Unstable Explosion Flames and Acoustic Oscillations

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Introduction

Earlier studies, involving flame cine photography and planar laser induced fluorescence of OH, have shown in detail how a spherical explosion flame becomes unstable [1]. Cracks first appear in the flame surface, to be followed by the further development of a fully cellular structure. As the flame propagates the range of unstable wavelengths generated by the Darrieus – Landau instability increases, ranging from the diameter of the flame down to the real flame thickness, where the structure is stabilised by thermal diffusion. The increase in the wrinkled flame surface area continues to accelerate the flame. The flame speeds that can be attained are significantly higher at negative Markstein numbers [2]. Such Markstein numbers are favoured by high pressures and mixtures in which the deficient reactant is the more diffusive; these were chosen for the present study.

It has been known for some time that under certain circumstances the explosion of an initially quiescent mixture results in the acoustic emission of a 'ping' [3]. Further examination of the pressure record in such cases has shown a relatively high frequency oscillation, superimposed on the expected pressure rise. Indeed, these high frequency oscillations can attain a magnitude that would have destroyed the pressure transducer [3]. In the present work the initial pressure was increased in 1 bar increments; the 'ping' heard at 1 bar progressed to an alarming 'scream' at 5 bar, and it was decided to proceed no further. Pressure records were taken for a variety of explosions and this paper describes the results of the analyses of these records for both laminar and turbulent flames.

Experimental

A 380 mm diameter spherical stainless steel vessel capable of withstanding initial pressures of up to 15 bar and initial temperatures of up to 600 K, with extensive optical access through 3 pairs of orthogonal windows of 150 mm diameter, was employed. Turbulence could be generated by four identical, eight bladed, fans, symmetrically disposed in a regular tetrahedron configuration. The fans created a central region of uniform, isotropic turbulence with negligible mean gas velocity. Turbulence parameters were measured by laser doppler velocimetry and the rms turbulent velocity was found to increase linearly with fan speed. The integral length scale, L, was found by two point correlation at 1 bar to be 20 mm and independent of fan speed [4].

Iso-octane - air and hydrogen - air mixtures, were studied for a range of equivalence ratios, ϕ, initial temperatures and pressures. The laminar burning velocity, u_l, and Markstein number, Ma_{sr}, of the mixtures used are given in Table 1. Mixtures were centrally ignited in the bomb and the pressure recorded via a Kistler 701 pressure transducer and sampled, with 10 bit resolution, at 50 kHz. The spark was generated by a 12 V automotive coil, controlled by a Lucas electronic controller. Further experimental details are in [5].

Results

Shown in Fig. 1 are pressure records from laminar spherically iso-octane - air flames ignited at an initial pressure of 5 bar. As the equivalence ratio is increased from fuel lean to rich the time in which the flame reached its maximum pressure steadily decreased even though u_l decreased after peaking around ϕ =1.1 [6]. The measured mean values of the peak pressures were all within 90 % (98 to 99 % in most cases) of the calculated equilibrium, adiabatic, constant volume combustion values. At ϕ = 1.2 there was evidence of high frequency oscillations at the peak pressure, which become very strong for ϕ = 1.3 and 1.4. In those cases the amplitudes of the oscillations were approximately 8 % of the peak pressure. The oscillations had a dominant frequency of about 1.5 kHz at the peak pressure, which compares approximately to the transit time for an acoustic wave across the diameter. The peak amplitudes of the pressure oscillations were greater for ϕ = 1.3 and 1.4 than for the lower values of ϕ and these seem to be generated by the sudden acceleration in the burning rate around 75 ms after ignition. There may be some influence of the stationary fans in helping to destabilise the flame, but similar phenomen have been revealed in spherical and cubical vessels [3].

High frequency oscillations also were observed with lean hydrogen - air mixtures, although they only become apparent at elevated pressures. Shown in Fig. 2 are pressure records for spherically expanding laminar hydrogen air flames $0.3 < \phi < 0.9$. Here the instability was most apparent at $\phi = 0.5$ and 0.6. At equivalence ratios below this it appeared to decay, probably due to the low laminar burning velocities and resultant flame buoyancy.

Discussion

It would appear that the highly unstable flames are strongly accelerated by the rapid wrinkling of their own surface. This generates strong pressure waves which can be non-orthogonal with parts of the flame surface, to produce further wrinkling and generation of vorticity by the Taylor instability and further reinforce the pressure waves. It is of interest to make a very approximate estimate of the burning velocity, u_f, in the final stages of the explosion. To do this, the expression given in [7] was employed:

$$u_f = \frac{\left(\frac{dP}{dt}\right)_{\max} V^{1/3}}{(36\pi)^{1/3}(P_e - P_o)\left(\frac{P_e}{P_o}\right)^{1/\gamma}} \tag{1}$$

Values of u_f found in this way and normalised by of the original mixture are presented in Fig. 3. There could be a twofold increase due to the increase in u_l as a result of compression, but the figure nevertheless shows the large increases in burning rate that must be attributed to very low or negative Markstein numbers and instabilities, see Table 1. This correlation is clear for iso-octane. With hydrogen, however, the situation is more complex, as Ma_{sr} is negative for all $\phi < 1$ and actually increases at very lean equivalence ratios.

The question arises as to the extent to which such increases in burning velocity can occur in turbulent flames. This was studied in explosions at various fan speeds, up to 67 Hz. Shown in Fig. 4, for an unstable iso-octane explosion, is the way the initial increase in turbulence both decreases the rate of burning in the final stages and eventually suppresses the acoustic oscillations. The changes of u_f / u_l with u' / u_l are shown in Fig. 5. For the rich mixture, the instability and associated high value of u_f / u_l when the fans were at rest, was eventually suppressed by the turbulence when u' / u_l exceeded about 3. Thereafter, the increase in burning velocity with turbulence followed the expected trend. No such initially dominant effect of flame instability was observed with the stoichiometric mixture.

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References

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Iso-octane - air 358 K, 5 bar			Hydrogen - air 300 K, 5 bar		
ϕ	u_l (m/s)	Ma_{sr}	ϕ	u_l (m/s)	Ma_{sr}
0.8	0.21	4.0	0.3	0.07	-5.1
0.9	0.28	4.0	0.4	0.17	-8.4
1.0	0.31	3.0	0.5	0.34	-11.2
1.1	0.30	0.9	0.6	0.57	-12.1
1.2	0.26	-2.3	0.7	0.88	-12.0
1.3	0.22	-6.6	0.8	1.19	-9.8
1.4	0.18	-12.0	0.9	1.50	-7.0
1.5	0.13	-18.4	2.2	2.85	13.3
1.6	0.11	-26.0	2.3	2.75	13.9

Table 1. Laminar burning velocities and Markstein numbers for the mixtures in this study. Little direct data exists: most of the data are estimates based on [1] and [5] for iso-octane and [8] and [9] for hydrogen. The Markstein number, Ma_{sr}, is defined in [5].

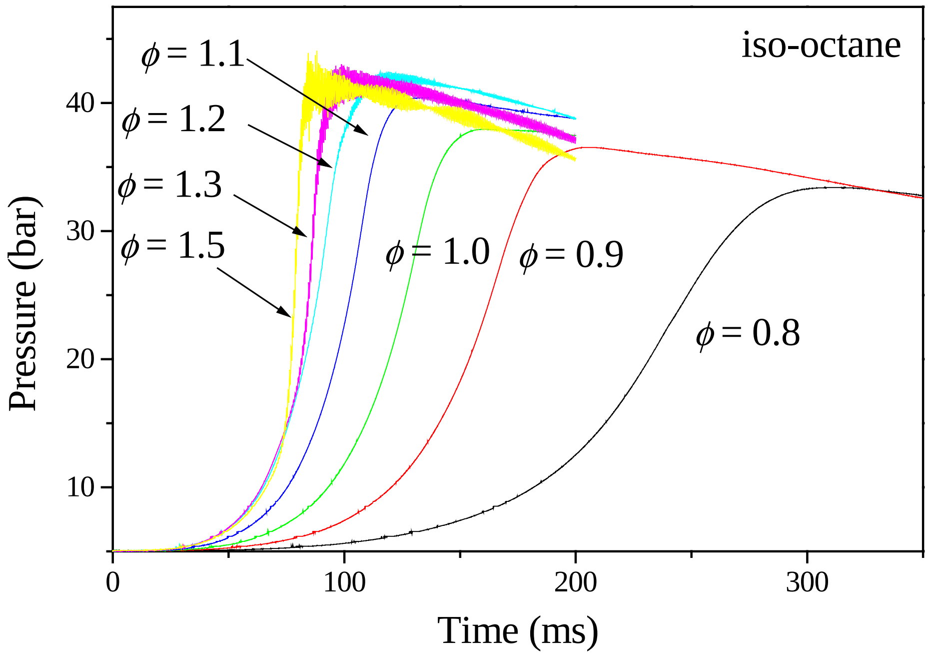

Fig. 1. Pressure records from spherically expanding laminar iso-octane - air flames, initial pressure = 5 bar and initial temperature = 358 K.

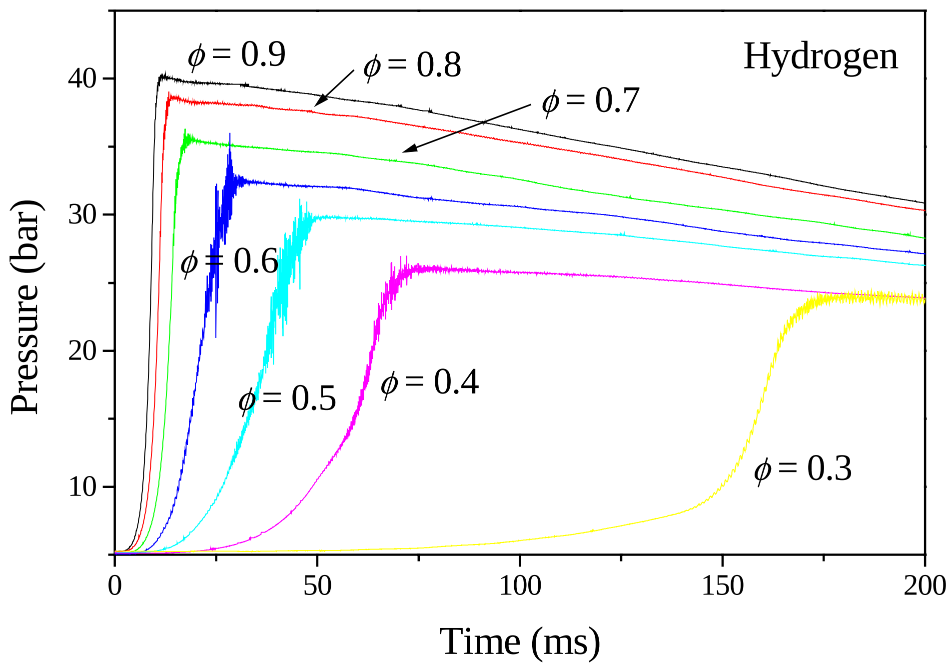

Fig. 2. Pressure records from spherically expanding laminar hydrogen - air flames, initial pressure = 5 bar and initial temperature = 300 K.

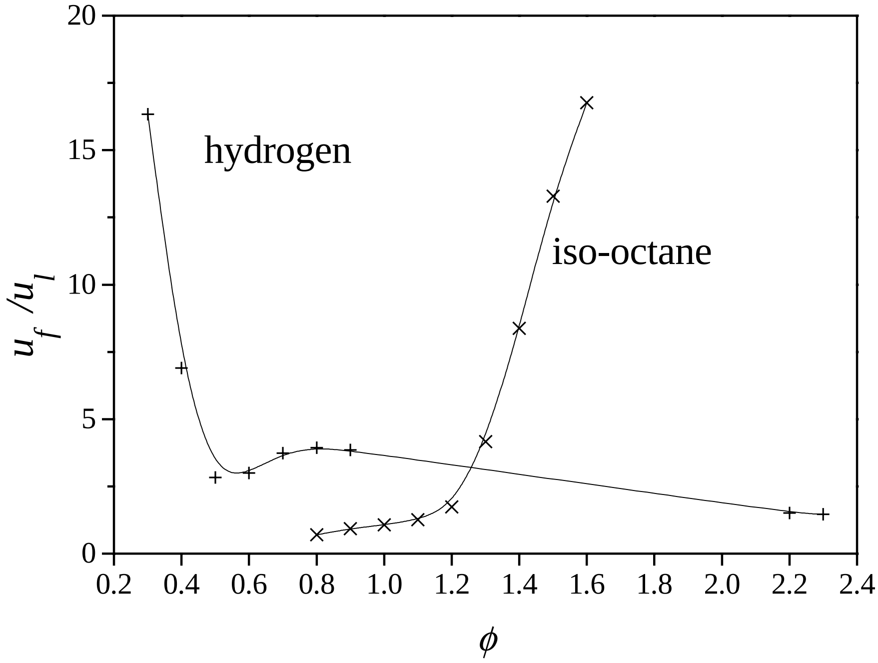

Fig. 3. The normalised burning velocity u_f / u_l against equivalence ratio, ϕ, for both hydrogen and iso-octane.

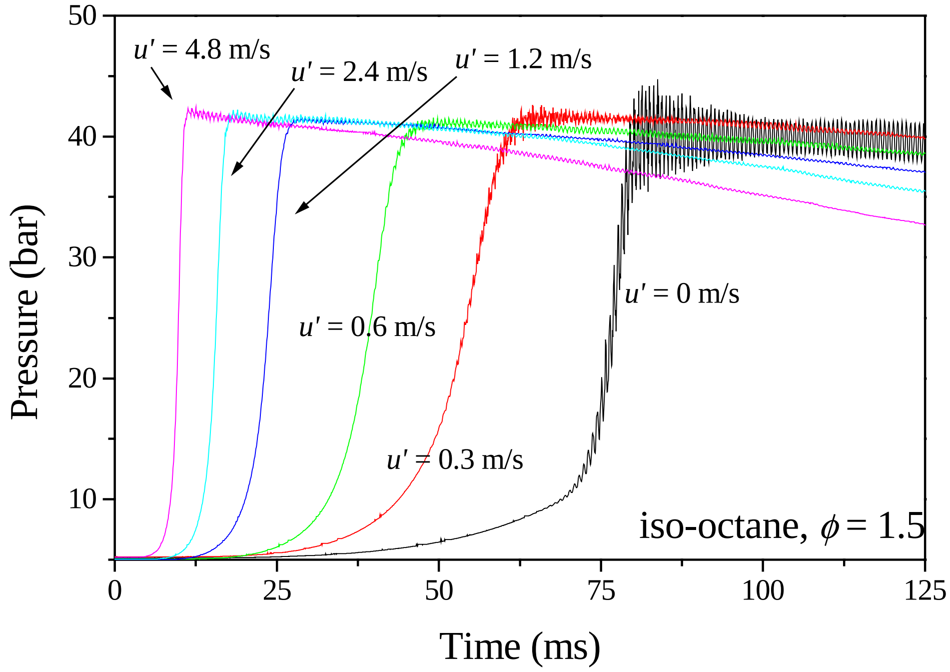

Fig. 4. Pressure records from turbulent iso-octane - air flames at $\phi = 1.5$, initial pressure = 5 bar and initial temperature = 358 K.

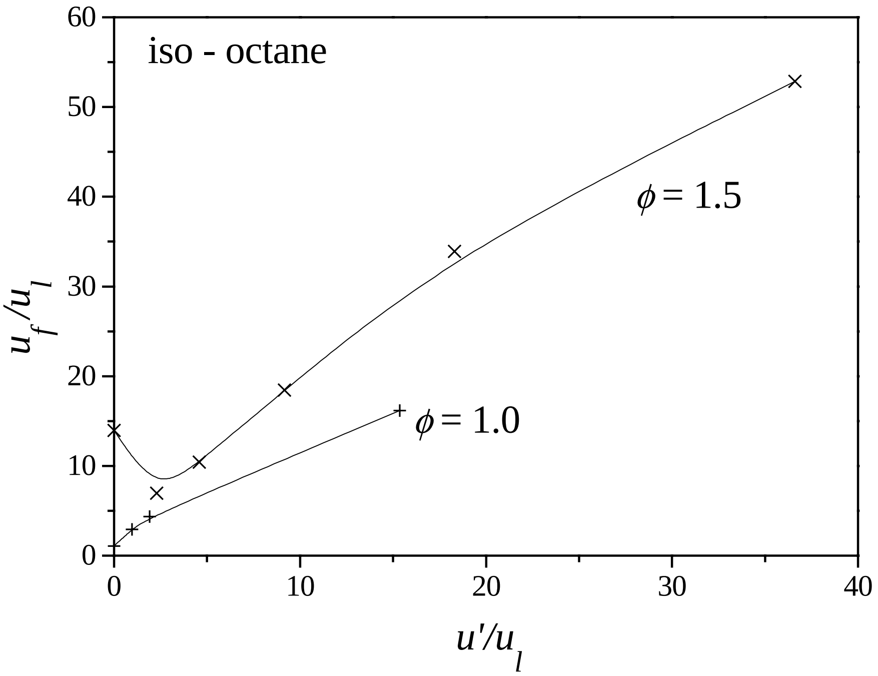

Fig. 5. The normalised burning velocity u_f / u_l against turbulence intensity u' / u_l for iso-octane - air flames at $\phi = 1.0$ and 1.5.