3-D flame patterns in a backward facing step mesoscale combustor for non-adiabatic wall conditions

Malhar Malushte, Sudarshan Kumar
Combustion Research Laboratory, Indian Institute of Technology, Bombay
Mumbai, Maharashtra, India

1 Introduction

The need and urge towards the miniaturization of electro-mechanical devices and the consequent necessity for micro-power generation (milli-watts to watts) with low-weight, long-life devices has led to the recent development of the field of micro-scale combustion. Fabrication of the devices using Micro Electro Mechanical Systems (MEMS) or rapid prototyping techniques, with their favorable characteristics for mass production and low cost also motivates the research in this area. Heat recirculation, flame wall coupling and thermal and kinetic quenching makes the flame dynamics very intricate.

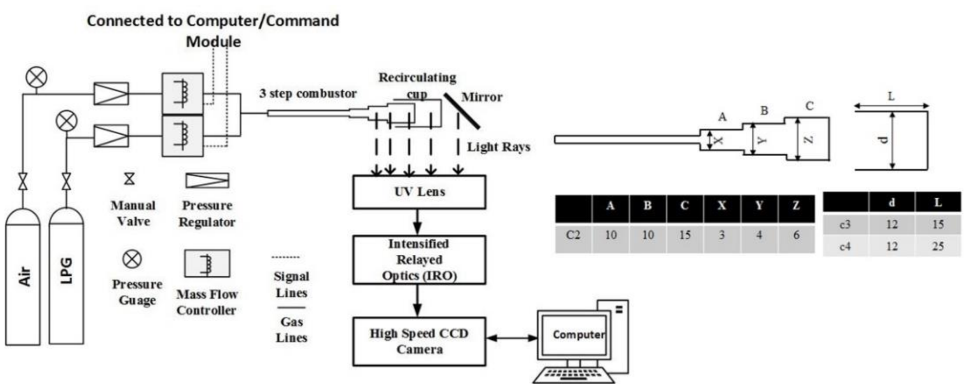
The flame dynamics in a straight tube with a positive wall temperature gradient along the direction of the fluid flow are initially investigated by Maruta et al. [1,2]. Stable and unstable flame patterns like cyclic oscillations, *FREI* (Flame Repetitive Extinction and Ignition), weak flames were observed for a range of operating conditions. Analytical study of Fursenko et al. [3] indicated that *FREI* is a transition state between high velocity and low velocity flame stability limits and occurs due to thermo-diffusiion and thermal-wall coupling. Experimental study on different designs of Swiss-Roll combustors has been carried out by Kim et al. [4] and detailed flame stability limits are reported. They observed that the mean temperature and flame stability were governed by the fraction of radiant heat loss and input energy to the combustors. NO_x emissions were found to be relatively lower due to their lower operating temperature and these emissions were observed to decrease with the size of the combustor. The formation of isolated reaction zones was observed by Miesse et al. [5] when they studied laminar CH_4-O_2 diffusion flames in an alumina micro-burner with chemically treated walls to avoid wall radical quenching. Kumar et al. and Fan et al. [6 - 9] studied the flame characteristics of different fuels like CH_4, C_3H_8, *DME* in the radial micro-channels where they observed the formation of various flame patterns such as rotating, spiral, oscillating, stable flames. Kink like structures, Pelton wheel like cups were also observed on the flames. Different two and three backward step combustors [10] have reported experimental studies to understand the effect of step length, ϕ, $\dot{m}_f$, and material of combustor on flame stability limits, flame position, temperature profile and emissions. Increase in the length of first step broadened upper and lower flame stability limits while length of second step did not show any significant change in flame stability limits. Lower thermal conductivity of the combustor material helped significantly improving the flame stability limits due to improved heat recirculation through solid combustor walls[10-11]. Deshpande and Kumar [12] and Taywade et al. [13] observed the formation of spinning flames in microcombustors with different fuels with their spinning frequency varies from 100-150 *Hz*.

Correspondence to: malushtemalhar@gmail.com

Analytical and numerical studies have been carried out by researchers to understand the flame dynamics in micro combustor systems. A simple heat recirculating model of a burner studied by Ronney [14] includes heat transfer from hot combustion products to fresh reactant stream through reactor walls. A non-linear analysis of flame front with bifurcation theory was proposed to predict various unstable propagation phenomena such as *FREI* and oscillating flames [15]. Investigations on the effect of channel height, inflow velocity wall temperature on flame dynamics for premixed flames with *Le=1* using *2D* thermos-diffusive model show that flame/wall interaction is the mechanism leading to the observed flame instabilities[16]. Richer dynamics in the wider tubes with azimuthal spinning, closed and open axis-symmetric flames were observed for a certain range of operating conditions. A recent modeling effort with reduced order methods to understand the main mechanisms for occurrence of *FREI* concluded that *FREI* instability occurs due to hydrodynamics [17] whereas other authors researchers concluded that chemical reaction balance results in the formation of these unstable FREI modes [18][19]. These FREI oscillations of flame are explained through numerical studies on propagation of the flame kernel by observing the change in the species in the flow stream. Bifurcations are caused by intermediates like CH_3, *CO, H* and *OH* [18].

Most of the earlier studies focused on investigating the effect of various parameters on unstable flame propagation modes through numerical studies. Few experimental studies in straight channels with a specific temperature gradient show the formation of different flame regimes observed for radial channels. The motivation for present work comes from the need to study the flame dynamics in backward facing stepped combustor, which can be directly applied in a practical application along with heat recirculation to improve the flame stability limits.

2 Experimental set up



	A	B	C	X	Y	Z
C2	10	10	15	3	4	6

	d	L
c3	12	15
c4	12	25

Figure 1. Experimental set up and combustor dimensions (mm).

Figure 1 shows the schematic diagram of the present experimental setup. The dimensions of the combustor and the heat recirculating cup are summarized in the Figure. Combustor is fabricated with quartz glass material by fusing the tubes of different diameters to form the desired three stepped geometry. Similarly, the heat recirculating cup is manufactured. Both cup and combustor and fixed in a special holder to ensure that they are concentric to each other. High speed imaging system consisting of a *CCD* camera capable of capturing 3600 *fps* with 1Mpixel resolution, intensified relay optics (*IRO*) to amplify the light intensity of the low luminous small flames and a UV lens. This system is employed for detailed analysis of unstable flame propagation modes. The system is triggered by programmable timing unit which is operated through a computer, and Davis imaging software package. Longitudinal view as shown in the figure is taken directly through the lens, and the end view of the combustor (to observe the simultaneous movement in the transverse plane) is taken with the help of a mirror setup installed at 45^o. The air and fuel flow rates are metered from the pressurized tanks through precise electric mass flow controllers (accuracy ± *1.5 %* of full scale) and controlled with the help of command module connected to a computer. The range of the flow rate meters for air and fuel is 0 – 1*LPM* and 0 – 0.2*LPM* respectively.

3 Results

In this work, experimental studies are carried out on a three step backward facing micro combustor for a range of *LPG*-air mixture flow velocities, V_{IN} varying from *1 – 8 m/s* and mixture equivalence ratio, ϕ varying from *0.6 - 1.4.* To delineate the role of heat recirculation on flame stabilization, heat recirculating cups are chosen (details reported in Fig. 1). Different types of unstable flames occurring and their respective behavior is reported in this work. This study will help provide a wide database to understand the intricate flame dynamics in backward step combustors for a range of operating conditions.

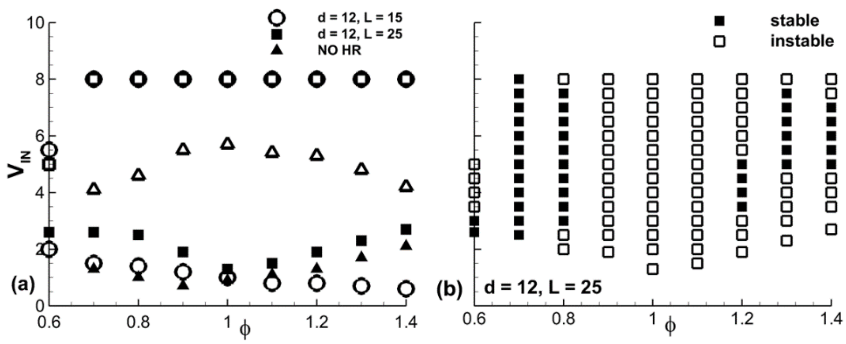


Figure 2. (a) Flammability limits and (b) flame stability regime diagram, stable and unstable flame shown by filled and unfilled symbols respectively.

Figure 2 shows the flammability limit and stability regime diagrams for the combustor with heat recirculation done with the aid of cup. The dimensions of the cup in turn significantly affect the heat recirculation and result in improved flame stability limits [13]. Figure 2a shows the variation of flame stability limits as a function of mixture flow velocity and mixture equivalence for three different configurations. (i) No heat recirculation (ii) Heat recirculation with a cup of d = 12 mm and L = 15 mm (iii) Heat recirculation with a cup of d = 12 mm and L = 25 mm. Higher flame stability limits are significantly affected by heat recirculation as distinct higher limits found for cases with and without heat recirculation. The flame stability limits are relatively wider for near stoichiometry mixtures as compared to very lean and very rich mixtures. Stable (filled symbols) and unstable (unfilled symbols) flame propagation modes for a range of mass flow rate and mixture equivalence ratio conditions are shown in regime diagram in Fig. 2b.

Very rich flame dynamics of stable and unstable flame propagation modes is observed. Analysis of transition of these flames from one propagation mode to another was observed with the help of high speed imaging facility. For all other governing parameters constant except equivalence ratio (not shown here), it is seen at low equivalence ratio, the flame remains stable and anchored. Flame starts moving upstream as the equivalence ratio increases, and becomes unstable as mixture conditions become richer. A significant upstream movement in the anchoring point of the flame can be attributed to increased burning velocity of the mixture due to increase in mixture equivalence ratio, thereby hinting at mixture burning velocity along with increased heat recirculation playing a dominant role in the formation of various flame propagation modes and movement of flame anchoring point. As observed in literature, here also *FREI* flames are observed for rich mixtures. Except very few numerical studies, the dynamically rich *3D* (simultaneous translation and rotation) flame patterns with repeatable nature are observed experimentally for the very first time. Such typical flame dynamics is shown in instantaneous flame photographs over a period of cycle for different types of flames observed in Fig. 3. For 2D (column 1 of Fig. 3), a conical flame pulsates in the combustor from its third step to cup without any rotational or folding/unfolding action. In the case of 3D flames, along with the pulsation in the axial direction, there is azimuthal rotation of flame, often with an unfolding and folding motion over a cycle. Stable anchored conical flame in all frames of S column. X flame is a flame rotating without folding motion. *FREI* exhibits properties similar to 3D flames. In the third frame from the top there is no visible evidence of flame, which is seen for a number of frames. Here the flame extinguishes. Further again it self-ignites and small flamelet can be seen emerging in fourth frame which goes on developing.

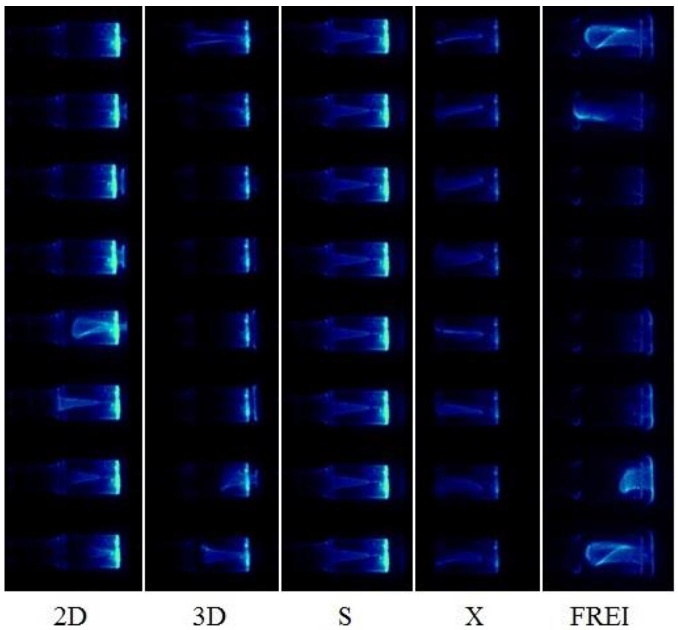


Figure 3. Instantaneous flame photographs for different type of flames observed. Each column shows six instantaneous images over a period of cycle. *2D* is for only pulsating flame, *3D* for flame having simultaneous pulsating and rotational motion, *S* for stable anchored flame, *X* (flame seen by naked eye as letter 'x') for rotating flamelet and *FREI* for flame repetitive extinction and ignition.

With the help of high-speed imaging frequency of the unstable flames was obatined and are given in Fig. 4. Distinct type of repetitive flame patterns have particular nature in frequency. Rotating flamelets or 'X' type of flames are observed for almost complete range of mixtures. The velocity range of the X flames changes with the equivalence ratio but the range of magnitude of the frequency remains same as indicated in Fig. 4a. And at a particular velocity, it is found that frequency of rotation increases with mixture conditions changing from lean/rich mixtures to near stoichiometric. This delineates the connection between the flame speed and frequency of rotation. There is no big change in the magnitude of the frequency of 3D or 2D flames with velocity, but with equivalence ratio as shown in Fig. 4b. Also, 2D(pulsation only) flames are found to have larger frequency than the 3D(rotation + pulsation) flames. In few cases it is also observed after high-speed imaging that in 3D motion, flames fold and unfold in a conical geometry, over a period in a cycle. In some cases a secondary frequency of pulsation is also noted. This effects can be said to caused by the thermal wall coupling due to heat recirculation.

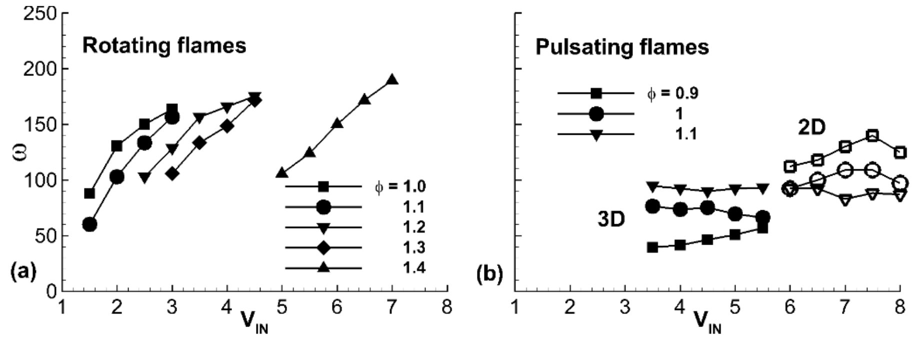


Figure 4. Behavior of frequency with mixture inlet velocity for (a) rotating flames and (b) pulsating flames

4 Summary

First indications of the presence of 3D flames in mesoscale channels is experimentally seen. Flame wall coupling and consequent change in physics makes the dynamics intricate. Transition from stable to unstable region and vice versa, and different forms of unstable flames, for change in ϕ (thermo-diffusive – *Le* change) while V_{IN} constant and change in V_{IN} (hydrodynamics) while ϕ constant, is not a lone effect of hydrodynamic instability or thermos-diffusive instability or flame wall coupling, but a combined effect of all three mechanisms. Another notable observation found is, the type of instability (flame pattern) depends on the initial perturbation. At constant governing conditions different types of flame patterns can form depending upon the previous disturbance or conditions.

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