Propagation of Symmetric and Non-symmetric Flames in Channels

Anne Dejoan, Carmen Jiménez and Vadim N. Kurdyumov

Department of Energy, CIEMAT, Madrid, Spain

27th International Colloquium on the Dynamics of Explosions and Reactive Systems, Beijing, July 28th - August 2nd, 2019.

Abstract

Symmetry loss of premixed flames propagating in narrow planar channels is investigated. It is found that, depending on the flow rate, the Lewis number, the thermal expansion and the heat loss intensity, a bifurcation phenomenon can appear, leading to the existence of multiple solutions at the same set of parameters. In particular, the parametric influence on the critical bifurcation values is presented. Time-dependent simulations reveal that, as a general rule, symmetric flames are unstable with subsequent formation of non-symmetric flames. These results can be very important for practical applications, affecting, for example, the point of flashback.

General formulation

The non-dimensional governing equations are

$$\frac{\partial\rho}{\partial t}+\frac{\partial(\rho[u+u_f])}{\partial x}+\frac{\partial(\rho v)}{\partial y}=0,$$

$$\rho\Big(\frac{\partial u}{\partial t}+[u+u_f]\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\Big)=-\frac{1}{a^2}\frac{\partial p}{\partial x}+Pr\Big[\frac{1}{a^2}\frac{\partial^2 u}{\partial y^2}+\frac{4}{3}\frac{\partial^2 u}{\partial x^2}+\frac{1}{3}\frac{\partial^2 v}{\partial x\partial y}\Big],$$

$$\rho\Big(\frac{\partial v}{\partial t}+[u+u_f]\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\Big)=-\frac{1}{a^4}\frac{\partial p}{\partial y}+Pr\Big[\frac{1}{a^2}\Big(\frac{4}{3}\frac{\partial^2 v}{\partial y^2}+\frac{1}{3}\frac{\partial^2 u}{\partial x\partial y}\Big)+\frac{\partial^2 v}{\partial x^2}\Big],$$

$$\rho\Big(\frac{\partial Y}{\partial t}+[u+u_f]\frac{\partial Y}{\partial x}+v\frac{\partial Y}{\partial y}\Big)=\frac{1}{Le}\Big(\frac{\partial^2 Y}{\partial x^2}+\frac{1}{a^2}\frac{\partial^2 Y}{\partial y^2}\Big)-\omega,$$

$$\rho\Big(\frac{\partial \theta}{\partial t}+[u+u_f]\frac{\partial \theta}{\partial x}+v\frac{\partial \theta}{\partial y}\Big)=\Big(\frac{\partial^2 \theta}{\partial x^2}+\frac{1}{a^2}\frac{\partial^2 \theta}{\partial y^2}\Big)+\omega,$$

$$1=\rho(1+q\theta),$$

$$\omega=\frac{\beta^2}{2Le\,u_p^2}(1+q)^n\rho^n Y\exp\Big\{\frac{\beta(\theta-1)}{1+q(\theta-1)/(1+q)}\Big\}.$$

$$\Big(\frac{\partial\theta}{\partial y}\pm b\,a\,\theta\Big)\Big|_{y=0,1}=\frac{\partial Y}{\partial y}\Big|_{y=0,1}=u\big|_{y=0,1}=v\big|_{y=0,1}=0,$$

Here $a=h/\delta_T$ is the channel width; $q=(T_a-T_0)/T_0=QY_0/c_pT_0$ is the heat release parameter; $Pr=\mu c_p/\lambda_g$ is the Prandtl number, with μ the viscosity of the mixture; $Le=\lambda_g/\rho_0 c_p\mathcal{D}$ is the Lewis number, with $\mathcal{D}$ the mass (fuel) diffusivity, $\beta=E(T_a-T_0)/\mathcal{R}_g T_a^2$ is the Zel'dovich number; where $b=(\lambda_w/\lambda_g)(\delta_T/h_w)$ is the heat transfer parameter. The limiting cases of adiabatic and isothermal walls correspond to $b\to 0$ and $b\to\infty$, respectively.

The following integral

$$S=\int_{-\infty}^{\infty}dx\int_{0}^{1/2}[\theta(x,y,t)-\theta(x,1-y,t)]dy \qquad (1)$$

helps to identify the symmetry of the solutions for the 2d case.

Influence of the channel width

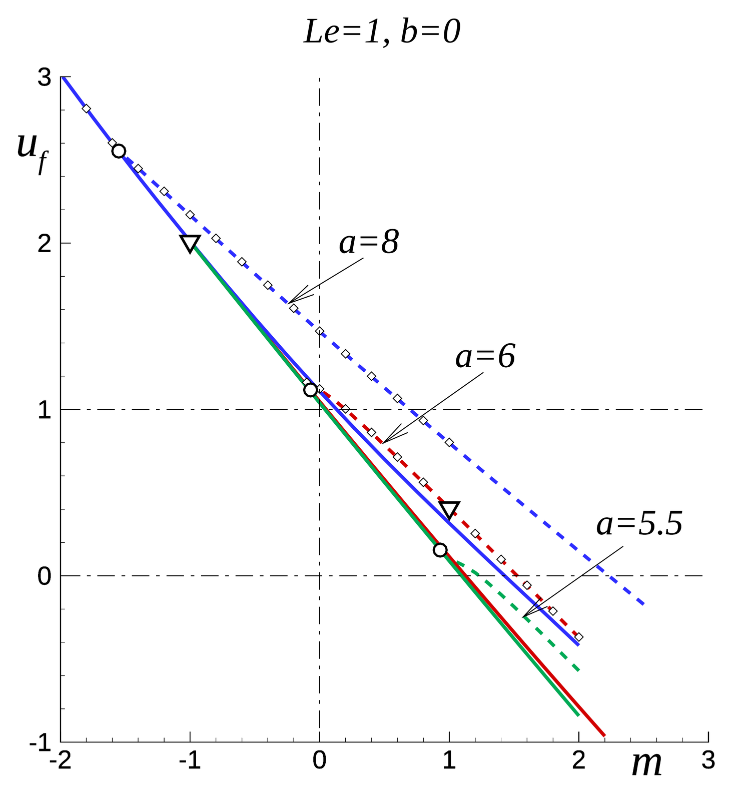

Fig. 1: The computed flame velocity $u_f=U_f/S_L$ as a function of the non-dimensional flow rate $m=U_0/S_L$ for $Le=1$ and several values of a, all results for $\beta=10$, $q=5$ and an adiabatic channel, $b=0$. Solid and dashed lines represent symmetric and non-symmetric flames calculated with $n=2$, respectively; diamond symbols correspond to the cases with $n=1$ (only for $a=6$ and 8); the bifurcation points are marked with open circles.

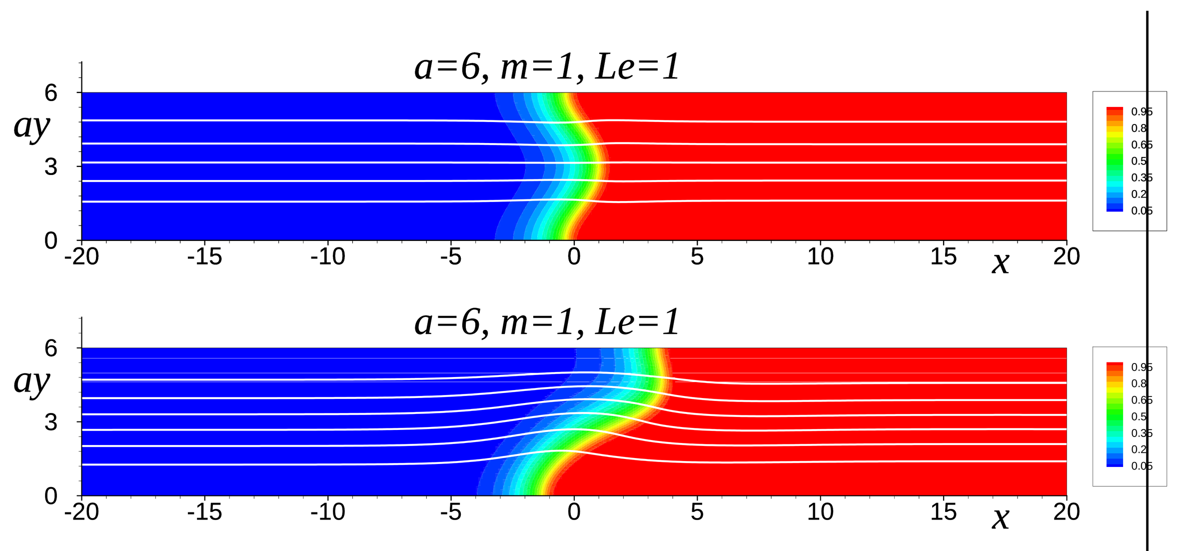

Fig. 2: Symmetric (upper plot) and non-symmetric (lower plot) steady flames (color isotherms) and streamlines (white lines) in an adiabatic channel, for $a=6$, $m=1$, $Le=1$, $\beta=10$, $q=5$, $n=2$.

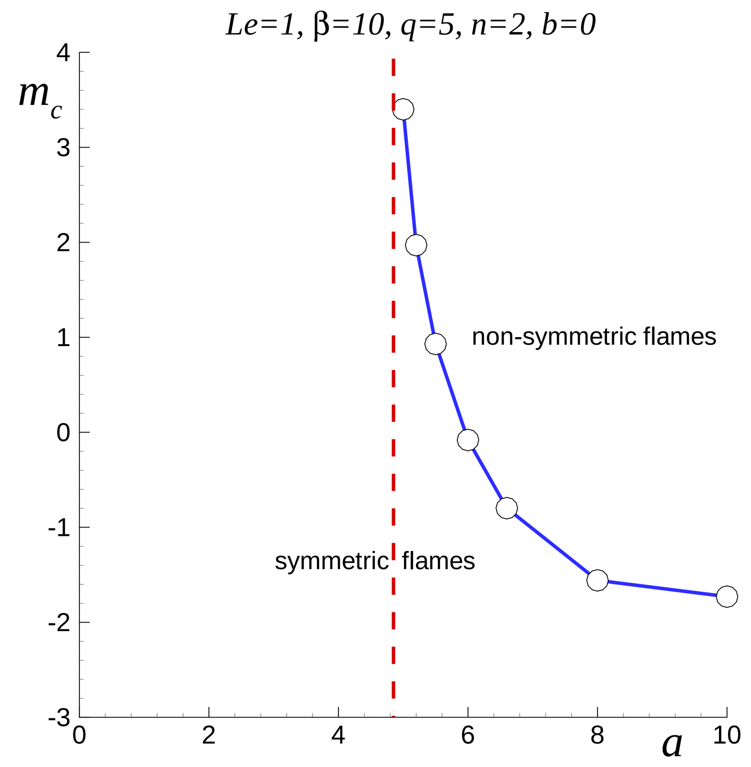

Fig. 3: The bifurcation point m_c plotted as a function of the channel width a for $Le=1$, $\beta=10$, $q=5$, $n=2$ and $b=0$; the non-symmetric solutions exist above the curve; the vertical dashed line shows the approximate critical value of a.

Influence of thermal expansion and heat losses

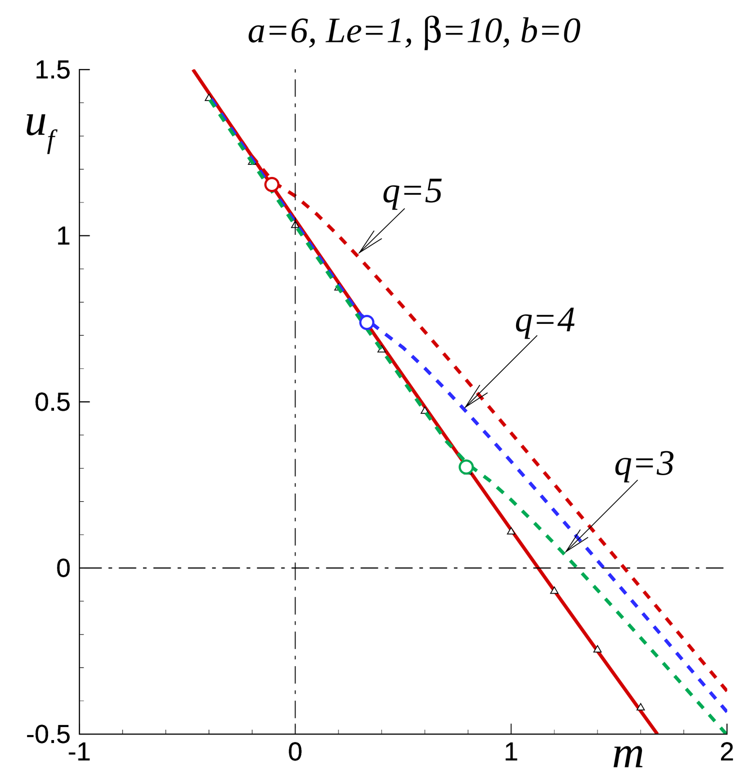

Fig. 4: The computed flame velocity $u_f=U_f/S_L$ as a function of the non-dimensional flow rate $m=U_0/S_L$ for $Le=1$ and several values of q; all curves calculated for $a=6$, $\beta=10$, $n=2$ and an adiabatic channel, $b=0$; the bifurcation points are marked with open circles.

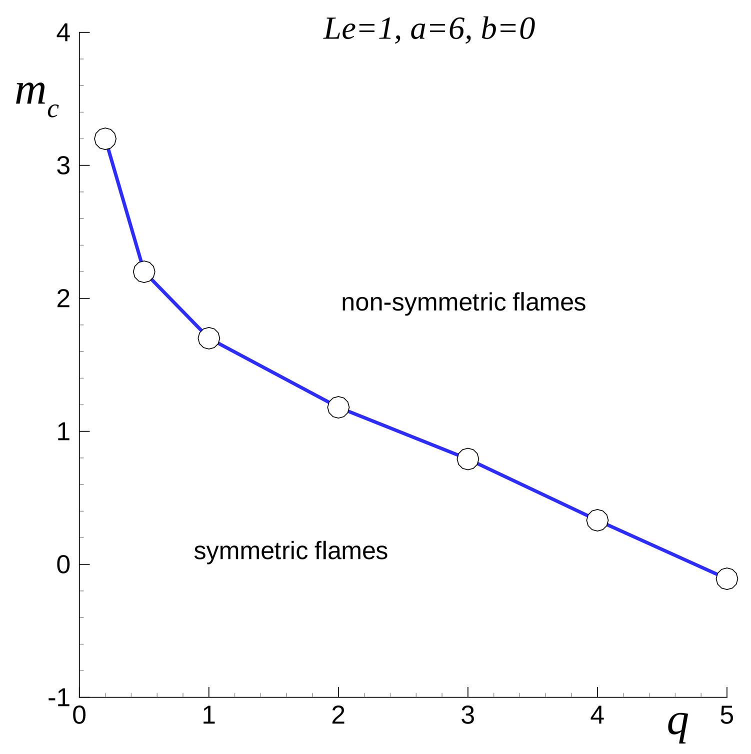

Fig. 5: The bifurcation point m_c plotted as a function of the thermal expansion parameter q, calculated for $a=6$, $Le=1$, $\beta=10$, $n=2$ and $b=0$; the non-symmetric solutions exist to the right of the curve.

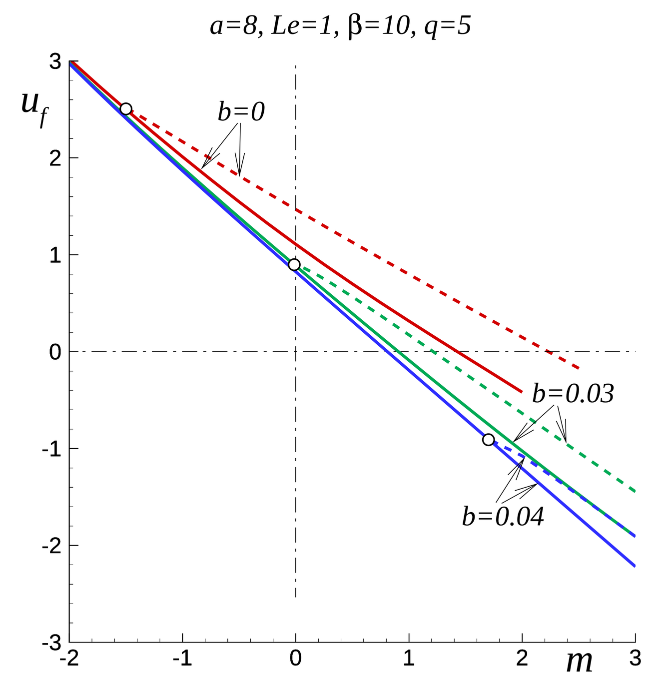

Fig. 6: The computed flame velocity $u_f=U_f/S_L$ as a function of the non-dimensional flow rate $m=U_0/S_L$ for $Le=1$ and several values of b. Solid lines - symmetric flames, dashed lines - non-symmetric flames; all curves calculated for $\beta=10$, $q=5$, $n=2$; the bifurcation points are marked with open circles.

Influence of the Lewis number

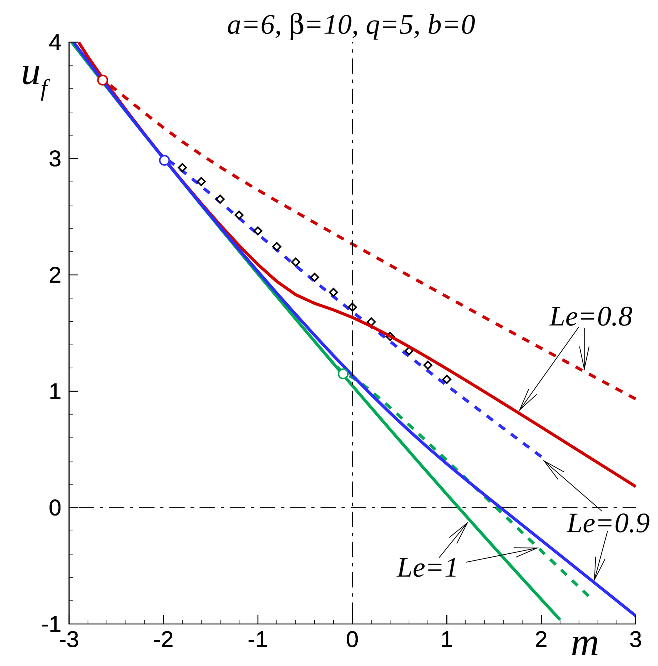

Fig. 7: The computed flame velocity $u_f=U_f/S_L$ as a function of the non-dimensional flow rate $m=U_0/S_L$ calculated for several values of Le in an adiabatic channel, $b=0$: solid and dashed lines represent symmetric and non-symmetric flames, respectively, calculated with $n=2$; diamond symbols show the results calculated with $n=1$ (only for $Le=0.9$); all curves calculated for $a=6$, $\beta=10$ and $q=5$; the bifurcation points are marked with open circles.

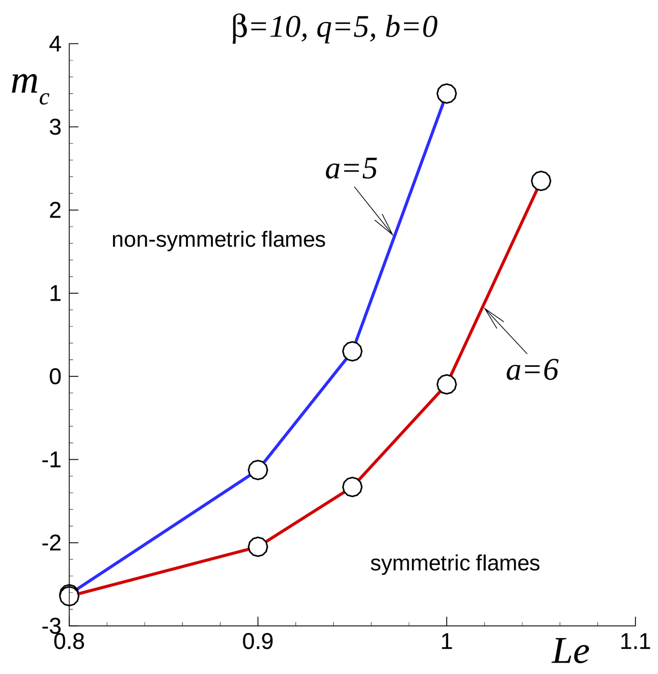

Fig. 8: The bifurcation point m_c plotted as a function of the Lewis number Le, calculated for $a=5$ and 6, $\beta=10$, $q=5$ and $b=0$; the non-symmetric solutions exist above the curves.

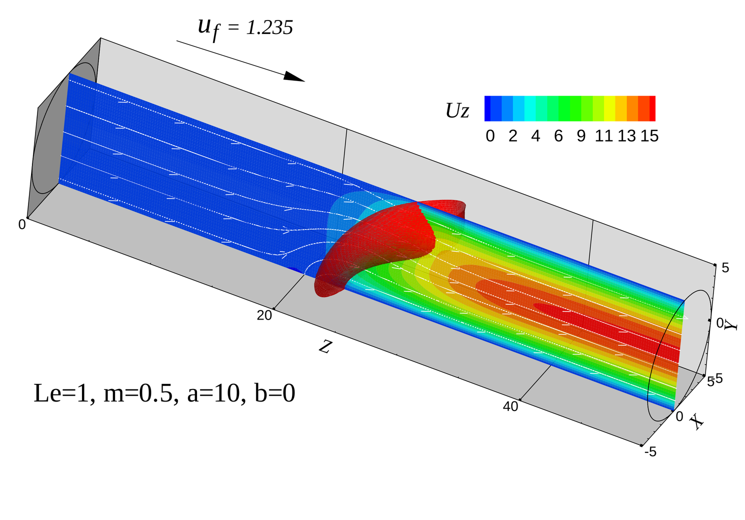

Fig. 9: 3D circular adiabatic channel: iso-surface temperature value $\theta=0.99$