Development of Instabilities in Closed Vessel Laminar and Turbulent Explosions

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Introduction

Flame instabilities and pressure oscillations can be appreciable in high pressure laminar explosions, particularly of gaseous mixtures with negative Markstein numbers. After central ignition, as a critical Peclet number is exceeded, the flame begins to wrinkle as a result of Darrieus-Landau, D-L, instabilities and thermal-diffusive effects. Consequently the burning velocity continually increases. This acceleration can create pressure waves strong enough, if aligned non-orthogonally to parts of the flame surface, to produce further wrinkling with vorticity generated from the Taylor instability. In order to observe the development of instabilities at the higher pressures in the later stages of explosions, mixtures were ignited simultaneously at two diametrically opposite sparks close to the wall of the bomb. In this way, two near-identical imploding flames, at significantly higher pressures than the initial value, came into the field of view of a central window [1]. This technique also was used to study instabilities in turbulent flames.

Apparatus

The spherical stainless steel bomb had three pairs of orthogonal windows of 150 mm diameter. The internal radius of a sphere with the same internal volume as the bomb, R_o, was 192.78 mm. Four peripheral fans, driven by electric motors, close to the wall of the bomb mixed the reactants. They also created turbulence in the studies of turbulent flame instabilities. The integral length scale of the turbulence, l, was 20 mm. Electric heaters provided up to 6 kW for heating the vessel and iso-octane-air mixtures to 358 K. Pressures were measured with a Kistler 701 pressure transducer. Energies of about 26 mJ were supplied from separate 12 V automotive ignition coils to the two diametrically opposite spark plugs. The spark gaps were 11 mm from the inside wall. The two flame fronts were observed by schlieren photography with a high speed Phantom digital camera running at 3,700 frames/s with 256 × 256 pixels. Cartesian coordinates of the flame front, measured from the images, were processed to give appropriate polar coordinates using Adobe PhotoShop.

Results and Discussion

Laminar flames

Shown in Fig. 1 are the temporal variations in measured flame radii and pressure during a highly unstable iso-octane–air explosion at an equivalence ratio, ϕ, =1.6. The initial conditions were 0.5 MPa and 358 K. When the two flames came into the field of view they were already unstable from D-L and thermal-diffusive effects. The method of obtaining the burning velocity, u_n, for the two imploding flames is described in [1], as is the way allowance can be made for flame instability to derive the laminar burning velocity, u_ℓ, from u_n. Values of u_n, plotted against pressure, are shown in Fig. 2. Initially the value was approximately 0.6 m/s, about 6 times that of u_ℓ at the same pressure and temperature. Just before the two flames flattened and then touched a further instability developed, indicated by both fluctuations on the pressure record and, just prior to this, flame front oscillations, in which both flames moved in harmony. The latter are indicated on the enlarged sub-diagram on Fig. 1.

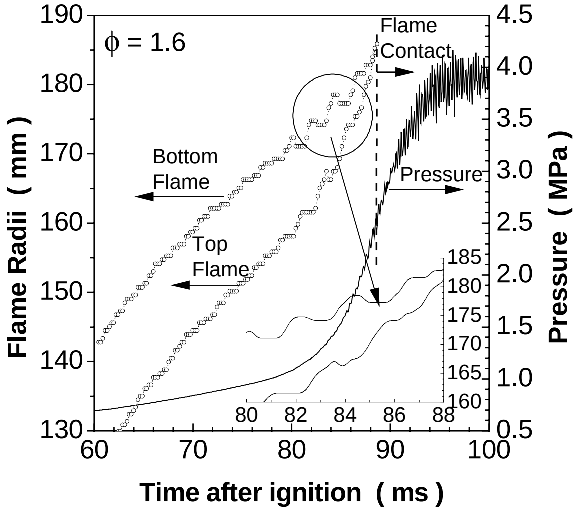

Fig. 1. Flame radii and pressure. Initial conditions: 0.5 MPa and 358 K.

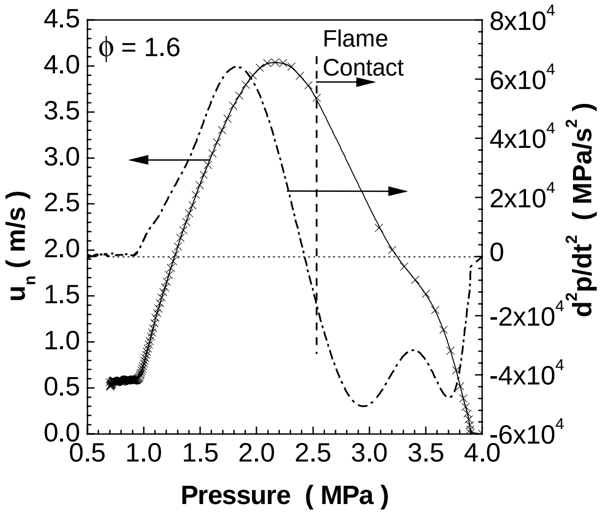

Fig. 2. Values of u_n and d^2p/dt^2, derived from Fig. 1.

It is postulated that this second instability and the associated very large increase in u_n, apparent on Fig. 2, were due to Taylor instabilities. The triggering pressure oscillations probably arose from rapid changes in the reaction rate. The burning rate is given by [1]:

$$\rho_u u_n A = C\frac{dp}{dt}, \text{ where } C = \frac{4}{3}\frac{\pi R_o^3 \rho_o}{(p_e - p_o)}, \tag{1}$$

ρ_o and ρ_u are the unburned gas densities, originally, and at time, t. A is the total flame front area, p_o, p_e and p are original, final and time, *t*, values of pressure. The rate of change of the reaction rate can be expressed as:

$$\frac{d^2p}{dt^2} = C^{-1}\,\frac{d(\rho_u u_n A)}{dt} = C^{-1}\left(A\frac{d\rho_u u_n}{dt} + \rho_u u_n \frac{dA}{dt}\right) \tag{2}$$

Values of d^2p/dt^2, obtained from the smoothed pressure record, are given by the broken curve on Fig. 2. The contributions to this term from the separate two differentials on the right of Eq. (2) are given on Fig. 3. Values of *A* were obtained from the flame photographs and the flame geometry. The steep rise in u_n on Fig. 2 is associated with that in d^2p/dt^2. Figure 3 shows the main contributor to this is the feed-back term $(A/C)d(\rho_u u_n)/dt$. Prior to the onset of the second instability, u_n was increasing continually with the increasing wavelengths of the D-L - thermal-diffusive instability. After the leading flame edges had flattened and touched, the longest available wavelengths to wrinkle the flames decreased. This tended to *decrease* the wrinkling and u_n. In contrast, the Taylor instability tended to *increase* u_n.

Eventually $(A/C)d(\rho_u u_n)/dt$, after attaining a maximum value, passed though zero, as did d^2p/dt^2. Thereafter, both terms became negative and although u_n decreased, the high rate of change of the reaction rate, indicated by fairly high negative values of d^2p/dt^2, continued to drive the pressure fluctuations.
No significant second, Taylor, instability was observed with iso-octane-air mixtures for $\phi \leq 1.1$ at initial pressures and temperatures of up to 1.0 MPa and 358 K. This instability first appeared at ϕ =1.2, only as Markstein numbers became markedly negative. It would appear that only then did the flame fronts became sufficiently responsive to pressure oscillations to generate Taylor instabilities and additional flame wrinkling with associated increases in u_n. The consequent strong feed-back mechanism generated further wrinkling.

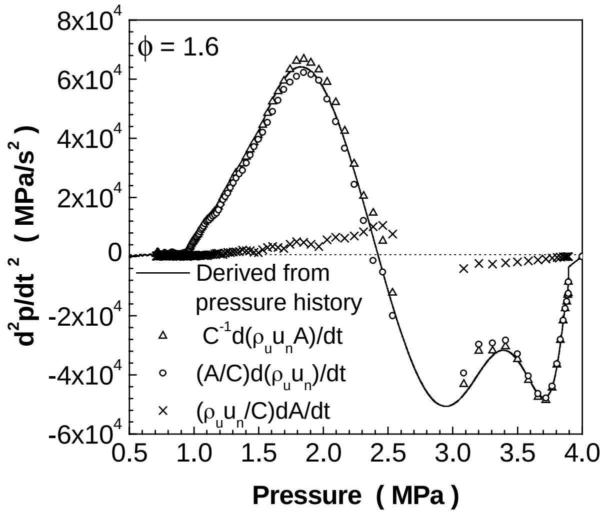

Fig. 3. Different terms in Eq. (2) for conditions of Fig. 1.

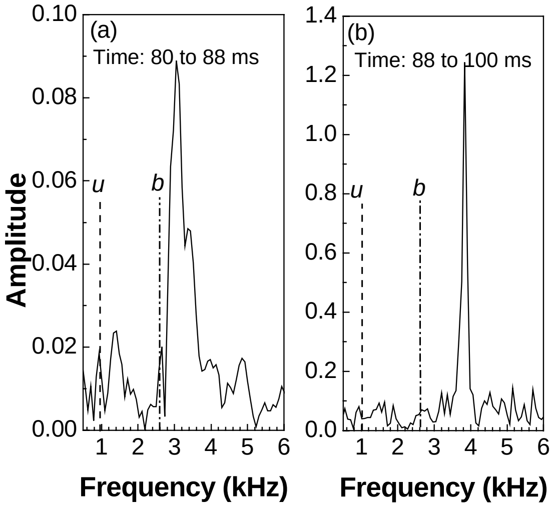

Fig. 4. Fourier analyses spectra over different times. Conditions of Fig.1.

The pressure oscillations about the smoothed mean were subjected to Fourier analysis, with the results shown in Fig. 4(a) and (b) for two different time intervals for the signals. In each case a dominant frequency was observed. The broken lines, *u* and *b* indicate reciprocal times for a sound wave to travel across the bomb diameter through unburned and burned gas, respectively. In Fig 4(a), for the earlier time interval, these values are slightly less than the two observed peak amplitudes. In Fig. 4 (b), for the later time interval, there is less unburned gas and the single observed peak is closer to that expected for acoustic waves in burned gas.

Turbulent flames
With both central and wall ignitions, an increase in the speed of the fans from rest, and hence in the effective rms turbulent velocity, u'_k, decreased the amplitudes of the pressure oscillations. Even with a low value of u'_k of 0.22 m/s there was little evidence of an increase in turbulent burning velocity, u_t, due to Taylor instability, although the turbulence increased u_t above u_n. Measurements in several turbulent flame implosions yielded the experimental points, indicated by the symbols and full line curve in Fig. 5. They show the changes in u_t/u_ℓ with u'_k/u_ℓ at 2.0 MPa and 428 K, ϕ =1.4, for which u_ℓ=0.105 m/s. The Markstein number was estimated to be about -12. When u'_k =0 the value of u_t was taken as that of u_n

for an unstable laminar flame under the same conditions. In contrast, the broken line represents a purely turbulent, initially linear, relationship passing through u_t/u_ℓ =1 at u'_k/u_ℓ =0. The initially greater experimental values of the full line curves give an approximate indication of the enhancement of u_t due to D-L instability. Such enhancements are predicted in [2, 3]. In the present case, as u'_k/u_ℓ increased above 2, the dominant length scale for instabilities probably became the integral length scale and the turbulent contribution to u_t overwhelmed any contribution due to instability.

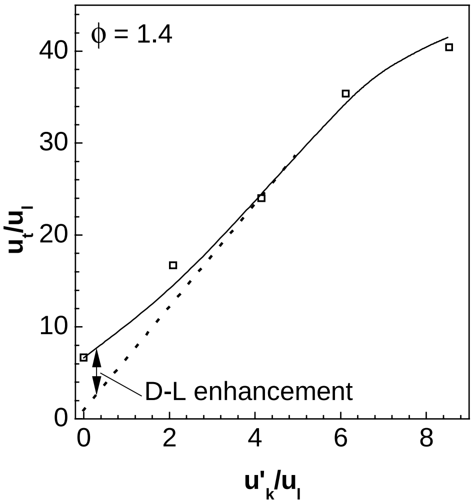

Fig. 5. Variation of u_t/u_ℓ with u'_k/u_ℓ for ϕ =1.4, 2.0 MPa, 428 K.

Conclusions

Explosion flame kernels of iso-octane mixtures at high pressures have been studied experimentally. With initially quiescent mixtures, the burning velocity was enhanced progressively, to well beyond the laminar value at the particular temperatures and pressures, by D-L instabilities. Eventually, at a sufficiently high pressure and rate of change of the reaction rate, Taylor instabilities were observed, provided the Markstein number was sufficiently negative. A feed-back mechanism further enhanced the burning rate. In turbulent flames no marked Taylor instabilities were observed and the D-L instabilities seemed to disappear at fairly low levels of turbulence.

References

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2. P Cambray, G Joulin 1994 “Length scales of wrinkling of weakly-forced, unstable premixed flames,” *Combust. Sci. Tech.* 97: 405-428.

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