Flame propagation and thermal performance in a microscale n-heptane combustor with porous medium

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1 Introduction

The requirement of compact, efficiency, human compatible, lightweight power system makes the researchers turn their attention to the microscale combustion, which has a higher gravimetric power density and gravimetric energy density than the lithium battery used nowadays[1,2,3]. Because of serious heat loss in the microscale combustor, caused by the huge area/volume ratio, the combustion is hard to be stable. In order to improve the stability of the combustion in such devices, researchers proposed several methods, including the catalysis, Homogeneous Charge Compression Ignition (HCCI), heat recirculation, etc, which can obtain a good heat management, reduce the heat loss and get a stable combustion. But, different from gas fuels (hydrogen, methane, etc.), the combustion of liquid fuel in the microscale combustor is hard to sustain because of the atomization and droplet break-up, evaporation, mixing and reaction. Furthermore, researchers developed two methods to improve the stability of flame: electrospray technology and the liquid film of fuel, which increase the area/volume ratio and evaporation rate.

In this paper, a new microscale combustor is designed and studied, using n-heptane as the liquid fuel. In the inner pipe of microscale combustor, a porous medium is inserted in which the fuel is injected. The liquid fuel is absorbed, evaporates and mixes with air. The flame progagation and heat loss is studied in this paper.

2 Experimental System and Numerical Method

The experimental system is shown in Fig 1. The air and n-heptane are injected into the microscale combustor separately as the oxidant and fuel. The combustor is a quartz tube, in which a piece of polyacrylonitrile fiber is set. A capillary made of stainless steel is inserted into the porous medium from the left side of the combustor and the outer and inner diameter are 0.4mm and 0.24mm. The temperatures on the outer surface of the inner pipe of the combustor are measured using 0.5mm K-type thermocouples (*To-i*). And the outer surface of the outer pipe is measured by the infrared camera (*To-o*). The air

Nomenclature	
To-i	Outer temperature of inner pipe
To-o	Outer temperature of outer pipe
Ti-i	Inner temperature of inner pipe
Re	Reynold number
Va	Volume flow rate of air
Vf	Volume flow rate of fuel
m_f	Mass flow rate of fuel
Hr	Heat loss
H	Heat conducted

volume flow rate (*Va*) and n-heptane volume flow rate (*Vf*) are controlled by the gas mass flow controller and a syringe pump. Besides the single outer pipe combustor (model-A), a vacuumed double outer pipe combustor (model-B) is also studied in this paper.

On the basis of experiment, model-A is also studied using the numerical computation method. The laminar model and pressure based implicit solver are used. The porous medium is simplified as balls in the numerical model. The total number of grid is 83722. The surface emissivity of quartz wall is defined as 0.72[4] and the convection heat transfer coefficient of high temperature horizontal circular tube is defined as Equation (1) [5]. The Discrete Phase Model (DPM) based on the Euler-Lagrange method is employed to simulate atomization of n-heptane and droplet's movement. The reaction rate of n-heptane/air is controlled by Arrhenius's law, and the one-step reaction mechanism is chosen.

Fig 1 Experiment System

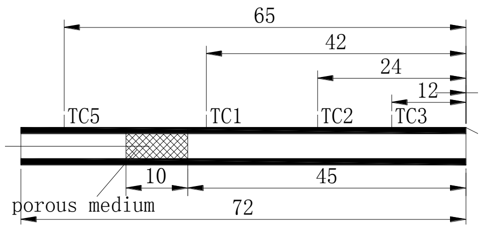
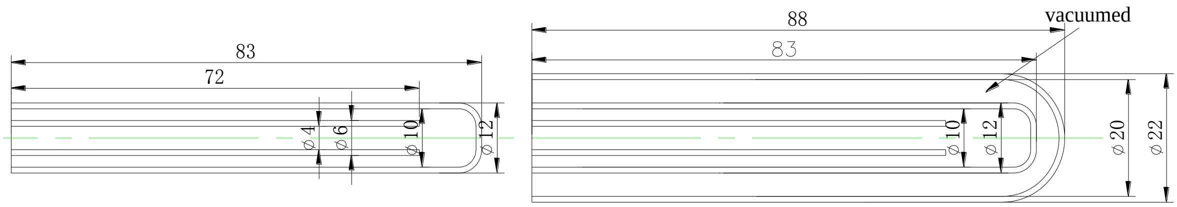


Fig 2 The Thermocouples on the inner pipe (mm)



model A model B

Fig 3 The single outer pipe combustor (model A) and double outer pipe combustor (model B)

$$h = \frac{\lambda_f}{D} Nu_w = \frac{\lambda_f}{D} 0.23 (Gr \bullet \Pr)_f^{0.25} \left(\frac{T_w}{T\infty} \right)^{0.424} \tag{1}$$

In Equation (1), h represents the convection heat transfer coefficient between outer surface and atmosphere; D is the outer diameter of tube; T_w is the surface temperature of microscale combustor (*To-o*); T_∞ is the atmosphere temperature; the air heat transfer coefficient, the Gr and $\Pr$ are the values when $T_f = 0.5(T_w + T_0)$.

$$C_7H_{16}+11O_2=7CO_2+8H_2O \tag{2}$$

Reaction rate
$$\omega = A C_F^a C_O^b \exp(-E_a / R_u T) \tag{3}$$

In Equation (3), E_a=125.6kJ/mol ,and $A = 1.4 \times 10^6$ m^3/mol • s^{-1}.

3 Results and Discussion

3.1 The Experimental Phenomena

Fig 4 shows the flame shape in model-A under different Res when n-heptane flow rate is V_f=0.04mL/min (m_f=0.453mg/s) and V_f=0.08mL/min (m_f=0.906mg/s). It can be found that the flame moves towards the inner pipe exit and the flame shape changes with air velocity and Re. When Re=68, the flame stays at the right side of the porous medium, with irregular shapes and low brightness; when 68<Re≤178, the flame shape becomes a cone and brighter; when Re≥178, the flame stays at the outlet of the inner pipe, and becomes a clear blue cone, as well as the pipe wall near the end is red-hot because of high temperature. Besides of Re, the mass flow rate of fuel also has a great influence on the

combustion: when m_f=0.906mg/s, the flame leaves the surface of porous medium under low Re; when Re increases, the flame moves downstream, and the upper Re boundary is higher and the flame are much brighter. To be noticed, the flame location only depends on Re, which can be shown in Fig 6. In this figure, the original point of Y axis lies on the right side of porous medium.

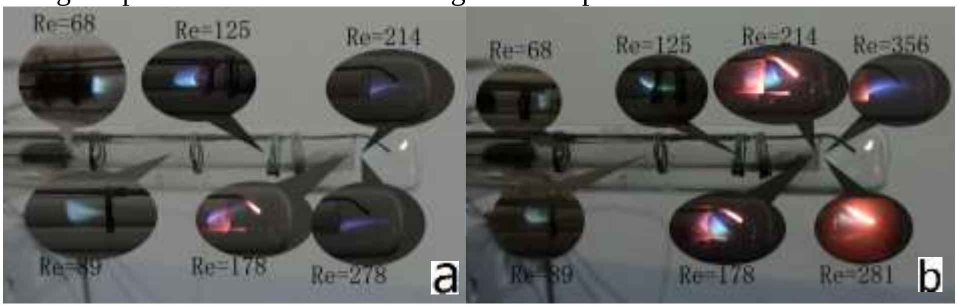


Fig 4 The flame shape and location when m_f=0.453mg/s (a)and m_f=0.906mg/s (b)

3.2 Simulation Result

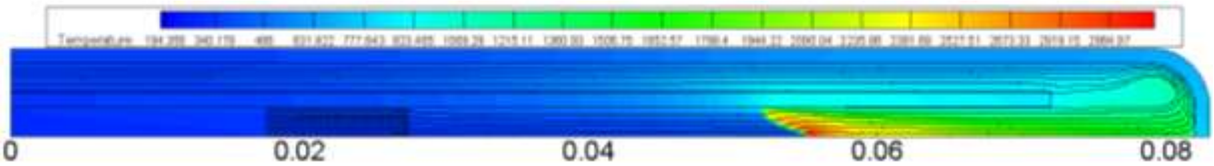


Fig 5 The temperature contour when m_f=0.453mg/s，Re=132

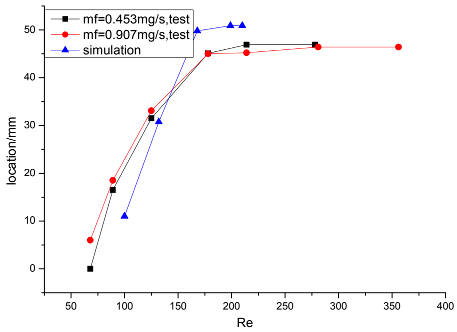


Fig 6 The flame location varies with Re and n-heptane flow rate

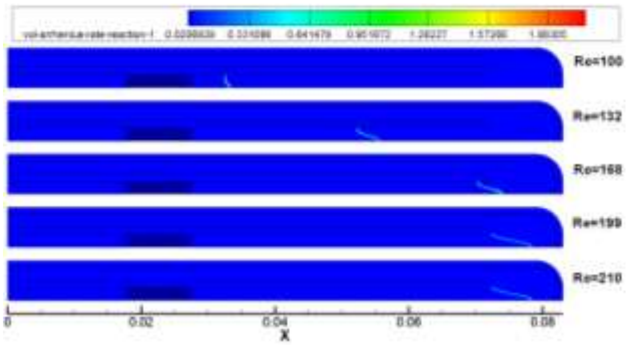


Fig 7 The reaction contour of n-heptane/air under different Res

Fig 5 shows the temperature contour when m_f=0.453mg/s; Fig 6 shows the variation of flame positions with Re in the experiments and numerical simulation, which indicates that the simulated location agrees well with the test results; and Fig 7 shows the one-step reaction contour of n-heptane/air in the microscale combustor under different Res. Therefore, the numerical simulation method is employed to study the problem.

The main reaction zone can be divided into 3 zones: preheat zone, combustion zone and cooling zone. The combustion in the combustor is very complex. When Re is low, the flame is located in the inner pipe and the exhausted gases in the annular channel heats the incoming mixture in the inner pipe through the tube wall, as well as the exhausted gases is heated by the after burning gas in the inner pipe, which can be found in Fig 8. In this figure, *To-i* and *Ti-i* are different, so the directions of heat transfer are also different along the axial direction. On the upstream of the flame, the temperature of gas increases and *To-i* is higher than *Ti-i*, so the heat is transferred from the exhausts in annular channel to the inner gas through the pipe at this area. Meanwhile, on the downstream of flame, the temperature of gas declines and the *Ti-i* is higher than *To-i*. As a result, the heat is transferred from the after burning gas to the gases in annular channel, which is shown in Fig 9(a). When Re is high and the flame is located on the outlet of the inner pipe, the high temperature gases flow along the annular channel and heat the gas in the inner pipe, which improves the stability of combustion. The heat released from the microscale combustor to the surrounding through the outer pipe and loss gases is shown in Fig 9(b).

It is generally believed that the Re number has little influence on the mixing of fuel/air in the microscale combustor, which depends on the molecular diffusion, because of the low Re number [6]. But it can be found that the location of flame in the microscale combustor would be different under various Res, which would has effect on combustor's working states, such as the temperature distribution.

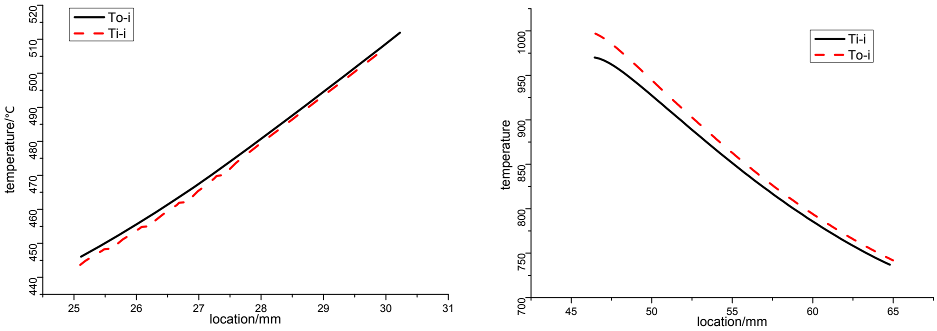


Fig 8 *To-i* and *Ti-i* in different position

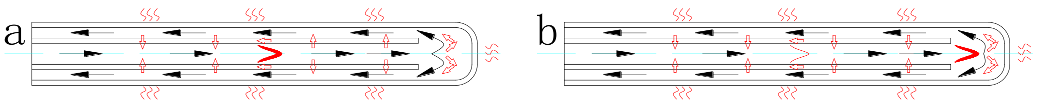


Fig 9 The flow direction and the heat transfer direction

3.3 Effect of Outer Pipe on Temperature Distribution in the Combustors

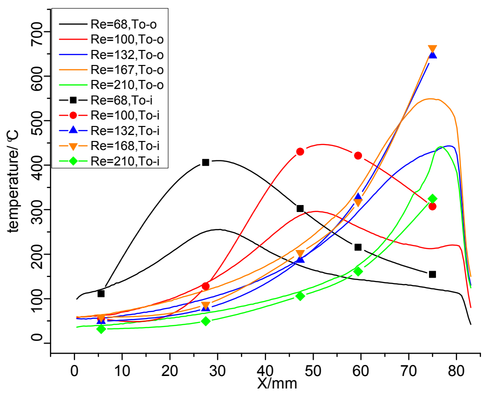


Fig 10 The *To-o* and *To-i* when m_f=0.453mg/s in model-A

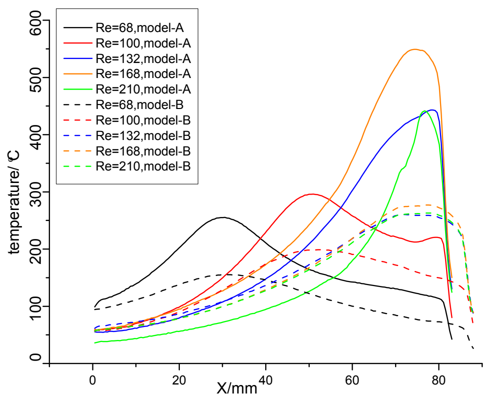


Fig 11 The *To-o* of model-A and model-B at different Re

In order to understand effects of outer pipe on temperature distribution in the microscale combustor, *To-i* is measured by the K-type shielded thermocouple in the experiment, and *To-o* is also measured and recorded by the infrared camera. Based on the above analysis, when the flame stays in the inner pipe, the hot gases at the downstream of flame heat the gases in the annular channel through the pipe wall. Meanwhile, the fuel/air mixture at the upstream of flame is preheated by the gases in the annular channel and is also heated by the flame. In Fig 10, when Re is low, the locations of the highest temperatures on inner and outer pipe are the same. The gradient of *To-i* near hot spot is large and the temperature gradient far from the location is small, besides that the gradient of *To-o* is small. When Re becomes larger, the flame stays in the region between the exit of inner pipe and the bottom of outer pipe, *To-i* and *To-o* increase along the X axis, and then *To-o* drops down quickly because of the huge area/length rate at the bottom of outer pipe.

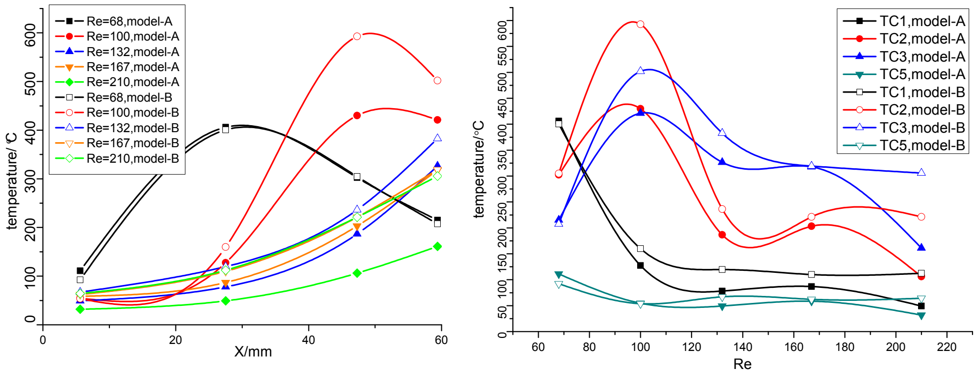


Fig 12 The *To-i* in model-A and model-B at different Re

Besides model-A, model-B is also studied in this paper, in which the temperature distribution is shown in Fig 12 and Fig 11. The distribution of *To-i* is similar in model-A and model-B when Re is low; when Re is larger, *To-i* in model-A is lower than that of model-B, because there is less heat loss in model-B. The *To-o* of model-A is always higher than that of model-B, and the hot spot corresponds with the flame. In fact, the vacuumed double outer pipe decreases the convection heat loss and more combustion heat is used to preheat the incoming mixtures, which will improve the stability of flame in the combustor..

3.4 The Heat Loss in Model-A and Model-B

The area/volume rate of a microscale combustor is usually bigger than the traditional burner, so the flame becomes unstable. It is very necessary to carry out research on the heat loss in a microscale combustor. Using the wall temperature distributions of model-A and model-B and Equation (1), the heat loss from the outer pipe (*Hr*) is calculated. And the combustion heat release at different Re is calculated using the equilibrium composition which is computed using CEA software. The heat loss rate is defined as *Hr/H*..

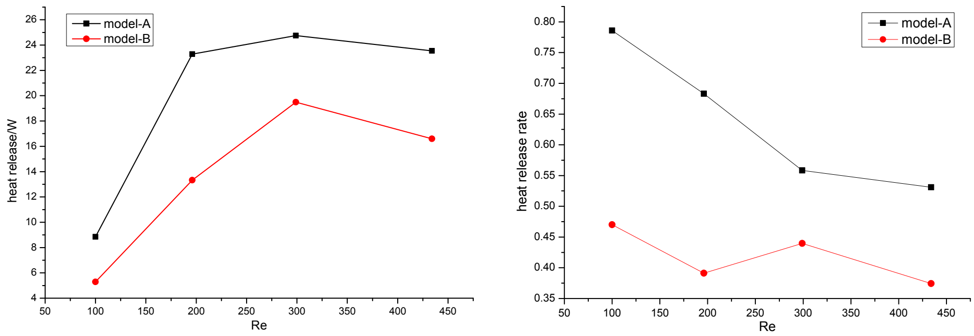


Fig 13 The heat loss (*Hr*) and heat release rate of model-A and model -B

The *Hr* and the heat loss rate in model-A and model-B are shown in Fig 13 The heat loss (*Hr*) and heat release rate of model-A and model -B. The *Hr* in model-A and model-B both increase first and then tend to be not changed with Re's increasing. Obviously, the *Hr* of model-B is always lower than that of model-A, because of the lower *To-o* in model-B. By Equation (1), the calculated convection heat transfer coefficient is larger when the temperature of the outer surface is higher; therefore the heat loss of the combustor becomes much more serious. In model-A and model-B, the heat loss rate is also different. The heat loss rate of model-A is always larger than that of model-B. But the heat release rate of model-A straightly goes down, as well as that of model-B is rise and fall.

4 Conclusion

In the microscale combustor with porous medium, the combustion is influenced by many factors.

1. The flame position is dependent on Re. As the Re increases, the flame goes to the downstream gradually. When the mass flow rate of fuel increases, the flame becomes brighter and the inner pipe becomes more red.
2. When the flame stays in the inner pipe, the *To-i* is higher than *Ti-i* at the upstream of the flame, but the *Ti-i* is higher than *To-i* at the downstream of flame. When the flame stays outside of the inner pipe, the incoming mixtures are preheated by combustion products in the annular channel. Such heat transfer in the combustor is good for the flame stability.
3. In model-A, the hot spots of *To-i* and *To-o* depend on the flame location, and *To-o* decreases quickly at the bottom of the outer pipe. *To-o* of model-B is always lower than model-A, and *To-i* of model-B is always higher.
4. Heat loss and heat loss rate of model-B are always lower than that in model-A. Heat loss in model-A changes between 55%~80%, while that in model-B varies between 37%~47%.

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