Experimental Studies on the Dynamics of Premixed Methane-Air Flames in Various Aspect Ratio Channels

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1 Introduction

Study of flame propagation in micro and meso scale channel is of fundamental importance in the development of micro reactive systems. Maruta et al. [1] have carried out experiments to investigate the characteristics of premixed methane-air and propane-air flames in straight cylindrical quartz tube by simulating thermally thick walls. They obtained stable flame branches in high and low flow rate regions. Various dynamic behaviors such as repetition of extinction and ignition, and pulsating flames were observed at intermediate flow rates. Studies on the combustion behavior of methane-air mixture in narrow radial channel have been reported by Kumar et al. [2, 3] and Fan et al. [4]. The different regime diagrams have been observed with Pelton type, Dragon type flames and various other flame propagation modes. The experiments of Ju and Xu [5] in meso-scale tubes with diameters ranging from 3 to 8 mm revealed that depending on the tube width, flow velocity and wall thermal properties, multiple (fast and slow propagation) regimes existed for self-propagating methane–air and propane–air flames. In a more recent numerical study on flame propagation in diverging channels, Kumar [6] has reported the behavior of stabilized flames in channels of various divergence angles. Kumar [6] has observed the formation of mushroom and tulip shaped flame structures. Despite many studies, hydrodynamic and thermal diffusive instabilities of freely propagating flame, development of boundary layers, flame-wall coupling, hydrodynamic flame-wall interaction due to wall friction, surface reactivity and/or radical quenching are the different problems related with the propagation of these flames [7].

The aim of the present work is to investigate the flame stabilization behavior in meso-scale rectangular diverging channels of different aspect ratios. In most of the micro combustors studied, the flame is stabilized at a location where combustible mixture flow decelerates along the flow path [6]. These configurations followed either a systematic or sudden velocity gradient which enhances the flame stability limits and controls the location of flame stabilization point. This velocity gradient also helps in avoiding the flame flashback. One of the parameters which may affect the flame dynamics inside the channel is height to length ratio and this has not been considered earlier. Therefore, there is a need to investigate and understand the characteristics of flame stabilization inside the channels of different aspect ratios. The understanding of flame propagation in such channels will lead in the development of micro combustors.

In the present work, a configuration of rectangular diverging meso-scale channels of 15° diverging angle and inlet aspect ratio (inlet height to width ratio) of 5, 10 and 15 were chosen. The inlet width was 2 mm while width was different for different aspect ratio channels. This essentially means that the flow area increases linearly with the axial distance which leads to a decrease in the flow velocity. Methane–air mixture is used for detailed investigations which are reported in this paper. Fuel–air mixture flows through the channel with a flow divergence in the transverse direction depending on the aspect ratio. The flame is expected to stabilize at a location where the flow velocity equals the local flame propagation velocity. In the present configuration of diverging channels, the fuel–air mixture is simultaneously subjected to a positive temperature gradient and flow divergence. A positive temperature gradient in the direction of fluid flow is maintained with external heating to simulate the heat recirculation through the solid walls and to avoid thermal coupling between the solid and gas phase. This also helps in flame ignition and stabilization in these channels.

2 Experimental setup

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The schematic diagram of a typical 15° channel with aspect ratio of 15 is shown in Fig. 1. The starting point of diverging section is considered as reference point and marked as "o". X-axis is in the axial direction and Y-axis is in transverse direction. Same divergence was given to all three channels to have uniformity. To simulate the combustion heat recirculation through solid channel walls, a positive temperature gradient is maintained in the direction of fluid flow. The experimental setup and measurement details were same as that was used in authors' earlier study [8].

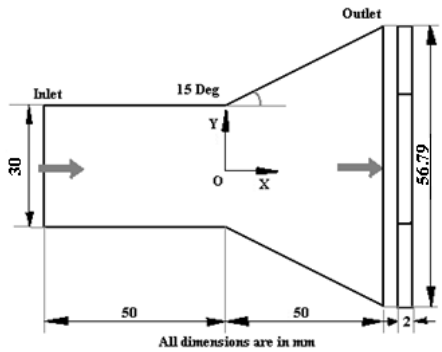

Figure 1. Schematic of 15° channel and aspect ratio of 15

3 Results and Discussion

Wall temperature profile

The wall temperature profiles on the inner side of quartz plates both in axial and transverse direction were measured in advance with airflow to examine the effects of flow on the wall temperature profile. To quantify the effects of mixture flow rate on the wall temperature profile, wall temperature measurements were carried out over a range of air inflow velocities. Temperature measurements for the bottom wall at two different flow velocities for 15° channel are shown in Fig. 2a. It is concluded from the temperature profiles that the temperature gradient increases with the decrease in the flow rate and the peak wall temperature is reached near the exit of the channel. Fig. 2b shows the measured temperature profiles in transverse direction with an airflow velocity of 0.2 m/s through the delivery tube for 15° channel. The temperature is measured for every 20 mm distance from reference point. It is observed that temperature is almost uniform across the transverse direction with slightly high temperature near side walls. The top plate is heated due to convection and radiation from the bottom plate [11]. Both of these mechanisms play significant roles in the heat transfer between the top and bottom plates. Therefore, the measured temperatures of both plates are expected to be quite similar, with a slightly lower temperature of the top plate (~20 – 50 K). Similar wall temperature profiles were observed for other channels as well.

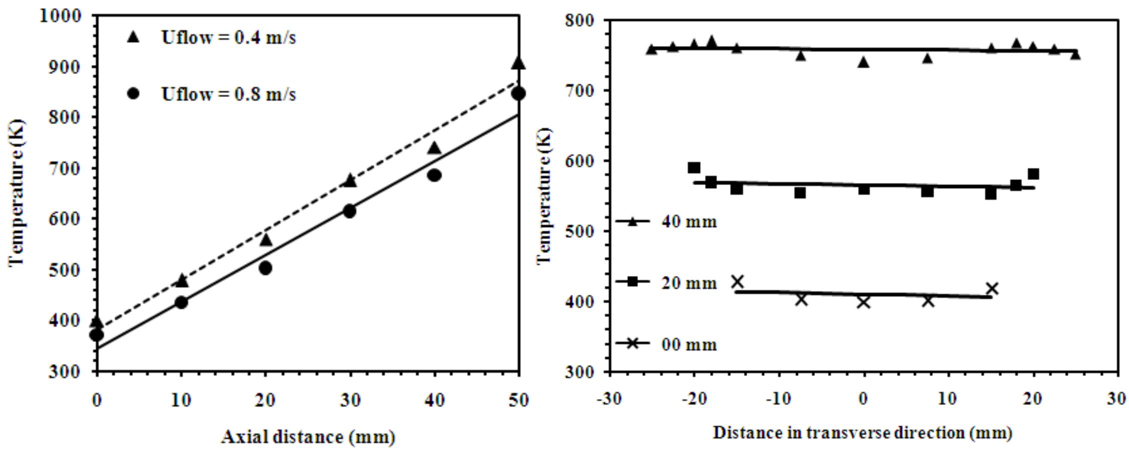

Figure 2. Bottom wall inside temperature profile in a) axial and b) transverse direction for a channel of 15 aspect ratio

Preliminary observations

Preliminary parametric studies were carried out to classify the different flame propagation mode observed in the present work. Mixture equivalence ratio, divergent angle and mixture velocity are important parameters which affect flame stability in these channels. The mixture mass flow rates were varied from 0.3 SLM to 6.5 SLM. The preliminary observations show that, a flame can be stabilized for a range of equivalence ratio $\Phi = 0.7$ to $\Phi = 1.3$ for all the channels. Preliminary visual observations with direct photographs of flames were carried out with a DSLR camera. A high speed camera (Casio-EX-FH20) was used to measure the frequency of oscillations of flames. These are followed by detailed parametric studies. The following schemes were used to classify the various flame modes observed during the experiment.

1) Flame propagation mode with flat shape is termed as planar flames.
2) Flame propagation mode with concave shape is termed as negatively stretched flames.
3) Flame propagation mode with convex shape is termed as positively stretched flames.

Formation of these different flame propagation modes is due to the area variation along the fluid flow and increased heat transfer from flame to unburned mixture for such small scale channels.

Planar flames

The flow inside the high aspect ratio channels flow profile observed is somewhat rectangular even for very low Reynolds numbers Re. flame propagation mode at small inlet flow velocity was observed to be flat [9]. This flame propagation mode with flat shapes was observed in high aspect ratio channel for a range of mixture equivalence ratios varying from 0.8 to 1.3 and inlet mixture velocity range of $0.25 < V < 0.45$ m/s.

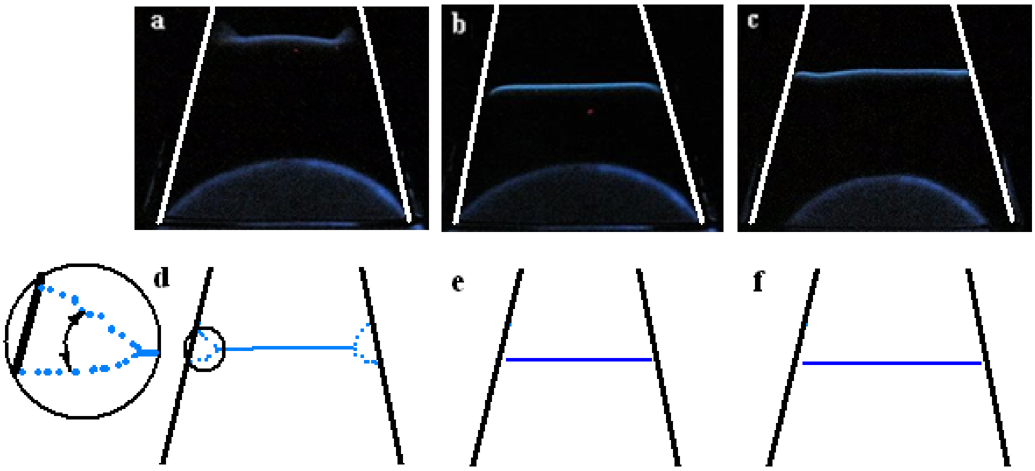

Figure 3. Planar flames observed for high aspect ratio channels

These flames were observed channels of aspect ratio 10 and 15. Corresponding line diagrams for this type of flames are shown along with actual photographs in Fig. 3. For lean mixtures, planar flames were observed for $0.35 < V < 0.40$ m/s conditions with low luminous intensity and were partially stable in which flame front at the centre was stable and flame front near the walls was oscillating. An enlarged view of the oscillating flame front near the wall is is shown in Fig. 3d. The flame near the side wall first stabilizes at a particular location and then travels downstream again and then comes back to upstream position. Photograph shown in Fig. 3a was obtained for $\Phi = 0.8$, $V = 0.4$ m/s with a channel of aspect ratio 10. For rich mixtures planar flames were observed for a somewhat extended inlet mixture velocity range, $0.25 < V < 0.55$ m/s. All planar flames observed for rich mixtures were stable. Photographs shown in Fig. 3b and Fig. 3c are observed for $\Phi = 1.1$ at $V = 0.4$ m/s in 10 and 15 aspect ratio channels respectively. Line diagrams of stable planar flames are shown in Fig. 3e and 3f respectively.

Negatively stretched flames

After the stabilization of planar flame, it was observed that flame front moved towards the upstream with an increase in the inlet mixture velocity. This mode of flame propagation was of concave shape with respect to unburned mixture and termed as negatively stretched flames. This mode was observed in very high aspect ratio channels only (Aspect ratio = 15) and for rich mixtures. These flames were observed in the mixture equivalence range of $1.0 \leq \Phi < 1.3$ and mixture velocity range of $0.40 < V < 0.65$ m/s. All these flames observed were stable for all the channels. These negatively stretched flames were both asymmetric and symmetric in shape as shown in Fig. 4. Photographs shown in Fig. 4a and Fig. 4c are negatively stretched flames observed at $\Phi = 1.0$ and V = 0. 5 m/s (asymmetric) and at $\Phi = 1.1$ and V = 0.5 m/s (symmetric) for 15 aspect ratio channel respectively. Line diagrams corresponding to these types of flames are shown in Fig. 4b and Fig. 4d respectively. These flames have not been observed for small aspect ratio channels.

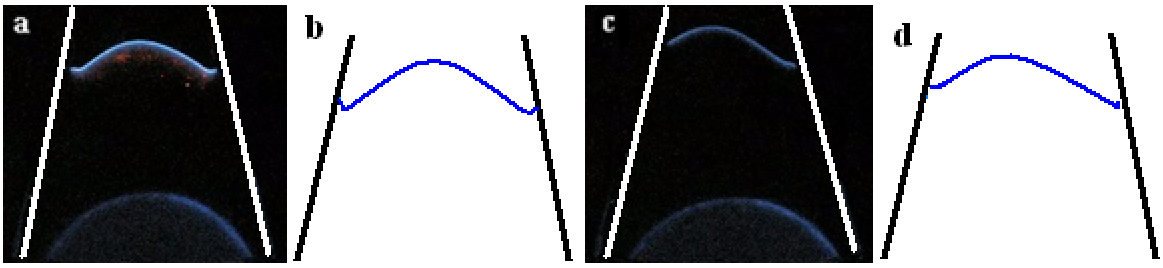

Figure 4. Photographs and line diagrams of negatively stretched flames for 15 aspect ratio channel

Positively stretched flames

For medium and high aspect ratio channels, with further increase in inlet mixture velocity it was observed that flame front moved towards the downstream. For such cases, the flame shape was convex with respect to unburned mixture and in present work termed as positively stretched flames. For small aspect ratio (Aspect ratio = 5) channel and all inlet mixture velocity and mixture equivalence ratio conditions, this was the only mode of flame propagation. These flames were observed for both lean and rich mixtures. For lean mixtures, these flames were observed for all inlet mixture velocity conditions($0.3 < V < 2.25$ m/s) and for rich mixtures, they observed for $0.7 < V < 2.6$ m/s. Photographs shown in Figs. 5a 5b are asymmetric stable and partially stable flames observed for $\Phi = 1$ and at V = 1.0 m/s and V = 1.4 m/s respectively for small aspect ratio (AR = 5) channel. Photographs shown in Fig. 5c and Fig. 5d are symmetric stable and partially stable flames observed for $\Phi = 1.0$ and $\Phi = 0.9$ at V = 1.2 m/s respectively for medium aspect ratio (AR = 10) channel. An enlarged view of instability near the walls is shown in the same figure. This partially stable flame first stabilizes at a particular location and then travels downstream again and then comes back to upstream position as shown in Fig. 5e.

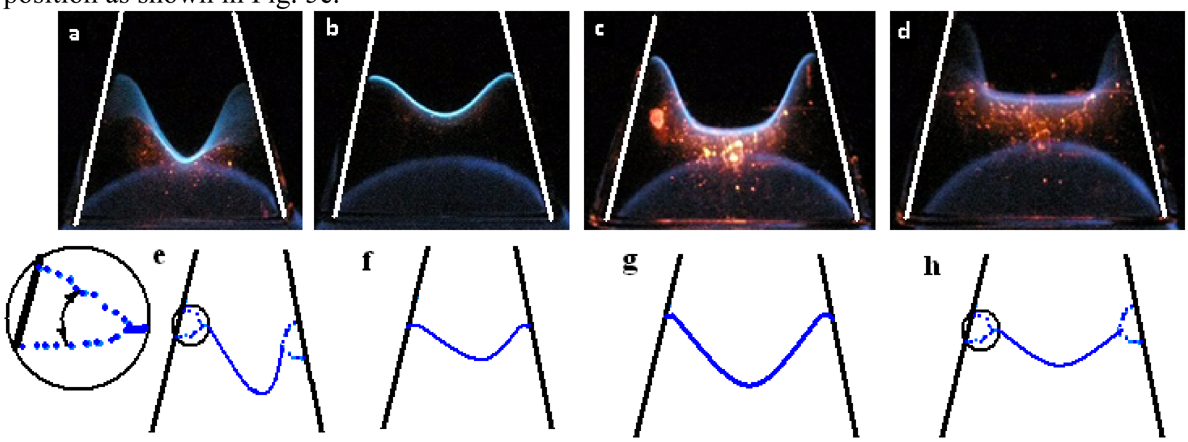

Figure 5. Photographs and line diagrams of positively stretched flames in different channels

Flame stability limits

To understand the effect of aspect ratio on the propagation of flame front, stability limits of all three channels are plotted in Fig. 6. The experiments were carried out for a range of mixture equivalence ratios varying from 0.7 to 1.3. Inlet mixture velocities were varied over a range starting from 0.2 m/s to 2.6 m/s. The minimum inflow velocity at which a flame stabilizes inside the channel is considered as low velocity limit of flame stabilization. Maximum velocity limit is considered for a case where flame moves out of the channel. For the given range of flow rates, flame extinction occurs for mixtures $\Phi < 0.7$ and mixtures $\Phi > 1.3$. Low velocity stability limits were decreasing with increase in aspect ratios for all values of equivalence ratio. Increased high velocity stability limits were observed with decrease in the aspect ratios for all mixtures. Marginal effect of increase in aspect ratio was observed for aspect ratios above 10. Maximum flame stability limits were observed to occur at $\Phi = 1.0$ for all channels. Increase in the aspect ratio improves the low velocity stability limits, making the reactive system safer by avoiding flash back.

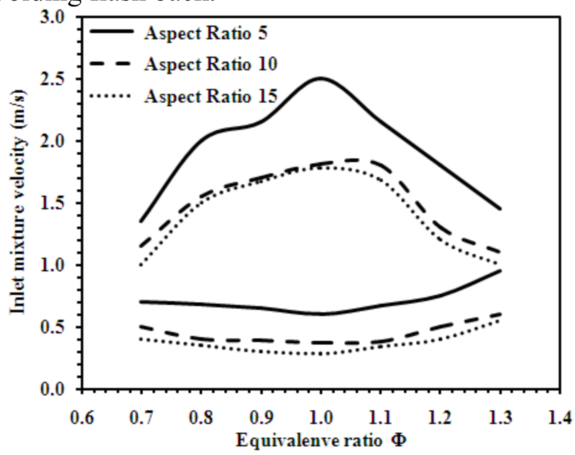

Figure 6. Flame stability limits for different channels

Effect of inflow velocity

Effect of inflow velocity on the flame position in the axial direction is shown in Fig. 7 for all the channels and for stoichiometric mixtures. Flames moved upstream with an increase in flow velocity for lower flow rates where as flames moved in downstream direction for high flow rates. Two different velocity branches were observed inside all the channels. Flames observed to stabilize inside the channel at high velocity for small aspect ratio channel.

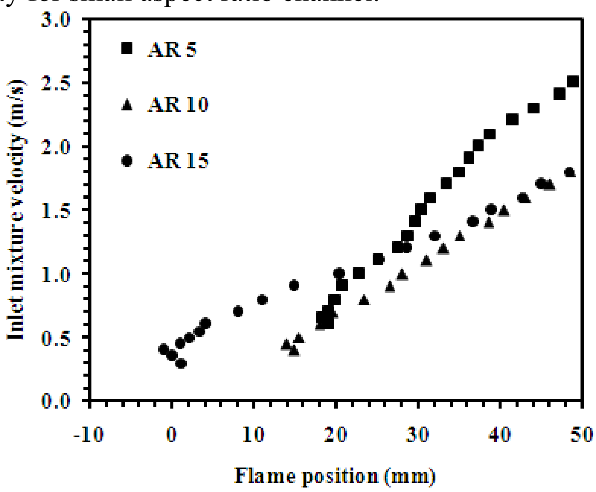

Figure 7. Flame behavior in different channels at $\Phi = 1.0$

4 Conclusion

Flame stability limits were experimentally investigated in three different diverging meso-scale channel configurations. These investigations were carried out with methane–air mixtures for a wide range of operating conditions by varying mixture flow rate and equivalence ratio. The investigations showed the existence of both stable and partially stable flame propagation modes for different conditions of channel aspect ratio, inlet mixture velocities and mixture equivalence ratios. Partially stable flame propagation mode was observed for lean mixtures at all velocity ranges and for rich mixtures at intermediate velocities. In this mode, the flame behavior was observed to be stable at centre and unstable near side walls. The measurements of the flame position showed that it increases linearly with increase in the mixture flow rates. Three basic flame shapes were observed:

1) Planar flames observed at low mass flow rate and all equivalence ratios.
2) Negatively stretched flames observed at moderate mass flow rate for rich mixtures only.
3) Positively stretched flames observed at high mass flow rate for both lean and rich mixture.

Increased low velocity stability limits were observed with increase in aspect ratio while decrease in high stability limits was observed with the same. The detailed study of such diverging channels will help in designing an efficient micro-combustor by providing a wide range of flame stability limits. Laminar burning velocities of premixed mixtures can also be extracted using the planar mode of flame propagation at high preheat temperatures which will be helpful in designing reactive systems.

References

[1] K. Maruta, T. Kataoka, N.I. Kim, S. Minaev, R. Fursenko, (2005) Characteristics of combustion in a narrow channel with a temperature gradient, Proc. Combust. Inst., 30 (2005) 2429–2436.

[2] S. Kumar, K. Maruta, S. Minaev, (2007) Experimental investigations on the combustion behavior of methane-air mixtures in a new micro scale radial combustor configuration, J Micromech Microeng, 17 900.

[3] S. Kumar, K. Maruta, S. Minaev, (2007) On the formation of multiple rotating Pelton-like flame structures in radial microchannels with lean methane–air mixtures, Proc. Combust. Inst., 31 3261–3268

[4] A. Fan , S. Minaev, S. Kumar, W. Liu, K. Maruta, (2008) Regime diagrams and characteristics of flame patterns in radial microchannels with temperature gradients, combust. Flame, 153 479-489

[5] Y. Ju., B. Xu, (2006) Effects of channel width and lewis number on the multiple flame regimes and propagation limits in mesoscale, Combust. Sci.Technol., 178 1723–1753.

[6] S. Kumar, Numerical studies on flame stabilization behavior of premixed methane-air mixtures in diverging mesoscale channels, Combust. Sci. Technol., in press

[7] V. N. Kurdyumov, G. Pizza, C. Frouzakis, J. Mantazaras, (2009) Dynamics of premixed flames in a narrow channel with a step-wise wall temperature, Combust. Flame, 156 2190–2200.

[8] M. Akram, S. Kumar, (2010) Experimental studies on dynamics of methane-air premixed flame in meso-scale diverging channels, 8th Asia Pasific Conference on Combustion.

[9] M. Akram, S. Kumar, (2011) Combust. Flame, (Under review).