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Flame instability in a Hele-Shaw cell: thickness effect

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Abstract

An Hele-Shaw burner is a convenient device for studying the development of premixed flame instabilities in a quasi-two dimensional configuration. It is possible to ignite a plane flame at the top of the cell, and to measure quantitatively the growth rates of the instability by some simple image analysis. Starting from this linear growth rate, it is also possible to forecast the non-linear evolution of the flame for short times using a Sivashinsky equation. We study here the effect of the thickness of the Hele-Shaw cell on the growth rate and compare the results to theoretical predictions and numerical simulations. In addition to the usual Darrieus Landau instability of flames propagating in tubes, it has been predicted in the literature that in a Hele-Shaw geometry, two further effects come into play, Saffman Taylor instability and the effect of heat losses. We discuss here the relevance of these two effects.

Introduction

Hydrodynamic flame instabilities (see the recent book [1] for a review) can be important for turbulent burning, particularly at high pressure [2] and there are some hopes that they can be simulated using a model equation such as the Sivashinsky nonlinear equation [3] for the flame front propagation. However precise experimental studies of the hydrodynamic instability are relatively scarce, and even the propagation of a laminar flame in a tube can lead to a very complex non-linear evolution if the tube is large enough [4]. It has been suggested in [5] and first obtained experimentally in [6], to study flames in a quasi two dimensional configuration in a Hele-Shaw cell. We will show here that this configuration allows quantitative measurements of the growth rates of the instability and of the non-linear evolution, and study the effect of the cell thickness on the instability properties of propane air flames.

Specific Objectives

We study here, following the paper [7], where qualitative results in this configuration were presented, flames propagating in a Hele-Shaw burner where the flame dynamics is more easily recorded with a high-speed camera than in a cylindrical burner.

The burner consists of two glass plates 0.50 m wide and 1.5 m high, separated by a gap width of 4.7 or 3.8 mm. After each run, the airflow is opened and maintained until the tube walls have cooled to ambient temperature. The flow of combustible, (propane in this article), is then adjusted to the desired equivalence ratio and a 2D inverted V-flame is ignited at the top of the burner with a lighter. Closing the valve at the bottom of the burner then stops the flow and the downward flame propagation is recorded thanks to a high-speed camera (Fig. 1).

It will be shown in this paper that it is possible in this configuration to measure the growth rates of the instability for different equivalence ratios and cell thicknesses.

These measurements lead to important parameters of the non-linear modelling with the Sivashinsky equation: a cut-off wavelength λ_c and a characteristic growth rate σ of the most unstable perturbation with wavelength $\lambda_{max} \sim 2\lambda_c$. Let us recall that in the literature, the growth rates of the Darrieus-Landau instability have only been measured twice, first by Clanet and Searby for very lean propane air flames [8] by using an acoustic field to create initially a plane flame, then by Truffaut and Searby [9] for rich propane air flames by studying the development of the instability on an oblique flame. The present Hele-Shaw configuration leads to another type of measurement, but naturally the thickness of the cell plays a role in the value of the growth rates we obtain, we discuss here these effects.

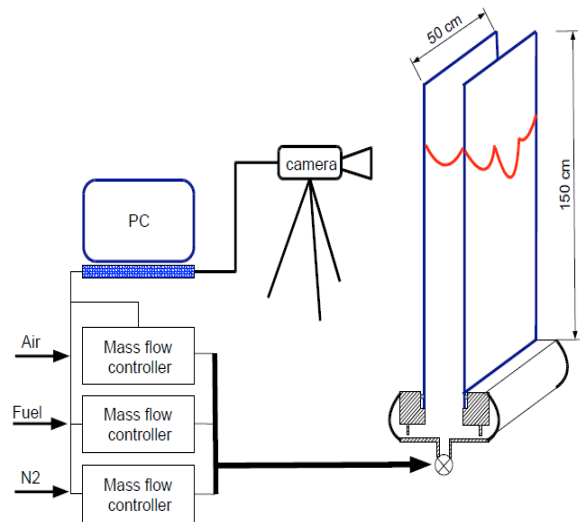


Figure 1: Experimental set-up

Results and Discussion

Experiments are performed with propane-air mixtures whose laminar flame speeds in a tube are known. Introducing a plate with periodic indentations a few centimeters above the burner exit, it is possible to force the flame response at the desired wavelength, (wave vector $K=2\pi/\lambda$). The initial flame contour appears relatively flat (Fig. 2), then Fourier analysis of the successive records of the flame contour can give access to the linear growth rate of the excited perturbations of the flame (the slope of the linear regime in Fig. 3). Using this procedure, we obtain the growth rate for different wavelengths of perturbations (we will show figures of growth rate versus wave vector for different thicknesses in Figures 5 and 6). Let us note however that it is difficult to measure growth rates for wave vectors very far from the most amplified wave vector, which is observed anyway even without specific forcing.

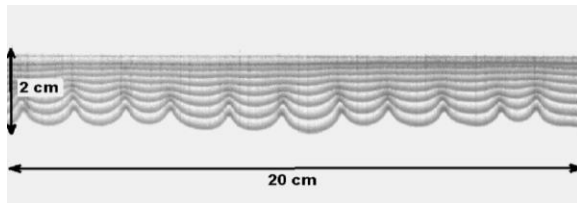


Figure 2: Flame front at successive moments, close to the top of the Hele Shaw cell, showing the linear development of the hydrodynamic instability

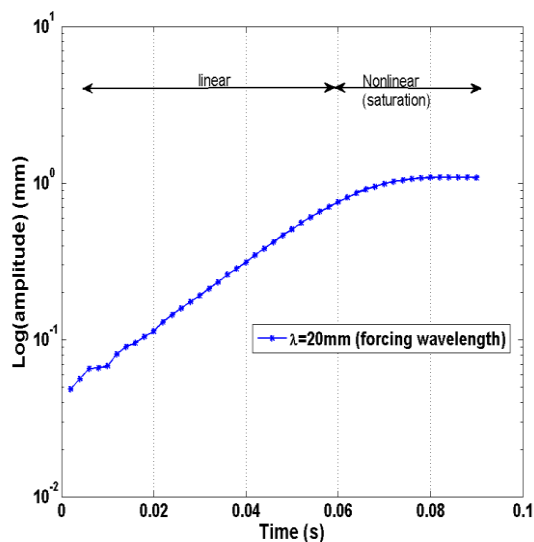


Figure 3: Amplitude of the Fourier mode versus time, showing the linear regime

This method for measuring growth rates does not work in all cases, the inverted V flame at the top of

the burner is cellular itself for rich propane air mixtures (equivalence ratio 1.3 for instance), so the above method is not available in this case. For propane, the results will be reported for lean or stoichiometric propane air mixtures.

Having obtained the growth rate of the instability, this growth rate is an essential ingredient of a non-linear modelization of the flame. The Sivashinsky equation [3] essentially describes the normal propagation of a front submitted to an instability corresponding to the growth rate we have just measured. We show in Figure 4 a comparison with experimental results: Fig 4.a, experimental fronts at different time superimposed on the same figure, Fig 4.b evolution given by the Sivashinsky equation, starting from the experimental front highlighted in black. Although not all the features of the experiments can be obtained by the model equation, the agreement is very good on a time of approximately 10 times the characteristic time of the instability (the characteristic time is the inverse of the growth rate of the most unstable wavenumber). The cusps on the different fronts correspond to the red points and the width of the domain shown in Figure 4 is 16 cm.

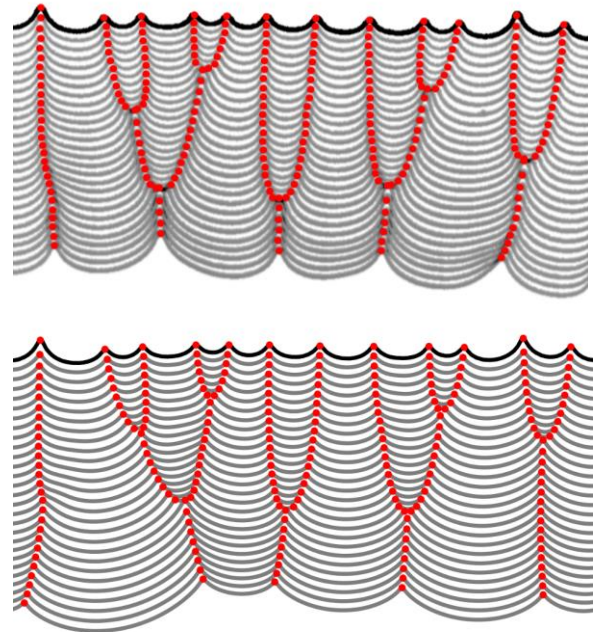


Figure 4: Non-linear evolution (flame fronts at different times) of the instability for an equivalence ratio of 0.9 and a Hele-Shaw thickness of 3.8 mm Fig 5.a: experiment, Fig 5.b Sivashinsky equation,

We now turn to the role of the thickness of the Hele-Shaw cell on the instability properties of the flame. Let us first recall the theoretical and numerical results

in this configuration. In the pioneering paper by Joulin and Sivashinsky suggesting to use this experimental configuration [5], these authors analyzed (unfortunately without including Markstein lengths) two effects which modify the usual Darrieus Landau instability in tubes. The first effect is the Saffman Taylor effect: the dispersion relation is modified by friction terms, which increase the growth rate. The second effect is the role of heat losses, studied in a low gas expansion case. Another type of study are the two papers by Kang Baek and Im [10] [11], which also study friction and heat losses effects, but numerically.

We could summarize the results of these papers in the following simplified way; both Joulin Sivashinsky and Kang Baek Im argue that the Saffman Taylor effects are small for a typical value of the thickness. For the heat losses, Kang Baek Im obtain, with an effective two dimensional analysis, that heat losses reduce the growth rate for large Lewis number, and increase the growth rate for low Lewis number.

In the propane air case of the present paper, we have obtained results, as explained before, for lean or stoichiometric mixtures. So the Lewis number we have are typically larger than one. We give growth rates for two thicknesses (4.7 mm and 3.8 mm) and for two values of the equivalence ratio (0.9 and 1).

In Figure 5 is shown the case equivalence ratio 0.9. The red, upper curve corresponds to a thickness 4.7 mm, the green lower curve to 3.8 mm. It can be seen that the growth rate is lower for a smaller thickness, suggesting, in agreement with theory, that the Saffman Taylor effects are small and that the heat losses is the most important effect, leading in a Hele Shaw cell for lean propane to lower growth rates.

In Figure 6 is shown the stoichiometric case, with the same type of curves, red curve 4.7 mm, green curve 3.8 mm. It is seen that the larger thickness always corresponds to a more unstable case for low wavevectors: this would suggest that the effective gas expansion in the cell is lower for a smaller thickness. The situation is less clear for higher wave vectors; it seems that the curve for a smaller thickness decreases more slowly than the 4.7 mm case. This could be interpreted as saying that with heat losses the Markstein number is lower with heat losses, which is also suggested by the solid curves in both Figures 5 and 6, which are a fit of the experimental points with the classical dispersion relation of Clavin and Garcia-Ybarra [12] for flames in tubes. Note also the lower effective expansion ratio E (ratio of density on both sides of the flame) in both figures for the smaller thickness.

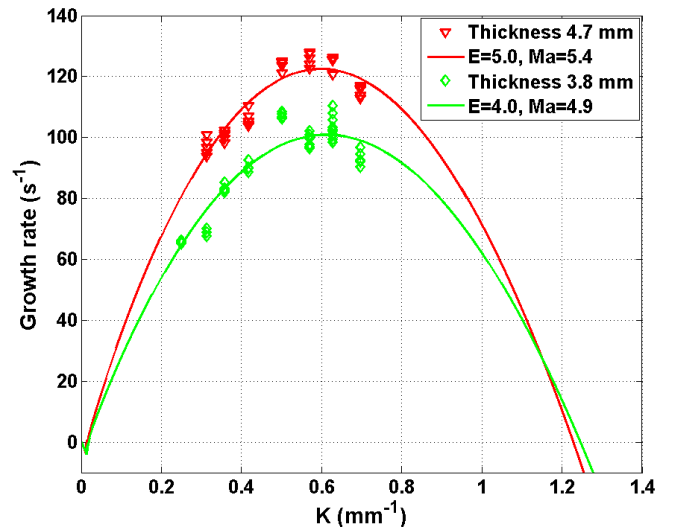


Figure 5: Growth rate of the instability versus wavevector for propane air flames with equivalence ratio of 0.9 and a Hele-Shaw thickness of 4.7 mm (red) and 3.8 mm (green). Solid curves: fit with a Clavin Garcia dispersion relation (expansion ratio E , Markstein number Ma).

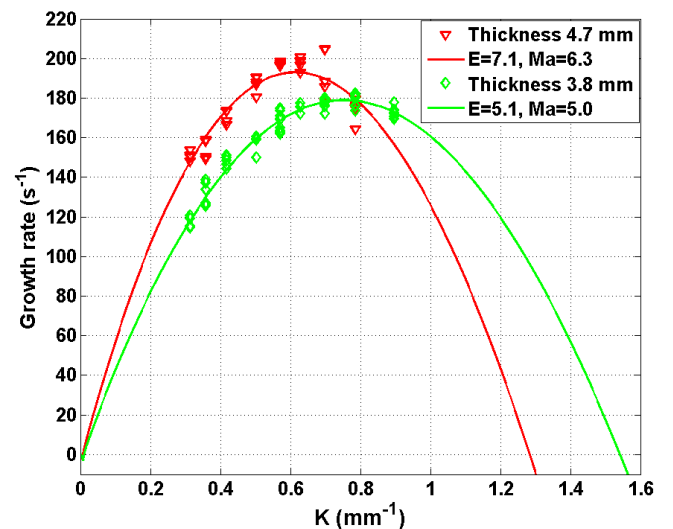


Figure 6: Growth rate of the instability versus wavevector for propane air flames with equivalence ratio of 1.0 and a Hele-Shaw thickness of 4.7 mm (red) and 3.8 mm (green). Solid curves: fit with a Clavin Garcia dispersion relation (expansion ratio E , Markstein number Ma).

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Conclusions

We have seen in this paper that the Hele-Shaw burner configuration is extremely useful, quantitative results difficult to obtain in 3D have been obtained here, both for the dispersion relation of the hydrodynamic instability and even for the non linear evolution. The growth rates are not completely modified compared to the few measurements we have for 3D flames, however for propane air lean or stoichiometric mixtures, the effective expansion ratio is lower with heat losses, but the Markstein length is also lower. It also seems that in our experiments in a Hele Shaw burner, heat losses effects are larger than Saffman Taylor friction effects.

Acknowledgements

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