Dynamics of premixed flames in a narrow channel with a step-wise wall temperature

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1 Formulation

Despite its relevance to many practical applications (micro- and meso-scale combustion, gas turbines, internal combustion engines, fire hazard and safety), flame propagation in ducts is not fully understood. In addition to the instabilities of a freely propagating flame, i.e. hydrodynamic and thermal-diffusive effects, a flame in a narrow enclosure experiences developing boundary layers, heat transfer to and from the walls, radical quenching and/or surface reactivity. The non trivial interaction of these processes gives rise to the wealth of peculiar combustion dynamics observed experimentally as well as numerically [1-8].

Consider a combustible mixture at initial temperature T_0 flowing in a channel of height h with mean velocity U_0. In what follows, x' and y' denote the (dimensional) longitudinal and transverse coordinates, respectively. The temperature of the wall is maintained at T_0 (upstream value) for $x' < 0$ and at T_w (downstream value) for $x' > 0$, where $T_w > T_0$. The chemical activity is modeled by an irreversible single-step reaction of the form F $\rightarrow$ P + Q, where F denotes the fuel, considered to be deficient, P the products, and Q the heat released per unit mass of fuel. The combustion rate, Ω, is assumed to follow the Arrhenius law, $\Omega = \rho^2 \mathcal{B} Y \exp(-E/R_g T)$, where ρ, $\mathcal{B}$, Y, E, R_g and T are the density, the pre-exponential factor, the fuel mass fraction, the activation energy, the universal gas constant and the temperature of the mixture, respectively.

In this work the diffusive-thermal model is adopted, formally assuming that the mixture density ρ, kinematic viscosity ν, thermal diffusivity $\mathcal{D}_T$, heat capacity c_p, and molecular diffusivity $\mathcal{D}$ are all constant. Consequently, the flow is not affected by combustion and the velocity profile is that of the Poiseuille flow. The non-dimensional temperature is defined as $\theta = (T - T_0)/(T_e - T_0)$, where $T_e = T_0 + QY_0/c_p$ is the adiabatic flame temperature based on the initial temperature T_0 and the upstream fuel mass fraction Y_0. Similarly, $\theta_w = (T_w - T_0)/(T_e - T_0)$ is the non-dimensional temperature of the walls. The planar burning velocity, S_L, and the thermal flame thickness defined as $\delta_T = \mathcal{D}_T/S_L$, are also used in order to formulate the problem in non-dimensional form. Notice, that both S_L and δ_T are based on the initial temperature T_0.

Choosing h to measure the coordinates and U_0, $h^2/\mathcal{D}_T$ and Y_0 to normalize the velocity, time and mass fraction, respectively, $x = x'/h$, $y = y'/h$, and the system is modeled as

$$\theta_t + m\sqrt{d}\, v\, \theta_x = \theta_{xx} + \theta_{yy} + d\, \omega, \quad Y_t + m\sqrt{d}\, v\, Y_x = Le^{-1}(Y_{xx} + Y_{yy}) - d\, \omega, \tag{1}$$

where $\omega = (\beta^2/2Le u_p^2) Y \exp\left\{\beta(\theta - 1)/[1 + \gamma(\theta - 1)]\right\}$ and $v = 6y(1 - y)$.

The following non-dimensional parameters appear in the above formulation: the Zel'dovich number, $\beta = E(T_e - T_0)/R_g T_e^2$, the Lewis number, $Le = \mathcal{D}_T/\mathcal{D}$, the heat release parameter, $\gamma = (T_e - T_0)/T_e$, the

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reduced Damköhler number, $d = h^2/\delta_T^2$, and $m = U_0/S_L$ is the non-dimensional flow velocity measured with respect to the planar burning velocity.

The boundary conditions for the temperature and mass fraction are:

$$Y_y\big|_{y=0,1} = 0,\ \theta\big|_{y=0,1} = \begin{cases} \theta_w, & x > 0, \\ 0, & x < 0; \end{cases}\ x \to -\infty :\ \theta, (Y-1) \to 0;\ x \to \infty :\ Y_x = \theta_x = 0. \quad (2)$$

The factor $u_p = S_L/U_L$ arises in ω if the planar flame speed, S_L, is used to define the thermal flame thickness $\delta_T = \mathcal{D}_T/S_L$. Here, $U_L = \sqrt{2\rho\mathcal{B}\mathcal{D}_T Le\beta^{-2}}\exp(-E/2R_gT_e)$ is the asymptotic value of the velocity of the planar flame calculated in the high activation energy limit, $\beta \gg 1$. This factor (u_p) is introduced for convenience in order to have the non-dimensional planar flame speed exactly equal to one for finite values of β.

In what follows, we consider flames with $Le = 1$. The Zel'dovich number and the heat release parameter were assigned the fixed values $\beta = 10$ and $\gamma = 0.7$, considering these values representative for many hydrocarbon combustible mixtures. The numerical value of u_p calculated for $\beta = 10$, $\gamma = 0.7$ and $Le = 1$ is $u_p \approx 0.942$. The focus of this paper is to understand the influence of the non-dimensional flow velocity, $m = U_0/S_L$, and the wall temperature, θ_w.

2 Selected numerical results

We present here only the results obtained for a narrow channel with $d = 5$. Three different flame types, all symmetric with respect to $y = 1/2$ and with the maximum temperature point located on the symmetry plane, were obtained over the range of velocities considered ($m \leq 5$). The flame position x_w and the maximum temperature θ_m are plotted in Fig. 1 as functions of the non-dimensional velocity m. The solid segments of the curves correspond to stable steady states (weak flames at small m, and symmetric flames at large m), while the dashed segments correspond to unsteady states (symmetric oscillatory flames, exhibiting periodic ignition and extinction).

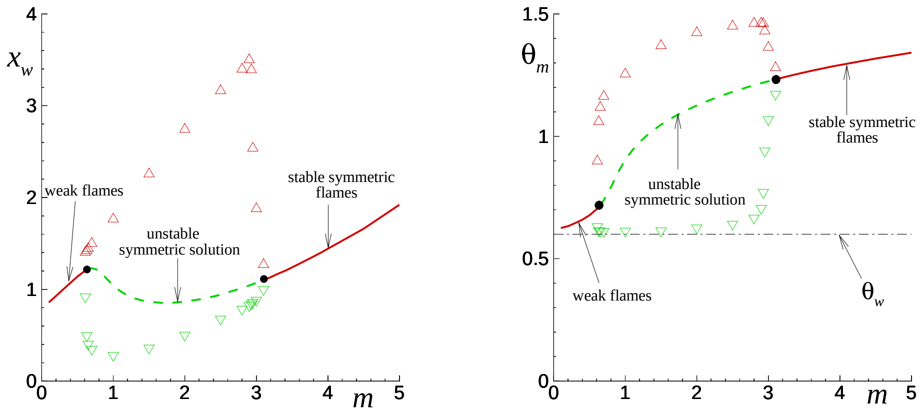

Figure 1: Flame position x_w (left plot), and maximum temperature θ_m (right plot) versus non-dimensional flow velocity m for $\theta_w = 0.6$, $d = 5$ (solid line: steady states, dashed line: unsteady states, Δ and ∇ mark the maximum (ignition point) and minimum (extinction point) values during the oscillation period, filled circles mark the critical values).

At low velocities ($m \lesssim 0.61$), the flame is anchored at $x_w \approx 1.0$ and the maximum temperature θ_m exceeds the wall temperature θ_w only slightly, see Fig. 1(right). Due to their low heat release, these

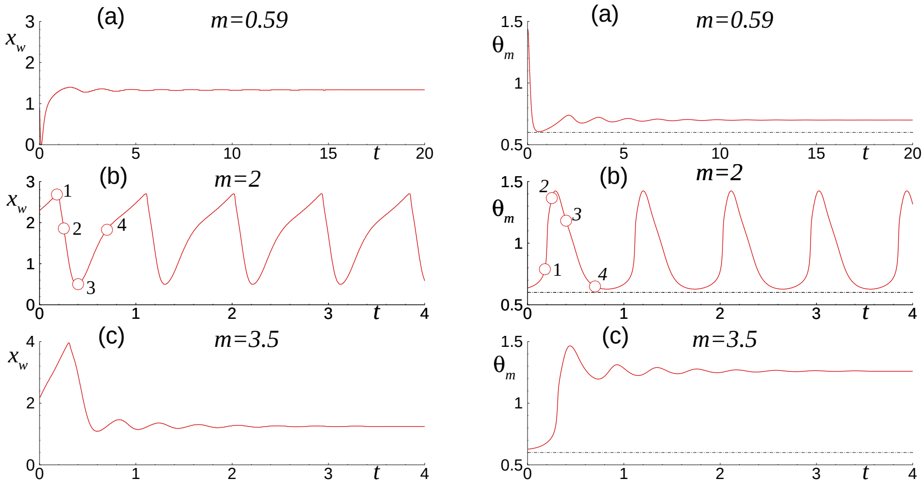

Figure 2: Time history of the flame position x_w (left plot) and the maximum temperature θ_m (right plot) at selected values of the non-dimensional velocity m ($m = 0.59$ weak flame, $m = 2$ periodic ignition/extinction (symmetric oscillations), $m = 3.5$ steady symmetric flame; $\theta_w = 0.6$, $d = 5$). The dot-dotted lines in (b) represent the wall temperature $\theta_w = 0.6$.

flames will be referred to as weak flames. Fig. 2 (top plots) show the time history of the flame location and the maximum flame temperature, revealing that the steady state is approached in a quickly-decaying oscillatory manner ($\theta_m \approx 0.59$).

At intermediate velocities ($0.61 \lesssim m \lesssim 3.1$), marked in Fig. 1 with dashed segments, the solution loses stability at a supercritical Hopf bifurcation at $m \simeq 0.61$, and oscillatory flames exhibiting repetitive ignition and extinction are obtained. The upper (Δ) and the lower (∇) triangles in Fig. 1 mark the maximum (ignition point) and minimum (extinction point) values of x_w and θ_m during an oscillation period. For $m = 2$, the flame position x_w oscillates between between a location slightly $x_w \simeq 0.5$ and $x_w \simeq 2.7$, following the oscillations of the maximum temperature θ_m between a value slightly above the wall temperature θ_w (extinction) and 1.4 (ignition) with a constant period ≈ 0.91, (Fig. 2, middle plots). The isotherms at the four instances corresponding to the points marked in the middle plots of Fig. 2, are plotted in Fig. 3 (left plot).

As the inflow velocity is increased, the upstream propagation is increasingly restricted till for $m \gtrsim 3.1$ the oscillation amplitude shrinks to zero at a second supercritical Hopf bifurcation. The ignition/extinction mode ceases, and a new steady symmetric flame is obtained, Fig. 2 (bottom plots). These flames burn more intensely than the ones at low m, and the maximum temperature in the domain is significantly higher than the wall temperature. Numerically, the same sequence of combustion modes were also observed at the low inflow velocity range in the lean premixed hydrogen simulations in micro- [7] and meso-scale channels [8] using detailed chemistry and transport, albeit at conditions that differ significantly from the conditions considered here.

The flame response curve described in Fig. 1, for $d = 5$ and $\theta_w = 0.6$, is, as expected, extremely sensitive to the value of the wall temperature. As shown in Fig. 3 (right plot), a small reduction in θ_w from 0.6 to 0.54 is sufficient to qualitatively alter the diagram: the transition from the weak to the ignition/extinction flame is supercritical for wall temperature $\theta_w \leq 0.57$, but becomes subcritical at $\theta_w = 0.54$. The dash-dotted line in Fig. 3(right) indicates the region of hysteresis, where two stable combustion modes, mild combustion and periodic ignition/extinction, can be observed at the same parameter values. Depending on the initial condition and/or external perturbations, either flame type can be realized at such conditions. On the other hand, the supercritical transition from the ignition/extinction to the

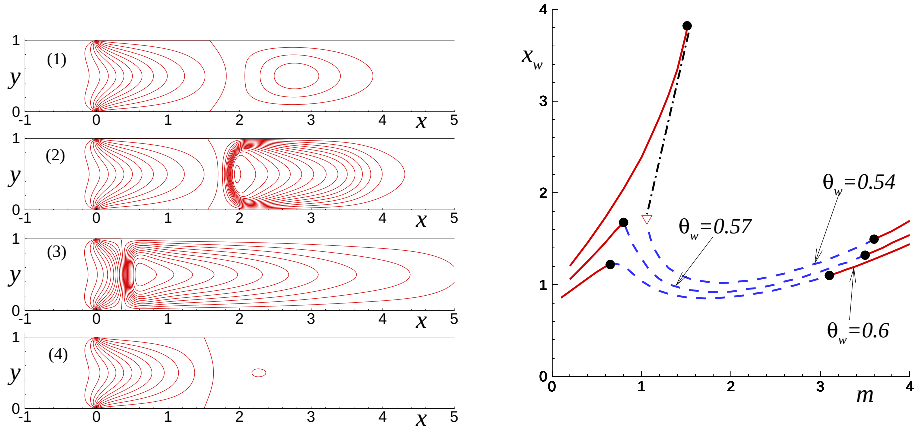

Figure 3: Left plot: Repetitive ignition/extinction (symmetric oscillations) mode: isotherms at intervals 0.05 from $\theta = 0$ to θ_{max} ($\theta_{max} = 0.789$, 1.358, 1.182, and 0.648, in (1) to (4), respectively) at the four instances marked as $1, 2, 3, 4$ in Fig. 2 ($m = 2$, $\theta_w = 0.6$, $d = 5$). Right plot: Steady flame position x_w versus the non-dimensional velocity m for $d = 5$ and different wall temperatures θ_w (solid segments: stable solutions, dashed segments: periodic solutions, dash-dotted segments: unstable solutions). For $\theta_w = 0.54$, the triangle indicates the turning point.

steady symmetric flame is not affected by θ_w significantly. At even lower θ_w, only unstable solutions leading to flame extinction are obtained, as will be discussed in the next section.

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