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MODELISATION AND FORECAST OF PREMIXED FLAMES

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Summary We demonstrate here the possibility to compare the evolution of an analytical flame corresponding to a pole solution of the Sivashinsky equation with the evolution of an experimental flame. The experiment used as a benchmark consists of the propagation of a quasi two-dimensional propane-air flame in a Hele-Shaw burner. A best approximation of the experimental flame at an initial time is first calculated by fitting with a limited series of pole-based functions. The trajectories of the poles are then integrated numerically in time and the evolution of the front they are representing is finally compared with the evolution of the experimental flame.

INTRODUCTION

Even when propagating in a medium initially at rest, premixed flames can undergo intrinsic destabilizations and folding among which the Darrieus-Landau instability. As a consequence, the surface and velocity increase up to higher values that fluctuate in time. These fluctuations result from nonlinear processes occurring on the flame surface, which can be described as a succession of local singularities, called cusps, that are created and then compete and eventually merge. A Hele-Shaw burner [1, 2, 3] appears to be an adequate apparatus for quantitative analysis of this dynamics in a quasi two dimensional configuration. It allows comparison with the Sivashinsky equation [4], which is generally used as a description of the non-linear dynamics involved in the instability. This equation can be derived in the limit of small unburnt to burnt gas expansion ratios $\theta = \frac{\rho_u}{\rho_b}$ and accounts for the evolution of the position $\phi(x, t)$ of the flame taken as a discontinuity. The extension to larger expansion ratios, proposed by Joulin and Cambay [5] is used in this study in the following non-dimensional form : $\phi_t + \frac{a}{2}\phi_x^2 = \Omega \left(\frac{\phi_{xx}}{k_c} + I(\phi, x) \right)$. In this equation with unity laminar flame-speed, lengths have been rescaled by the width of the flame front divided by 2π , k_c stands for the non-dimensional cut-off wave number, the linear operator $I(\phi, x)$ corresponds to multiplication by $|k|$ in Fourier space, $\Omega = \frac{\theta}{\theta+1} \left(\sqrt{\frac{\theta^2+\theta-1}{\theta}} - 1 \right)$ is Darrieus-Landau coefficient and a is taken from Kazakov 2005 [6] where $A = \frac{2\Omega}{ak_c} = \frac{1}{k_c} \frac{(\theta+1)^2(\theta-1)}{4\theta^2}$.

According to Thual et al. [7] this equation admits exact, "pole-decomposable", 2π -periodic solutions in the form

$$\phi = -A \sum_{n=1}^N \left\{ \ln \left(\sin \left(\frac{x - z_n(t)}{2} \right) \right) + \ln \left(\sin \left(\frac{x - z_n^*(t)}{2} \right) \right) \right\} \quad (1)$$

and each pole z_n evolves according to the following coupled ODE's :

$$\dot{z}_n = -\Omega \sum_{p \neq n} \frac{1}{k_c} \cot \left(\frac{1}{2} (z_n - z_p) - i \operatorname{sign}(\operatorname{Im}(z_n)) \right) \quad (2)$$

In this work we propose to compare the flame front dynamics described by this set of ODE to the dynamics observed in a real experiment.

POLE DECOMPOSITION OF AN EXPERIMENTAL FLAME FRONT

In order to compare the flame front evolution described by system (2) with an experimental flame front we should start with conditions as close as possible to the conditions from which the Sivashinsky equation is derived (i.e small slope hypothesis). A propane air flame (equivalence ratio 0.7) is thus ignited as an inverted V-flame on top of vertically oriented Hele-Shaw cell (two glass plates 50cm large and 150cm high separated by a thin gap of 5mm) then the flow is stopped by closing the valve at the bottom of the cell and a nearly planar flame starting is downward propagation. The evolution of the flame is recorded using a high-speed camera (500fps). Figure 1a extracted from this sequence is a typical frame exhibiting 7 cusps. It is used as reference front for fitting with decomposition (1) by way of Levenberg-Marquardt least-squares algorithm. The 126mm field of view is chosen so that the right and left limits are sufficiently far from cusps and with horizontal tangent in order to better satisfy the periodicity of the functions. Moreover in order to assure continuity between the right and left limits we rotated the front by 0.025 radians. For such a flame, we assumed $k_c = 19.2$ according to the linear growth rate measured from initial flat interface. The minimum number of poles for a reasonable agreement for the shape was found to be 12. The locations of these poles are represented by points under the frame, with vertical coordinate corresponding to their imaginary part. Poles with small imaginary part in the complex plane induce physical cusps visible at the same abscissa. The resulting analytical solutions are superimposed in red on the picture.

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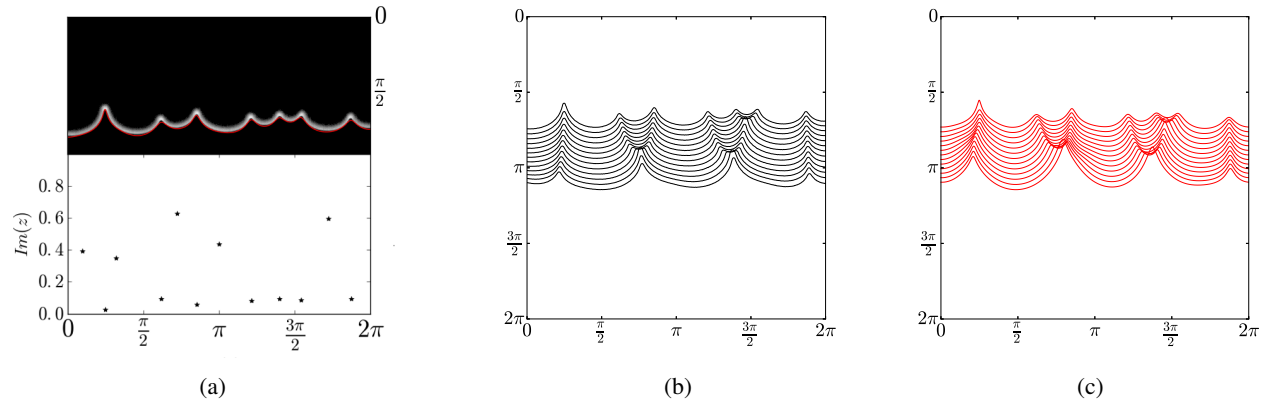


FIGURE 1 – (a) Fitting of the flame front (top) and associated pole positions in the complex plane (bottom). (b) Evolution of the experimental flame front. (c) Evolution of the pole solutions according to the system of ODE (2).

Evolution in time

The system of equations (2) corresponding to pole trajectories is integrated numerically in time starting from the solution obtained above. We assumed $\theta = 6.4$ and a laminar flame speed of $0.22m.s^{-1}$. These values could eventually be corrected due to the heat and momentum loss in the Hele-Shaw cell. The evolution of the simulated front reported in fig 1c exhibits three cusp mergings and favorably compares to the evolution of the experimental one reported on figure 1b at the same instants.

CONCLUSIONS

The quantitative agreement in time and length scale proves that although the Sivashinsky equation is derived in a small expansion limit, it appears to be valid for real flames with expansions around $\theta = 6$ with a good accuracy. Moreover, the complex dynamics of the front can be reduced to the calculation of the trajectory of a limited number of pole pairs in the complex plane (12 pairs for the evolution of a front with 7 cusps in our case). A perspective for this study would be to validate the ability of this method to simulate premixed flame fronts for a wider range of gas mixtures and equivalence ratio.

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