

Experiment on microscale flames stabilized on surface of annular porous media

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Abstract: The characteristics of the surface-stabilized flame on a porous medium in an annular microscale channel were studied experimentally with methane/air mixture. In the pressure drop characteristic study, three porous media with the same pore diameter and different porosities were used and compared. The substitution of the air for the mixture was verified accurately at first. Then the relationship expression of the air pressure drop characteristic was acquired for each porous medium according to the Forcheimer correlation. The third porous medium was selected for the following research, as it had the expression closer to the Darcy's law. As for the ignition characteristic study of the surface-stabilized flame, a reasonable criterion was established for the flammability limit determination. Based on the criterion, the result showed that the limit reached the minimum value when the mixture equivalence ratio was 0.9. During the extinction characteristic study, through the well-designed operating procedure, the experiment was conducted to obtain the strict extinction limit of the surface-stabilized flame. It was indicated that the extinction limit at mixture equivalence ratio of 0.8 was the least.

Key words: pressure drop; flammability limit; extinction limit; microscale combustion;
porous media; surface-stabilized flame; premixed combustion

CLC number: V231.2

Document code: A

The demand for micro power systems becomes more urgent with the rapid development of micro-electromechanical systems (MEMS). Compared with the disposal chemical battery, the micropower devices based on fuel combustion have a higher power density. Thus, they have already drawn extensive international interest of study^[1-2]. However, the micro combustion is influenced by scaling factors such as low Reynold number, short residence time, and significant heat loss from the high surface to volume ratio^[2-5]. The large heat loss has become an important issue during micro combustor development. With the increase of heat loss inevitably affects the flammability and extinction limits, it will result in poor stability characteristic of the flame, which will be a key problem encountered in the

development of micro-combustors. Meanwhile, large heat loss results in a poor thermal efficiency of the combustor.

Good thermal management techniques become effective measures to solve the above problems related to considerable heat loss^[3]. A large number of scholars designed Swiss-roll combustors using the regenerative principle to reduce heat loss, while the fuel-air mixture was fully preheated to achieve so-called excess enthalpy of combustion, the flammability limit, and combustion efficiency were improved^[4-6]. Catalytic combustion technology could achieve stable, self-sustaining combustion at low temperature in microscale space, which would reduce heat loss to some extent^[7-8]. In porous media combustion, heat release can be used to preheat the react-

Received: 2016-04-06

Citation: LIN Peihua, LIN Yuzhen, XUE Xin, et al. Experiment on microscale flames stabilized on surface of annular porous media [J]. Journal of Aerospace Power, 2017, 32(12): 2955-2963.

ants, which would result in less heat loss. Simultaneously, the mixing of the gas fuel and the air can be enhanced. Hence, with advantages of high reaction rate, wide extinction limit, and low pollution emission, porous media have a real potential regarding microscale combustion^[9]. Experiments showed that a new type of combustor using porous media could reduce heat loss significantly, resulting in improved combustion stability^[10]. Microscale combustion concept presented in this paper used a porous medium to stabilize the surface flame. The experimental investigation was carried out on the characteristics (pressure drop, ignition, and extinction) of the flame of CH₄/air mixture in an annular passage.

Many scholars did a lot of researches in micro combustion employing the porous media. Concerning with numerical simulation, McIntosh, et al.^[11] analyzed the flame speed under different loads with a simplified model. Diamantis, et al.^[12] conducted numerical study into the combustion within the porous media. The radiation efficiency and pollution emission were compared. As for experimental investigation, Marbach, et al.^[13] utilized heat recirculation together with the flame stabilized on the surface of a porous inert medium (PIM) made of silicon-carbide coated carbon foam. Measurements included the carbon monoxide and nitric oxides concentrations, the product gas temperatures at the combustor exit, and the temperature profiles on the exterior surface. Li, et al.^[14] adopted hydrogen to investigate the wall temperature and emitter efficiency of a flat combustor under flow conditions of various equivalence ratios, various mixture flow rates, and different positions of porous media experimentally. WANG Hongmin, et al.^[15] measured and analyzed the detailed axial temperature variation of the porous medium burner experimentally during startup and switch-off processes for the premixed CH₄/air combustion. A micro gas turbine combustor with a sintered porous chamber wall as the inlet was tested and simulated by JIANG Liqiao, et al.^[16] They measured the pressure drop ratio of

the porous inlet, the exit gas temperature, and the combustion efficiency. In Ref. [17], experiments were conducted to study the effect of the porous medium structural parameters (the pore diameter d_p and the porosity ϵ) on the blow-out performance of the surface flame stabilized on a circular porous medium. The effects of inlet mixture temperature and existence of restricted domain were also studied^[18-19].

From the literature, there were limited studies on the characteristics (pressure drop, ignition, and extinction) of the surface-stabilized flame on porous media in microscale annular passage. Pressure drop plays a significant role in the performance of a micro combustor. Ignition and extinction characteristics of the flame evaluate the combustion stability. The use of an annular passage is closer to the structure and dimensions of microscale combustors of practical application. Therefore, it is necessary to carry out the experimental study on the above characteristics of the mentioned surface-stabilized flame. The study could provide an important reference value for the optimization of the microscale combustor design. In addition, the experimental data was fit with the Forcheimer correlation (a second-order polynomial) during the pressure drop study. At the same time, a reasonable criterion was established for the flammability limit determination, and a proper operating procedure was set up for the extinction limit experiment.

1 Experimental system

The porous medium used in this experiment is called sintered metal powder porous medium. It used the stainless steel powder as raw material which was molded and then sintered with high temperature. With the rigid structure, the porous medium was characterized by a large number of internal voids containing connectivity or semi-connected pores. The two important parameters to describe the characteristic of the porous media were the pore diameter d_p and the porosity ϵ ^[20]. Table 1 gives the average d_p and ϵ of the porous

media used in this paper. All the three porous media had the same shape dimensions (an outer diameter of 15 mm, an inner diameter of 6 mm, and a thickness of 5 mm), as shown in Fig. 1.

Table 1 Pore diameters and porosities of three porous media

Case	$d_p/\mu\text{m}$	$\epsilon/\%$
1	50	20
2	50	30
3	50	50



Fig. 1 Annular sintered metal powder porous media

Fig. 2 shows the entire experiment system. It consisted of an air line, a methane line, a mixing section, an annular channel, and a measuring system. The air line was formed by a gas supply with high pressure of 9 MPa, a shut-off valve, two pressure regulators, three pressure gauges, a switching valve, an air filter, and a CS200A mass flow rate controller. The first

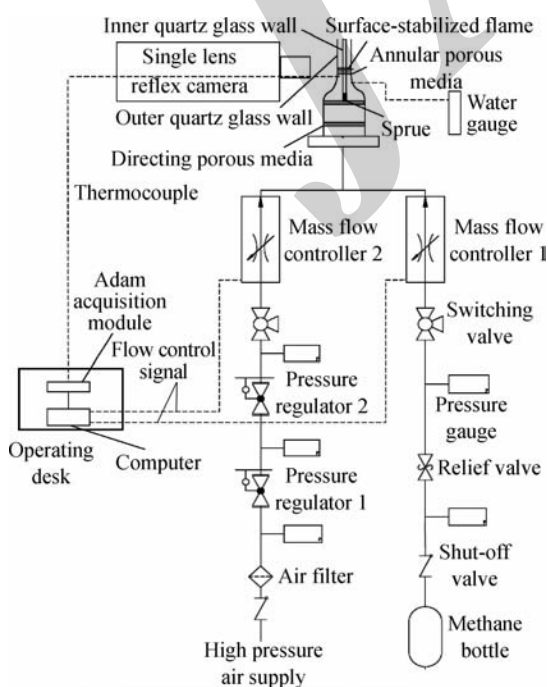


Fig. 2 Schematic of the experimental system

pressure regulator was used to reduce the air pressure from 9 MPa to about 1 MPa, and the second pressure regulator was used from 1 MPa to the value among 0.05~0.35 MPa when mass flow rate was not more than 10 L/min. The methane path was formed by a 40L methane bottle, a shut-off valve, a relief valve, two pressure gauges, a switching valve, and a CS200A mass flow rate controller. The methane in the bottle had purity over 99.9%. Both the mass flow rate controllers had a response time less than 1 s. The accuracy varied based on the mass flow rate, that were: $\pm 0.35\%$ full scale (FS) when mass flow rate was less than 35% FS; $\pm 1.0\%$ set point (SP) when mass flow rate was no less than 35% FS. The range of the air mass flow rate controller was 5 L/min, while that was 500 mL/min corresponding to the methane.

The methane and air were directed and mixed uniformly in the mixing section after passing through the respective path. The mixing section included the sudden expansion part, the directing part, and the converging part. The three parts were located separately from the entrance and each directing porous media (as shown in Fig. 3). The sudden expansion part caused the formation of vortices at the entrance. The vortices promoted the uniformity of mixture concentration field. Then they were eliminated in the directing part by the directing porous media, which was the type of sintered metal mesh^[20]. As the inside surface of the converging part was designed with the shape of the Vidor Brzezinski curve^[21], the flow was accelerated and directed to one dimensional velocity-uniform flow finally in this part.

After the mixture had passed out of the mixing section, it flowed through the annular channel (as shown in Fig. 3), above which it would be ignited by the lighter. The channel consisted of four parts: an annular porous medium, two quartz glass tubes, and a base seating, with the structure and dimensions given in Fig. 4. Based on the experience of the previous study, the depth of the groove in the base seat-

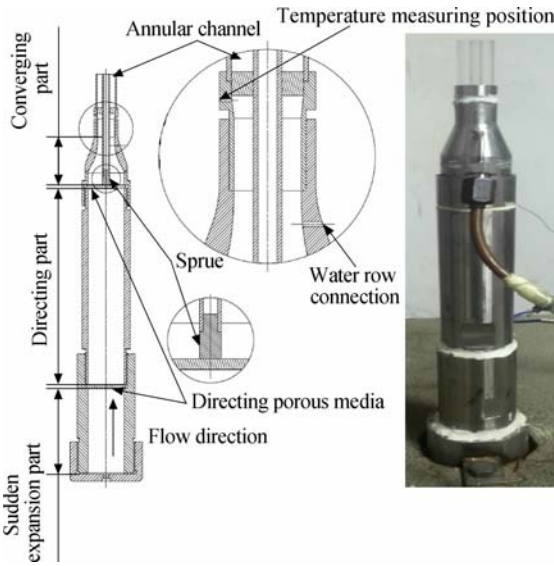


Fig. 3 Schematic diagram and picture of the mixing segment and annular channel

ing was designed as 2 mm. If the groove was too shallow, it was not conducive for fixing the quartz glass tube. On the contrary, the quartz glass tube was easy to be fit too tight, the heat stress after combustion would cause cracks in the quartz glass tube. A sprue was inserted from the bottom of the inner tube to prevent the mixture flowing through inside the inner quartz glass tube to atmosphere. It was connected to the inner tube by the silicone rubber, as shown in Fig. 3. The sprue was also connected with the upper directing porous media, to prevent the inner tube and the sprue from being blown out by the air flow at large mass flow rate for the system cooling.

The measuring system was formed by a temperature acquisition system, a water row, and a camera system. The temperature acquisition system adopted a K-type sheathed thermocouple with a diameter of 0.5 mm for the mixture temperature measurement. It was inserted into the hole of the base seating until the measuring point reached the center of the local ring of the channel. The hole had a diameter of 0.7 mm and it was located 1 mm distance below the lower surface of the porous medium, as described in Fig. 3. The temperature data were acquired with the Adam acquisition module. The results could be displayed in the program panel in the comput-

er. The pressure drop between the upside and downside of the annular porous media was measured by the water gauge, as shown in Fig. 2 and Fig. 3. The camera system shown in Fig. 2 employed a Nikon D300 single lens reflex (SLR) camera to take the pictures of the flames. The International Organization for Standardization (ISO) sensitivity was set at the automatic control mode with the actual value of 200. The exposure mode was set at the automatic program control with the actual shutter speed of 1/250 s and aperture value of F5.6.

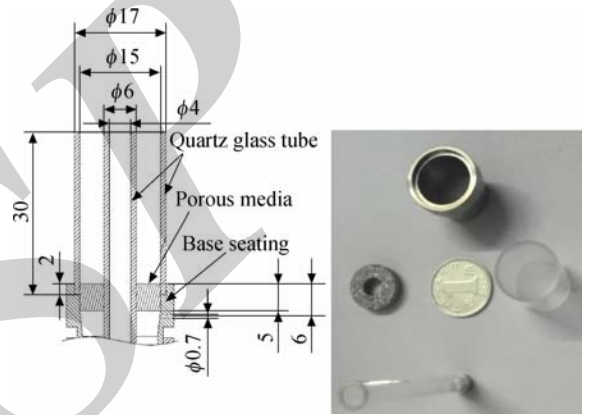


Fig. 4 Small parts in the annular channel (unit:mm)

2 Results and discussion

2.1 Pressure drop of porous media

In the pressure drop experiment of the porous media, the upper and lower water levels of the water gauge should be recorded when the characteristic velocity of the flow reached the designed minimum value. The mentioned characteristic velocity referred to the average velocity of the flow before entering the annular porous media. The corresponding water levels could be obtained with the increase of the characteristic velocity by the given step.

For the convenience of the experiment and prevention of the methane emission to the atmosphere, the air was applied instead of the CH_4/air mixture in the experiment. The pressure drop was firstly compared between the air and the mixture at the equivalence ratio $\phi = 1.0$ to evaluate the error of this substitution. The

porous medium used in this test had a pore diameter $d_p=50\mu\text{m}$ and porosity $\epsilon=50\%$. The pressure drop was measured respectively under the same mass flow rate (instead of the flow velocity for the instrument operation convenience). The test result is shown in Fig. 5. When the flow velocity V was less than 0.2 m/s approximately, the pressure drop characteristic curve of the air coincided with the mixture. When V was no less than 0.2 m/s approximately, the error between the two increased slowly with V . However, the error still kept 100 Pa or less at $V=0.6\text{ m/s}$, the relative error was 3% or less. The pressure drop characteristic of air could be identified with that of the mixture.

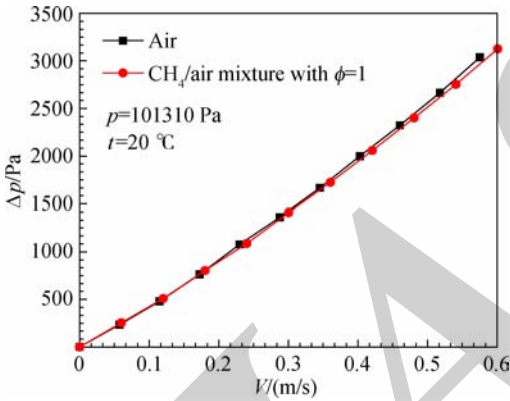


Fig. 5 Comparison of pressure drop between air and CH_4/air mixture at $\phi=1.0$, $d_p=50\mu\text{m}$, $\epsilon=50\%$

The pressure drop characteristics of the three porous media can be seen from Fig. 6. With the same d_p , the pressure drop Δp decreased with the increase of ϵ . That was because

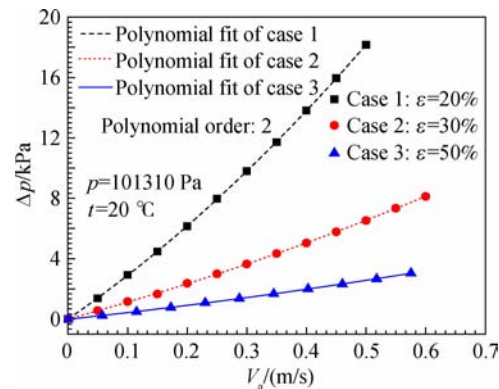


Fig. 6 Pressure drop of the three porous media ($d_p=50\mu\text{m}$)

the increase of ϵ meant more pore passages inside the porous media and the reduction of the flow resistance thereby.

The Forcheimer empirical correlation^[20] was applied to fit the relation between the experimental data of the pressure drop Δp and the air flow velocity V_a

$$\frac{\Delta p}{h} = V_a \frac{\mu}{\psi_v} + V_a^2 \rho \frac{1}{\psi_i}$$

Wherein, h represents the thickness of the porous media, $h=0.005\text{ m}$; μ represents kinetic viscosity, $\mu=1.81\times 10^{-5}\text{ Pa}\cdot\text{s}$ according to the table in Ref. [22]; ρ represents the air density, $\rho=1.165\text{ kg/m}^3$ by calculation; ψ_v represents the viscous through coefficient (m^2); ψ_i represents the inertia through coefficient (m). After the second-order polynomial fit of the data shown in Fig. 6, it was easy to obtain the fitting values of ψ_v and ψ_i of the three porous media. It can be seen from Table 2 that all the R_{adj}^2 (it refers to the adjusted relation coefficient R_{adj}^2 in the linear regression of the function) reach more than 0.999 , very close to 1 , indicating that the fitting optimizations are good.

Table 2 Viscous and inertia through coefficients of the three porous media

Case	$\psi_v/10^{-12}\text{ m}^2$	$\psi_i/\mu\text{m}$	R_{adj}^2
1	3.42	0.318	0.99998
2	8.69	1.23	0.99992
3	22.00	3.14	0.99986

As shown in Fig. 6, the third porous media (case 3 shown in Table 1 and Table 2) has an expression closer to linear than the other two. It means that this case could fit the Darcy's law properly. As we know, only when under the laminar condition (about the definition of the laminar flow, please refer to page 20 in Ref. [20]) the flow through porous medium would obey the Darcy's law^[20]. Therefore, it could be inferred that the flow inside the case 3 porous medium could be taken as a laminar flow when this porous medium was applied^[20]. The third porous medium was selected as the object in the

following research.

2.2 Ignition characteristic of surface-stabilized flame

2.2.1 Ignition process of surface-stabilized flame

During the ignition characteristic experiment, the CH_4/air mixture at $\phi=0.9$ and $\dot{m}_{\text{mix}}=0.02\text{ g/s}$ was ignited by a lighter about 30 mm above from the top of the glass tube. The flame propagated to the porous media in opposite direction of the flow. Then a stable surface flame formed on the porous media. The whole process was illustrated in Fig. 7. Firstly, the flame appeared pale blue and evenly distributed at the exit of the glass tube (Fig. 7(a)), due to the uniform flow field there^[17]. After the flame propagated a certain distance along the tube, the local flow field turned irregular^[17] for the effect of the porous media. In consequence, the shape of the transient flame became asymmetric (Fig. 7(b)). When the flame spreaded onto the surface of the porous media, it could stabilize there if the heat loss was not so much (Fig. 7(c) and Fig. 7(d)). On the contrary, the flame quenched instantly or the surface flame formed but quenched after a period of time (as a result of the delayed heat loss).

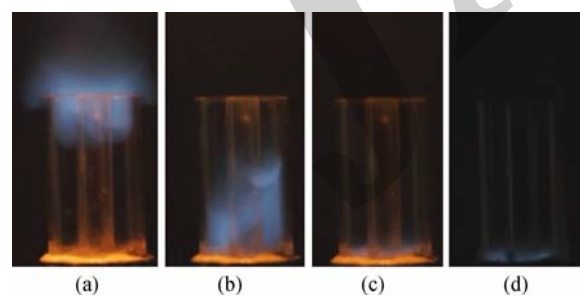


Fig. 7 Ignition process of surface-stabilized flame
($\phi=0.9$, $\dot{m}_{\text{mix}}=0.02\text{ g/s}$)

2.2.2 Flammability limit of surface-stabilized flame

As for the flammability limit experiment of the surface-stabilized flame, there were two options of the start point for ignition; a small non-flammable or a high flammable mass flow rate. For the latter one, the extra procedure was nee-

ded to cool the system before the next operating point to eliminate the effect of the heating on the ignition. Therefore, the former one was selected. Then, the mass flow rate was gradually increased with the step of 0.001 g/s until satisfying the criterion of the flammability limit (shown below).

The ignition could be deemed successful only when the surface-stabilized flame could self-sustain for 10 s at given ϕ and $\dot{m}_{\text{mix}}$. The time 10 s was determined by the experience that the surface flame in some circumstances could self-sustain only for a short time, usually no more than 5 s. The measured mixture temperature should be cooled by the air to below 25 °C before each attempt of ignition (the mass flow rate of cooling air $\dot{m}_{\text{c,a}}=0.1\text{ g/s}$), if necessary. The process was repeated until either a total of three successful or two unsuccessful ignition attempts were recorded. The mixture temperature decreased with the increase of time under the cooling of the air blow, as illustrated in Fig. 8. It showed that the temperature decline tended to be smooth when the temperature approached to the temperature of the atmosphere (19.5 °C). The setting of reignition below 25 °C was result of balancing the cooling time and the steadiness of the temperature with the increase of time. The steadiness helped to ensure the thermal system consistency before all ignition attempts.

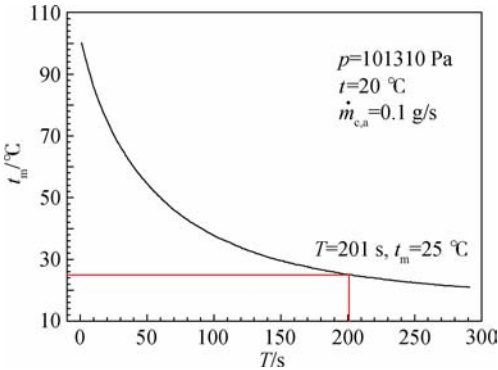


Fig. 8 Mixture temperature variation with the increase of time

The flammability limit (i. e. the minimum mass flow rate for the self-sustained combus-

tion, as characterized by three successful ignition attempts, with a maximum of one unsuccessful ignition attempt) at given equivalence ratio was established by repeating the above procedure. The Reynolds number (Re) limit of universe adoption would be defined and then obtained with the parameters setting shown in Ref. [23]. The result from Fig. 9 indicated that the surface-stabilized flame could self-sustain for more than 10s after ignition only when $0.6 \leq \phi \leq 1.1$. It was worth mentioning that we could see the tube-exit flame or the double-layer flame (consisting of the tube-exit and tube-inside flames) when $\phi > 1.1$, shown in Fig. 10. The limit became wider with the increase of ϕ when $0.6 \leq \phi \leq 0.9$ and it became narrower when $0.9 \leq \phi \leq 1.1$. The limit reached a minimum value at $\phi = 0.9$ but not $\phi = 1$. The similar result was obtained by JiIANG Liqiao, et al. [16]. The reason might be that the concentration field of the mixture was not so uniform above the porous media. Some fuel-rich locations still existed

there at $\phi = 1$, which was unfavorable for successful ignition. In contrast, the mixture at $\phi = 0.9$ could achieve self-sustained combustion in worse condition.

2.3 Extinction characteristic of surface-stabilized flame

2.3.1 Extinction process of surface-stabilized flame

In the extinction characteristic experiment, the mixture was firstly ignited at $\phi = 0.9$ and $\dot{m}_{\text{mix}} = 0.02 \text{ g/s}$ to form the stable surface-stabilized flame. Then the combustion self-sustained for a period of time to establish the steady state of thermal equilibrium, which was indicated by the appearance that the mixture temperature increased no more than 0.1°C in one minute [23]. After that, $\dot{m}_{\text{mix}}$ gradually decreased with the step of 0.001 g/s . The system reached new steady state at each mass flow rate. The above process was repeated until the extinction (the flame disappeared by the naked-eye observation) occurred, as shown in Fig. 11. It was known that the content of carbon reduced with the decrease of $\dot{m}_{\text{mix}}$. As a result, the flame became

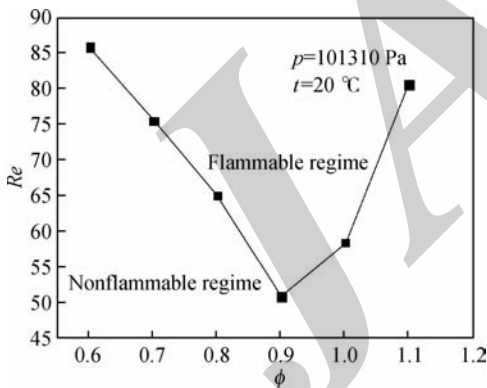


Fig. 9 Flammability limit of CH_4/air mixture

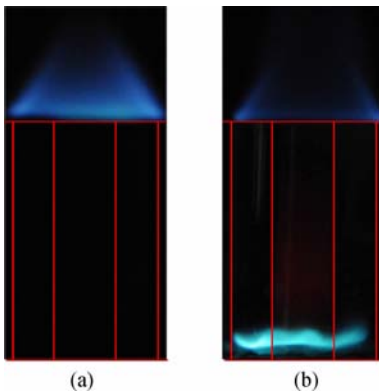


Fig. 10 Tube-exit flame and double-layer flame

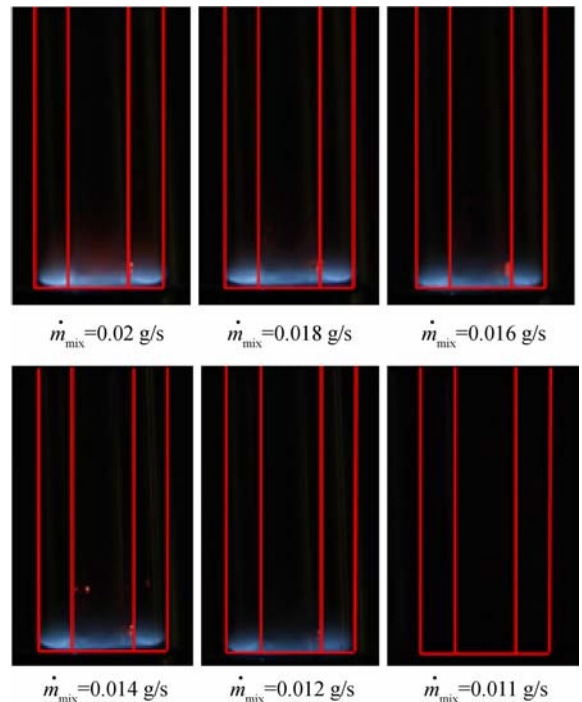


Fig. 11 Extinction process of the surface-stabilized flame ($\phi = 0.9$)

thin and the color turned from bright blue to pale blue. When $\dot{m}_{\text{mix}}$ decreased to 0.011 g/s, the flame quenched due to the large heat loss.

2.3.2 Extinction limit of surface-stabilized flame

For the extinction limit (i. e. the minimum mass flow rate before extinction) experiment, the mixture was firstly ignited successfully according to the results of the flammability limit experiment. Based on the procedure mentioned above, the extinction limit of the surface-stabilized flame could be obtained at the equivalence ratios in accordance with the flammability limit. Meanwhile, considering the heat from combustion, the extinction limit could be worse than the flammability limit. Hence, ϕ should be appropriately extended to both richer and leaner sides to obtain the corresponding limit. The experiment result showed that the maximum ϕ of the extinction limit ($\phi = 1.2$) was greater than that of the flammability limit ($\phi = 1.1$), while the minimum equivalence ratios were the same ($\phi = 0.6$). Fig. 12 describes the full result of extinction limit. The limit became wider with the increase of ϕ when $0.6 \leq \phi \leq 0.8$, and it became narrower when $0.8 \leq \phi \leq 1.2$. The limit arrived at a minimum value at $\phi = 0.8$, but not $\phi = 1.0$, similar with the flammability limit. And the reason might be the same either.

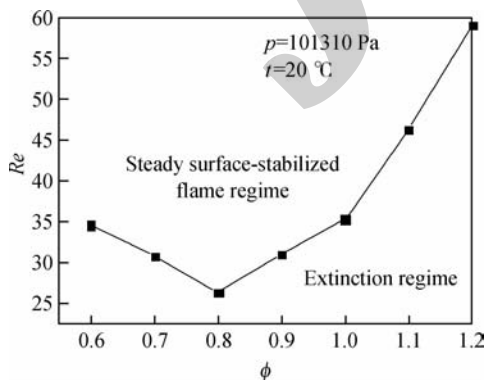


Fig. 12 Extinction limit of CH_4/air mixture

3 Conclusion and prospect

1) Three porous media with the same d_p and different ϵ were utilized to conduct the air (in-

stead of the mixture) pressure drop characteristic experiment. The Forcheimer correlation was adopted to fit the relationship expression of the pressure drop characteristic for each porous medium. The third porous medium was selected for the flammability and extinction limits experiments for it had the expression that could meet the Darcy's law the best.

2) For the ignition characteristic study of the surface-stabilized flame, the flammability limit was determined according to a reasonable criterion. The result showed that the limit becomes wider with the increase of ϕ when $0.6 \leq \phi \leq 0.9$, and it became narrower when $0.9 \leq \phi \leq 1.1$.

3) In the extinction characteristic study of surface-stabilized flame, the strict extinction limit was acquired by the well-designed operating procedure in the experiment. The limit reached the minimum value at $\phi = 0.8$.

Next, the study would be conducted on the other combustion characteristics of the surface-stabilized flame on the porous media. The experimental approach would be taken to obtain the temperature distribution along the annular channel wall. The exhaust gas composition and combustion efficiency would be measured at the same time. Numerical analysis would also be carried out to obtain deep understanding into the microscale flames.

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(编辑:陈 越)