Dynamics of hydrogen/air premixed flames in a 2mm height planar microchannel

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1 Introduction

Combustion at the meso- and micro-scale has recently attracted a lot of interest in attempts to harness the high specific energy of fuels in miniaturized devices to generate power [1]. Progress in the fundamental knowledge of meso- and micro-scale combustion and in the understanding of reactor thermal management is essential for the further development of such systems.

It has been shown experimentally [2] and numerically [3] that combustion at such small scales shows interesting features that have not been observed in larger devices. Experiments at these scales face additional difficulties and cannot easily provide the detailed description needed to understand the phenomena involved. In most cases, most of the published numerical investigations employ strong simplifying assumptions, which in turn can have a strong effect on the obtained results.

In this work, we present a detailed numerical study of the combustion dynamics of a premixed fuel-lean hydrogen/air (ϕ=0.5) flame in a 2.0 mm planar channel with an imposed fixed temperature profile on the walls.

2 Method of Approach

The channel consists of two parallel, infinitely wide plates, with a length-to-height ratio of 10. The boundary conditions at the gas-wall interface are zero flux for all species, and fixed temperature profile ramping in a hyperbolic tangent fashion from the temperature of the cold inflow mixture, T_{IN}=300K, to the wall temperature, T_W=960K, over the initial 1.0mm of the channel length. At the channel inlet, uniform profiles for the species mass fractions, temperature, T_{IN}, and inflow velocity U_{IN}, are applied. Finally zero-Neumann conditions were used at the outflow boundary and buoyancy was neglected.

A parallel code based upon the spectral element method is used to solve the 2D continuity, momentum, energy and species conservation equations in the low Mach number limit. The gas phase chemistry, described by the mechanism of Yetter et al. [4], and mixture-averaged transport properties were implemented via Chemkin.

The spatial resolution in the streamwise direction is 0.0416mm (481 grid points) resulting in 9 grid points within the flame thickness L_f (L_f=0.387mm). In the transversal direction the resolution is slightly higher.

3 Results and Discussion

Simulations were performed for mixture inflow velocity U_{IN} varying in the range of 5 to 550 cm/s, for which the flame stabilizes within the channel. Five different types of flames were observed which will be referred to as ignition-extinction, closed symmetric, open symmetric, oscillating, and asymmetric.

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For the lowest inflow velocity, U_{IN}=5cm/s, a periodic sequence of flame *ignition and extinction* is obtained. Fig. 1 depicts the temporal variation of the maximum temperature inside the channel: the value changes periodically at a frequency of 33Hz between the wall temperature T_W, 960K, and the flame temperature, 1536K.

As indicated by the contour plot of the OH mass fraction in Fig. 2, for 20<=U_{IN}<=95cm/s, the *closed symmetric flames* display temperature and species mass fractions profiles that are symmetric with respect to the channel mid-plane. The flames were located close to the inlet section, and were pushed downstream by increasing U_{IN} (Fig. 3, showing the streamwise location of the temperature maximum plotted as a function of the inflow velocity).

When the inflow velocity is increased from U_{IN}=95cm/s to U_{IN}=100cm/s, the flame opens in the middle, forming two separate branches burning close to each of the channel walls, but remaining symmetric with respect to the mid-plane (Fig. 4). This *open symmetric flame* remained stable for U_{IN} up to 470cm/s. As U_{IN} was increased, the two branches stabilized further downstream (Fig. 3), became more elongated in the streamwise direction, and were pushed closer to the channel walls.

The increase of the inflow velocity from 470 to 500cm/s resulted in a change of the flame shape which resumed a single-branch shape asymmetric with respect to the channel mid-plane. Two different flame structures, one with OH mass fraction maximum located close to the upper (*upper asymmetric flame*) and another close to the lower wall (*lower asymmetric flame*) were obtained (Fig. 5). These two asymmetric flame structures, which coexist for the same value of U_{IN}, were stable when the inflow velocity was in the range 175<=U_{IN}<=550cm/s. For higher inflow velocity the flame can no longer be stabilized within the channel.

Starting from the asymmetric flame at U_{IN}=175cm/s, the decrease of the inflow velocity to U_{IN}=150 cm/s resulted in a flame exhibiting self-sustained oscillations (*oscillating flames*). The maxima of all species mass fractions and temperature shift periodically between a position located above the channel mid-plane and one below it. This limit-cycle behavior was observed for the inflow velocity range 100<=U_{IN}<=230cm/s. The temporal evolution of the maximum temperature inside the channel for U_{IN}=174cm/s is shown in Fig. 6(a), along with the contour plots of the OH mass fraction profiles at the marked time instants, Fig. 6(b, c, d, e).

4 Summary of combustion dynamics

The five burning modes are summarized in the flame stability diagram of Fig. 7, showing the inflow velocity ranges where the different flame types were obtained. The variable *Ymax* used to indicate the different flames structures measures the vertical distance from the lower plate of the furthest from the inflow point on the iso-level 0.007 of the H_2 mass fraction. For the ignition-extinction, closed and open symmetric flames, marked by the filled rhomboid, filled and open squares, respectively, *Ymax* is equal to one, whereas for the oscillating flame *Ymax* varied between the heights marked by the open circles. Finally, the ranges of the upper (corresponding to Fig. 5(a)-(c)), and lower (corresponding to Fig. 5(d)-(f)) asymmetric flames are marked by the filled and open triangles, respectively.

As it can be clearly seen, up to four different stable flames (oscillating, upper asymmetric, lower asymmetric and open symmetric) can be obtained for the same value of the inflow velocity.

5 Conclusions

The dynamics of fuel-lean premixed hydrogen/air combustion in a planar micro-channel were investigated by means of transient direct numerical simulation using detailed chemistry and transport. The inflow velocity was varied so that nearly all possible streamwise flame positions inside the channel have been analyzed. Rich flame dynamics were observed showing transitions between ignition-extinction, steady closed symmetric, open symmetric, upper and lower asymmetric flame and oscillating flames.

References:

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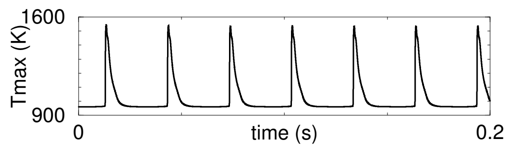

Fig. 1. Ignition extinction type flame at U_{IN}=5cm/s: temporal variation of the maximum temperature inside the channel.

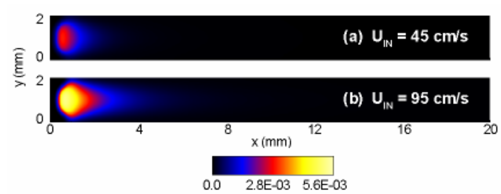

Fig. 2. Closed symmetric type flames; in (a) and (b) the OH mass fraction is represented for U_{IN} respectively 45 and 95cm/s.

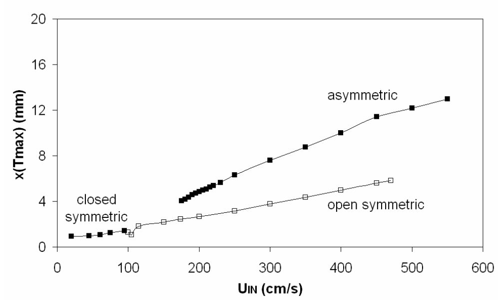

Fig. 3. Flame penetration for the closed symmetric, asymmetric, and open symmetric flames: stramwise position of the maximum temperature at different U_{IN}.

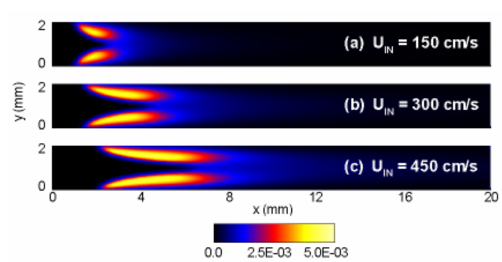

Fig. 4. Open symmetric type flames; in (a), (b), and (c) the OH mass fraction is represented for U_{IN} respectively 150, 300 and 450cm/s.

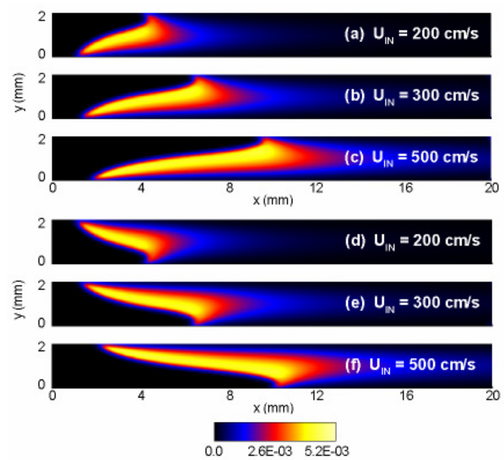

Fig. 5. Asymmetric type flames; (a, b, c) upper and (d, e, f) lower asymmetric flames: OH mass fraction for different values of the inflow velocity U_{IN} (U_{IN}=200cm/s, U_{IN}=300cm/s, U_{IN}=500cm/s).

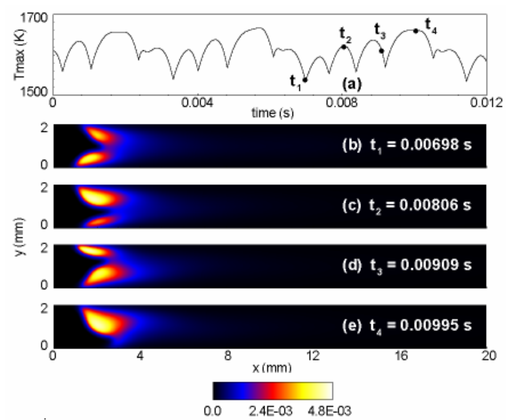

Fig. 6. Oscillating type flame at U_{IN}=174cm/s; (a) temporal variation of the maximum flame temperature; (b) to (e) provide the OH mass fraction at the four times t_1 to t_4 showed in (a).

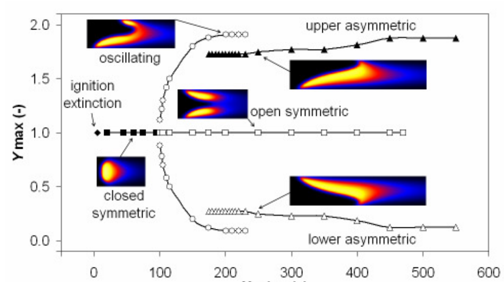

Fig. 7. Flame stability diagram.