Combustion characteristics of n-heptane droplets in a horizontal small quartz tube

Junwei Li*, Rong Yao, Zuozhen Qiu, Ningfei Wang

School of Aerospace Engineering, Beijing Institute of Technology，Beijing 100081

Abstract

To understand the effect of micro straight pipe on the stability of the droplet formation and combustion, n-heptane is used as fuel in 4mm internal diameter quartz tube. The results show that without heating, droplets were easily formed, and when the fuel flow rate is lower than 40μL/min, the flame is influenced by dripping. But evaporation rate is mainly affected by the flame position. It was found that without external heating, it is difficult to form droplets when the n-heptane flow is lower than 60μL/min. Droplet evaporation is greatly influenced by air flow rate. The flame is more easily formed on fuel-rich condition than fuel-lean condition. The lower is air velocity, the higher the wall temperature is, the higher evaporating rate of fuel droplet and lower droplets drop frequency.

1. Introduction

With a strong desire for lighter and longer lasting electronics, combustion in micro-channels emerges as an important field. Combustion of high energy density fuels in small channels can be used in a wide variety of applications. It should be noted that the majority of literature on the micro-combustion has been focused on combustion of gaseous hydrocarbons such as methane and propane. In practical applications, the use of liquid hydrocarbons is more realistic.

Dealing with liquid fuels combustion in micro-combustors would require additional research efforts in fuel evaporation and mixing. The droplet evaporation and combustion process play a crucial role on the combustion stability in the aviation engine, liquid rocket engine and internal combustion engine. Therefore, droplets evaporation and combustion was always a hotspot in combustion research. Many researchers have conducted experiments on droplet evaporation for many years, and a lot of theoretical models were proposed. However, droplets combustion in micro or meso-scale channels is still a significant challenge due to larger surface area, small quenching distance as well as significantly reduced residence time for mixing and combustion. To understand evaporation and combustion characteristics of droplet in micro channels, experiments were carried out in this study. N-heptane was used as liquid fuel, and droplet formation process and interaction with flame at different conditions were studied.

2. Experimental setup

A schematic diagram of the experimental setup is shown in Fig. 1. N-heptane is delivered by a digital syringe pump (Longer, Model LSP01-1A) and a syringe. The syringe is connected with a capillary tube(ID 0.26 mm, OD 0.4 mm), which injects liquid fuel into the combustor (Fig. 2). The air flow rate is controlled by a mass flow controller (Sevenstar, D0727A, 0–5SLM).

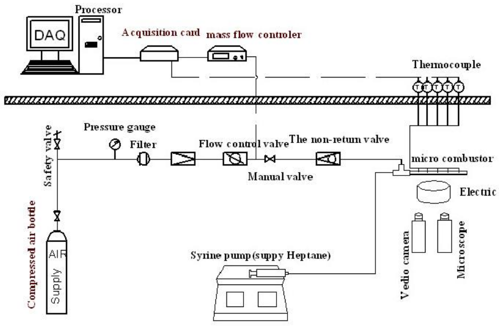


Fig. 1 Schematic of experimental setup

Pressed air is regulated to one atmosphere. Wall temperatures of the combustor are measured by four shielded K-type thermocouples of 0.5mm bead size. Surface temperatures are also measured by an infrared camera (FLIR, Model A40). A digital microscope with a magnification of 250 and maximum frame frequency of 120 fps is used to record the position and shape of droplet and flame, placed in the front of the combustor.

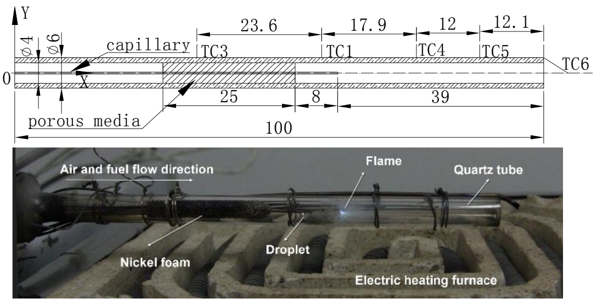


Fig. 2 Schematic diagram of combustor

Schematic diagram of the combustor is shown in Fig. 2. It consisted of a small quartz inner tube (IT), a piece of PM and a stainless steel capillary tube. The inner tube has a length, inner diameter, and outer diameter of 100, 4, and 6 mm, respectively. The IT was mounted horizontally on a stainless steel tee joint, with one end open to the atmosphere. A cylindrical foamed nickel with length of 25 mm, outer diameter of 4 mm is used to support the capillary, and the distance between the foamed nickel and the capillary tip is 8 mm. The capillary tube was pierced through a piece of foamed nickel. N-heptane of 99.9% purity was used as liquid fuel. When n-heptane is feed, small droplets are hanged on the tube tip. When the combustor is heated, the foam can help heat the capillary tube and enhance liquid fuel

*Corresponding author: david78lee@gmail.com

evaporating. In order to study effects of external heating on flame stability, an adjustable electric heater was placed under the combustor and wall temperature can be varied in the tests, as shown in Fig. 2. During the experiments, at first, the combustor is heated to a desired temperature for a long time and then liquid n-heptane is injected into the combustor. Finally, mixtures are ignited at the combustor exit using an alcohol burner.

Since power demand of a micro power device is in the range of 10w-50w, in this paper, experiments are carried out under conditions of equivalence ratio (Φ) in the range of 0.7-1.3 and fuel flow rate in the range of 20μl/min-90μl /min.

3. Results and discussion

3.1 Combustion characteristic of n-heptane droplet without heating

Under normal conditions, the combustor is at room temperature and droplets are formed. Existing of fuel droplets may cause combustion oscillation and flames extinguishment. At this section, the combustor is not externally heated and experiments at different fuel flow rates (20μL/min~90μL/min) and equivalence ratio were conducted.

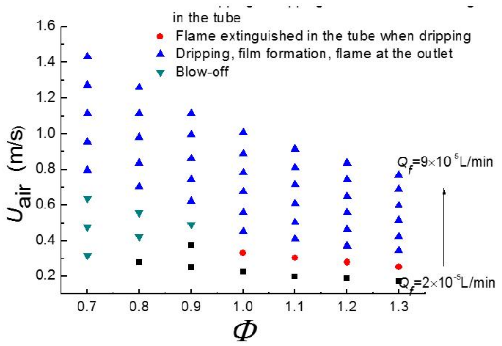


Fig. 3 Flammable limits under no heating condition

Fig. 3 shows the combustion zone of the combustor. According to different combustion phenomena, such as droplet dripping, liquid film forming and flames position, the zone is divided into four subzone. In the first subzone, droplet is suspended at the capillary tip of and stable flame appears in the combustor. In the second subzone, droplets drop on the wall and become vapor immediately, leading to unsteady flames and repeated ignition and extinguishment. Therefore, the droplets affect period of the flames oscillation. In the third subzone, droplets drop and become film on the wall. And the flame is stable. In the fourth subzone, fuel film is formed on the wall and flame cannot be sustained.

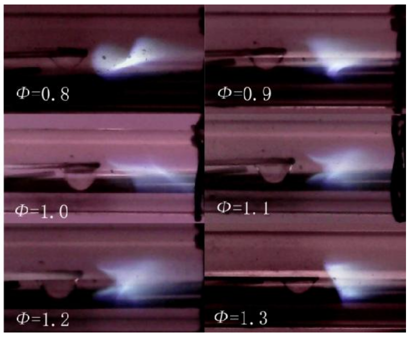
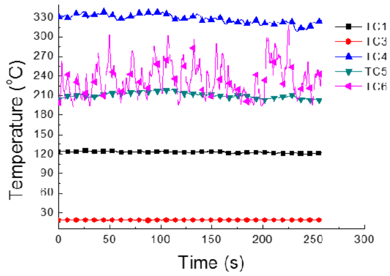
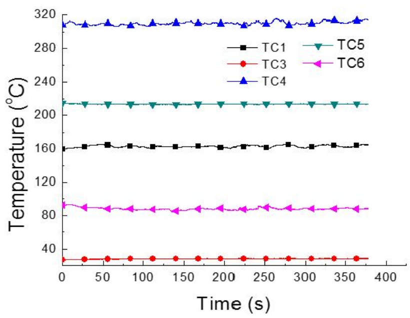


Fig. 4 Photos of flame and droplets at Q_f=20μL/min



(a) *Φ*=0.9



(b) *Φ*=1.3

Fig. 5 Temperature variation of tube wall and exhaust gas at Q_f=20μL /min,

Droplets distribution and flame shape are shown in Fig. 4. With changing of *Φ*, flames shape changes greatly and the flame length tends to decrease. At small equivalence ratios, lower part of the flame is brighter than the upper part due to more time needed to mix fuel and air. But at a larger equivalence ratio, the flame is much closer to the droplet and becomes stable. Temperature change of wall and exhaust over time is illustrated in Fig. 5. It indicates that the wall temperature remains unaffected by dropping of the droplets. But the exit temperature TC6 is greatly affected by the droplet dropping at *Φ*=0.9. Furthermore, Fig. 5 shows that when *Φ* is 1.3, temperatures keep unchanged over time. It concludes that droplets combustion in the micro combustor is mainly influenced by evaporation rate of droplets and heat feedback from the flame.

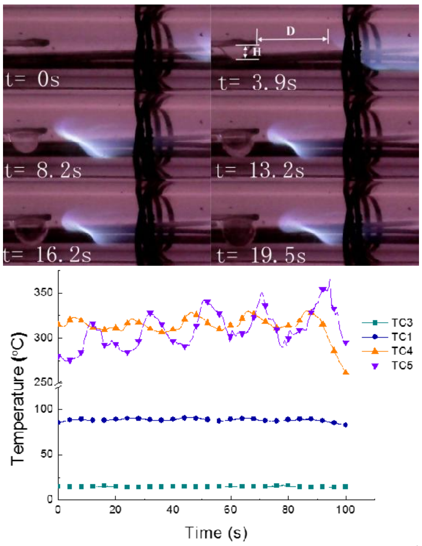


Fig. 6 Photos of flame and droplet and temperature variations with time at Q_f =30μL/min，Φ=1.1

Fig. 3 shows that if Q_f =30μL/min, there is no fuel film on the wall due to hot wall. When Φ is 0.7or 0.8, the flame stays at the combustor exit, and is easily blown out. When Φ increases to 0.9, height and width of the droplets are both 2.3mm, and the flame is stable in the combustor. But when Φ>1, the unburnt mixture is ignited at the exit and the flame quickly moves into the combustor, approaching the droplet. The flame stays near the droplet and does not extinguish until droplet drops. Fig. 6 illustrates the droplet change and flame movements in the combustor. It shows that at Φ=1.1, the flame becomes unstable and is easily disturbed by the droplet forming and dropping.

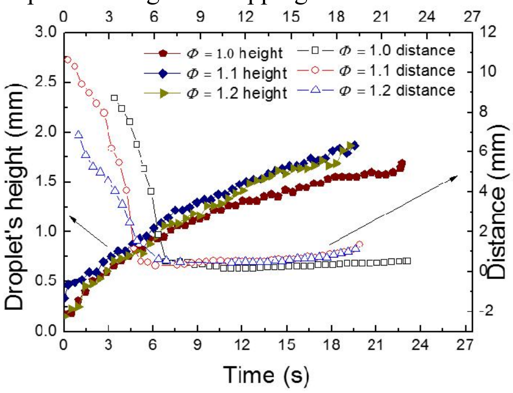


Fig. 7 Distance and droplet height variation with time at Q_f =30μL/min

To get a deep view of the flame propagation in the combustor, an alcohol lamp is used to ignite the unburned mixture at the exit. When Q_f =30μL/min, if the flame is blown out, the mixture will be reignited and the flame moves upstream. The droplet height (H) and the distance (D) between the flame and the capillary tip are plotted in Fig. 7. In this figure, it can be seen that when Φ is 1, 1.1 and 1.2, the mean periods of the droplet dropping are 22.7s, 19.5s and 19.2s respectively. Furthermore, Fig. 7 shows that the flame stays a constant distance from the capillary tip until extinguishment. Before the position of the flame is unchanged, the flame approaching speeds are different at different equivalence ratios. According to D and the moving time in Fig. 7, the approaching speed (U_{flame}) can be calculated. U_{flame} is 1.24m/s, 1.78m/s and 1.12m/s for Φ = 1, 1.1 and 1.2, respectively. Before the droplet dropping, heights of the droplets are 1.69mm, 1.86mm and 1.86 mm for the above Φ respectively.

As n-heptane flow rate increases to a value larger than 40μL/min, the flame can't be easily blown out. The reason is that fuel film is on the wall and the evaporation rate changes little.

3.2 Combustion characteristics at wall temperature of 180℃

To enhance evaporation of liquid fuel, the combustor is heated by a heater to keep mean wall temperature at 180℃, higher than the boiling point of n-heptane. Experiments were conducted at different fuel flow rates and equivalence ratios. Fig. 8 shows combustion modes of the combustor under heating conditions. According to experimental results, the combustion zone can be classified five subzones, which include steady flames without droplet forming, unsteady flames without droplet, droplet dripping with steady flames, droplet dripping with unsteady flames, and flames blown out.

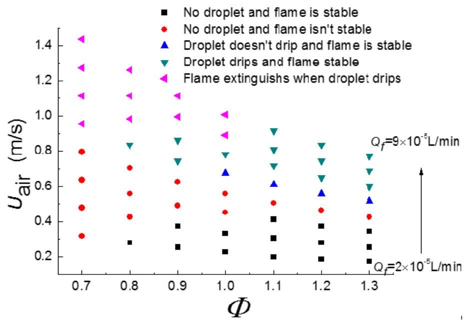


Fig. 8 Combustion status under heating condition

It can be seen in Fig. 8, when Q_f <60μL/min, there is no droplet forming at the capillary tip. The reason is that the wall temperature is heated up to 180℃, and the nickel foam heats the capillary, resulting liquid n-heptane becoming vapor. When Q_f is 60μL/min, in the case of U_{air}>0.74m/s, droplets drops from the capillary tip. In the case of U_{air} <0.74m/s, the droplet is suspendd at the tip. However, in the case of Q_f >60μL/min, droplets always drops on the wall, but no film is formed in all tested conditions due to hot wall.

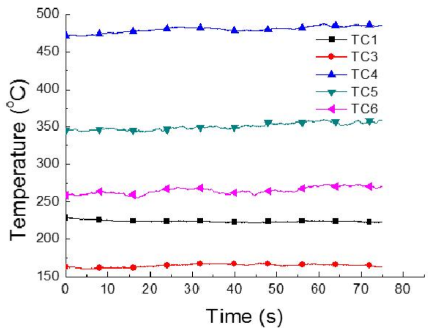


Fig. 9 Temperature of tube wall and exhaust gas at the condition of Q_f =20μL/min, Φ=0.9

In the case of external heating, if Q_f =20μL/min, liquid n-heptane completely becomes vapor and steady flames stays near the capillary tip. When Φ=0.7 and U_{air} =0.32m/s, the air flow is larger, which blows out the flame. But when the air flow is slowed, in the case of Φ=0.9, Fig. 9 indicates that the temperatures of wall and exhausts become stable due to no droplets formed. The temperature of TC4 in Fig. 9 is 145℃higher than that of TC4 in Fig. 5. Similarly, the temperature of TC5 in Fig. 9 is also 140℃higher than that of TC5 in Fig. 5. But, the temperature of TC6 changes little, which is about 260℃.

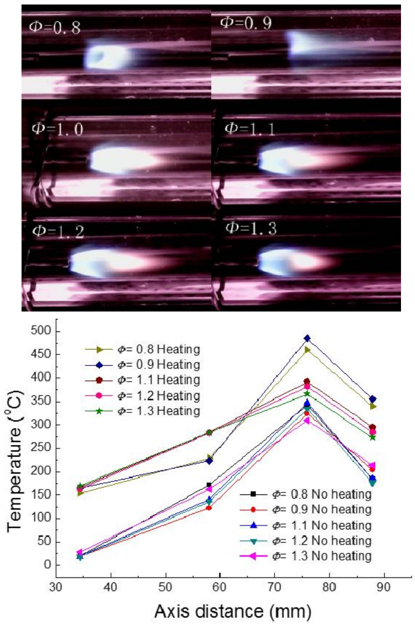


Fig. 10 Flame photos and wall temperature distribution at Q_f =20μL/min under heating conditions

Fig. 10 shows that when Q_f is =20μL/min and Φ changes from 0.8 to 1.3, droplets disappear and the flame is attached the capillary tip. With increasing of equivalence ratio, the flame moves closer to the tip. When Φ>1, flames is adhered at the tip and does not moves forward. Furthermore, Fig. 10 demonstrates that wall temperature in the case of heating is always higher than that no heating, especially at the downstream part of the combustor. With increasing of equivalence ratio, temperature at middle wall increases due to flame moving upstream. Additionally, the maximum wall temperature in the case with external heating occurs at Φ=0.9. But that occurs at Φ=1.1 in the case without heating.

Fig. 8 also indicates that at Q_f =60μL/min, distinct phenomena occur at different equivalence ratios, which is summarized in Table 1. This table indicates that when Φ is larger than 1, the flame can be sustained. When Φ decreases, the flames is blown out as soon as the droplet drops.

Table 1 Combustion state with Q_f = 60μL/min

Phenomenon description	Φ	U_{air} (m/s)
The flame is stable and the droplet does not drop	1.0	0.68
	1.1	0.61
	1.2	0.56
	1.3	0.52
Flame oscillates at the exit when droplet drops	0.8	0. 84
	0.9	0.74
Flame extinguished with the fuel droplet drop	0.7	0.96

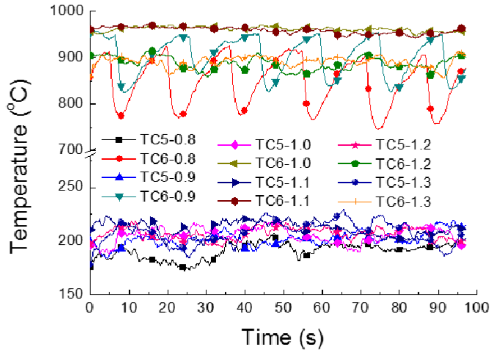


Fig. 11 Temperature of tube wall and exhaust gas at Q_f =60μL/min，

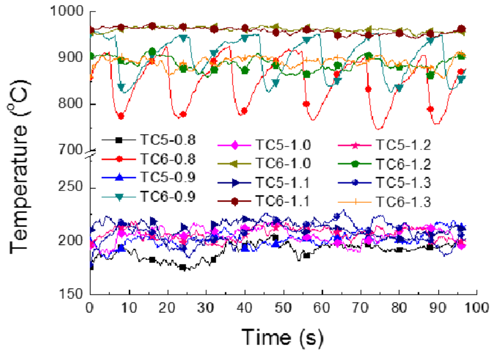


Fig. 11 shows that in the case of Φ = 0.8, there is a large temperature oscillation at TC6, due to periodical dropping of fuel droplet. Amplitude of the temperature oscillation is 143.8℃. But when Φ is increased to 1.3, the temperature curve of TC6 becomes flatter, indicating a stable flame. The large temperature changes in these two cases can be attributed to formation and dropping of the droplets. When Φ = 0.8, the airflow rate is larger than that at Φ = 1.3 and the droplet temperature is lower. When the droplet drops on the wall, it becomes vapor immediately due to wall temperature up to 180℃. The sudden change of fuel vapor concentration leads to equivalence ratio change and hence the flame position and temperature are changed accordingly. However, when Φ = 1.3, the droplet does not drop and the flame becomes more stable.

When Q_f >60μL/min, n-heptane droplets form at the capillary tip and become larger, finally falling on the wall. But due to high wall temperature, liquid film can’t be sustained. When Q_f is 90μL/min, droplets always drop in all cases. If Φ≤1.0, the flame is blown out when droplet drops. But if Φ≥1.1 , the flame is stable at the exit when droplet drops.

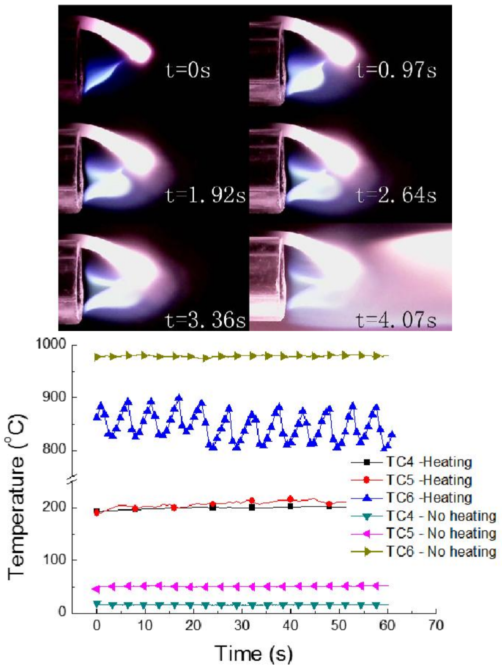


Fig. 12 Photo sequence of droplet and temperature variation with time at Qf =90μL/min，Φ=1.3

Fig. 12 shows that the flame always stays at the exit. In the case of heating, the temperature TC6 oscillates greatly with an amplitude of about 100℃ due to no film formed on the wall. In contrast, in the case of no heating, a fuel film is formed on the wall and the flame steadily stays the combustor exit. Therefore, it can be concluded that heating is advantageous for fuel vaporization, but at larger fuel flow rates, the flame becomes unstable and is easily blown out.

3.3 Effects of air velocity on droplet combustion

Effects of fuel flow rates on flame stability are studied with a fixed equivalence ratio of 0.9 and Q_f variations from 10 to 30μL/min.

Fig. 13 Photos of droplet and flame shape

Fig. 13 shows that when Q_f was 10μl/min, the flame went into the tube after mixture gases was ignited at the outlet of tube and no droplet was formed. Finally the flame remained at the outlet of capillary. When Q_f was greater than 15μl/min, there was droplet at the capillary end. With the increase of the flow rate, the droplet would drop, which had great influence on the flame stability. At the same time, liquid film would be formed and the position of flame moves from the inside to the outlet of tube. The specific conditions at different heptane flow rates are listed in Table 2.

Table 2 The combustion phenomena under different flow speeds

Heptane flow rate (μl/min)	Is there a droplet	Droplet drips or not	Whether the liquid film can be formed
10	×	—	—
15	√	×	—
20	√	√	×
25	√	√	√
30	√	√	√

Heptane flow rate (μl/min)	Whether combustion is stable	Position of flame	Quench or not when droplet drips
10	√	Outlet of capillary	—
15	√	Inside of tube	—
20	×	Inside of tube	quench
25	√	Outlet of tube	Not quench
30	√	Outlet of tube	Not quench

When Q_f =10μl/min, the air flow rate was low and the flame stabilized at the outlet of the capillary, which heated the capillary strongly. Due to small heptane flow rate, the heptane can evaporate completely at the outlet of capillary and no droplet came into being. The combustion can be seen as spray combustion and the left lateral of flame was vertical to the flow direction. When Q_f was 15μl/min, the air flow rate increased, which made the flame have a certain distance from the outlet of capillary. So the heating effect of flame on the fuel reduced. Combined with the increase of fuel flow rate, the fuel droplet is generated at the end of capillary. Under the influence of droplet evaporation, the left lateral of flame inclined obviously and formed a certain inclined angle with the flow velocity. When Q_f equaled 20, 25 or 30μl/min, the evaporation capacity was insufficient, which made droplet appear and drip at the end of capillary.

When Q_f=20μl/min, the fuel flow rate was relatively small. After the droplet dripped and evaporated, a new droplet appeared. In the process of the new droplet increased, the flame was extinguished due to insufficient fuel evaporation amount. In order to investigate the change laws of droplet dripping, flame propagation, the flame of combustion and the temperature of combustor as well as the interaction between them, an alcohol lamp was fixed in the outlet of the straight tube as the ignition source during the experiment. When the mixed gas reached the combustion condition, the flame was ignited and passed into the tube. In the beginning, the flame can only reach the half of tube. Over time, the temperature of tube increased and the flame can pass to nearby the droplet after the droplet drips. Finally, the law of oscillation tends to remain unchanged. When Q_f = 25 or 30μl/min, the droplets drip in the bottom of the tube and form liquid membrane. The liquid membrane can't evaporate completely before the droplet dripped, which ensured the enough content of fuel in the mixed gas. Because of this, the flame would not be extinguished in the outlet of tube and would oscillate slightly when the droplet dripped.

Under different flow rates, the variation of nozzle temperature with time is shown in Fig. 14. As the figure shows, the variation trends of nozzle temperature are different at different flow rate of fuel. When the flow rate was 10 or 15 μl/min, the temperature was stable in the end. And in other experimental conditions, the temperature changed with the drippage of droplet.

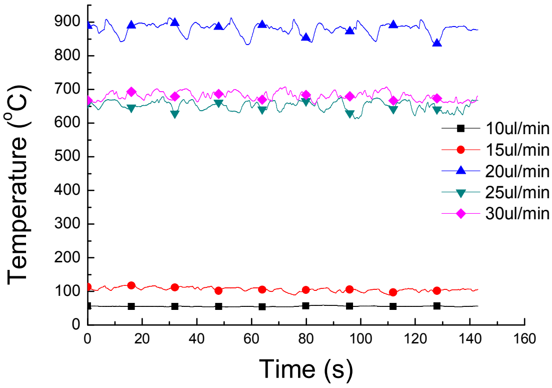


Fig. 14 Nozzle temperature changed with time under different flow rates

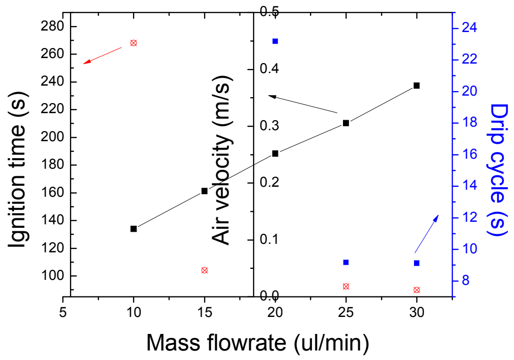


Fig. 15 The ignition time and liquid drip period

The variation of ignition time and droplet drip period with flow rate is shown in Fig. 15. It can be seen from the figure that ignition time and the drip period of droplet shorten gradually as the flow rate of heptane increases.

4.Conclusion

In this study, experiments on n-heptane droplet combustion in a micro combustor were conducted. Effects of fuel flow rate, equivalence ratio, external heating and air flow velocity were studied. It can be found in the following.

1) In case of no heating, unstable combustion occurs due to formation of fuel film on the combustor wall and dripping of droplet. The evaporation rate is mainly affected by the flame position which is affected by the air flow velocity. With the increase of droplet size, evaporation rate increases gradually, and this has certain influence on the flame position.
2) External heating make the formation and dripping of droplet difficult when the fuel flow rate is small. Therefore, the combustion is stable. But when the flow rate is large, lean burn flame can easily been blown off due to the instantaneous evaporation when droplet dripping, and unstable combustion be caused. Droplet vaporization and dripping mainly affected by the gas temperature which is controlled by air flow velocity.
3) When the equivalence ratio is fixed, the flow rate has a great influence on the flame position. And due to droplet dripping, when Q_f >20μl/min, the flame can't be stabilized in the combustor.