Response of 2D Flames to Sinusoidal Pressure Waves

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Abstract

A detailed numerical study of the response of two-dimensional premixed flames to sinusoidal pressure waves is presented. It was found that for pressure input waves of the order of kHz the flame responds in a oscillatory unstable way. The increase of the amplitude of the pressure waves decreases the time for the burning velocity to become unstable.

Introduction

This study reports on numerical experiments of premixed flames in a two-dimensional domain, which are disturbed by a pressure waves. Initially, the flame is slightly wrinkled in the direction perpendicular to the main flow. From experimental, theoretical and numerical research it is known that acoustic interactions play an important role in the development of premixed flames. They are especially important when the rippling of the flame front is enhanced and accelerates the flame. Under an external force, small instabilities can be enhanced and create more and more deviations of the flame front. This instability is called the Rayleigh-Taylor instability (RTI). It is believed that the early phases of an explosion are governed by this instability. Experimentally [1] and numerically [2] it has been found that in a weakly wrinkled laminar flame under a pressure gradient, fingers of unburnt gas penetrate into the burnt region due to the difference in acceleration along the flame front.

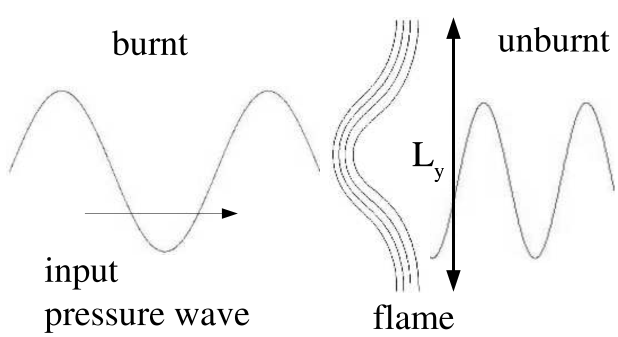


Figure 1: Schematic representation of the experiment

The large-scale explosion tests performed at Spadeadam as a part of the SCI Phase 2 project [3] were set up to examine explosions in realistically large geometries. However, one of the unexplained observations was that in some experiments very large, rapid oscillations in over-pressures were measured. This study is based on the hypothesis that these high frequency oscillations are mainly the result of the interaction of the flame with pressure waves, which are generated by the flame itself and reflected by objects in the rig and the rig walls.

The aim of the current work is to investigate the influence of the instability on the flame development and acceleration. This was done by performing 2D numerical simulations of the RTI in detail and investigating the effect of different types of pressure disturbances and disturbance wavelengths. The pressure waves in this study have a sinusoidal nature. Effects of the pressure-flame interactions are measured in changes of the overall burning velocity u_0, which is defined as $u_0 = \frac{1}{\rho_u A_0} \int_V \rho \dot{Z} dV$. Here, A_0 is the area of the initial flame and ρ_u the density of the unburnt gases.

Work by McIntosh [5] showed that the relationships between the time scales and length scales involved in pressure-flame interactions are crucial in order to identify the nature of the interaction. For the cases reported here the pressure gradients are small (but not neglected) throughout the combustion region and the inner reaction zone is certainly not affected by the pressure field (that is the reaction zone simply moves as a contact discontinuity). We define the non-dimensional perturbation length scale Λ' as the ratio of the disturbance length scale L_y to the flame thickness δ.

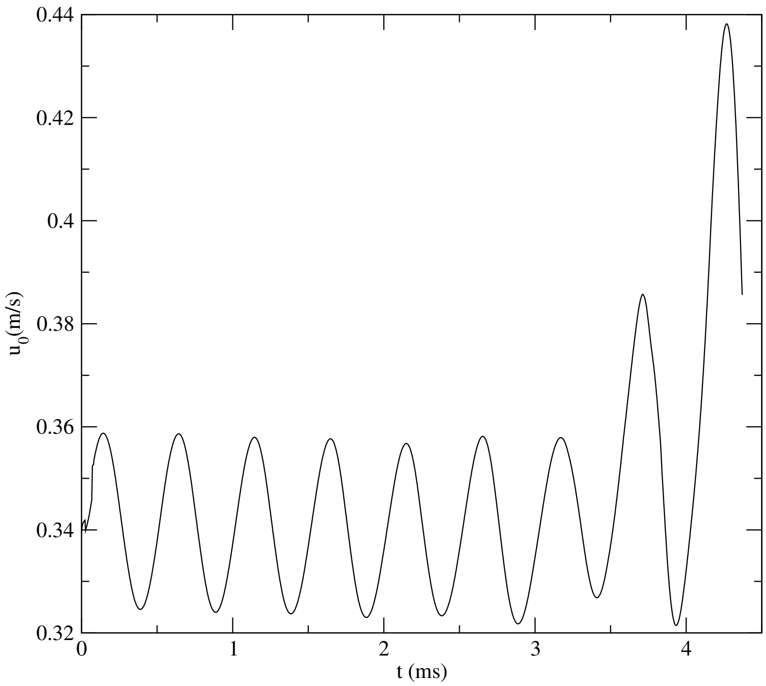
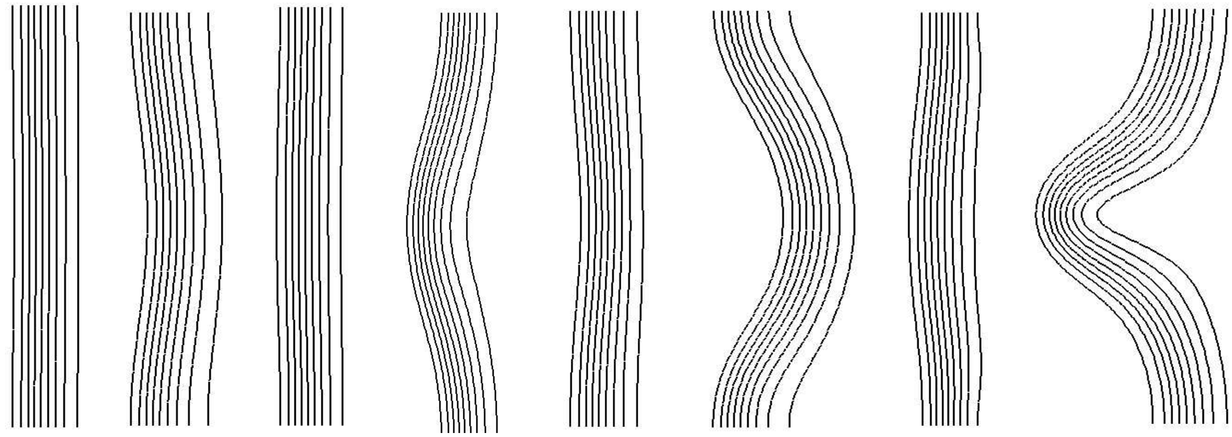


Figure 2: Evolution of the burning velocity; f = 2 kHz, Δp = 0.03 bar,

Numerical Method

The transport equations of mass, momentum, energy and species were solved numerically using a flux-corrected transport algorithm called LCPFCT on a uniformly distributed, orthogonal grid. The presented form of the LCPFCT algorithm has been developed at the US Naval Research Laboratory [4]. The algorithm was used to solve the transport equations in the two dimensions.

To generate the initial small ripple on the flame surface, a sinusoidal lateral density disturbance is imposed, as in [2]. Then for all times after this, a constant amplitude, sinusoidal fluctuation of pressure in time is imposed on the burnt side (i.e. the left side in Fig 3). Periodic boundary conditions, were imposed on the top and bottom, and outflow boundary conditions on the unburnt side.



(a) (b) (c) (d) (e) (f) (g) (h)

Figure 3: Time sequence of temperature contour plots of the flat states and maximum wrinkling; f = 2 kHz, Δp = 0.03 bar

Results and Discussion

The impact of several input parameters on the flame propagation was measured. These include the disturbance wavelength (i.e. L_y in Fig. 1), and the amplitude and frequency of the imposed pressure waves. In the current work a premixed methane-air flame was taken as an example and single-step chemistry was used. Results were obtained from numerical simulations of a two-dimensional flame, on which sinusoidal disturbances in pressure were imposed. The frequency of the pressure waves was of the order of 1kHz-3kHz. The experiments showed that imposing small magnitude pressure oscillations enhances the wrinkling of the two-dimensional flame after every cycle, eventually resulting in an unstable, oscillatory flame. The value of Λ' was 3.3.

In Fig. 2 the evolution of the burning velocity u_0 is plotted for a case where $f = 2kHz$ and $\Delta p = 0.03$ bar. After about six full oscillations in pressure the amplitude of u_0 increases to significantly higher values. For this case temperature contours of the last four pressure oscillations are depicted in Fig.3. From the plot in Fig.2 it might appear that u_0 responds linearly to the imposed pressure fluctuations. But, in fact, when a closer examination is made, even at the outset there is an unstable process. This is illustrated in Fig 4 where the time period between the minima and maxima of the fluctuations is plotted against time. From this plot, it is apparent that the instability grows directly from the start and that the time it takes for the flame to evolve from an apparently flat flame to a wrinkled one increases (e.g. Fig.3(e)-3(f)), whilst the time taken for the reverse procedure (e.g. Fig.3(f)-3(g)) shortens during this process. Other tests using sinusoidal pressure fluctuations, showed that for lower values of Δp the unstable behaviour becomes apparent at a later stage. This behaviour was confirmed by other simulations, in which the pressure was only linearly increased on a similar time scale. These showed that that a two-dimensional flame will respond directly to the pressure amplitude. However, the Rayleigh-Taylor instability does become apparent after some time. It was observed that this delay time shortens with an increasing pressure amplitude.

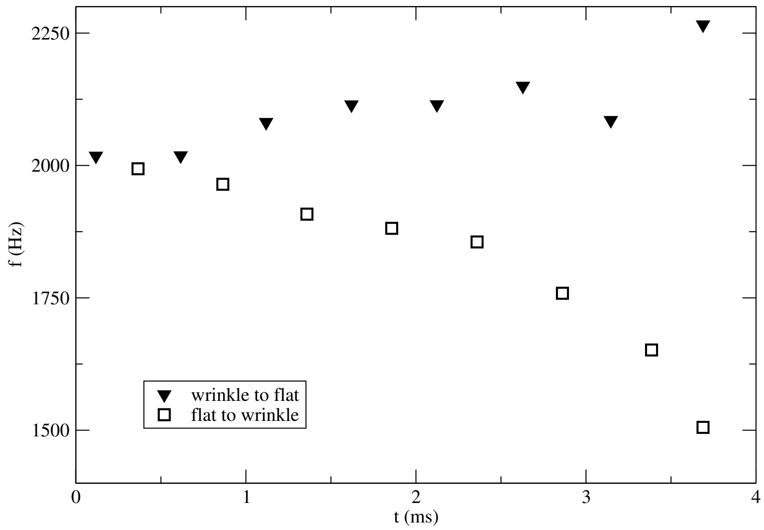


Figure 4: Typical frequency (derived from time it takes from flat to wrinkled flame and vice versa); f = 2 kHz, Δp = 0.03 bar

Conclusions

From this study on the response of two-dimensional premixed flames it may be concluded that for imposed sinusoidal pressure waves of the order of kHz the flame will react in an oscillatory unstable manner. The larger the pressure amplitude, the earlier the instability becomes apparent.

Acknowledgments

The work is sponsored by BP. The authors thank Proffesor Elaine Oran for her advice and supply of the LCPFCT algorithm.

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