Effects of stoichiometry on premixed flames propagating in planar microchannels

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Abstract

Recent studies have shown that for flames freely propagating in narrow channels differential diffusion-induced instabilities may result in non-symmetric solutions and/or oscillating and rotating propagation modes [1]. This has been shown in the context of lean mixtures for which a single species transport equation with a single Lewis number of the deficient reactant can be used to represent the propagation problem. Here the effect of varying the stoichiometry on the symmetry breaking is investigated, using a two-reactant model and within the framework of the diffusive-thermal (constant-density) approximation. The computations show that near-stoichiometric mixtures stabilize the flame to symmetric solutions and that both the fuel and oxidizer Lewis number (Le_F and Le_O, respectively) are responsible for the break of symmetry.

We consider a premixed flame propagating to the left at velocity U_f in a planar adiabatic channel of height h. The mixture is at initial temperature T_u and immersed in a Poiseuille flow given by the velocity components $u(y) = 6U_0(y/h)(1 - y/h)$ and $v(y) = 0$, with U_0 the mean velocity. The chemical reaction is modeled through $\nu_F F + \nu_O O \to$ Products $+\ Q$, where F and O denote the chemical symbols of the fuel and the oxidizer, ν_F and ν_O the corresponding molar stoichiometric coefficients, and Q is the heat of combustion per mole products.

In what follows, we define the equivalence ratio of the mixture as usual $\phi = sY_{F_u}/Y_{O_u}$, where $s = \nu_O W_O/(\nu_F W_F)$, and Y_{F_u} and Y_{O_u} correspond to the mass fraction of fuel and oxidizer in the fresh unburnt region at $x \to -\infty$. To avoid the discussion of lean and rich mixtures separately, a convenient parameter $\Phi = (\nu_1 W_1 Y_{2_u})/(\nu_2 W_2 Y_{1_u})$ is introduced [2]. The subscripts 1 and 2 stand for the deficient and abundant reactants, respectively, and replace the subscripts F and O as appropriate.

Introducing non-dimensional variables $Y_1 = Y_1'/Y_{1_u}$, $Y_2 = \Phi Y_2'/Y_{2_u}$ and $\theta = (T - T_u)/(T_a - T_u)$, with Y_1' and Y_2' the deficient and abundant reactant mass fraction, respectively, and T_a the adiabatic temperature of the mixture, and using h and $h^2/\mathcal{D}_T$ as the reference units of length and time, respectively, the steady problem reduces to the integration of the following equations in a reference frame moving with the flame

$$\sqrt{d}\{u_f + 6\,my(1-y)\}\frac{\partial \theta}{\partial x} = \Delta\theta + d\,\omega, \tag{1}$$

$$\sqrt{d}\{u_f + 6\,my(1-y)\}\frac{\partial Y_i}{\partial x} = \frac{1}{Le_i}\Delta Y_i - d\,\omega \qquad i = 1, 2, \tag{2}$$

where the reaction rate, with unity reaction order, is given by

$$\omega = \frac{\beta^2}{2\mathcal{L}s_L^2} Y_1 Y_2 \exp\left\{\frac{\beta(\theta - 1)}{1 + \gamma(\theta - 1)}\right\}, \tag{3}$$

with $\mathcal{L} = Le_1 Le_2(1 + \mathcal{A})/\beta$ and $\mathcal{A} = 1 + \beta(\Phi - 1)/Le_2$, and subject to the boundary conditions

$$\begin{aligned} x \to -\infty: &\quad \theta = Y_1 - 1 = Y_2 - \Phi = 0, \\ x \to +\infty: &\quad \partial\theta/\partial x = \partial Y_i/\partial x = 0, \qquad i = 1, 2, \end{aligned} \tag{4}$$

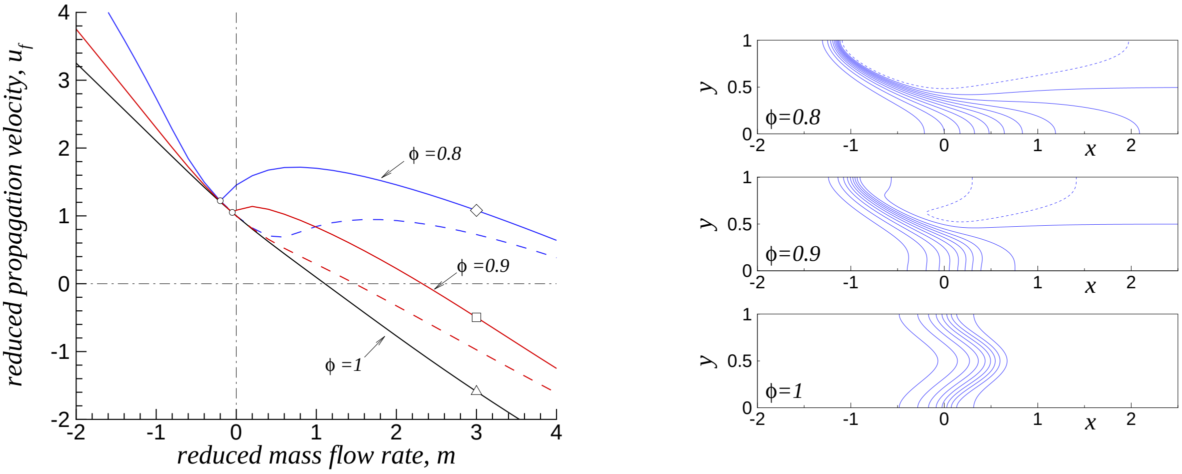

Figure 1: Left: the variation with the flow rate of the flame propagation velocity for $\phi = 0.8$, 0.9, and 1. Dashed curve: non-stable symmetric solutions. Solid curve: stable solutions. Right: flame structure given by the isotherms at intervals of 0.1 for the conditions marked with symbols $\diamond$, $\square$, and $\triangle$. Dashed lines indicate isotherms above the adiabatic temperature for $\theta = 1.1$ ($\phi = 0.8$) and $\theta = 1.04$ ($\phi = 0.9$)

The following parameters appear in the formulation: the Zel'dovich number $\beta = E(T_a - T_u)/\mathcal{R}T_a^2$, with $\mathcal{R}$ the universal gas constant, the heat release parameter $\gamma = (T_a - T_u)/T_a$, the reduced mass flow rate $m = U_0/S_L$, with S_L the burning velocity of the planar flame, the propagation velocity of the flame $u_f = U_f/S_L$, and the Damköhler number $d = (h/\delta_T)^2$, with $\delta_T = \mathcal{D}_T/S_L$ representing the thermal flame thickness.

In the computations shown in Fig. 1, we selected $Le_F = 0.3$, $Le_O = 1.4$, $\beta = 10$, and $\gamma = 0.8$ as representative of hydrogen-oxygen mixtures in nitrogen-diluted inert gas. Flame propagation in channels of the order of 1 mm, $d = 20$, was considered. For assisted flow, $m < 0$, the flame is symmetric. Increasing m towards positive values we find a bifurcation point, marked with $\circ$ in Fig. 1 (left), where the symmetry of the flame is broken, and only non-symmetric solutions are found. Such flames are stable and propagate faster than their symmetric counterparts (dashed curve), hard to find experimentally because of their unstable nature. Near-stoichiometric mixtures (see $\phi = 1$ curve) possess, however, such a markedly stable character than only symmetric stable solutions was found for all values of m, as anticipated in a different context in [3]. For lean mixtures, the present problem reduces to that solved before in [1].

References

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