Premixed flame propagation between two closely spaced parallel plates

D. Fernández-Galisteo [a], **J. Gross** [b], **and P.D. Ronney** [b]

[a] *Department of Energy, CIEMAT, Spain*

[b] *Department of Aerospace and Mechanical Engineering, University of Southern California, Los Angeles, CA, USA*

35th International Symposium on Combustion, San Francisco. August 2014.

Introduction

The propagation of slow quasi-isobaric premixed flames between two closely spaced and adiabatic plates is studied. The results can be of particular interest in microscale combustion where the confined flow modifies the intrinsic flame instabilities. For example, the viscosity contrast across the flame (Saffman-Taylor instability) becomes non-negligible for sufficiently close plates [1, 2]. We are interested to show a simple formulation that allows the study of flame instabilities at these scales.

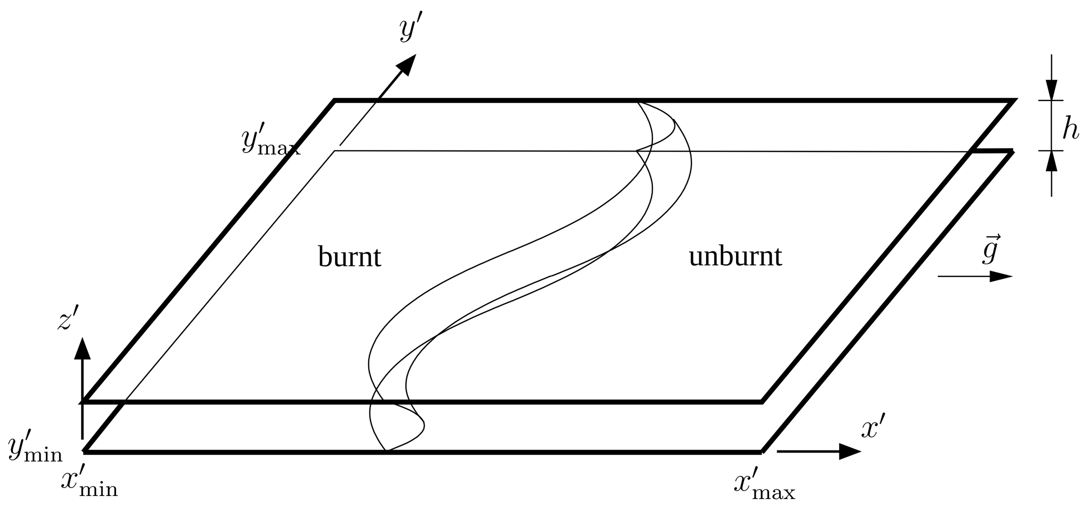

Fig. 1: Sketch of the Hele-Shaw cell in a cell gap of size h

Formulation

The present formulation emerges for plates sufficiently close, that is, in the limit of small Peclet number, $Pe = h/\delta_T << 1$, where $\delta_T = \mathcal{D}_T/S_L$ is the thermal thickness and S_L is the adiabatic flame speed. An averaging of the conservation equations over the direction z' perpendicular to the plates is applied [3]. S_L and δ_T are used as the reference scales for appropriate non-dimensionalization. The reduced formulation is written for a global Arrhenius step $F + O \to P$ and constant specific heat c_p, and becomes

$$\rho\frac{\partial\theta}{\partial t} + \rho U_x\frac{\partial\theta}{\partial x} + \rho U_y\frac{\partial\theta}{\partial y} = \nabla\cdot(\mu\nabla\theta) + \omega, \tag{1}$$

$$\rho\frac{\partial Y}{\partial t} + \rho U_x\frac{\partial Y}{\partial x} + \rho U_y\frac{\partial Y}{\partial y} = \frac{1}{Le}\nabla\cdot(\mu\nabla Y) - \omega, \tag{2}$$

where

$$\omega = \frac{\beta^2}{2s_L^2 Le}\frac{(1+\gamma)^{2-\sigma}}{(1+\gamma\theta)^2}Y\exp\left\{\frac{\beta(\theta-1)}{1+[\gamma/(1+\gamma)](\theta-1)}\right\},$$

together with the reduced Darcy's law for the z-averaged velocity

$$U_x(x,y;t)\,\vec{e}_x + U_y(x,y;t)\,\vec{e}_y = -\frac{\nabla p - \rho G\vec{e}_x}{\mu}, \tag{3}$$

the pressure deviation field from the ambient

$$\Delta p = (1+\sigma)G\frac{\partial\rho}{\partial x} - \frac{\sigma}{\rho}\nabla\rho\cdot\nabla p - \gamma\mu\left[\nabla\cdot(\mu\nabla\theta) + \omega\right], \tag{4}$$

and the equation of state

$$\rho = 1/(1+\gamma\theta). \tag{5}$$

The following parameters appear: $\beta = E(T_a - T_u)/R{T_a}^2$, $\gamma = (T_a - T_u)/T_u$, $Le = \mathcal{D}_T/\mathcal{D}_F$, the buoyancy effect G, the temperature-dependent viscosity ratio in the form $\mu = \mu'/\mu_u = (1+\gamma\theta)^\sigma$ and the reduced planar flame speed $s_L = S_L/(S_L)_{asp}$, where $(S_L)_{asp} = \sqrt{2Le\mathcal{B}\lambda_b/(\beta^2 c_p)}\,(\rho_b/\rho_u)\exp(-E/2RT_a)$. The boundary conditions for the reduced 2D problem (1)-(5) correspond with periodic conditions at y_{min} and y_{max}, together with $p = 0$ at x_{min} and $U_x = 0$ at x_{max}.

Results

Time-dependent computations were carried out in a domain large enough to capture the wrinkled flame structures correctly. The initial condition was chosen in the form of three hot spot at $(x,y) = (0,0)$, $(0,50)$, and $(0,100)$.

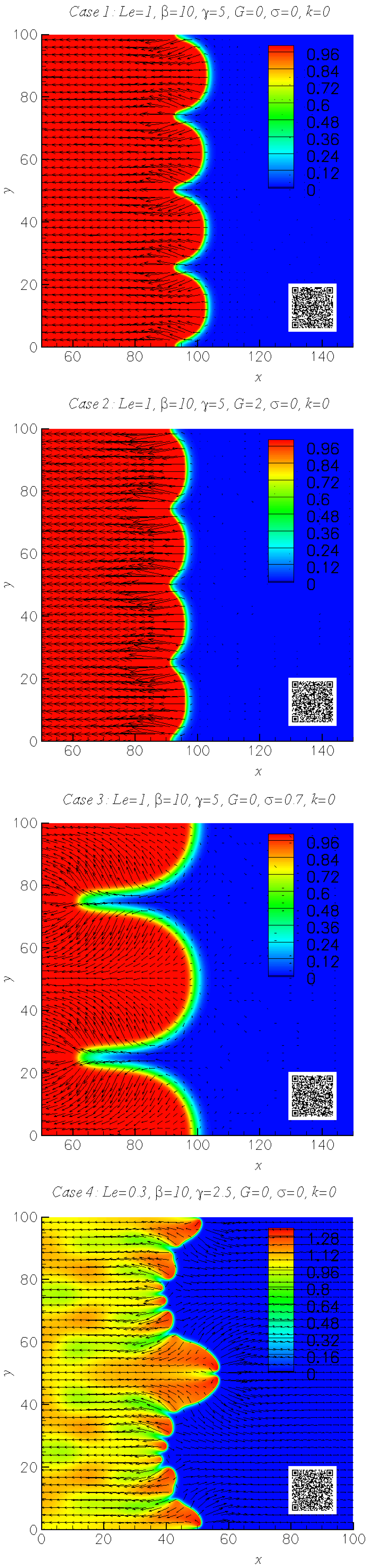

Fig. 2: Flame front (given by isotherms contour) and flow velocity vectors calculated for four differents cases.

Fig. 2 depicts four cases, where the effects of bouyancy, viscosity contrast and differential diffusion on the flame stability have been isolated. The only effect included in case 1 as a baseline is thermal expansion. After a small period of acceleration due to the hot-spot initial conditions, case 1 and 2 show a 4-wave mode that propagate steadily before the occurrence of cell splitting and merging. Case 3 and 4 show a 2-wave mode propagation, although smaller wrinkled structures appear into the longest wrinkles in case 4 caused by the diffusive-thermal instability, as seen experimentally [1]. These structures modifies the global flame front speed, which is plotted in Fig. 3. The front speed (S_T/S_L) is defined as

$$S_T/S_L = \frac{\iint_{xy}\omega\,\mathrm{d}x\,\mathrm{d}y}{L_y},$$

being L_y is the length in the y component.

The baseline thermal-expansion case 1 shows $S_T/S_T \approx 1.5$. This value is enhanced by 30% when the viscosity contrast is included, showing an important effect in very confined flows. Downward case 2 is slower than upward case, but still has velocities larger than one. Downward case 2 does stabilize the wrinkles in case 1 and slow the front velocity. The Low Le case 4 has a drastic effect on the front speed due to the emergence of the small cellular-like wrinkled structures. In all cases cell splitting and merging appears in the computations after a period of steady propagation.

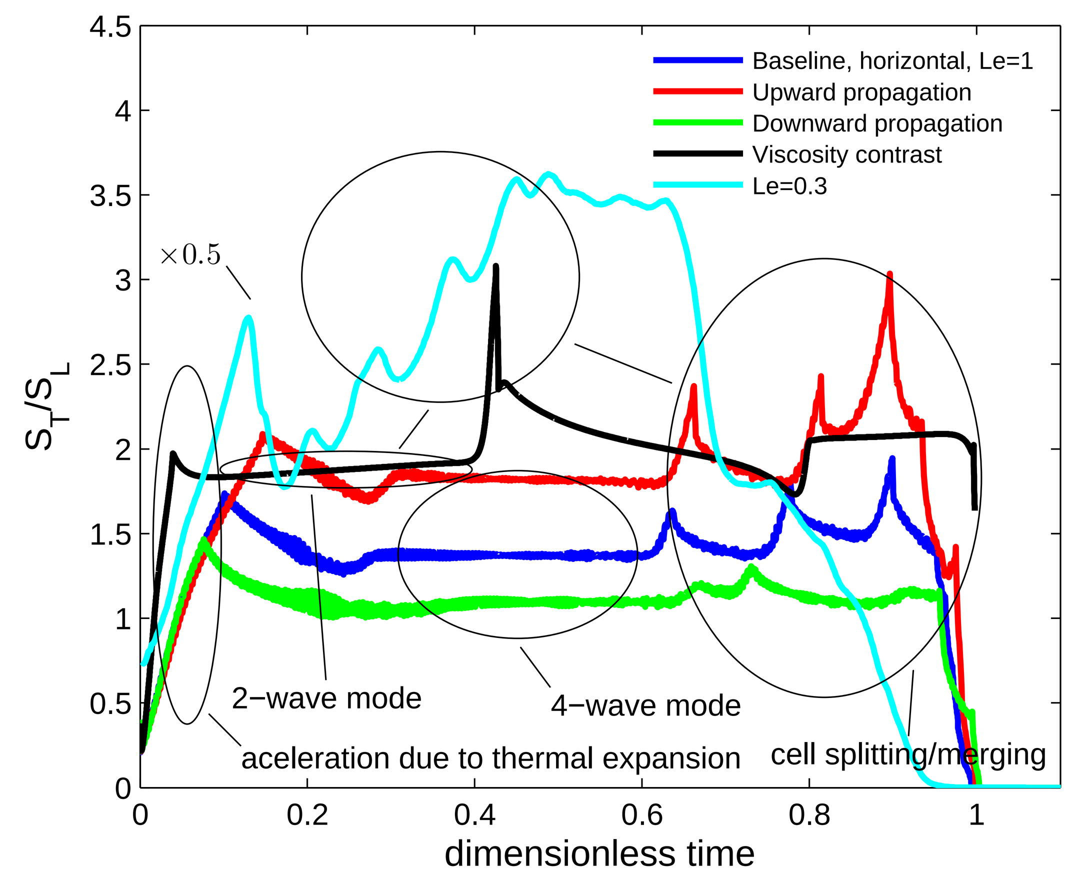

Fig. 3: Dimensionless front speed with the reduced time.

Future work

The validity of the results obtained in the limit $Pe << 1$ needs to be checked with 3D computations, where the effect of the curvature in the third coordinate z' plays a role.

References

[1] J. Gross, X. Pan, P. D. Ronney. Spring Technical Meeting, Combustion Institute, Western States, Section, March 24-25, Pasadena, CA.

[2] S. H. Kang, H. G Im, S. W. Baek. Combust. Theory Modelling 7 (2003) 343-363.

[3] V. N. Kurdyumov, M. Matalon. Proc. Combust. Inst. 34 (2013) 865-872.

GOBIERNO DE ESPAÑA
MINISTERIO DE ECONOMÍA Y COMPETITIVIDAD
Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
USC University of Southern California