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Flame dynamics in a heated meso-scale radial channel

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Abstract

Combustion dynamics in a heated meso-scale radial channel made of quartz glass were experimentally investigated. Wall temperature profiles were generated by an external heat source to simulate the practical situation of heat-recirculating type mini-combustors. It was found that asymmetric stable flames appeared in the radial channel at lower inlet velocities. Moreover, the height of the flame front was less than the gap distance of the radial channel, indicating fuel leakage from the channel exists. At larger inlet velocities, the asymmetric flame front became very unstable. Stochastic transitions between asymmetric unstable flame and spiral-like flame were observed and captured with an image-intensified high-speed video camera. The movie recordings demonstrated that the formation of the spiral-like flame originates from local splitting in the unstable flame front. The inner flame front moved upstream and ignited the fresh fuel close to it, while the outer one can survive by burning the leaked fuel from the gap between the inner flame and the top disc. Thus, a rotating spiral-like flame was formed. Due to the unbalance between the radial component of flow velocity and the flame speed, the inner flame front was pushed outward and merged with the outer one, which led to the regression from the spiral-like flame to asymmetric unstable flame. Numerical study on the flow fields revealed that flow field grows unstable at larger inlet velocities. The unstable flow field and flame quenching near the top wall surface are expected to play key roles in those flame dynamics.

Keywords: Meso-scale combustion; Stochastic flame dynamics; Asymmetric flame; Spiral-like flame; Flow instability

1. Introduction

Flame pattern formations have been extensively investigated. For instance, cellular flame [1,2], kink flame [2], rotating spiral flame [3–6], target flame [6], and triple flame [7], etc., have been experimentally observed and theoretically analyzed in both premixed and non-premixed combustion systems. Various kinds of flame instabilities, such as thermal-diffusive, hydrodynamic, buoyancy driven, and viscous fingering, etc., have been reported in the literature [8–11]. These phenomena are quite complex as the process is governed by the coupling of fluid dynamics, heat and mass transfer, and chemical reactions.

Recently, with the emerging of various MEMS devices, such as portable electric products, micro robots, micro aerocrafts, micro combustors, there

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is an urgent demand for micro power generation systems. Combustion based micro power generation system is a promising alternate to chemical batteries due to the much higher energy densities of hydrocarbon fuels [12]. Therefore, micro- and meso-scale combustions have received great attention in the past decade [12–15]. However, the increased heat losses and wall radical quenching arising from the large surface area-to-volume ratio make it difficult to sustain a stable flame under small scales [16–18]. It is thus critical to adopt some thermal management measures, for instance, heat recirculation, in the design of micro combustors. The "Swill roll" combustor is a good example of heat-recirculating-type configurations and it has already been implemented to anchor flame in micro- and meso-scale burners [19,20]. Through this technique, the cold fresh mixture can be preheated by the hot burnt gas via the solid walls.

Many contributions have been made to understand the fundamentals of combustion at reduced scales with heat recirculation. To facilitate direct observation of the flame in micro configurations, Maruta et al. [21,22] used a micro-tube made of transparent quartz. In their experiments, in order to simulate the heat-recirculating effect through the solid walls, and also to keep a constant wall condition, a temperature profile of the tube wall was generated with an external heat source before the introduction of fuel. They observed a flame mode with repetitive extinction and ignition (FREI). After that, similar flame oscillation phenomena were reported by many other researchers [23–26]. Nonlinear analysis revealed these flame dynamics in the micro-channel with constant temperature profile [27]. Later, Minaev et al. [28] predicted flame splitting phenomenon in heated micro-channel and Fan et al. [29] confirmed this through experiment. Very recently, Nakamura et al. [30] numerically investigated the flame splitting phenomenon during the FREI processes. This work successfully revealed the details of the multiple ignition kernels in the flow reactor.

Kumar et al. [31–33] and Fan et al. [34–38] conducted experiments to study the flame pattern formations and transitions of CH_4/air and DME/air mixtures in heated micro- and meso-scale radial channels. This geometrical structure can be used as a combustion chamber for micro-power generation systems, such as disk-type micro-gas turbine [39]. In addition to conventional circular flame, a variety of non-stationary flame patterns, such as rotating Pelton-wheel-like flames, traveling flames, and spiral-like flame (see Fig. 1), etc., were discovered. Fan et al. [35] numerically reproduced the single and double Pelton-wheel-like flames. In this work, they used a two dimensional thermo-diffusive model and did not consider the effect of flow. The traveling flame observed in this radial channel was interpreted by Minaev et al. [40] based on a thermo-diffusive model. However, the spiral-like flame cannot be reproduced using the same model. From [34] it was found that the spiral-like flame appears at large inlet velocities and large channel gaps. Meanwhile, it was shown that higher wall temperature level cannot improve the stability of the spiral-like flame [36]. Those facts give us some hints that flow instability, or together with some other factors, might play an important role in the formation of the spiral-like flame.

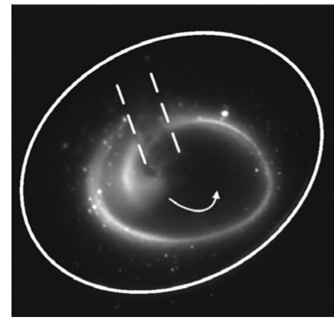

Fig. 1. Appearance of the spiral-like flame [31].

The main focus of the present work is to reveal the formation mechanism of the spiral-like flame. We should bear in mind two important questions: one is what causes the splitting of flame front, and the other is why the outer flame front can maintain during the rotating processes. As the spiral-like flame only appears in the radial channel with a gap distance larger than 3.0 mm, we conduct investigation of flame dynamics in a radial channel with a 4.0 mm gap in this paper. The effect of the flow instability will also be numerically studied.

2. Experimental

2.1. Experimental setup and method

A schematic diagram of the experimental setup is shown in Fig. 2. Two quartz discs (Ø50) are maintained parallel to each other within an accuracy of ±0.1° to form a radial channel. A delivery tube of a 4.0 mm diameter was connected to the center of the top disc. The gap distance of the two discs is 4.0 mm. Before the fuel supply, the radial channel was pre-heated by a porous metal burner from the bottom. A cold air flow was fed into the channel while heating. After about 30 min, the wall temperature profile became steady. The temperature profiles of the inner surfaces of the radial channel were carefully measured with a 250 μm K-type thermocouple, as shown in Fig. 3. The moving step of the thermocouple was 1.0 mm, which was controlled by a transverse micrometer. The measured tempera-

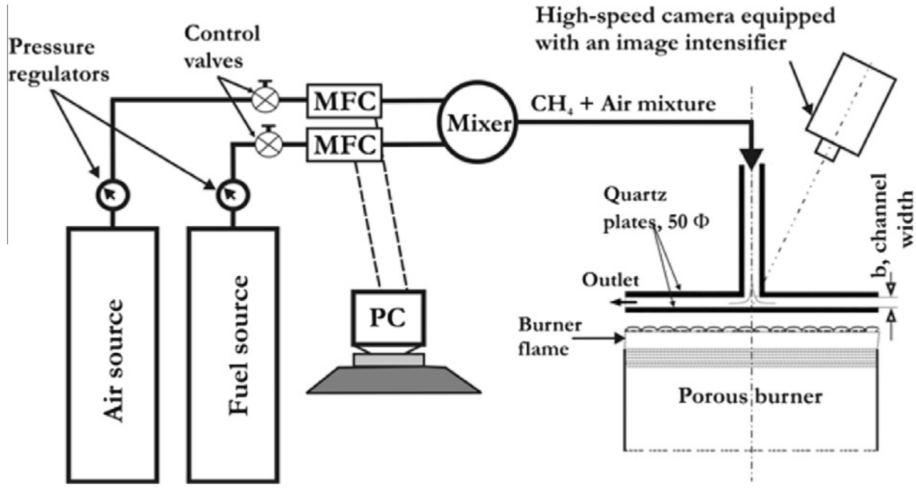

Fig. 2. Schematic diagram of the experimental setup.

tures were corrected for heat losses from the thermocouple bead and the corrected temperatures are accurate to ±5 K. From Fig. 3, it can be seen that the wall temperature increases with the increase of the radial distance. The maximal values of the bottom and top discs were 1000 K and 850 K, respectively. The wall temperature difference is up to ∼150 K. More importantly, the temperature profiles were noted to be asymmetric.

Methane gas at atmospheric pressure was used as fuel. The flow rate of the supplied fuel–air mixture was monitored through electric mass flow controllers within an accuracy of ±1%. In order to maintain a rigorous laminar flow in the delivery tube, the maximum value of the inlet velocity was set at 6.0 m/s, where the representative Reynolds number is ∼1542. Flame photos from side viewpoint were taken by a still digital camera. The flame dynamics were recorded with an image-intensified high-speed video camera at a rate of 250 fps (frames per second) with a shutter speed of 1/250 s. The length of the movie recording is less than 2.0 s. As the thickness of the two quartz discs is 2.0 mm, they could be regarded as thermally thick walls, i.e., the wall temperature profiles could be considered to be constant during the movie recording process.

2.2. Experimental results

2.2.1. Asymmetric stable flames

At first, we report the stable flame observed in the heated radial channel, which is expected to be helpful in explaining the formation mechanism of the spiral-like flame. Figure 4 illustrates two flame photos taken by a still digital camera from side viewpoint. From Fig. 4a it is noted that when the inlet velocity was 2.5 m/s, the flame is a stable

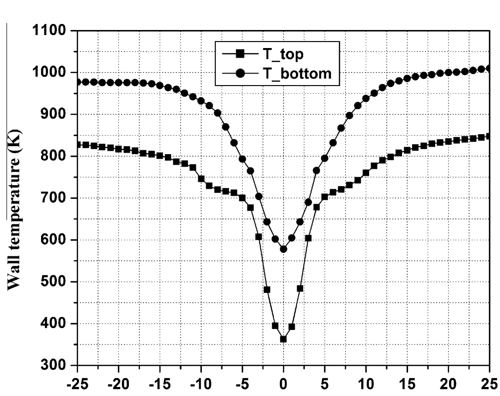

Fig. 3. Measured wall temperature profiles at the inner surfaces of the bottom and top discs at inlet air velocity $V_{in} = 2.0$ m/s.

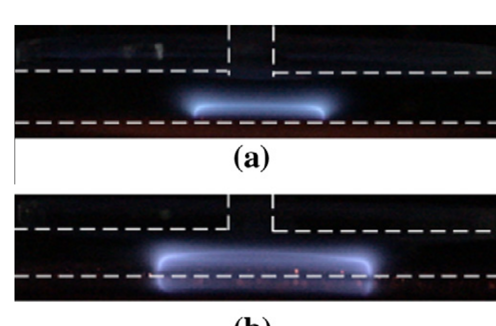

Fig. 4. Flame photos from side viewpoint at different inlet velocities. The dashed lines indicate the inner surface of the two disks and the delivery tube: (a) $V_{in} = 2.5$ m/s, $\phi = 1.0$; (b) $V_{in} = 4.0$ m/s, $\phi = 1.0$.

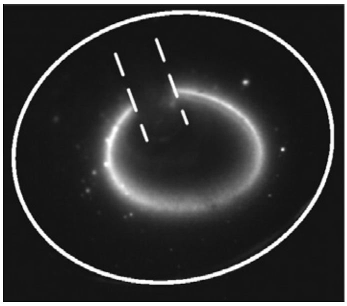

Fig. 5. Stable asymmetric flame at $V_{in} = 3.0$ m/s and equivalence ratio $\phi = 1.0$.

one but there is a little asymmetric in the flame front. As the inlet velocity was increased to even larger, e.g., 4.0 m/s, the asymmetry of flame front is more obvious, as shown in Fig. 4b. Figure 5 shows an image captured by the high speed video camera from a top-down viewpoint. The inlet velocity of fuel/air mixture is 3.0 m/s. This figure further confirms the existence of stable asymmetric flame. This phenomenon is accordance with the asymmetric wall temperature profile shown in Fig. 3.

One more important thing should be mentioned is that the flame cannot fully fill the gap of the radial channel, i.e., flame is quenched by the inner surface of the top wall. Thus, it is undoubtedly that some fuel will leak out without completely burning. This is a key fact that is expected to play an important role in the formation of the spiral-like flame.

2.2.2. Flame dynamics

With the further increment of the inlet velocity, flame becomes very unstable. Stochastic transitions between the asymmetric unstable flame and

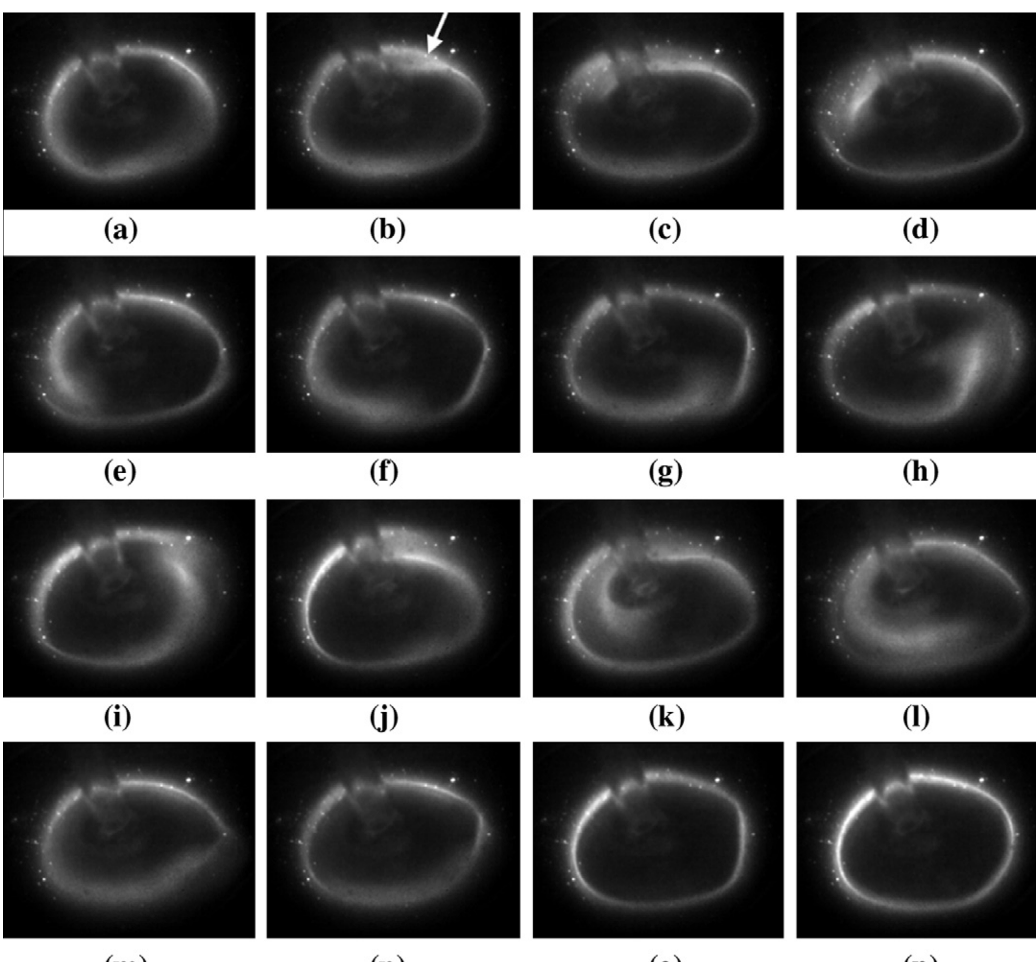

Fig. 6. Stochastic transitions between the unstable circular flame and the spiral-like flame: I. The inlet mixture velocity $V_{in} = 6.0$ m/s and the equivalence ratio ϕ = 1.0.

the spiral-like flame occur frequently. Figure 6 is an example of these flame dynamics. From Fig. 6a it is seen that the flame front is an asymmetric unstable circle with non-uniform luminosity. Soon after, some location (indicated by the white arrow) of the flame front is splitted into two parts, as shown in Fig. 6b. If we examine it carefully enough, the fact is that the upper part of the flame front is pushed upstream. The inner flame front soon ignites the fresh fuel/air mixture close to it. Recalling that there is no flame near the top surface of the channel, fuel leakage must exist. Thus, the outer flame front can sustain by burning the leaked fuel. A counterclockwise rotating spiral-like is thus formed, as shown in Fig. 6b–l. However, the outgoing flow velocity is larger than the radial component of flame speed at small radial locations. Thus, the inner flame front will be pushed outward and merge with the outer flame front, as depicted in Fig. 6m. Therefore, the rotating spiral-like flame returns to the asymmetric unstable flame, as shown in Fig. 6n–p. This will be further discussed in Section 4 after the numerical simulation of the flow field.

Figure 7 demonstrates a similar stochastic transition between the asymmetric unstable flame and the spiral-like flame. The difference between this process and that shown in Fig. 6 is that the rotating direction of the spiral-like flame is clockwise. Another dynamic process is shown in Fig. 8, in which the flame splitting occurs in the opposite side of that in Figs. 6 and 7. The reason for why we present Figs. 7 and 8 here is that these two processes help to verify that those transition dynamics are stochastic, not depending on the splitting location and rotating direction.

3. Numerical simulation of flow field

As mentioned above, these flame dynamics are expected to have a close relationship with the flow field. To completely reveal the mechanisms of these flame phenomena, simulation of the combustion process with detailed chemistry is necessary. But as a first step, it is still of meaning to investigate the independent effect of flow instability separately. Moreover, little attention has been paid to the effect of flow field in our previous studies. Other researchers have reported that the impinging jet from the delivery tube may lead to an asymmetric and/or unstable flow field in similar configurations with a relatively large gap distance [41,42]. If the flow field becomes asymmetric and/or unstable in the present mesoscale radial channel at relatively high velocities,

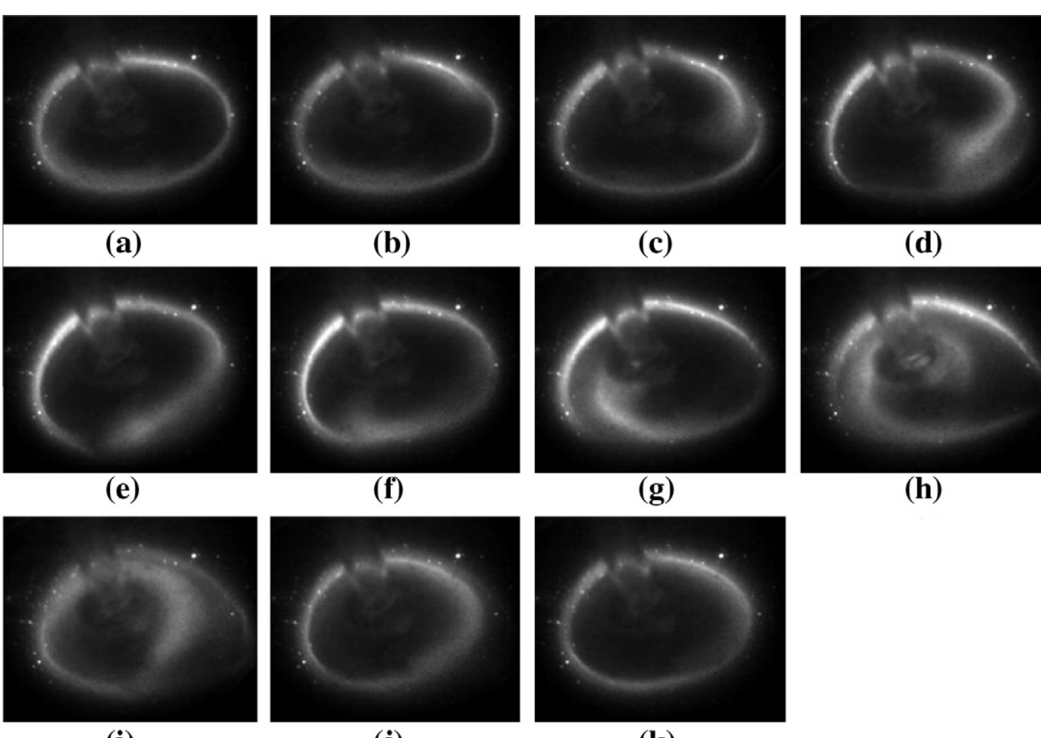

Fig. 7. Stochastic transitions between the unstable circular flame and the spiral-like flame: II. The inlet mixture velocity $V_{in} = 6.0$ m/s and the equivalence ratio $\phi = 1.0$.

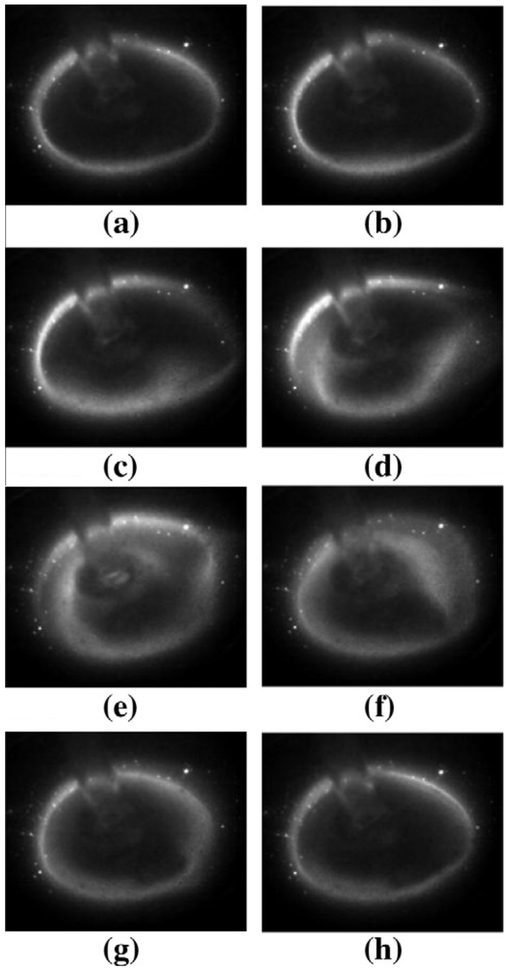

Fig. 8. Stochastic transitions between the unstable circular flame and the spiral-like flame: III. The inlet mixture velocity $V_{in} = 6.0$ m/s and the equivalence ratio $\phi = 1.0$.

it will undoubtedly exert some effect on flame instability. This stimulates us to investigate the instability of the flow field through numerical simulation.

For this, we performed numerical simulation of the isothermal flow field in the radial channel using the CFD software package, Fluent 6.3. The Geometry of the meso-scale radial channel is schematically shown in Fig. 9. The maximal inlet velocity used in the experiments was 6.0 m/s, corresponding to a Reynolds number of ~1542 in the delivery tube. The Reynolds number in the radial channel is much smaller due to the increasing cross section area along the outgoing flow direction. Thus, three dimensional, unsteady laminar model was adopted in the numerical simulation. A length of 40 mm is used for the delivery tube to get a fully developed velocity profile at the inlet port of the radial channel. At the exit of the radial channel, a pressure boundary condition is set. Due to the length limit of this paper, other details of the computation are not addressed here.

Figure 10 illustrates the effects of inlet velocity on the contours distributions of velocity magnitude in the horizontal central plane when the gap distance is 4.0 mm. From Fig. 10a it is seen that when the inlet velocity is not larger than 2.0 m/s, the flow field in the radial channel is symmetric and stable. As the inlet velocity is increased to 3.0 m/s, flow field becomes somewhat asymmetric, but it is still stable in general, as shown in Fig. 10b. With the further increase of inlet velocity up to 6.0 m/s, the flow field in the radial channel grows asymmetric and unstable, which is clearly seen in Fig. 10c. The evolution of flow field presented in Fig. 10 demonstrates that there exists a critical velocity at which the flow field transits to asymmetric and unstable.

Effect of the gap distance on the contours distributions of velocity magnitude in horizontal central plane is demonstrated in Fig. 11 when the inlet velocity is fixed at 5.0 m/s. From Fig. 11a it is noted that when the gap distance is 3.0 mm, the flow field in the radial channel is symmetric and stable. As the gap distance is increased to 4.0 mm, the flow field becomes asymmetric with weak instability in the region of small radius. With the further increase of gap distance up to 5.0 mm, the symmetry and stability of flow field are broken in the whole channel, which can be clearly seen from Fig. 11c. The evolution of flow field presented in Fig. 11 shows that the critical velocity depends on the gap distance of the radial channel.

The flow field in the radial channel was also investigated by other researchers [41,42]. Yoshimatsu and Mizushima [41] experimentally investigated the instability and transition of radially outgoing flow between two parallel discs. Through flow visualization, they demonstrated that the flow was steady and symmetric at small Reynolds numbers, but became asymmetric above a critical Reynolds number. These works [41,42] qualitatively verifies our numerical simulations.

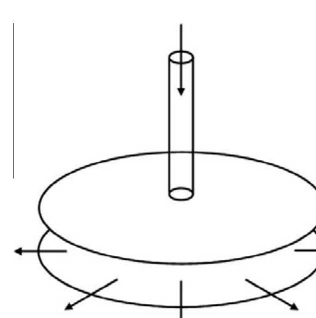

Fig. 9. Geometry of the meso-scale radial channel.

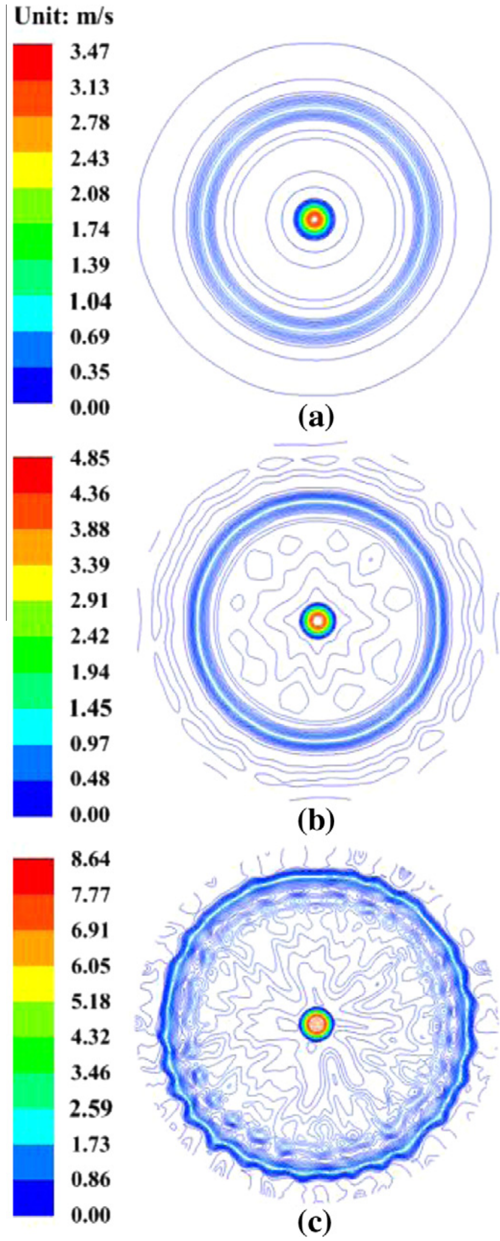

Fig. 10. Effect of the inlet velocity on the contours distributions of isothermal flow field in the horizontal central plane at $b = 4.0$ mm: (a) $V_{in} = 2.0$ m/s; (b) $V_{in} = 3.0$ m/s; (c) $V_{in} = 6.0$ m/s.

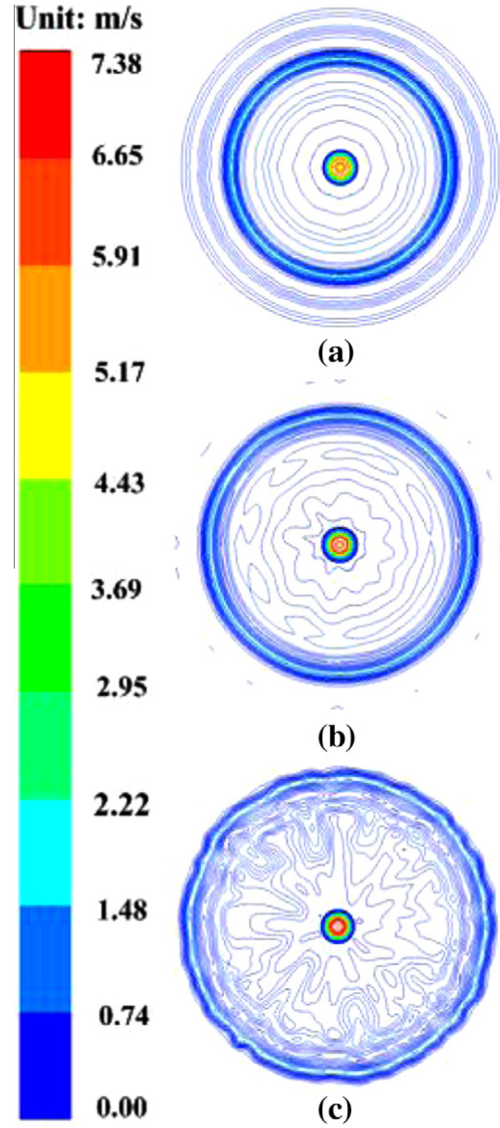

Fig. 11. Effect of the gap distance on the contours distributions of isothermal flow field in horizontal central plane at $V_{in} = 5.0$ m/s: (a) $b = 3.0$ mm; (b) $b = 4.0$ mm; (c) $b = 5.0$ mm.

4. Brief discussions

From the simulation results of the flow field, one can see that when the channel gap and inlet velocity are relatively large, the flow field is asymmetric and unstable. This may cause the flame front to become asymmetric and unstable if fuel is added and ignited in the radial channel. The unstable vortexes may push the flame front upstream at some locations, which can lead to the splitting of flame front, as have been shown in Figs. 6 to 8. The inner flame head will ignite the fresh mixture in the vicinity of it. Because the tangential flow velocity is very small as compared with the burning velocity, the inner flame head will propagate in the circumferential direction with a high speed. At the same time, as there is no flame near the inner surface of the top disc, fuel leakage from this gap must exist. This is the reason why the outer flame front can survive after the splitting of the original flame front. Based on the above two reasons, the rotating spiral-like flame is thus formed. But at locations where the radial component of flow velocity is greater than the flame speed, the flame front will be pushed downstream. This may result in the merging of splitted flame fronts as one. Therefore, the rotating spiral-like flame returns to the unstable asymmetric flame. As the flow field is unstable, those dynamic processes occur stochastically and repetitively.

5. Concluding remarks

Combustion characteristics were experimentally investigated in a heated meso-scale radial channel. Observation from a side viewpoint showed that the flame height is less than the gap distance of the channel. Stochastic transitions between the asymmetric unstable flame and the rotating spiral-like flame were captured with a high-speed video camera. Numerical simulations indicated that the flow field became asymmetric and unstable at large gap distance and inlet velocity. Under the effect of flow instability, flame splitting occurred at some locations. The inner flame front moved upstream and ignited the fresh fuel close to it, while the outer flame front survived by burning the leaked fuel from the gap between the inner flame and the top disc. Thus, a rotating spiral-like flame was formed. Due to the unbalance between the radial component of flow velocity and the flame speed, the inner flame front was pushed outward and merged with the outer one, which led to the regression from the rotating spiral-like flame to the asymmetric unstable flame. Those frequently occurred flame dynamics demonstrate that flame pattern formations and transitions in the meso-scale radial channel are very complicated.

Acknowledgements

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