Flame Dynamics inside Rectangular Meso scale Channels

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Abstract. The present work is focused on the experimental study of flame dynamics in preheated meso-scale straight channels of various aspect ratios (2, 5, 12 and 15) and inlet dimensions. Premixed methane-air mixture were used for the reported experiments. To maintain a positive wall temperature gradient inside the channel, the lower part of the rectangular channels were heated at a constant temperature using an external electric heater. Laminar premixed flames were stabilized inside these channels. Various flame propagation modes such as concave, planar, and convex flames with respect to unburned mixture. Concave flames lead to flashback whereas convex flames lead to blowout. Increase in aspect ratio and decrease of flow velocity leads to flame flashback.

1. Introduction
The advancement of combustion systems such as gas turbine combustors, spark ignition engines etc. motivated a large part of the combustion community over the last decade to study the flame propagation using meso scale channels [1]. This inspired the researchers globally to get deeper understanding of the combustion processes such as reactivity, diffusivity, and exothermicity of various fuel-air mixtures. Through the gaps of the order of quenching distance, flame propagation is desirable to control in these micro combustors [2]. The flame front could not propagate in such narrow gaps because of the heat losses occurred from flame front to walls due to larger volume to surface area ratio, which increases proportionally as the combustor size decreases and can make the flame unstable which eventually results in flame quenching. Stable flame is required in the combustor to work efficiently. Therefore several methods have been proposed by the researchers to overcome this difficulty.

Over the years, numerous flame propagation studies have been carried out to upgrade the performance of meso-scale combustors. Mysterious issues in premixed flame propagation in micro or meso scale combustor has not yet been completely unlocked. Some of the critical issues associated to flame propagation in very small channels are thermal diffusive and hydrodynamic inconsistency of a propagating flame [3], formation of boundary layers, flame-wall interaction, hydrodynamic flame-wall interaction induced by wall friction, radical quenching [4-8]. To reveal the phenomena of flame propagation characteristics in meso scale channels, Chao et al. [9] have experimented flame stabilization using cylindrical quartz tubes with varying diameters. Similar study was carried out by Maruta et al. [4] on characteristics of methane-air premixed flames propagation in cylindrical quartz tube with a wall temperature gradient along the fluid flow direction. They achieved stable flames in very low and high flow rate regions. Other dynamic properties such as flame with repetitive extinction.
and ignition (FREI) and fluctuating flames were reported at moderate flow rates. Several propagation regimes such as flashback, static flame front, flickering and blow out were reported by Evans and Kyritsis [10] in their study of non-adiabatic ducts on meso-scale for both methane and propane. Numerical simulations of flames in micro scale channels were also studied by Pizza [5] with lean premixed mixture of hydrogen/air with a constant wall temperature and height varying from 0.3 to 1.0mm. They had also concluded the existence of flames with repetitive extinction and ignition (FREI) for low inflow velocity conditions. Further increase in the flow velocity resulted in the formation of a stable asymmetric flame. A similar study was carried out by Pizza et al. [6] showed some new flame propagating modes like open and closed both stable and unstable, symmetric and asymmetric for meso scale channels of height ranging between 2.0 and 7.0mm. Characteristics of flame propagation were investigated by Khandelwal and Kumar [11] using rectangular diverging channels. This work shows different propagation modes of a flame in straight rectangular channels of 2, 5, 12, and 15 aspect ratios. This study is essential from application viewpoint because some flame propagation modes like partially stable flames can lead to poor combustion resulting in loss of combustion efficiency. The main goal of this study is to minimize formation of unstable flames in meso-scale combustors and to conserve maximum thermal energy at the flame area. Therefore a systematic detailed study on the dynamics of flames in straight rectangular channels with different aspect ratios is presented.

2. Experimental method

2.1. Experimental setup

The schematic diagram of the experimental set-up with detailed dimensions of a typical 15 aspect ratio channel is shown in figure 1. A premixed Ch4–air mixture is supplied through the inlet of the channel at 300 K. The methane-air flow rates can be controlled using Aalborg mass flow controllers which are connected to the PC. Rectangular straight mesoscale channels of 2, 5, 12, 15 aspect ratios were chosen. The inlet height was maintained at 2mm and the width was varied. Quartz is chosen because of its low thermal conductivity and expansion, high heat capacity and transparency of the walls to help visualize the flame front location in the channel. The investigations reported in this paper has been carried out using methane-air mixture. The channels were placed exactly 10 mm above the heater and the overlap distance was also kept approximately 10 mm from the exit of the channel. With the help of a level indicator the channel was kept parallel to the burner within an accuracy of ±0.1. The quartz channel was heated constantly throughout the experimental investigations to exclude the effect of varying temperature distribution with heating rate on the observed flame patterns. The rate of heat release through the combustion of methane–air mixture is relatively very small (60 W) as compared to the heat release rate of sintered metal burner (800 W) which ensures thermally thick walls and avoids thermal coupling between solid and gas phase.

![Figure 1: Schematic of experimental setup](image-url)
3. Results and Discussion

In the present experiments, various flame propagation modes are observed. These propagation modes are classified into three different categories based on their appearance as planar flames, concave flames and convex flames.

3.1 Planar flames

Flame propagation modes at different flow velocities in low-aspect-ratio channels (2 and 5) were observed to be flat/planar. Flat shaped flame propagation mode were spotted for a range of mixture equivalence ratios $\Phi$, varying from 0.8 to 1.1 and inlet mixture velocity depending upon the external heating rates supplied to preheat the channel walls.

Photographs of planar flames observed inside low-aspect-ratio channel for various equivalence ratios and flow velocities are shown in figure 2. The mixture is ignited at the exit of the channel and the flame front moves inside. The flame front then becomes planar and completely stable at a location where the flow velocity matches the burning velocity of the mixture at that temperature. The location of flame depends on the mixture inlet velocity and external heating rates.

![Figure 2: Planar flames spotted with different flow rates inside low-aspect-ratio channels (AR 2 and 5)](image)

3.2 Concave and Convex flames:

The flame front for certain conditions of the inlet velocity and mixture equivalence ratios are of concave and convex shape, termed concave and convex flames. The photographs of these concave and convex flames in are shown in figures 3a and 3b for $\Phi=1.0$ and $U_{\text{inlet}}=0.55\text{ m/s}$ $U_{\text{inlet}}=0.6\text{ m/s}$ in 12° and 15° aspect ratio channel. The concave flames were observed in very high-aspect-ratio channels only (aspect ratio > 10) at moderate flow rates, whereas Convex flames were observed in all channels. In high-aspect-ratio channels, convex stretched flames were observed at high inlet velocities.

![Figure 3a: Photographs showing concave flames in AR 12 and 15 channels at $U_{\text{inlet}}=0.55$ m/s](image)

![Figure 3b: Photographs showing convex flames in AR 12 and 15 channels at $U_{\text{inlet}}=0.6$ m/s](image)
3.3 Effect of mixture equivalence ratio $\Phi$ on flames

The mixture equivalence ratio effect on the position of the flame in various aspect ratio channels is shown in figure 4. It is observed that the flames were stabilized near the exit of the channel for rich and very lean mixtures. For mixtures within the range of ($\Phi$ 0.9~1.0) the flames stabilized inside the channels away from the exit and closer to the inlet. It is also observed that the flames at $\Phi$=1.1 propagated much faster than the flames of mixtures of other equivalence ratios. This is because of the low burning velocities of these mixtures in comparison to mixtures near stoichiometric conditions.

![Figure 4: Effect of equivalence ratio $\Phi$ on flame position in various channels](image)

3.4 Effects of flow inlet velocity on flames

Effects of flow inlet velocity on the stabilization of flames inside the channels were investigated in the axial direction for 5AR channel with varying mixture equivalence $\Phi$ ratios in figure 5. The flame gets stabilized at a place where the inlet flow velocity matches the burning velocity of the mixture. Changes occurred in the location of flame stabilization depends on factors such as temperature gradient and heat loss from flame to solid walls effects the location of flame stabilization.

![Figure 5: Effect of flow velocity on flame position with varying equivalence ratios for 5AR channel](image)
4. Conclusion
In this article, flame dynamics has been studied experimentally using preheated mesoscale straight channels of various aspect ratios. Premixed methane-air mixtures were used to carry out the investigations for a range of operating conditions by varying both equivalence ratios and inlet flow rates. The lower area of the quartz channels were heated at a constant temperature with an external heating source burner which resulted in formation of linear temperature gradient along the axial direction inside the channels. Three types of flame propagation modes were observed during the experiments planar flames, concave flames and convex flames. Stretch free flames were observed only for low aspect ratio channels at moderate flow rates. These flames were observed to be symmetric or asymmetric to the x axis. Convex flames were observed in high aspect ratio channels (AR 12 and 15) with high inflow rates more than 0.5 m/s. The investigations showed the existence of concave flames in high aspect ratio channels at flow rates less than 0.5m/s for all equivalence ratios. Flames with repetitive extinction and ignition (FREI) was observed at very low mass flow rates.

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