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Combustion in micro-channels with a controlled temperature gradient

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ABSTRACT

In recent years many studies were undertaken in the field of micro-combustion, experimentally and numerically. In the present work, a new experimental device was developed. It consists of a micro tubular channel with an external heating provided by three hydrogen/oxygen flames positioned at the downstream side of the tube. This system ensures a uniform heating inside the channel. As described in previous studies, three distinct flame behaviors were observed: stable flames at high flow velocity, flames with repetitive extinction and ignition (FREI) in the middle flow range, and weak flames, at low flow velocity. This experimental study on the combustion of methane/air mixtures in a microchannel was undertaken to provide detailed information on flame behavior over a wide range of equivalence ratios (0.5–1.5) and flow velocities. Finally, a detailed analysis on the flame instabilities was performed. The results show a good agreement with several numerical results, and the study on FREI frequencies reveals a particular trend of instability with the change of the experimental conditions.

1. Introduction

Nowadays the growing need for low fuel consumption systems makes very attractive the development and the application of MicroElectroMechanical (MEMS) devices, which may produce more energy than the modern batteries by using hydrocarbon fuels [1,2]. This concept is coupled with that of "excess-enthalpy" combustion [3], which led to the design of a new device, called the Swiss Roll combustors [4] consisting of a micro reactor where the reactants are preheated by burned gases, with the combustion zone at the center of a pair of spiral channels. Recently channels with an inner diameter lower than the quenching diameter have been used for this burner [5,6], and the combustion stabilization in such devices is a far from trivial problem [7,8]. In order to deepen and widen knowledge on micro-scale combustion, many studies have been performed [9,10]. With the reduction of the combustor's size, the difficulty to sustain a stable combustion increases, due to the larger surface to volume ratio. The effects of quenching, thermal and radical, both increase. However, with the continuous heating of the solid phase it is possible to sustain combustion in a tube having an internal diameter smaller than the ordinary quenching diameter and in lean conditions. Nevertheless, the management of the combustor flow and thermal conditions is required to reduce the wall effects [11]; the miniaturization enhances the heat losses [12] and, as shown in the previous studies, all the combustor design parameters influence the flame stabilization [13]. As observed by Popp and Baum [14], the wall heat flux increases with increasing wall temperature and the interaction between the flame and the wall is very fast: the higher the wall temperature is, the higher is the fuel consumption and the behavior of the reactive mixture changes, with an increase in concentration of H and OH species. High temperatures enhance the Soret effect, particularly for light species, resulting in a reduction of burning velocity [15,16]. As described by Maruta et al. [17], three distinct flame behaviors can be observed in narrow channels: bright and stable flames for high flow velocity, flames with repetitive extinction and ignition (FREI) in the intermediate flow rate range and weak flames at low flow velocity. The flame luminosity decreases with the reduction of the flow rate. The flame is stabilized in a certain position where balance between the flame temperature, wall heat losses and flow rate occurs.

The objective of this work is to provide detailed information on methane/air mixture flame behavior's in narrow channels. To this end, experiments at different conditions (flow velocity and equivalence ratio) were performed and instabilities analysis was conducted.

2. Experimental set-up

The experimental setup was designed to investigate the combustion in narrow channels with a premixed methane/air blend

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Nomenclature

d	tube diameter (mm)	St	Strouhal number, $f \times d/v$ (dimensionless)
v	average fresh mixture velocity (m/s)	τ_{EI}	time between extinction and ignition (ms)
φ	equivalence ratio (dimensionless)	τ_{IE}	time between ignition and extinction (ms)
f	FREI frequency (Hz)		

at atmospheric pressure. The micro reactor used here consists of a cylindrical quartz tube, inside which the gaseous mixture flows. This tube is heated from outside thanks to three blowtorches around the tube, separated from each other by 120°. This system ensures a stationary, homogeneous and Gaussian temperature profile starting from ambient temperature at the upstream side (gas inlet) to a maximum of 1600 K at downstream (gas outlet). This temperature slope allows the mixture to auto-ignite, overcoming quenching issues. The three external heat sources are fed by a hydrogen/oxygen mixture. The heating flames are then free of CH* species, which allows a better visualization of CH* chemiluminescence from the flame studied inside the microchannel.

The methane/air mixture is premixed in a small tank and six thermal mass flowmeters Brooks GF40 (error less than 1%) are used to feed the reactor. Each gas line (CH_4, O_2, N_2) has 2 flowmeters with overlapping flow rate ranges, allowing a good exploration of all flame regimes.

The temperature distribution along the outer side of the tube is measured by a FLIR A655sc thermal camera with a 640 × 480 pixels matrix, with a measurement uncertainty of ±3%. The operating range is selected between 300 and 2000 °C. The temperature measurements are taken in real time at a frequency of 10 Hz, which ensures a continuous recording of the temperature imposed to the micro reactor. An emissivity correction is carried out because in the operating spectral range of the camera (7.5–14 μm), fused silica emissivity varies with temperature, as shown by Sova et al. [18].

A Princeton Instrument spectroscopy EMCCD camera (ProEM 1600), equipped with a 105-mm Nikkor lens (f/2.8D), is used to detect the CH* signal at 430 nm. The CCD camera operates in a 1600 × 200 pixels matrix with a 16-bit output digitization. A band-pass filter (20BPF10-430) is used to observe the flame chemiluminescence through the quartz tube. In order to increase sensitivity and frame rate, binning operation and adapted exposure time are performed. The spatial resolution is 62 pixels/mm. For unstable flames the maximum recording frequency of 4260 Hz is used.

A schematic representation of the experimental apparatus is showed in Fig. 1. The temperature profile along the tube is displayed in Fig. 2. The origin of the horizontal axis is set at the maximum of the temperature profile.

Using this set-up, experiments were conducted over a range of flow rates from 0.03 m/s to 1 m/s in a 2.15 mm inner diameter tube and compared to those obtained in previous studies. Then experiments were performed in a 1.85 mm inner diameter tube over a range of equivalence ratios from 0.5 to 1.5. Finally, to further examine the unstable regime, a study on FREI frequencies was carried out and the results are discussed.

3. Results

3.1. Flame visualization

After auto-ignition in the downstream side, the flame propagates upstream and finally stabilizes in the temperature gradient where balance between the flame propagation velocity and the fresh gases flow rate is obtained. As observed in previous experiments by Maruta et al. [17], we also detected three dynamic flame behaviors depending on the inlet velocity: stable flames, Flames with Repetitive Extinction and Ignition (FREI) and weak flames.

Stable flames, set at a given position in the temperature gradient, show curvature that depends on the flow rate, as shown in

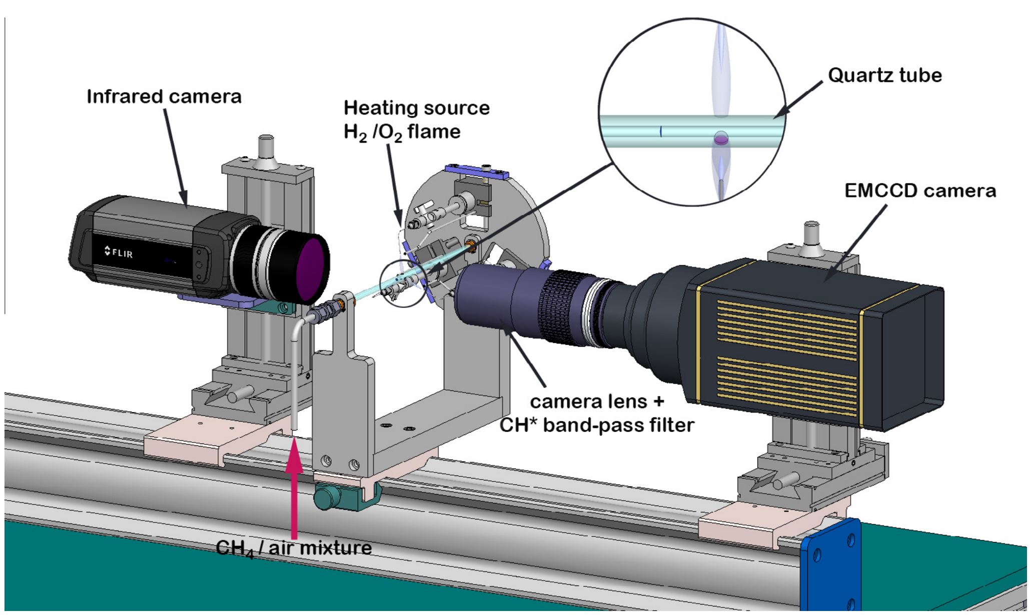

Fig. 1. The experimental set-up.