immediately after system reaches steady state and observing variations of the flame shape and temperature. In this section, ER=1 and Q_{air}=0.15L/min.

At the primary stage after stopping electrical heating, the flame is stable. But the flame length increase and luminous intensity of the porous medium decreases, as Fig. 7(a)-(c) shows, which means flame temperature and flame speed decrease. Then flame oscillation appears, the flame length increases sharply and then becomes very thin, as (d) and (e) show, which is similar to flame at Q_f=20μL/min and Q_a=0.27L/min. After that, the flame becomes stable again. Finally, the flame is extinct after some oscillations. From the analysis above, flame temperature and speed decrease in extinction process. Flame stability is deteriorated without external heating, which leads to extinction.



(Left) (Right)

Fig. 7 Time sequence of flame image (Left) and temperature curve (Right) after stopping heating at U=22.4V. (a) 0.11s, (b) 8.63s, (c) 16.27s, (d) 16.29s, (e) 16.30s, (f) 19.64s, (g) 19.81s, (h) 19.83s, (i) 19.88s, (j) 24.20s.

Temperature variation after stopping external heating at U=22.4V is shown in Fig. 7. After stopping heating, porous medium temperature (TC2) drops rapidly at a rate of 7.6℃/s. Wall temperature near porous medium (TC1) decrease at a lower rate, as shown in Fig. 7. Since reactants are heated by porous

medium before combustion, decrease of TC2 temperature leads to decrease of reactants temperature, which results in decrease of chemical reaction rate and affects the flame temperature and speed. According to porous medium preheating effect equation and relationship between flame speed and temperature[6], S_u=10+0.000342T^2, flame speed is estimated in extinction process. Flame speed decreases from 143.9cm/s to 102.5cm/s following the sharp drop in TC2 temperatures while gas temperature decreases from 43.5cm to 36.2cm/s. A significant decrease in the flame speed is bound to deteriorate flame stability. It can be seen in Fig. 7 that porous medium temperature is much higher than the boiling point of heptane, 98.4 ℃ when flame is extinct. So flame extinction is not caused by the change of heptane evaporation rate. In Fig. 7, TC6 temperature drops rapidly after the flame is extinguished, but it is always higher than TC2 temperature and exceeds TC1 temperature in the vicinity of 245 ℃ after the flame extinction. After flame extinction, air flow is mainly heated by porous medium and tube wall. The higher temperature of TC6 indicates heptane and oxygen are still undergoing low-temperature exothermic reaction after flame disappears. This phenomenon will be discussed in subsequent section.

In order to investigate effect of heating power on stability, voltage is varied from 9.6V to 22.4V, as Fig. 8 shows. The time between stopping heating and flame extinction is defined as the extinction delay time. Results show that extinction delay time increases with heating power. Although flame will be extinct without external heating, it can exist more than 15.7s, which is due to the thermal storage of porous medium. It is noted that TC2 temperature at extinction increases with heating power. Temperature of TC2 at extinction is 334.5 ℃ at U=22.4V, which is higher than steady state temperature at U=19.2V, 227.1 ℃. This indicates that extinction is not only related to the temperature, but also to the flame stability state.

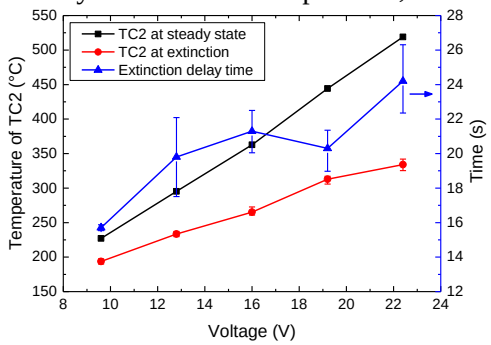


Fig. 8 Temperature of TC2 and hold time at various heating power.

To verify the low-temperature oxidation of heptane in porous medium, temperature of porous medium (TC2) and downstream gas (TC6) are measured before and after injecting fuel without ignition, as Fig. 9 shows. TC6 position is at x=2.5mm in this section. When U=9.6V, temperature of TC2 and TC6 decreases by 16.5 ℃ and 4.1 ℃ respectively after injecting heptane into porous medium because of the endothermic process of heptane evaporation and temperature rise. With increasing heating power, temperature drop of TC2 and TC6 decreases, which means that exothermic reaction occurs in porous medium at these experimental conditions. When U=22.4V, porous medium temperature decreases 10.5 ℃ and gas temperature rises 5.8 ℃ after heptane injection and no flame appears. Fig. 10 shows relationship between initial and final gas temperature during atomization of fuel in heated porous medium and air flow. Gas temperature after fuel injection gradually exceeds that before fuel injection. When air temperature is 330.7 ℃, gas temperature will rise 5.8 ℃ after injection heptane. In order to estimate heat release rate of low-temperature oxidation, sensible enthalpy change of reactants from initial temperature to TC6 is analyzed. Because conversion of heptane is very low due to short residence time[7], it is assumed that the mixture gas flowing out of the porous medium is still composed of heptane vapor and air. When no fuel is injected into porous medium, sensible enthalpy rise of air is due to absorbing heat from porous medium

and tube wall by convective heat transfer. When fuel is injected, sensible enthalpy rise increase about 22.9%~27.5% because of exothermic reaction.

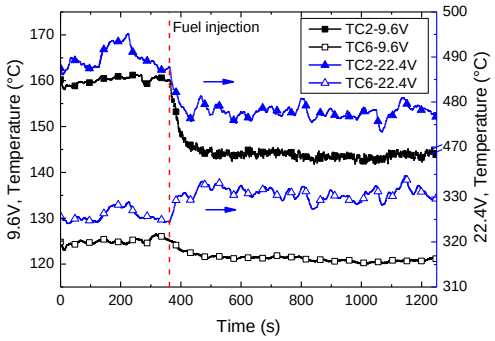


Fig. 9 Temperature curve of TC2 and TC6 before and after injecting fuel at *U*=9.6V and 22.4V.

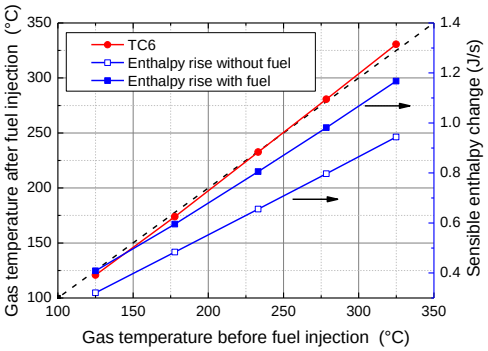


Fig. 10 Final gas temperature and sensible enthalpy rise at different heated gas temperatures.

Above all, possible reason of extinction is that TC2 temperature drop affects the chemical reaction rate, which reduces the flame temperature and propagation speed. This effect deteriorates flame stability and causes flame to oscillate and extinguish. Larger heating power is beneficial to flame stability, so extinction delay time increase with heating power. In addition, low-temperature reaction of heptane in porous medium is exothermal and affected by TC2 temperature. Reaction rate drop of the exothermic reaction can also deteriorate flame stability.

4 Conclusions

In this study, effects of external heating on flame stability in a micro porous combustor are investigated experimentally. Based on the above discussions, the main conclusions are as follows:

(1) External heating can extend flammable limits in micro porous combustor and the limits at heating temperature of 525.7 ℃ is much wider than that at normal state and normal scale.

(2) After stopping external heating, the flame oscillates and then becomes unstable, finally extinguishes. The time between stopping heating and flame extinction is defined as extinction delay time and it increases with heating power. The shortest delay time is 15.7s at *U*=9.6V.

(3) Temperature of mixture increase 5.8 ℃ after n-heptane is injected in to heated porous medium of 324.9 ℃, possibly because low-temperature oxidation reaction takes place. Its effect on flame stability in the micro-combustor needs further study.

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