# EXPERIMENTAL RESEARCH ON COMBUTION CHARACTERISTICS OF LIQUID FUEL IN STRAIGHT TUBES

**YANG Fei, LI Jun-wei, ZHOU Zhao-qiu, ZHANG Xin, WANG Ning-fei**
e-mail: yfimissyou1984@163.com.cn
School of Aerospace Engineering, Beijing Institute of Technology, Beijing 100081, China

**Abstract**: In order to study the liquid hydrocarbon fuel (n-heptane $c_7h_{16}$) of the combustion characteristics, in the paper we designed a burner consisting of a micro stainless steel tube which is used to dump the fuel and another thicker stainless steel tube (or quartz tube) as combustion chamber, and micro stainless steel tube's inner diameter is 0.24mm, the inner and external diameter of tube as combustion chamber were 4mm, 6mm, respectively. We investigated experimentally the combustion characteristics under the different conditions such as the equivalence ratio, fuel flow, mixed gas flow rate, material and so on. According to the experimental results, in the burner the process needs about 100s from ignition to achieving a steady state; the equivalence ratio changes from 0.45 to 1.65, the temperature of burner external wall first increases and then decreases, the equivalence ratio of 0.55 is equal to the boundary; the flame changes dark with the equivalent and mixed gas flow rate increasing, the shape becomes thinner and longer; surface temperature distribution of the stainless steel burner is less uniformity than that in the quartz tube, but the wall maximum temperature was lower. In short, this structure of the burner show poor combustion characteristics, we should change the structure and the experimental conditions to achieve better combustion characteristics.

**Keywords**: micro-combustion; liquid fuel; experimental research

## Introduction

With modern technology developing, the technology-based on MEMS micro-power system has also obtained much more concern. An important feature of micro-power system utilize the combustion of fuel or propellant in the micro-burner to produce the gas with high temperature and high pressure to drive turbines or other power units, which convert chemical into energy directly or indirectly other forms of energy, for example heat or power. Liquid hydrocarbon fuel has the high energy density as one of the greatest advantage, and thus what is used as fuel for micro-power system has a very good application prospect in this respect. That can be not only used as power sources for micro-satellites or micro-aircrafts, but also as micro-power based on fuel combustion. Liquid fuel has the advantages of small volume, high energy density, convenience of storage and transportation and less danger of explosion, so it has very nice practicality. However, there are some disadvantages of difficult volatility or easy formation of coke, which make it (liquid fuel) difficult for combustion. Clearly, in regard to liquid fuel combustion, good evaporation and abundant mixture with the air are the main requirements for the system. What's worse, in the micro-burner, because of the size decreasing, on one hand the addition of relative heat loss area make the flame unstable in the burner; on the other hand, the flame should not spread within such a small burner. Therefore, research on the combustion characteristics of liquid fuel in the micro-burner as the core component of micro-energy systems has attracted many researchers [1-6].

Currently, most studies selected gas combustion as the fuel in the micro straight pipe, ZHANG Yong-sheng et al experimentally investigated premixed combustion of hydrogen and air in the micro pipes, but never concerned about the characteristics of the flame shape [7-8]. CHENG qiang et al studied the internal temperature and the outer wall temperature in the burner with the preheat temperature and premixed gas flow rate changing, but didn't do the corresponding experiment [9]. LI Jun-wei et al experimentally studied and simulated combustion characteristics and heat loss in the micro-tube [10-11]; J. Li et al studied the transient flame characteristics and wall heat flux in the burner [12]; Yong Fan et al experimentally studied the premixed combustion flame within the ultra-thin quartz channel [13]; Takashi Sakurai et al studied the and combustion characteristics and reduction heat loss in the micro-burner[14]; Nam Il Kim the disturbance of inlet temperature to effect the flame propagation in the micro- tube [15]; Ai-wu Fan et al experimentally studied and simulated the flame structure in the semi-circular shaped combustion channel [16]; Jun-hu Zhou et al used internal electric heating to improve the stability of micro-combustion [17]; Christopher J. Evans the operating mechanism of the rich combustion zone in medium-scale and non-adiabatic tube [18]; Vijaykant Sadasivuni et al proposed a syringe to generate liquid fuel droplets, and verify it though the numerical simulation [19]; J. Chen et al Experimentally studied diffusion flame properties of liquid ethanol in the micro straight tubes [20]. Lin Bo-ying et al simulated constant volume ignition of n-heptane ($C_7H_{16}$) droplets in an inert porous medium [21]; Kang Quan-sheng et al experimentally studied thin film combustion characteristics in the small-scale pool [22].

In order to study the combustion characteristics of liquid n-heptane; we work the cylindrical burner; and carry out experimental study. In this paper, we do combustion experiments based on the fuel and oxygen/air in the quartz and stainless steel burner. Since n-heptane combustion with the mixture of oxygen and air, the reaction equations of n-heptane and gas: $C_7H_{16}+11(O_2+n*N_2) =7CO_2+8H_2O+11*n*N_2$, $(f/o)_{st}=100/（11*32+11*n*28）$ ($n$ means the molar ratio of nitrogen-oxygen in the gas mixture, $(f/o)_{st}$ means the mass ratio of fuel and gas mixture in theory), so the equivalence ratio $ER$ is that:

$$ER = \frac{u\cdot\rho_1 / (u_1\cdot\rho_2+u_3\cdot\rho_3)}{(f/o)_{st}} \tag{1}$$

( $\rho_1$ is the density of n-heptane, $u_1$ is the oxygen volume flow, $\rho_2$ is the density of oxygen, $u_3$ is the air volume flow, $\rho_3$ is the density of air), in paper $u$ means n-heptane flow, unit as mg/s $v$ means the velocity of gas mixture, unit as m/s.

## Experimental Setup and Model

### 1 Experimental system

This experiment is done in the micro and small testing experimental platform, the experimental system shown in Figure 1. Experimental system consists of fuel and oxygen/air supply system, testing and data acquisition system, ignition system, micro-tube burner and fixed stand and so on. Supply system includes high pressure cylinders, pressure reducer, valves, mass flow controller, check valve, liquid injection pump and pipes and so on. In experiment as long as we adjust the equivalence ratio of fuel and oxygen, and can receive reliably flame place. And then under circumstances of maintaining a stable combustion, we gradually change the oxygen/air flow, that is, the experiment changes the ratio of nitrogen and oxygen in the mixture to achieve the different conditions.

The main parameters are measured in experiments including air、oxygen and fuel mass flow, the different wall temperature of combustion chamber (Stainless steel tube and quartz tube) and the flame shape and position in the different conditions. The air and oxygen mass flow controller utilizes D0727A/ZM, measurement error is less than 2% of full scale.

One of obstacles in micro-scale combustion tests is the measurement of the extremely small fuel flow rates. A syringe pump, which provides an accurate measured flow rate, was used to pump the liquid fuel into the capillary tubes. The syringe pump controlled the fuel flow rates from 0.831nL/min to 54.155mL/min with a deviation of less than ±0.5% when it is more than 30% of Full scale. Since the syringe pump was driven by a step-motor, the fuel flow oscillated a period of:

$$T_{pump} = \frac{\pi \cdot r_{syringe}^{2} \cdot l}{Q} \tag{2}$$

One micro step of the step-motor drove the syringe a distance of $l = 0.156\mu m$. From Eq. (2), a flow rate of 1.83mg/s corresponds to a period of about 21ms, with 2.3mg/s corresponding to 28ms. The timescale of the experimental phenomenon was much longer than dozens of milliseconds; consequently, the liquid fuel pumped by the syringe pump can be considered to be continuous. K-type thermocouple is used to measure the wall temperature, CANON HF200 type camera is used to record the location and shape of the flame. Simultaneously, LABVIEW software is used to collect the gas flow and temperature signals, also send command signals, adjust the size of the flow mass flow controller and display the test temperature. A variety of sensor outputs are continuous analogue signals, in order to be computer acquisition, we need to use A/D converter to convert the analogue signals into digital signals which the computer can capture [10].

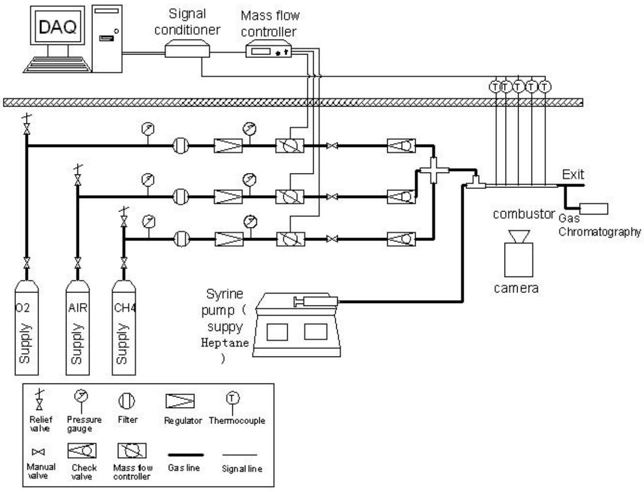
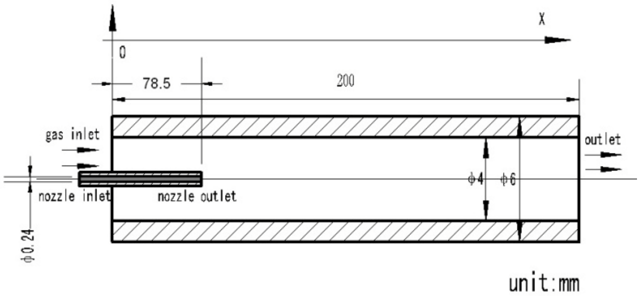


**Figure 1**. Experimental system figure

## 2 Experimental Model

The model for straight channel structure with the cylindrical shape is shown in Figure 2, laid horizontally. The section of the burner diameter is 4mm, thickness is 1.0mm. An micro stainless steel pipe with outer diameter of 0.4mm, inner diameter of 0.24 is inside stainless steel tube (quartz tube), which is used to inject liquid fuel into the tube to ensure that liquid fuel emitted is very little and the droplets will be very small. To facilitate to measure temperature distribution and observe flame shape, in this paper, we select two kinds of materials of stainless steel and quartz tube to experiment. The former is used to measure the surface temperature distribution, which is used to observe the shape and location of the flame. Figure 2a left is quartz tube, the axial distance of TC1、TC2、TC3、TC4、TC5 and coordinate origin is 78.5mm、100mm、112.8mm、126.5mm、147.4mm, separately; Figure 2a right is stainless steel tube, the axial distance of TC1、TC2、TC3、TC4、TC5 and coordinate origin is 78.5mm、89.2mm、100mm、121.5mm、143mm, separately。

(a) Physical figure



(b) Schematic figure

**Figure 2**. Combustor's physical and schematic figure

## Experimental results and analysis

### 1 Characteristics of Flame

（a）*ER*=0.55 （b）*ER*=0.89 （c）*ER*=1.08

**Figure 3**. The flame images with equivalence ratio changing

Passing into the appropriate amount of mixed gas and liquid n-heptane, and igniting at the right end of the tube, flame is passed to the tube and combusts stably there. Then we adjust the oxygen/air flow to achieve the different conditions, and capture flame images such as figure 3, figure 4 and figure 5. Because gas mixture is poured to the tubes without vortex, therefore the shape of the flame shape is thin and long. Figure 3 shows the mass flow rate of n-heptane was 1.83mg/s, and gas flow rate is 0.8m/s, the flame is changed in shape and brightness with the equivalence ratio changing, it can be seen from figure that with the equivalence ratio increasing from 0.55 to 1.08, flames in shape change from thick to thin and its length increases slightly. The brightness of the flame dims gradually from bright white to blue, the flame temperature decreases and its location moves downstream. It is possible because with the equivalence ratio increasing it reduce the oxygen content of the oxygen/air mixture, and oxygen is not adequately mixed with the liquid n-heptane, so inadequate combustion and releasing heat reduction.

（a）*u* =1.376mg/s （b）*u* =1.83mg/s （c）*u* =2.3mg/s

**Figure 4**. The flame images with n-heptane flow rate changing

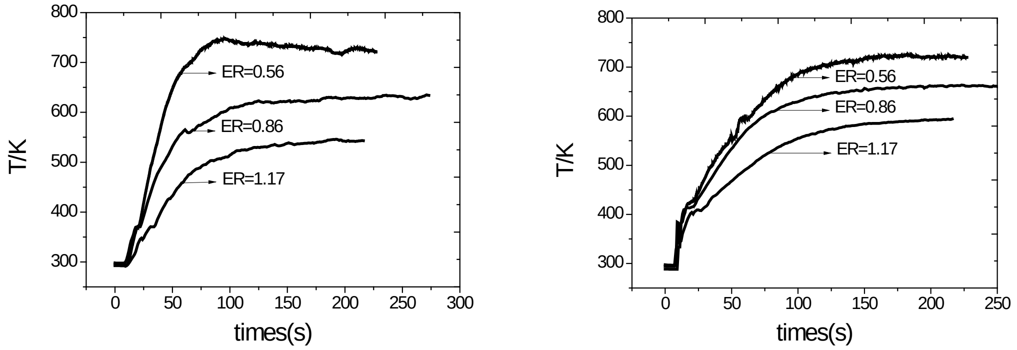
Figure 4 shows the operating conditions of ER of 1.08, gas mixture flow rate of 0.8m/s, the flame changes with the increase of n-heptane flow from 1.376mg/s to 2.3mg/s. From the figure it is clear that the shape and brightness of the flame has changed with the increase of n-heptane flow, the colour from blue to white and shape from a long and thin to thick and fat, the flame length is obvious increased, but the location of flame does not change, and the highest temperature point moves to the right, because under the same equivalence ratio increasing the fuel flow makes more n-heptane to participate in combustion reaction with oxygen, releasing more heat, part of the heptane need to response in the downstream, so the flame changes brighter and longer.

（a）*v*=0.6m/s （b）*v*=0.8m/s （c）*v*=1.0m/s

**Figure 5**. The flame images with the velocity of gas mixture changing

Figure 5 shows the n-heptane flow of 1.83mg/s and the ER of 1.08, the flame shape changes with the mixed gas flow rate increasing. It can be seen from the figure, with the gas flow rate increasing from 0.6 to 1.0m/s, the flame shape becomes from thick to long and thin, its brightness dimming, and its colour turns blue. In the course of the experiment, with the n-heptane flow rate and equivalence ratio unchanged, we only change the ratio of air and oxygen in order to increase the mixture flow rate. When the mixed gas flow rate increases, it needs to reduce the oxygen flow, and increased air flow, so that the oxygen content in the gas mixture is reduced, all the mixture temperature will drop. In addition, because there is no swirl of gas mixture, increasing gas flow rate will make the flame thinner.

## 2 The dynamic changes of wall temperature



TC2 wall temperature TC3 wall temperature

**Figure 6**. Real-time temperature changes under the condition of different equivalence ratio

Figure 6 shows the wall temperature curve under different equivalence ratio and time. Fuel flow is 1.376mg/s, TC2 and TC3 are the downstream wall temperature positions, shown in Figure 2. It can be seen from the figure, about 100s after the ignition flame is stable, two points temperature drop with the equivalence ratio increasing, that is said that temperature and equivalence ratio are negatively correlated. Because it makes incomplete combustion due to increasing the equivalence ratio, thereby reducing the heat release. Comparison of the two figures shows TC2 position temperature changes than the TC3 slowly in the first few seconds after the ignition, and after the time TC2 position temperature change than TC3 fast, it indicates the flame begins to spread from the TC3 location to TC2, and stabilizes in the upstream of TC2 position, then the two wall temperature reaches a steady state. The process time required for the two wall temperature is the same basically. In summary, it shows that when comparing with the time required in a steady burning state, the equivalence ratio almost take no effect and the main impact of combustion heat release.

## 3 Wall temperature distribution

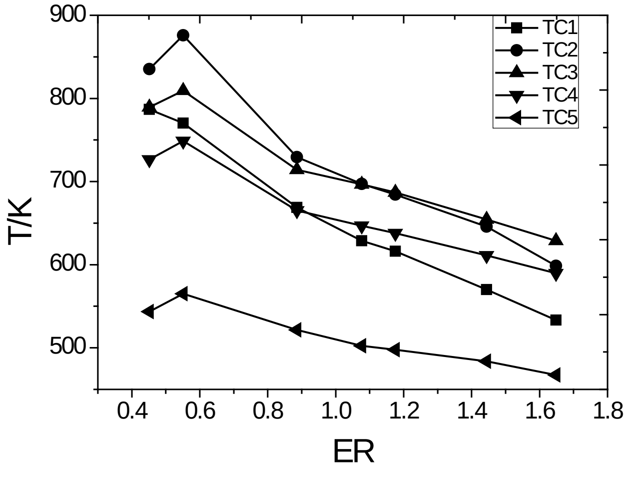


**Figure 7**. The curve of wall temperature under the condition of different equivalence ratio

Experiments change the equivalence ratio by adjusting the oxygen content in the gas mixture, accessing to the temperature of different locations. Figure 7 shows the changes of the point wall temperature with equivalence ratio at the operating conditions of the fuel flow 1.8347mg/s, the gas flow rate of 0.6m/s. With the increase of equivalence ratio from 0.45 to 1.65, that is from rich oxygen to rich fuel, as the boundary of the equivalence ratio ER = 0.55, the burner wall temperature distribution increases and then decreases; In addition, the equivalence ratio is from less one to more one, the changes of TC2 is first higher and then lower than TC3's, it shows the highest temperature moves from location TC2 to location TC3, flame moves downstream with the equivalence ratio increasing. The main reason is that it decreases oxygen content in gas mixture, increases the time to mix liquid n-heptane with oxygen, and the combustion reaction zone will move downstream to increase the response time.

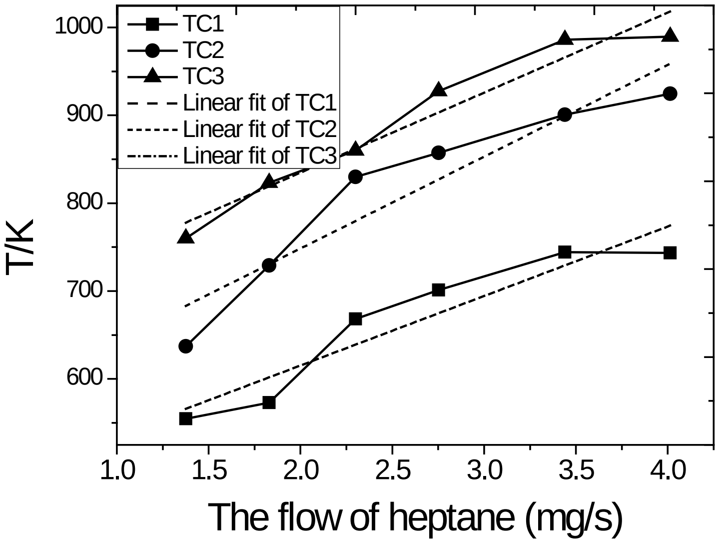


**Figure 8**. The curve of wall temperature distribution under the condition of different n-heptane flow rate

Figure 8 is wall temperature distribution of n-heptane - oxygen/air mixture in the combustion stainless steel burner, the operating conditions of equivalence ratio of 1.08, the gas flow rate of 0.8m/s, the curve of TC1, TC2 and TC3 with n-heptane flow increasing. It can be seen, the wall temperature of three positions is increased with n-heptane flow rise, mainly because with the equivalence ratio and flow rate unchanged, the degree of n-heptane reaction is unchanged, but the increased flow will increase the total heat release, and increase the heat transfer to the wall, so the temperature rises. within the measurement error of thermocouple, the linear fits of the data analyse the increase in surface temperature trends with the flow increasing, fitting line as shown in Figure 8, through calculating the changing rates of TC1, TC2 and TC3 are 78.125K*s/mg, 102.04 K*s/mg and 84.75 K*s/mg with n-heptane flow increasing, it shows the temperature of the TC2 location changes fastest, the same changes in the combustion flame is also the largest, this conclusion can be verified in Figure 4, because the TC1 location was the minimum temperature changes, the colour of flame has been blue, and TC2 location is the most obvious changes in the location of the flame, so the rate of temperature changes is the biggest, TC3 position is probably end position of the flame, the increasing flow in the rate of temperature will be less than the TC2 position.

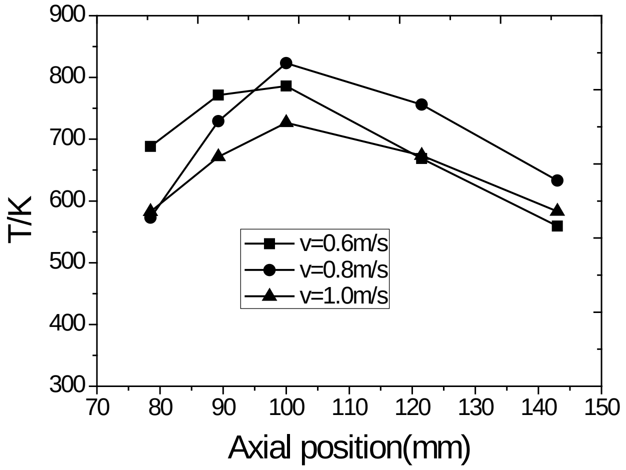


**Figure 9**. The curve of axial wall temperature distribution under the condition of different velocity of gas mixture

Figure 9 shows that the operating conditions of the equivalence ratio of 1.08, n-heptane flow rate of 1.83mg/s, the curve of wall temperature with the oxygen / air mixture flow velocity changing. In the figure shows: the left two-point temperature decreases with increasing gas flow rate, the right three-point temperature first increases and then decreases as the flow rate increases, consistent with the previous picture, because the gas flow rate increases to decline the oxygen content in gas mixture, both combustion reaction zone and heat will be moving downstream, and put down preheating the upstream gas and fuel, which leads to the decreasing of upstream temperature, so resulting in reducing wall temperature. Flame center position did not increase with the flow moving downstream, indicating that the fuel combustion in a fixed position; the downstream temperature of flame maximum temperature increases and then decreases with the gas flow increasing, indicating when the flow rate is 0.8m/s there are very good mixing and combustion for the gas mixture with fuel, the maximum heat release. When velocity is lower and the oxygen is larger, the flame burning position is close to fuel export. As the velocity increases, the oxygen content decreases and the flame temperature decreases, but the position remains unchanged.

## 4 The temperature distribution of the burner with different materials

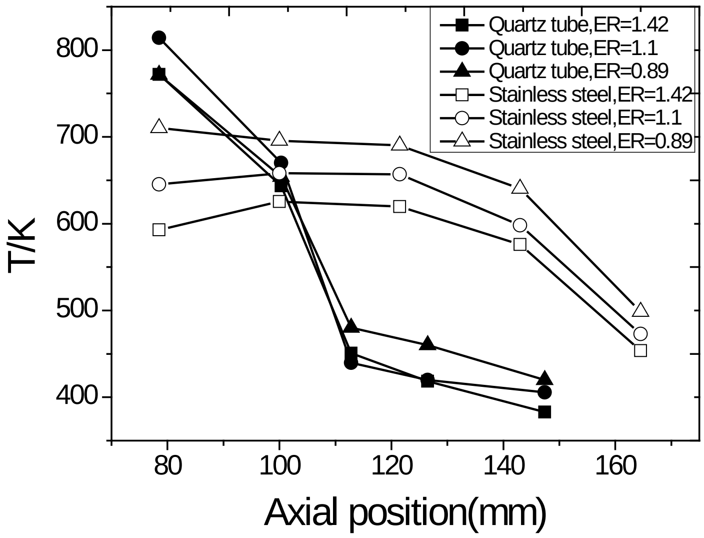


**Figure 10**. Axial wall temperature distribution with different material

Figure 10 shows the temperature distribution of different materials burners when the fuel flow is 1.8347mg/s, the equivalence ratio is 0.89, 1.1, 1.42 and the gas flow rate is fixed in 0.6m/s operating conditions. To measure the longer temperature distribution, we make the TC2 in Figure 2a right place the164.5mm axial position from the coordinate origin. It can be seen from the figure, at three equivalence ratio conditions temperature distribution on stainless steel and quartz burner is very different: 1. temperature distribution is relatively uniform on the Stainless steel; 2. as the equivalence ratio changes, temperature gradient on the stainless steel is larger than that on the quartz tube; 3. the maximum temperature on the stainless steel wall is lower about 100K than that on the quartz tube. Because of thermal conductivity of stainless steel is larger than quartz's. It makes the heat transfer faster in stainless steel, and temperature distribution is more uniform; emission rate of the stainless steel tube is smaller than that of the quartz tube, the heat radiation is larger, so the same heat production can cause a greater temperature change; It can be seen, the maximum wall temperature of the quartz tube will be higher.

## Conclusion

(1) The equivalence ratio has no effect in the time required for the stable combustion, but will affect the combustion heat release;

(2) As the boundary of the equivalence ratio ER = 0.55, the wall temperature distribution is first increasing and then decreasing with the equivalence ratio increasing, the boundary is different from gas fuel combustion;

(3) With the increase of n-heptane flow, the flame becomes bright and thick, wall surface temperature increases significantly, the temperature change rates of TC1, TC2, TC3 were 78.125K*s/mg, 102.04 K*s/mg, 84.75 K*s/mg;

(4) Flame turns dark with the equivalence ratio increasing, it does not get longer with the gas flow rate increasing, but becomes dark; temperature distribution of stainless steel tube is more uniform than that of the quartz tube, but the maximum wall temperature was lower.

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