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Combustion states distinction of the methane/oxygen laminar co-flow diffusion flame at high pressure

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ABSTRACT

Compared to turbulent combustion in practical combustion devices, a co-flow laminar diffusion flame is the simplest configuration from which the interactions between flow field and reactions can be readily studied. High pressure combustion experiments on the methane/oxygen laminar co-flow diffusion flame are conducted to distinguish combustion states from 0.2 to 4 MPa. The transition combustion state between the steady state and periodical pulsation combustion state is studied quantitatively. The results obtained using a Schlieren device show that the different formation heights of the vortices generated in the jet flame shear layer lead to different combustion states. Based on the combustion pressure and Froude number at the burner exit, the upper and lower limits for the transition combustion state are proposed as $Fr_{cr} = 9.8 \times 10^{-4}(p_r - 0.012)^{-1.87} \pm 4.0 \times 10^{-5}(p_r + 0.026)^{-2.48}$, respectively. The flame is in the steady combustion state when the flame Fr is smaller than the lower limit of Fr_{cr} . When the flame Fr is larger than the upper limit of Fr_{cr} , pulsation combustion takes place. For the pulsation combustion state, the relationship between the Strouhal number and Froude number is established as $St = 0.29 \times Fr^{-0.65}$.

1. Introduction

In a methane/oxygen liquid rocket motor, flame instability at high pressure (> 2 MPa) gives rise to local pulsation in the pressure and temperature fields, leading to inadequate burning that in turn leads to mechanical failure or even explosions [1,2]. Flame instability, especially pulsation, is associated with the interaction between the vortices in the flow of the flame. Turbulent combustion commonly occurs in practical combustion devices. The experimental measurements of turbulent combustion are restricted by the high level of intermittency due to turbulent motion and a relatively short residence time [3,4]. Turbulent combustion can be regarded as a combination of microlaminar combustion with turbulence mass transfer, and computational models such as the flamelet model are based on this theory [5]. For the turbulent flow in a rocket chamber, the magnitude of the Taylor micro-scale Reynolds number Re_λ is usually 10–100. Thus, the combustion features can be studied using a laminar flame with the same magnitude of Re . Compared to the devices used for turbulent combustion, the laminar co-flow diffusion flame experimental device has a simple configuration with controllable boundary conditions from which the interactions between the flow field and the reactions can be fundamentally modified and studied.

As a typical hydrocarbon fuel, methane is widely used in practical conditions. Many researchers have focused on the methane/air flame, while little information is available on the high-pressure methane/oxygen characteristics in the literature [3]. Miller and Maahs [6] studied the methane/air steady flame in a high-pressure chamber. Their study showed that with increasing pressure, the reaction mechanism of flame changes, resulting in the presence of increasing amounts of carbon in the flame. As a result, the flame shape undergoes a remarkable change with increasing pressure. A similar result was reported by Karatas, Intasopa and Gülder [7] in their studies of the hydrocarbon/oxygen flame at high pressure. Their work showed that increasing the combustion pressure effectively enhances the combustion intensity.

Pulsation features of the laminar diffusion flame have also been widely observed. Kimura [8] and Durox et al. [9] studied the stability of laminar diffusion flame, results shows that the flame flickering has relation with flame height, that the minimum height of flame is necessary to trigger the flickering. Similar phenomenon had been found by Zhang and Fang [10]. They studied the methane/air flame shape induced by oxygen concentration and air-velocity under microgravity conditions. The increasing of oxygen concentration in co-flow air decreases the flame height, which, in turns stabilized the flame. Lewis [11] studied the vortices structure of unsteady diffusion flame. The

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Nomenclature

Fr	Froude number [–]
St	Strouhal number [–]
p	Pressure [MPa]
Re_λ	Taylor microscale Reynolds number [–]
u	Characteristic velocity [m/s]
l	Characteristic length [m]
g	Gravity acceleration [m/s ²]
t	Time [s]

f_t	Pulsation frequency [Hz]
f_s	Sampling frequency [Hz]
N_{FFT}	Number of samples for FFT [–]
ΔR_f	Frequency resolution [Hz]
Subscripts	
cr	Critical [–]
r	Relative [–]
cent	Center line/Average [–]
crmax	Upper critical limit [–]
crmin	Lower critical limit [–]

velocity distribution near flame shear layer demonstrated that the flame flickering phenomenon is induced by vortices structure generated out of flame reaction zone. Charwath et al. [12] and Papadopoulos et al. [13] studied flame shape changing process during flame pulsation using radicals and soot distribution in methane/air diffusion oscillating flame. At the same time, theoretical analysis on flame pulsation process are provided by many researchers [8,9,14]. Darabkhani et al. [15] suggested that flame pulsation modes vary for different fuels. Three combustion states of the methane diffusion flame have been found by numerous researchers, namely, the steady, transition and pulsation combustion states. Hegde, Zhou and Bahadori [16] suggested that pulsation combustion initiation is not continuous and shows an intermittent behaviour, where a transition state is found between steady combustion and continuous pulsation combustion. For the laminar co-flow diffusion flame, the Kelvin-Helmholtz instability is considered the leading origin of flame pulsation, which has important implications in numerous applications involving non-reacting shear layers as well as reacting mixing layers [17]. However, most of the flame pulsation studies have been dedicated to the continuous pulsation combustion phenomenon, while the studies of transition pulsation combustion have been rare [18], and the critical conditions for the transition combustion state has not been studied in detail.

In this study, the stability characteristics of a laminar co-flow methane/oxygen diffusion flame were investigated at $p = 0.2$ – 4.0 MPa, the critical conditions for the three combustion states were measured, and the flame pulsation mechanism was determined using the Schlieren method.

2. Experimental facility and analysis method

2.1. Experimental facility

The experimental system is shown in Fig. 1 and includes the pressure combustion chamber and the control and measurement system. Three thermally based mass flow metres (Sevenstar D07-11C) were used to control the flow rates of methane, oxygen and nitrogen, and their maximum errors were less than 5% at $p < 5.0$ MPa. In the experiment, the methane mass flow rate was varied from 0.805 to 2.440 mg/s. A pressure transducer was installed on the top of the pressure chamber for monitoring the pressure. Experiments were conducted at 0.2, 0.3, 0.5, 0.7, 1.0, 1.5, 2.0, 2.5, 3.0 and 4.0 MPa.

The structure of the high-pressure combustion chamber is shown in Fig. 2. The design of the high-pressure combustion chamber is described in Ref. [3]. The inner diameter and height of the combustion chamber are 226 mm and 600 mm, respectively. Three view ports covered with quartz glasses were set on the chamber, providing sights of 0°, 90° and 180° for optical observation. A nitrogen inlet on the bottom was used to pressurize the chamber. The water mist coagulating on the view-port glasses was removed by high-pressure nitrogen gas. A spiral cooling pipe was placed above the burner to condense the water vapour of the flue gas in the chamber.

A co-flow burner (Fig. 1b) was installed in the centre of the high-pressure combustion chamber. Methane concentrically issued from the

burner port with an internal diameter of 3.01 mm into the oxygen stream. This burner port is encompassed by a chimney that has an internal diameter of 30 mm and is 80 mm higher than the burner port so that the combustion is conducted in an oxygen atmosphere. Glass beads were filled into the chimney to smooth the oxygen stream. To observe the co-flow flame, three windows covered with quartz glasses were set on the chimney.

2.2. Measurement method

Flame images were obtained using an SLR camera (Nikon D90, image resolution 4288×2848) that was mounted with a Nikkor 105 mm fixed-focus lens. The frequency and magnitude of flame pulsation were studied using a photomultiplier (ET Enterprises). The diffusion flame had a two-zone structure under a high-pressure environment, with an inner zone luminous in yellow and an outer zone in blue [3]. In the experiment, the variation magnitude of flame outer zone was larger than that of the inner zone during pulsation, and a short-pass filter (Thorlabs FES0500, cut-off wave length 500 nm) was placed in front of the photomultiplier to capture the light from the outer zone and transform it into a voltage signal. The voltage signal was input into a digital oscilloscope (Tektronix DPO 4032) to be recorded. The sampling frequency and time of oscilloscope are 1000 Hz and 10 s respectively. In the experiment, vertical scale was set at 200 mV/div, resolution of voltage signal is 62.5 μ V, typical random noise is less than 6.62 mV.

Based on the luminous intensity variation data, the flame pulsation frequency was obtained using the fast Fourier transform (FFT) algorithm [9,21–23], and different combustion states of the flame were distinguished by the short-time Fourier transform (STFT) algorithm [19,20].

Fig. 1. Experimental control and measurement system. (1) Co-flow burner; (2) Pressure chamber; (3) Viewport; (4) Schlieren Light Path; (5) Mass flow metres; (6) Valve group; (7) Gas cylinders; (8) DC power source; (9) Photomultiplier; (10) Shortpass filter; (11) Neutral density filter; (12) Oscilloscope; (13) High speed camera; (14) Pressure transducer; (15) Safety valve; (16) Back pressure valve.

Fig. 2. High-pressure combustion chamber and burner. (1) Chamber wall; (2) Viewports; (3) Co-flow burner; (4) Nitrogen inlet; (5) Methane inlet; (6) Oxygen inlet; (7) Colling pipe; (8) Chamber lid; (9) Back pressure valve; (10) Exhaust pipe; (11) Safety valve; (12) Pressure transducer; (13) Burner port; (14) Chimney; (15) Glass beads; (16) Oxygen tunnel; (17) Quartz glasses.

To analyse the flow field of the diffusion flame, the Schlieren method was used. The Schlieren device consisted of a sodium lamp, a slit, four concave mirrors, a knife-edge spatial filter and a high-speed camera. The light path of the Schlieren device is shown in Fig. 1. Flow field evolution during the experiment was obtained with a high-speed camera (Mikrotron MotionBLITZ EoSens Cube 7, image resolution 496×1316), with the frame rate set to 1000 fps.

It is commonly considered that self-induced flame pulsation is induced by Kelvin-Helmholtz instability in flow field at elevated pressure. Thus, flow parameter Froude number (Fr) is used in this study to describe flame flow field. Fr is defined as the ratio of the inertia force and the buoyancy force and is given by:

$$Fr = \frac{u^2}{l \cdot g} \quad (1)$$

where u is the average methane flow speed at the burner port, m/s; g is the gravity acceleration, m/s^2 ; and l is the characteristic length (here, l is the diameter of the burner port), m.

3. Results and discussion

3.1. Differences between the flame states

Three periods of flame luminous intensity histories recorded using an oscilloscope were chosen as examples and are shown in Fig. 3. Significant differences are observed between these data logs. In Fig. 3a ($Fr = 0.98 \times 10^{-3}$), the data log is smooth, with only a slight vibration. No pulsation appears in this state, and the flame is in the steady combustion state. In Fig. 3b ($Fr = 2.79 \times 10^{-3}$), with the growth in the Froude number, intermittent pulsation appears in the data log, indicating that the combustion is no longer steady. In this state, the regular pulsation behaviour did not form yet; thus, the flame is in the transition combustion state [16]. The experiments showed that the proportion of the pulsation segment will change with the variation in the Froude number of the flame, and, once the intermittent pulsation appears, growth in Fr leads to a larger proportion of the pulsation segment. As shown in Fig. 3c ($Fr = 7.83 \times 10^{-3}$), for conditions of larger Fr , the proportion of the pulsation segment is 1, showing that pulsation combustion has been formed. The pulsation amplitude in Fig. 3c is larger than that for the transition combustion state shown in Fig. 3b. With the increasing Fr number, the steady flame (Fig. 3a)

changes to the pulsation flame (Fig. 3c), while the curve in Fig. 3b shows the transition state between the steady flame and the pulsation flame.

To obtain the frequency features of the flame, the recorded luminous intensity histories were processed using the FFT method [21–23]. Fig. 4 shows the frequency-magnitude spectra at 3.0 MPa, for the same Froude numbers as those in Fig. 3. For the steady combustion state (Fig. 4a), the spectrum curve is flat in the high frequency region. The frequency of the fluctuation is less than 5 Hz and is due to unavoidable random comprehensive factors of the experimental system (system resonance, oscilloscope random noise and other factors). For the pulsation combustion state (Fig. 4c), the fluctuation power peak is observed at 34.4 Hz, and the first-order harmonic power peak at approximately 69 Hz is also observed, indicating that pulsation combustion appears at these conditions [24,25]. As mentioned above, the sampling frequency $f_s = 1000$ Hz, the sampling time is 10 s, and the number of samples for FFT processing is $N_{FFT} = 10000$. The frequency resolution ΔR_f for FFT method is:

$$\Delta R_f = f_s / N_{FFT} \quad (2)$$

Thus $\Delta R_f = 0.1$ Hz. For pulsation flame at $Fr = 7.83 \times 10^{-3}$, 3 MPa, FFT result shows the flame pulsation frequency is 34.4 Hz. In the transition combustion state (Fig. 4b), a faint power peak with a minor magnitude occurs at approximately 39 Hz, and the spectrum line is obviously different from those in Fig. 4a and c. For different combustion pressure, experiment results show that the spectrum curves in the same combustion states are similar, as shown in Figs. 4 and 5 (where Fig. 5a are curves for 1.0 MPa, and Fig. 5b are for 4.0 MPa).

As seen from the above analysis, the methane/oxygen diffusion flame can be found in three combustion states depending on the changes in the flow conditions (i.e. Froude number). Which means the transition from steady combustion to pulsation combustion is not happened immediately [16], where a transition combustion state is found. In this case, it is essential to find the initial and terminal points of the transition combustion state, which correspond to the critical conditions that distinguish among the three combustion states. Spectrums in Fig. 6 are located near the initial and terminal points of the transition combustion state, where Fig. 6a is for steady combustion state, Fig. 6b and c are for transition combustion state, Fig. 6d is for pulsation combustion state. It can be seen that the difference between Fig. 6a and b is minor, as well as Fig. 6c and d. To find the initial and terminal points of the transition combustion state, it is necessary to involve a method that combines time-dependent and frequency features, and the short-time Fourier transform (STFT) method was used for such analysis in this work.

The STFT method divides the long-time data log into shorter

Fig. 3. Flame luminous intensity history at 3.0 MPa. (a) $Fr = 0.98 \times 10^{-3}$, (b) $Fr = 2.79 \times 10^{-3}$, (c) $Fr = 7.83 \times 10^{-3}$.

Fig. 4. Flame luminous intensity FFT frequency-magnitude spectrums at 3.0 MPa. (a) $Fr = 0.98 \times 10^{-3}$, (b) $Fr = 2.79 \times 10^{-3}$, (c) $Fr = 7.83 \times 10^{-3}$.

segments (or windows) with equal length and then computes the Fourier transform separately for each short segment. Thus, the frequency and phase content of the local sections are determined over time [19,20]. In this study, the window length was set to 256 out of 10,000 data points (1000 points per second), and the processing results are shown in Fig. 7. In these patterns, the fluctuation amplitude in dB is coloured from red (maximum -1 dB) to purple (minimum -130 dB).

Since the power supply frequency is 50 Hz, the amplitude noise is observed at 50 Hz and 100 Hz (first harmonic frequency of the 50 Hz noise) in Fig. 7. At $Fr = 0.98 \times 10^{-3}$ (Fig. 7a), high dB flame fluctuation occurs in the low frequency region (noise band, close to 0 Hz), and this combustion state is named the steady combustion state. With increasing Fr number, a high dB power peak drifts in the vicinity of 40 Hz at $Fr = 2.79 \times 10^{-3}$ (Fig. 7b). However, this power peak is not continuous; rather, some breaks appear in the time-frequency pattern, indicating that periodic pulsation combustion is not formed. This combustion state is named the transition combustion state. The emergence of a power peak deviating from the noise band indicates the initial appearance of the transition combustion state. By further increasing the Fr number to $Fr = 7.83 \times 10^{-3}$ (Fig. 7c), the amplitude power peak is sustained near 35 Hz, and the harmonic power peak is found in the higher frequency region. In this case, periodic pulsation combustion is formed, and this combustion state is named the pulsation combustion state.

3.2. Flow field of different combustion states

To further analyse the features of the flame pulsation phenomenon with elevated pressure, the Schlieren method was used to study the flame flow field. Gas type, temperature difference and density difference lead to differences in the refractive index. A Schlieren device can capture this difference in the flame envelope and then obtain the details for the flow field pulse.

A comparison between the Schlieren image and flame photograph is shown in Fig. 8. The flame photograph was captured by an SLR camera (exposure of 1/3000 s, Fig. 8a) and shows the typical two zone structure of the methane flame under elevated pressure [3], with an inner yellow zone and an outer blue zone. Furthermore, in Fig. 8b, since the external light source is necessary in the Schlieren measurements, the outer zone of the flame where the luminous intensity is weak can hardly be observed in the Schlieren image (exposure of 1/2000 s). By contrast, the inner zone with greater luminous intensity is distinctly shown in the image. The boundary of the burnt gas and the gas heated by the flame, which is the interface between the high temperature gas and the colder ambient, is also distinctly visible in Fig. 8b. For the steady combustion state, this interface remains straight, and the flame flow field remains constant.

For the pulsation combustion state, significant differences can be found in both the SLR photographs and Schlieren images. The images in Fig. 9a and 9b were obtained simultaneously. In Fig. 9a, the flame tip is separating from the flame body, and a vortex ring can be vaguely observed below the separating flame tip. In Fig. 9b, at the same height as that in Fig. 9a, this vortex ring (first vortex ring) under the flame tip can be clearly observed. In addition to this vortex ring, another vortex ring (second vortex ring) is clearly observed at a lower position. Fig. 9a shows that this lower vortex ring is located outside the outer zone of the flame. At the top of Fig. 9b, a large disturbance zone appears above these vortices.

The evolution of the vortices is shown in Fig. 10. The pulsation frequency for the flame at 3 MPa and with $Fr = 7.83 \times 10^{-3}$ is 34.4 Hz (as obtained by FFT analysis described above); in other words, the flame pulsation period for these conditions is approximately 29.1 ms. Fig. 10 shows nine consecutive Schlieren images for two periods with intervals of 7 ms, together with the flame luminous intensity history at the same time. The trace of a vortex ring is marked by black arrows in the Schlieren images. At $t = 0$ ms, the flame luminous intensity reaches the minimum value, and the height of the inner flame is also the smallest. The vortex ring is not generated yet. With the expansion of the high temperature interface ($t = 7$ ms and 14 ms), the vortex ring emerges at $t = 21$ ms and then floats down stream and is finally

Fig. 5. Flame luminous intensity FFT frequency-magnitude spectrums at different pressure.

Fig. 6. Flame luminous intensity FFT spectrums at different Fr (3.0 MPa).

Fig. 7. Flame luminous intensity STFT time-frequency patterns at 3.0 MPa.

dissipated in the large disturbance zone. Then, at $t = 28$ ms, a new vortex ring is ready to form (marked with white arrows).

As found from the examination of Fig. 9, the vortex ring emerges outside the flame reaction zone and floats outside the flame surface. This result means that these vortices were generated in the shear layer induced by the jet flame [11]. For the pulsation combustion state, the position of the vortices generation is essentially constant. The inflexional velocity profile in flame shear layer (as shown in Fig. 10) is induced by velocity gradient distribution caused by density difference near the shear layer. Therefore, the flow is unstable, and vortices generate periodically at the same position in the sense of Kelvin-Helmholtz. The boundary between burnt gas and co-flow oxygen is

legible, and the flow is laminar around the flame plume. With the emergence and dissipation of these vortices, the flame reaction zone is entrained and deformed periodically together with the flame luminous intensity. As a result, the flame pulsation frequency is constant, as shown in Figs. 4c and 7c.

By contrast, for the transition combustion state, the vortex ring generation position shows large variation. The images in Fig. 11 are selected at the specific moments when the flame luminous intensity reaches the local minimum value. Noticeable differences in the vortex position are observed through the comparison of these images. For a higher generation position (Fig. 11a, for example), the flame reaction zone was not affected by the vortices, and the flame was steady

Fig. 8. Flame images of the steady combustion state (3 MPa, $Fr = 0.98 \times 10^{-3}$). (a) SLR photograph (b) Schlieren image.

Fig. 9. Flame image of the pulsation combustion state (3 MPa, $Fr = 7.83 \times 10^{-3}$). (a) SLR photograph (b) Schlieren image.

Fig. 11. Flame images for the transition combustion state with minimum flame luminous intensity (3 MPa, $Fr = 2.79 \times 10^{-3}$).

temporarily (leading to the breaks observed in Fig. 7b). The flame starts to flicker only when the vortices were generated at a lower position (Fig. 11b), and the flame reaction zone is entrained by vortices.

The results show that the flame pulsation phenomenon was caused by periodical generation of vortices in the shear layer outside the fuel jet mixing layer due to buoyancy-driven Kelvin-Helmholtz instability. Kimura [8] and Durox et al. [9] found that the minimum height of flame is necessary to trigger the flickering. For a low flame Froude number, the flame height is relatively low, the flow field around the flame is stable, and either no vortices are generated, or the vortices are generated high above the flame reaction zone. When the flame Fr increases, flame height increases, while the height of the vortex generation position is decreased. When the height is sufficiently low so that the flame reaction zone is affected by the vortices, the flame starts to flicker. In a specific interval, the vortices generation height is flexible, leading to the flame alternating between the steady and flickering. With a further increase in the flame Fr , flame height further increases, the vortices generation position becomes lower and is nearly invariable, leading to the periodic pulsation flame.

Fig. 10. Flow field evolution of the pulsation combustion state (3 MPa, $Fr = 7.83 \times 10^{-3}$).

Fig. 12. Combustion states distribution at different combustion conditions.

Fig. 13. Halfwidth variation of the transition combustion state at different pressures.

Fig. 14. Flame pulsation frequency in pulsation combustion state.

Fig. 15. Pulsation data fitting curve.

3.3. Zone division of combustion states

The buoyancy is primarily associated with the flames outside the fuel jet mixing layer, which significantly influences the combustion state of the laminar co-flow diffusion flame. Since the Froude number and pressure are related to the buoyancy, additional experiments were performed to investigate the effects of the Froude number and pressure on the flame combustion state.

Based on the flame luminous intensity variation with time for $Fr = 5 \times 10^{-4}$ to 3 and $p = 0.2$ –4.0 MPa, the combustion states of the methane/oxygen diffusion flame are distinguished by the STFT method (see Fig. 7), and the zone division of the flame combustion states is shown in Fig. 12, where the relative pressure p_r is the ratio of the combustion pressure to the fuel critical pressure (for methane, the critical pressure is 4.59 MPa). As seen from Fig. 12, in the logarithmic coordinate system, the flame transition state is in a belt zone. With the increase in the combustion pressure, the corresponding Froude number decreases for the transition combustion state, the area of the pulsation combustion state increases, and the area of the steady combustion state decreases.

In the transition combustion state, random flame vibration occurs, which is harmful to the combustion devices in numerous practical applications; therefore, identifying the specific condition at which the transition combustion state appears is important for practical device design. Fig. 13 shows the half width ΔFr variation of the transition state zone shown in Fig. 12. With the increasing in combustion pressure, density gradient increases, leading to larger velocity gradient near the flame shear layer. Flame turns to be more sensitive, and easier to lose stability. Thus, the width of transition combustion state decreases with increasing combustion pressure. As a result, the increasing in the combustion pressure leads to sharply decrease in ΔFr at $p_r < 0.1$, and ΔFr approaches zero at $p_r > 0.5$.

In Fig. 12, the centre line of the Froude number (Fr_{cent}) of the transition state zone is fitted by:

$$Fr_{cent} = 9.8 \times 10^{-4} (p_r - 0.012)^{-1.87} \quad (3)$$

In Fig. 13, the half width ΔFr of the transition state is fitted by:

$$Fr = 4.0 \times 10^{-5} (p_r + 0.026)^{-2.48} \quad (4)$$

Thus, the upper and lower limits of the Froude number for the transition combustion state zone are as follows:

$$\begin{cases} Fr_{cmax} = Fr_{cent} + \Delta Fr \\ Fr_{cmin} = Fr_{cent} - \Delta Fr \end{cases} \quad (5)$$

where Fr_{cmax} and Fr_{cmin} are the upper and lower limits, respectively. At a given combustion pressure, the flame is in the steady combustion

state at $Fr < Fr_{crmin}$; the flame is in the pulsation combustion state at $Fr > Fr_{crmax}$; and, at $Fr_{crmin} < Fr < Fr_{crmax}$, the flame is in the transition combustion state.

3.4. Flame pulsation frequency variation in the pulsation combustion state

In the pulsation combustion state, the flame pulsation frequencies at different combustion conditions is shown in Fig. 14. The flame pulsation frequency increases with combustion pressure, while decreases with methane flux.

To further investigate the effects of the combustion pressure and methane flux on the flame pulsation frequency, Froude number (Fr) and the dimensionless frequency Strouhal number (St) is employed. Strouhal number is defined as:

$$St = \frac{f_l}{l \cdot u} \quad (6)$$

where f_l is the flame pulsation frequency (Hz); u is the average methane flow speed at the burner port, m/s; g is the acceleration due to gravity, m/s²; and l is the characteristic length (here, l is the diameter of burner port), m.

The relation between St and Fr at $p = 0.2$ – 4.0 MPa is shown in Fig. 15. In logarithmic coordinates, all data points show a linear relation between St and $1/Fr$. While it appears that St is independent of the combustion pressure, the pressure actually influences the velocity of the laminar co-flow methane/oxygen jet flow, which finally results in the variations of Fr and St (see Eqs. (1) and (6)). Therefore, the dimensionless function relating the Strouhal number and Froude number may completely represent the behaviour of the flame pulsation frequency in pulsation combustion. With increasing Fr , the inertia force of the jet flow increases, and the Kelvin-Helmholtz instability induced by buoyancy is weakened, thus increasing the Froude number of the laminar co-flowing injection flow that leads to the flame pulsation frequency decrease (Fig. 15).

The dimensionless function relation in Fig. 15 is fitted as:

$$St = 0.29 \hat{A} \cdot Fr^{-0.65} \quad (7)$$

Hamins et al. [26] presented the dimensionless function relation (St - Fr) for the laminar co-flowing methane/air diffusion combustion, with similar results to those described by Eq. (7), albeit with the exponent of -0.57 rather than -0.65 . These results indicate that the Froude number has a greater effect on the Strouhal number of the methane/air diffusion flame than that of the methane/oxygen diffusion flame because the nitrogen dilution effect should be taken into consideration when air is used as the oxidizer. Compared to the methane/air flame, oxygen diffuses into fuel much more easily in the methane/oxygen diffusion flame, and the flame height becomes shorter, weakening the effect of buoyancy on the flame so that the effect of Fr on St becomes weak in the methane/oxygen diffusion flame.

4. Conclusion

The stability characteristics of the laminar co-flow methane/oxygen diffusion flame with a 3 mm injector were investigated from $p = 0.2$ to 4.0 MPa; the regions of the three flame combustion states were identified, the origins of the three combustion states were investigated by studying the flow field details captured using a Schlieren device, and the pulsation frequency characteristic of the flame was obtained. Some important conclusions were obtained as follows:

- (1). The methane/oxygen diffusion flame has three combustion states: the steady combustion state, transition combustion state, and pulsation combustion state. These states are caused by the different formation heights of the vortices generated in the jet flame shear layer.
- (2). The upper and lower limits of the Froude number for the transition

combustion state zone at a given pressure are given by:

$$\begin{cases} Fr_{crmax} = Fr_{cent} + \Delta Fr \\ Fr_{crmin} = Fr_{cent} - \Delta Fr \end{cases}$$

where $Fr_{cent} = 9.8 \times 10^{-4}(p_r - 0.012)^{-1.87}$ and $\Delta Fr = 4.0 \times 10^{-5}(p_r + 0.026)^{-2.48}$.

- (1). The flame is in the steady combustion state for $Fr < Fr_{crmin}$; the flame is in the pulsation combustion state for $Fr > Fr_{crmax}$; and the flame is in transition combustion state for $Fr_{crmin} < Fr < Fr_{crmax}$.
- (2). The dimensionless function relation between the Strouhal number and Froude number was found to be:

$$St = 0.29 \hat{A} \cdot Fr^{-0.65}$$

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.fuel.2019.01.113>.

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