The Experimental Study on the Droplets Combustion Oscillations in a Fine Straight Tube

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1 Introduction

In the last decade significant advances have been achieved in micro and meso-scale combustion in which power levels are in the range of 10 to 100W. For the micro and meso-scale combustion, flame stability has a great influence on the combustion efficiency. Because of smaller combustion zone, there is relatively large heat loss, resulting in flame stability very sensitive to the environment and perturbance. Especially for liquid-fuel burner, such as hydrocarbon fuels, influence of fuel injection perturbance is very significant, and stable combustion is hard to achieve[1]. But compared with the gas-fuel, liquid-fuel has higher energy density, portability, and safety[2]. In order to take advantage of the liquid-fuel, it is necessary to study the flame behavior and combustion characteristics of the liquid fuel in micro-scale. The combustion process of liquid fuel is complicated and hence, the residence time becomes long. The solutions of the liquid combustion can be divided into three ways. There are preheating vaporization, liquid film combustion, and spray[3]. For spray, because of low injection pressure, small injector diameter, high surface tension, liquid fuel gradually accumulates at the outlet of the injector, and drops on the wall of the burner. As a result, the combustion conditions would change, leading to combustion oscillation. In order to study the influence of fuel type and fuel flow rate on combustion instability, experimental researches on oscillation phenomenon and flame behaviors of droplets combustion in a fine straight tube are performed in this study. It is shown that the energy density and evaporation energy are key factors for the oscillations. The oscillation frequency increases with the fuel increasing, and the minimum amplitude occurs when equivalence ratio is slightly larger than 1. The frequency and amplitude of the temperature oscillations are analyzed using FFT.

2 Experimental Methods

2.1 Experimental system

Experiments were carried out on micro-combustion system which can provide air/oxygen flow, continuous liquid fuel supply, temperature measurement and recording, and the experimental photos, as shown in Figure 1. The facilities consist of a tank of air, gas lines, mass flow controllers, a syringe pump, a data acquisition system, and a fine straight tube combustor. The mass flow controllers are used to adjust the air flow rate, and the flow rate of liquid fuel is controlled by a syringe pump. Shielded K-type thermocouples are used to measure wall temperature of the combustor, which are installed on the wall of the combustor, as shown in Figure 2. The flame photos were taken by a video camera. The combustion occurs in the fine straight tube combustor. The error of the mass flow controller is less than 2% of full scale. The syringe pump pushes the liquid fuel into the capillary tube with the inner diameter of 0.26mm, with an error less than 2%. The frequency response of the thermocouple is 12.5Hz, which is twice larger than the signal frequency.



of the thermocouple

Figure 1. Schematic diagram of micro-combustion system

2.2 Combustor Model

In present study, the baseline model is a fine straight tube combustor, in which the combustion takes place, as shown in Figure 2. The baseline model has an inner diameter of 4mm, and an outer diameter of 6mm, a length of 100mm. The structure and photo of the combustor are shown in Figure 3. A larger quartz tube is put outside of the fine straight tube. The recirculated heat can preheat the cold gas. This measure can reduce heat loss of the combustor, and make the flame more stability. Length of the larger quart tube is 84mm, the inner diameter is 8mm, and the outer diameter is 10mm.



Figure 3. Schematic and photo of the combustion model

2.3 Experimental conditions

In order to study factors affecting combustion oscillations, the experimental conditions were designed, as shown in Table 1.' $\sqrt{}$ ' means it is an experiment case; and '---' means it is not an experiment. For convenience, shortened forms for the liquid fuels were used. Hy means n-heptane; Meth means methanol; Eth means ethanol; and Iso means isooctane. For all of the conditions, the air volume flow rate is 0.8L/min. For different fuels, the volume flow rates are fixed, and the experiments are performed. For n-heptane, the experiments at different volume flow rates were conducted. The volume flow rates are changed from 0.08 to 0.16 ml/min.

Fuel Rate ml/min	n-Heptane (Hy)	Methanol (Meth)	Ethanol (Eth)	Isooctane (Iso)
0.08	\checkmark			
0.09	\checkmark			
0.1	\checkmark	\checkmark	\checkmark	\checkmark
0.12	\checkmark			
0.14	\checkmark			
0.16	\checkmark			

Table 1: Experimental conditions and parameters

3 Results and Discussion

3.1 Flame Visualization

Experiments were conducted to study the flame characteristics in the micro tube combustor under droplets combustion conditions. Combustion oscillation was found in the experiments. Figure 4 shows snapshots of a flame evolution inside the combustor at the fuel volume flow rate of 0.09ml/min. The flame fluctuates periodically, and is in a state of dynamic balance. The temperature history is shown in Figure 5. The flame is intrinsically unsteady and oscillates periodically in response to the disturbance of the injected fuel. Factors influencing the oscillation will be discussed later.



Figure 4. Oscillating flame shapes of the n-heptane combustion



Figure 5. Temperature oscillation history of the n-hetpane Flame

3.2 Effect of Fuel Types

Since different fuels have different characteristics, such as energy density, evaporation performance, combustible performance, molecular weight, such features will affect their combustion. In this section, the influence of the fuel type will be studied. Figure 6 shows the energy density and evaporator energy of four fuels. It shows that the energy density of isooctane is the highest and its evaporating energy is the minimum, and ethanol has the lowest energy density and the highest evaporating energy. In addition, combustion properties of n-heptane and isooctane are very similar.



Figure 6. The energy density and evaporating energy of four fuels

Figure 7 shows the power spectrum of temperature fluctuations, which are analyzed using the Fast Fourier transformation (FFT). First order frequencies of n-heptane, ethanol and isooctane are 0.147Hz, 0.198Hz and 0.141Hz respectively. This is due to that ethanol need a lot of energy to evaporate, so the formation time of the droplets is shorter. The oscillation phenomena of n-heptane is the most obvious and stable, and the isooctane is less, then the ethanol. This situation can be explained as the N-heptane and isooctane have larger energy density and lower evaporating energy. According to Figure 7, the flame of methanol is not influenced by injected fuel, but not stability.



Figure 7. Power spectrum of temperature fluctuation of the four fuels

3.3 Effect of Fuel Flow Rate

Temperature amplitudes as a function of frequency under different n-heptane flow rates are plotted in Figure 8(a). The spectrum shows that the dominant frequencies at each flow rate are different. In Figure 8(b), it is obvious that the dominant frequency and oscillation amplitude are affected by fuel flow rate. They vary from 0.113Hz to 0.267Hz as the flow rate changes from 0.08ml/min to 0.16ml/min. It means that the dominant frequency augments with the increase of the flow rate. For the oscillation amplitude, it decreases at first and then increases with the increase of the flow rate. When the flow rate is 0.12ml/min, the oscillation amplitude reaches its minimum value. The equivalent ratio at this condition is slightly larger than 1. So the disturbance of the fuel injection has less impact on the flame stability.



Figure 8. (a) Power spectrum of temperature fluctuation of n-heptane combustion; (b) Temperature oscillation frequency and max non-dimensional amplitude variation with n-heptane volume flow rate

4 Conclusions

In the micro-combustor, if fuel spray combustion is used, liquid fuel accumulation could occur on the wall of the burner. This kind of perturbance can lead to the combustion oscillation. Fuel types have a great influence on the frequency and amplitude of the oscillation. If the fuel has higher energy density, the combustion oscillation is more stability; and the fuel has lower evaporating energy, the frequency of the oscillation is lower. In addition, the frequency augments with the increase of the flow rate. For the oscillation amplitude, it decreases at first and then increases with the increase of the flow rate, and get the minimum value when the equivalent ratio is slightly larger than 1.

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