Effects of stoichiometry on premixed flames propagating in planar microchannels: The effective Lewis number

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Introduction

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-specie transport equation with a single Lewis number of the deficient reactant can be used to represent the propagation problem. Here the effect of the stoichiometry on the symmetry-breaking bifurcation is investigated, using a two-reactant model and within the framework of the diffusive-thermal (constant-density) approximation.

Formulation

Consider a premixed flame propagating at velocity U_f in a narrow adiabatic channel of width h and immersed in a Poiseuille flow with mean velocity U_0. Consider the chemical reaction modelled with a two-reactant kinetics $\nu_F F + \nu_O O \rightarrow$ Products. The equivalence ratio of the mixture is defined as $\phi = sY_{F_u}/Y_{O_u}$, where $s = \nu_O W_O/(\nu_F W_F)$.

If we choose h and $h^2/\mathcal{D}_T$ as the reference length and time scales, and introduce $\theta = (T - T_u)/(T_{ad} - T_u)$ and $Y_i = Y_i/Y_{i_u}^{st}$, the dimensionless equations written in the reference frame moving with the flame become

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

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

where $i = 1, 2$, stands for the deficient and abundant reactant, respectively, and where

$$\omega = \frac{\beta^2}{2\mathcal{L}s_L^2}Y_1Y_2\exp\left\{\frac{\beta(\theta-1)}{1+\gamma(\theta-1)}\right\}, \quad (3)$$

with

$$\mathcal{L} = Le_1Le_2(1+\mathcal{A})/\beta,$$

and

$$\mathcal{A} = 1 + \beta(\Phi - 1)/Le_2.$$

The parameters are: $\beta = E(T_{ad} - T_u)/\mathcal{R}{T_{ad}}^2$, $\gamma = (T_{ad} - T_u)/T_u$, $m = U_0/S_L$, $u_f = U_f/S_L$, and $d = (h/\delta_T)^2$, with $\delta_T = \mathcal{D}_T/S_L$ the flame thickness and S_L the planar flame speed. The factor $s_L = S_L/(S_L)_{asp}$, where $(S_L)_{asp} = \sqrt{2\mathcal{B}\rho\mathcal{D}_T Y_{1_u}\frac{\nu_2 Le_1 Le_2}{W_1\beta^3}(1+\mathcal{A})\exp\left(-E/\mathcal{R}T_{ad}\right)}$. The parameter $\Phi = (\nu_1 W_1 Y_{2_u})/(\nu_2 W_2 Y_{1_u})$, where $\Phi = 1/\phi$ for lean mixtures and $\Phi = \phi$ for rich ones, is used to avoid the discussion of lean and rich mixtures separately.

The adiabatic temperature, $T_{ad} = T_u + \frac{QY_{1_u}}{c_p\nu_1 W_1}$, was hold fixed with the equivalence ratio by diluting the mixture, where Q is the heat of combustion.

Results

The computations were carried out with the parameters based on the characteristic values of diluted hydrogen mixtures at $T_{ad} = 1600$ K, that is, for $\beta = 10$, $\gamma = 0.8$, $Le_F = 0.3$, and $Le_O = 1.4$.

In Fig. 1 we show lean flames that suffer from symmetry-breaking bifurcations (the bifurcation point is marked with symbol ∘), in agreement with [1]. For values of m above the bifurcation point the solution has two branches. One corresponds to non-symmetric and steady flames (upper branch in solid curve), the other with unstable symmetric solutions (lower branch in dashed curve). For values of m below the bifurcation point the solution is symmetric and steady (solid curve).

As the mixture approaches stoichiometric conditions the flame adquires a symmetric shape for large m. Similar effects was observed in the context of flames propagating in narrow channels with a step-wise wall temperature [2].

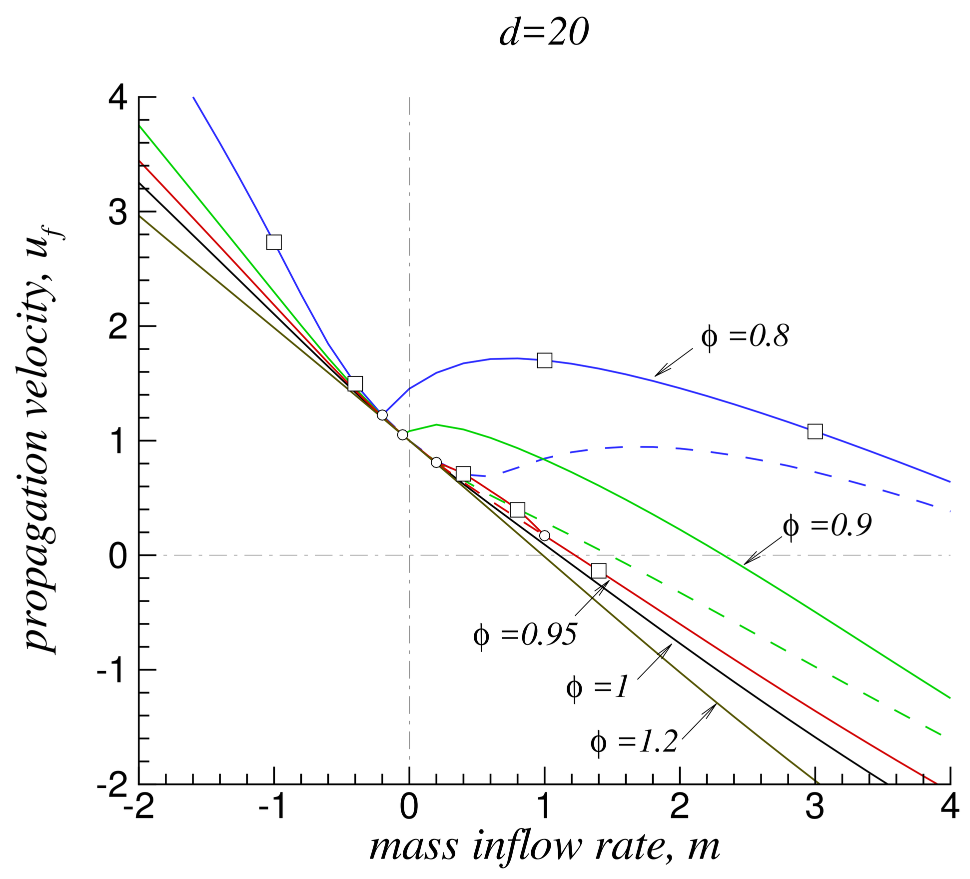

Fig. 1: Variation of the flame speed with the mass inflow rate for differente values of the equivalence ratio and $d = 20$.

For near-stoichiometric mixtures, we found that the double-valued region is limited to a small range; see $\phi = 0.95$ in Fig. 1. Depletion of the abundant reactant in the reaction zone seems to play a role in recovering the symmetric solution. When $Y_1 \sim Y_2 \sim 1/\beta$ in the reaction zone, the unequal diffusion rate of Y_2, given by Le_2, promotes the emergence of two zones with mass concentration below the equilibrum value $Y_{2_\infty} = (\Phi - 1)$ (marked with dashed curve in Fig. 2) and the symmetric solution is recovered.

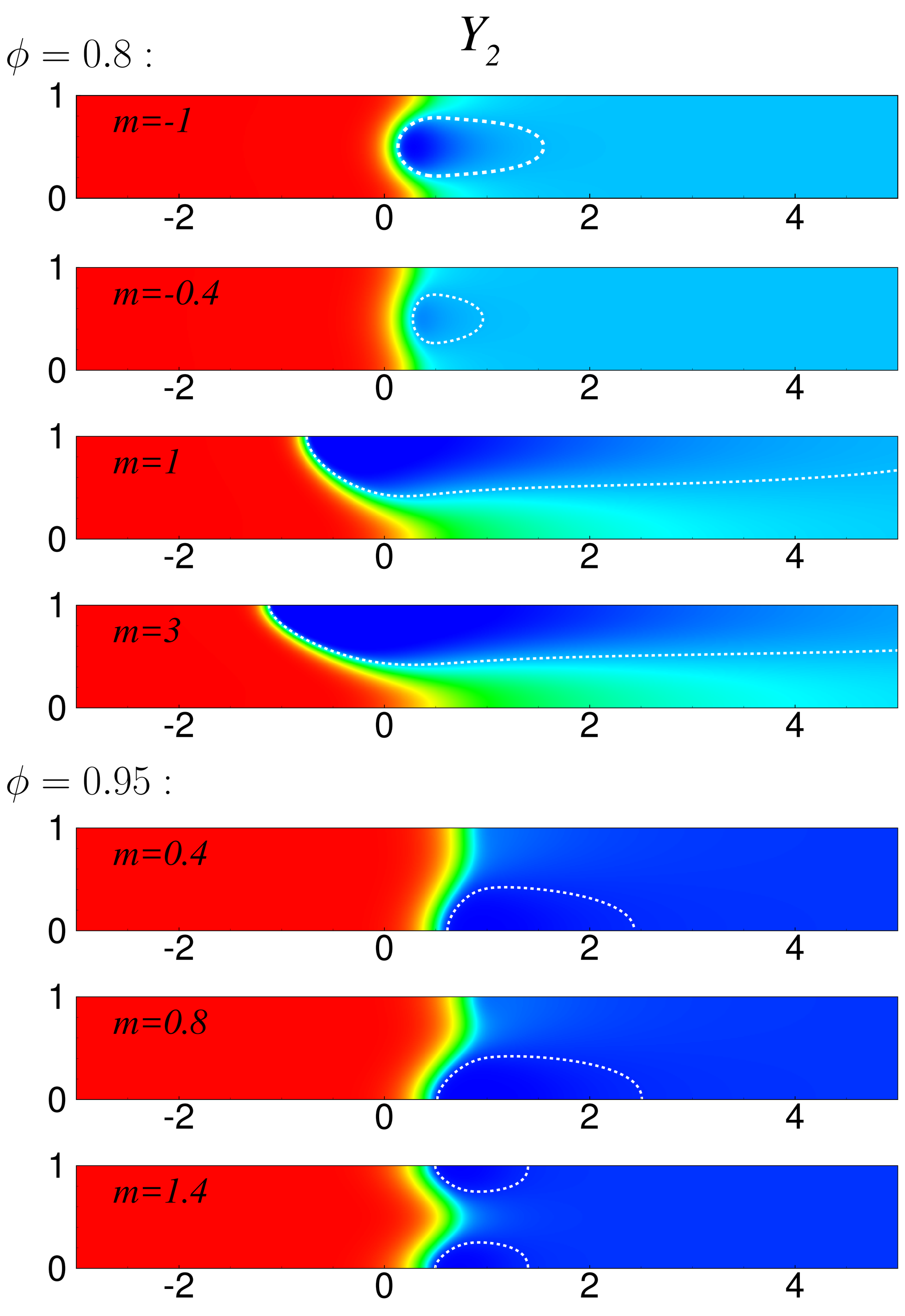

Fig. 2: Structure of the computed flames given by the isocontour of the abundant mass fraction Y_2 for the values of m marked (□) in Fig. 1.

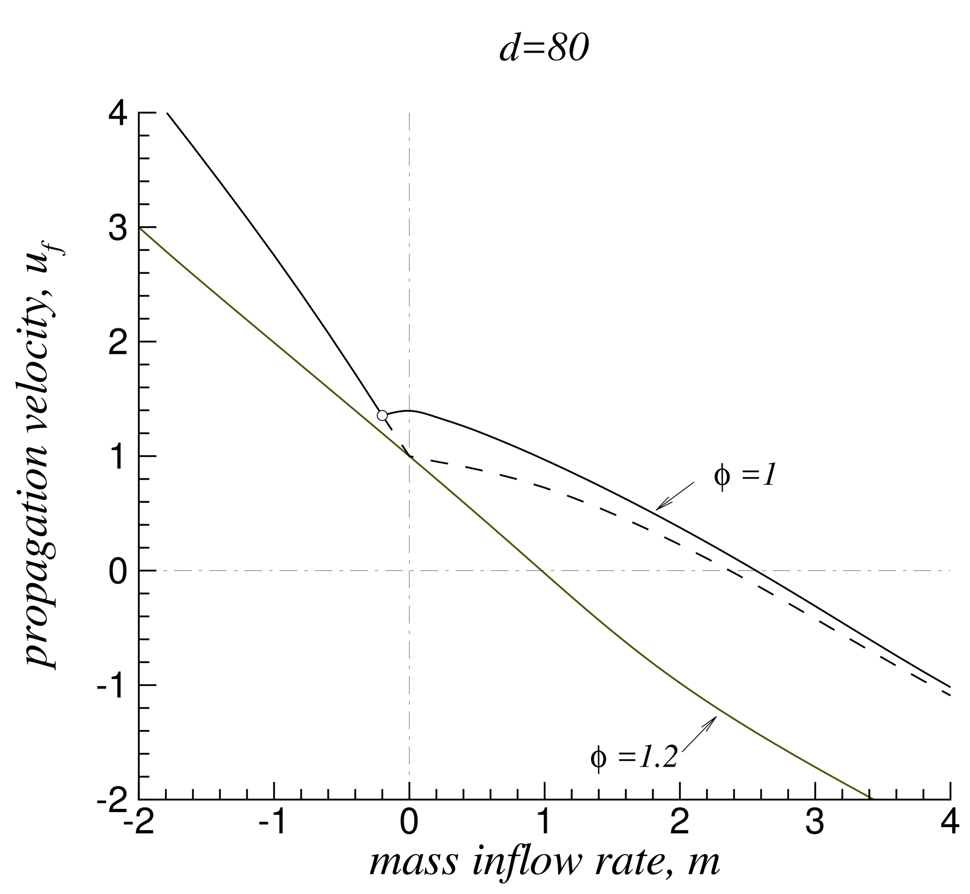

Fig. 3: Variation of the flame speed with the mass inflow rate for near-stoichiometric mixtures and $d = 80$.

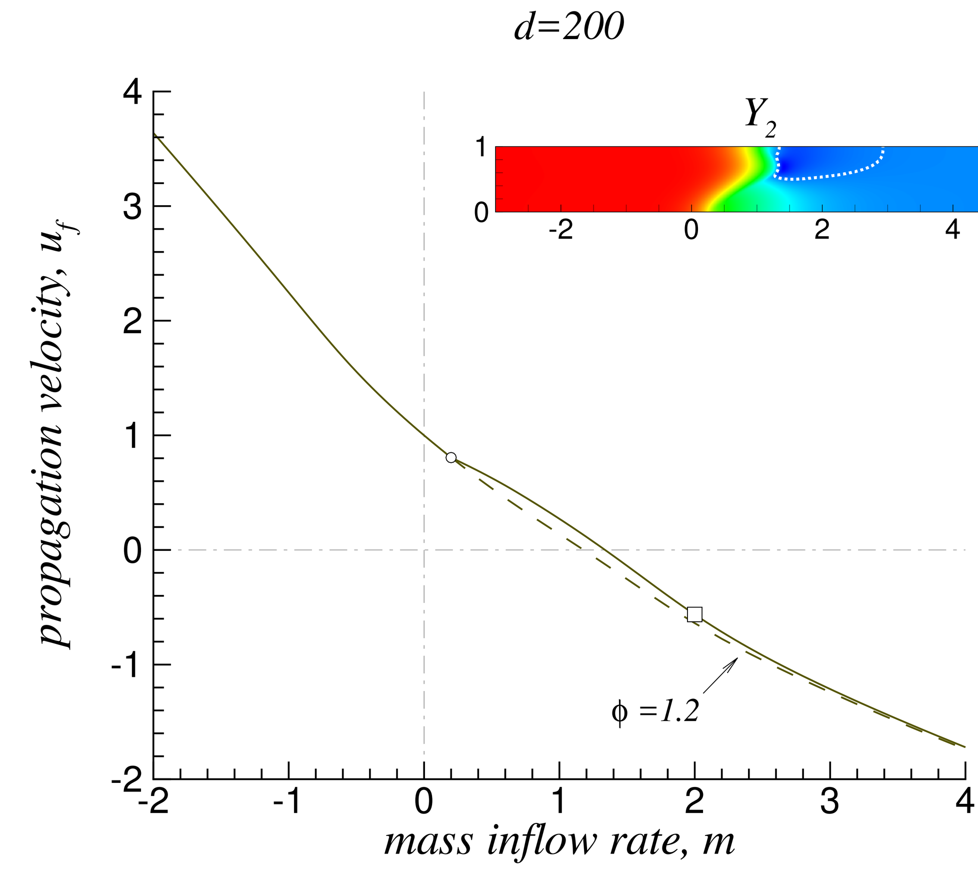

Fig. 4: Variation of the flame speed with the mass inflow rate for $\phi = 1.2$ and $d = 200$. Inset: the structure of the steady non-symmetric flame computed for $m = 2$, given by the isocontour of Y_2.

In Figs. 3 and 4 we show near-stoichiometric mixtures for $d = 80$ and 200, respectively. For some value $\phi \gtrsim 1.2$ we did not find non-symmetric solutions given any value of d and m.

The effective Lewis number

Joulin and Mitani [3] demonstrated that the stability of freely propagating flames described with two reacntats depends on an effective Lewis number, given by

$$Le_{eff} = \frac{Le_2 + \mathcal{A}Le_1}{1+\mathcal{A}}, \quad \text{with} \quad \mathcal{A} = 1 + \beta(\Phi - 1). \quad (4)$$

In the single-reactant theory [1], non-symmetric solutions arise only for $Le < 1$. As we seek the posibility of describing the onset of non-symmetric solutions in the context of two reactants, we plot in Fig 5 the function of Le_{eff} with ϕ, given in (4). Only flames with $Le_{eff} < 1$ should exhibit non-symmetric solutions.

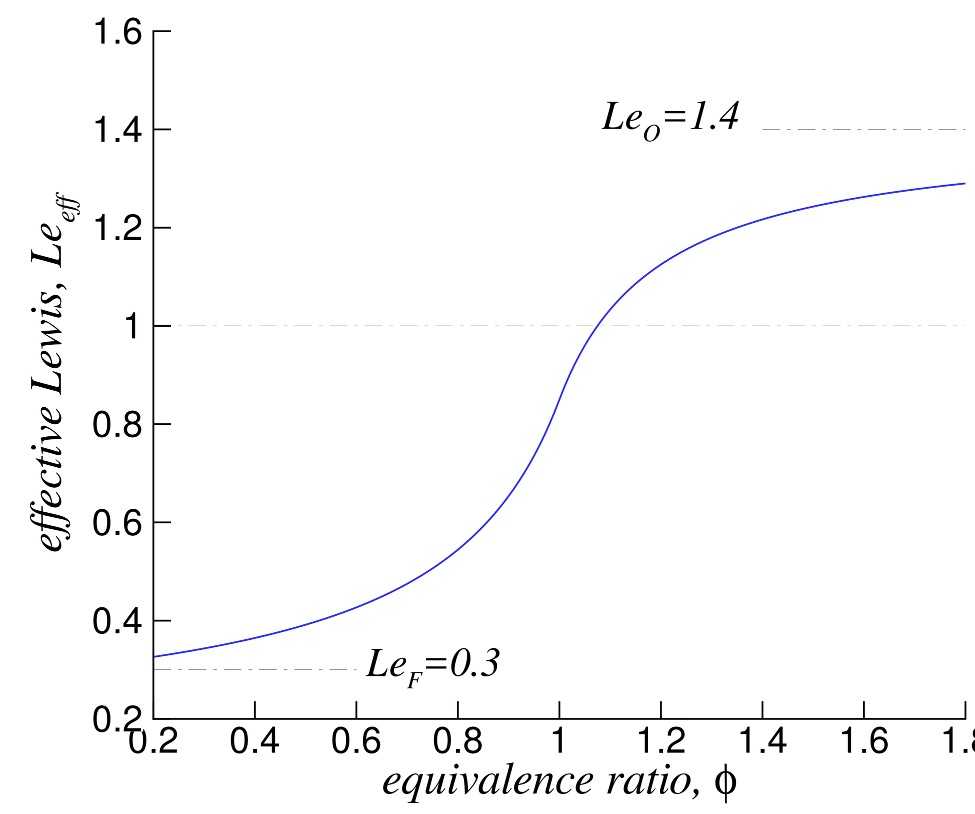

Fig. 5: The effective Lewis number with ϕ as given in [3].

References

[1] V. N. Kurdyumov. Combust. Flame 158 (2011) 1307-1317.

[2] M. Sánchez-Sanz, D. Fernández-Galisteo, and V. N. Kurdyumov. Combust. Flame 161 (2013) 1282-1293.

[3] G. Joulin and T. Mitani. Combust. Flame 40 (1981) 235-246.

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