Effects of Combustion Instabilities on Burning Velocities Enhancement In Premixed Flames

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***Abstract*—In high pressure laminar explosions, special behavior may exist called instability at negative Markstein numbers. This behavior will cause pressure oscillations and will have certain effects on burning velocities of the fuel mixture. Flame winkling begins to appear as a results of Darrieus-Landau, D-L, instabilities and thermal-diffusive effects at higher pecelt number (as critical value is exceeded). Consequently an increase of burning rate will take place. This increase is capable of creating a pressure waves strong enough, if aligned non-orthogonally to parts of the flame surface, which result in further wrinkling from the Taylor instability along with vorticity generation. In this work, an iso-octane mixtures were ignited at two diametrically opposite sparks close to the wall of the bomb at higher pressure in the later stages of combustion. An advantage of this technique is to allow for instabilities to take place and to view the two flames structures through a central window. More details about this method are found in [1]. This method was also applied to investigate instabilities effect on turbulent flames.**

Keyword-Hydrocarbon Fuel, Flames, Emissions, Combustion, Carbon Oxides.

I. INTRODUCTION

It was shown from Theoretical studies [2-4] and experimental researches [5-7] that Laminar spherical flames can become unstable above a critical Peclet number (the flame radius, r, normalized by the flame thickness, δ_l). These instabilities become manifest as flame wrinkling over a range of wavelengths. As a results, the laminar burning velocity, will be influenced and hard to evaluate experimentally. High Peclet number, Pe can increase at high pressures, (as in engines) due to the smaller flame thickness values of, δ_l. Also, it was found that as pressures increase the strain rate Markstein number, Ma_{sr} decreases [5,6,8,9]. The associated instabilities with these flames cause a continually increasing burning velocity. This work reports a study for iso-octane – air explosion at an equivalence ratio, ϕ=1.6. The initial conditions were 0.5 MPa and 358 K. With the emphasis on unstable flames. The mentioned method above was advantageous in that Peclet numbers were maximized by large flame radii and small flame thicknesses

II. SPECIFIC OBJECTIVES

The purpose of conducting this investigation is to study the structure of unstable flames, Bothe laminar and turbulent flames at high pressures and temperatures at late stages of combustion process where values of pressure, P, and temperature, T, will be high. These instabilities will start to develop when cells evolution start to appear on flame surface area and begin division. Also, the effects of such instabilities on the burning rates enhancement for laminar and turbulent spherical flames at certain conditions have been investigated.

III. EXPERIMENTAL

A 385.6 mm diameter spherical stainless steel bomb had three pairs of orthogonal windows of 150 mm diameter was used. The inside radius of the sphere, *Ro* , was 192.78 mm. The vessel and the used mixture (iso-octane-air mixtures) were heated by electric heaters (6 KW) up to 358 K. The integral length scale of the turbulence, l, was 20 mm. Pressures were evaluated by a Kistler 701 pressure sensor. An automotive ignition coils were used to supply the energies of about 26 mJ to the two diametrically opposite spark plugs with a gaps of 11 mm from the inside wall. High speed Phantom digital camera at 3,700 frames/s with 256 × 256 pixels was used to observed the two flame fronts by schlieren photography. The spherical stainless steel bomb was also equipped with four peripheral fans, driven by electric motors, for mixing the reactants and to generate turbulence. The flame front has Cartesian coordinates measured from original images and used to obtain the appropriate polar coordinates. This was done by using Adobe Photoshop. An output sample for this analysis is shown in Fig.1 below.

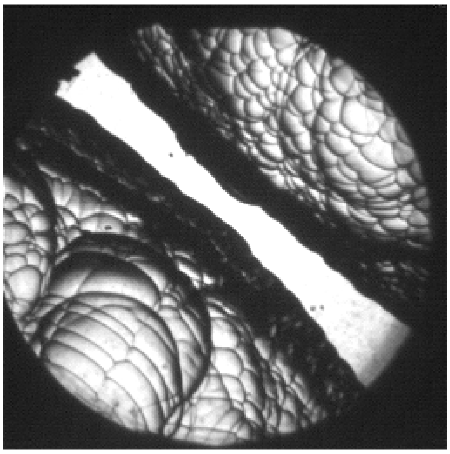

Fig. 1. Sample for schlieren image of the two kernels technique close to making contact.

All pressure—time records were monitored via the analogue to digital converter (ADC) system. The raw data were captured as voltage signals, Binary format, and converted into ASCII output readable files using FAMOS program. This voltage data was then processed to yield the variation of pressure with time, initially by a Fortran program.

IV. RESULTS AND DISCUSSION

A. Laminar flames

The measured flame radii and pressure variations are shown in Fig. 2 during a highly unstable iso-octane – air explosion. The equivalence ratio, ϕ, =1.6. with initial conditions of 0.5 MPa and 358 K. When the two flames were already unstable from D-L and thermal-diffusive effects at the time they came into the field of view. The method of obtaining the burning velocity, μ_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, μ_l, from μ_n . Values of μ_n , plotted against pressure, are shown in Fig. 3. Initially the value was approximately 0.6 m/s, about 6 times that of μ_l at the same pressure and temperature. An additional instability initiated, shown by both oscillations on the pressure record Just before the two flames flattened and then touched and, just prior to this, flame front oscillations, in which both flames moved in harmony. The latter are shown on the enlarged sub-diagram on Fig. 2.

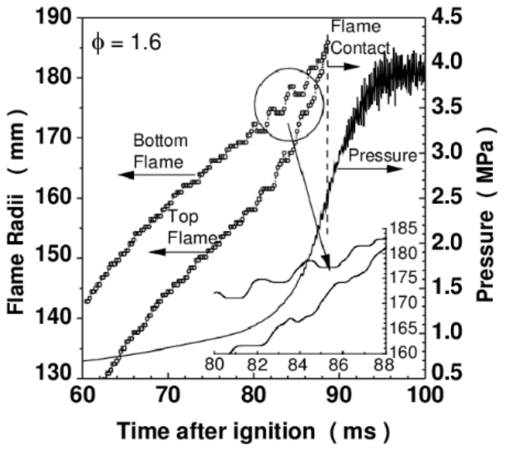

Fig. 2. Flame radii and pressure. Initial conditions: 0.5 MPa and 358 K.

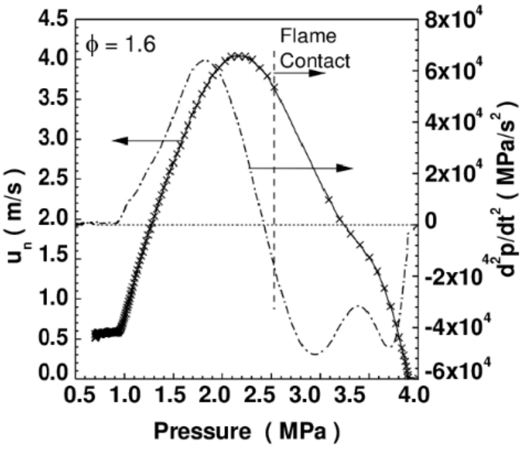

Fig. 3. Values of u_n and d^2p/dt^2, derived from Fig. 2.

It is postulated that this second instability and the associated very large increase in un , apparent on Fig. 3, were due to Taylor instabilities. Because of the rapid changes in the reaction rate , a triggering pressure oscillations arose.. The burning rate is given by [1]

$$\rho_u u_n A = C\frac{dp}{dt}, where\ C = \left(\frac{4}{3}\right)\frac{\pi R_0^3 \rho_0}{(p_e - p_0)} \qquad (1)$$

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

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

Values of d^2p/dt^2, obtained from the smoothed pressure record, are given by the broken curve on Fig. 2. Shown on Fig. 3, the contributions to this term from the separate two differentials on the right of Eq. (2). Values of A were found from the flame photographs and the flame geometry. The steep rise in un 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 $(A/C)\mathrm{d}(\rho_u u_n)/dt$. Prior to the onset of the second instability, un was increasing continually with the increasing wavelengths of the D-L - thermal-diffusive instability. After the two flame fronts (leading 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 .

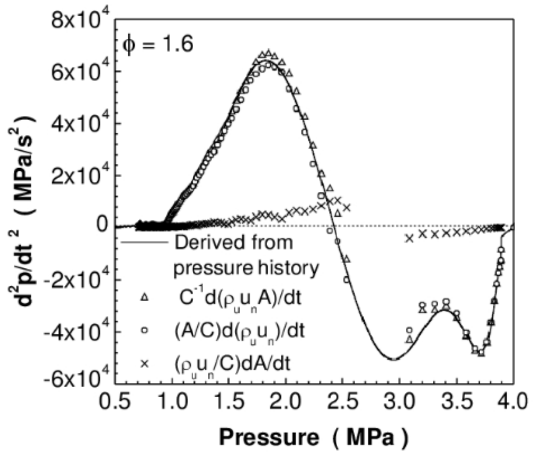

Fig. 4. Different terms in Eq. (2) for conditions of Fig. 2.

Eventually $(A/C)\mathrm{d}(\rho_u u_n)/dt$, 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.

On the other hand, with iso-octane-air mixtures for $\phi \leq 1.1$ at initial pressures and temperatures of up to 1.0 MPa and 358 K, no significant second, Taylor, instability was observed. This instability first appeared at ϕ=1.2, only as Markstein numbers became markedly negative. It would seem that Taylor instabilities and further flame wrinkling will be generated only when the flame fronts became adequately responsive to pressure oscillations. This will also be associated with increases in u_n. The consequent strong feed-back mechanism generated further wrinkling.

Shown in 5(a) and (b) for two different time intervals for the signals, the pressure oscillations about the smoothed mean and were subjected to Fourier analysis. In each case a dominant frequency was observed. The reciprocal times for a sound wave to travel across the bomb diameter is indicated by the broken lines, u and b through unburned and burned gas, respectively. In Fig 5(a), for the earlier time interval, these values are slightly less than the two observed peak amplitudes. However in Fig. 5 (b), there is less unburned gas and the single detected peak is closer to that expected for acoustic waves in burned gas, at the later time interval.

B. Turbulent flames

The scales range of the pressure oscillations is decreased due to an increase in the speed of the fans from rest, and hence in the effective rms turbulent velocity, $\underline{u'_k}$,With both central and wall ignitions. Even with a low value of $\underline{u'_k}$ of 0.22 m/s there was little evidence of an increase in turbulent burning velocity, $\underline{u_t}$, due to Taylor instability, although the turbulence increased $\underline{u_t}$ above u_n . Shown in Fig. 6, the measurements in numerous turbulent flame implosions yielded the experimental points. Results are indicated by the symbols and full line curve in the mentioned Figure. 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 un 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 [10, 11]. 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.

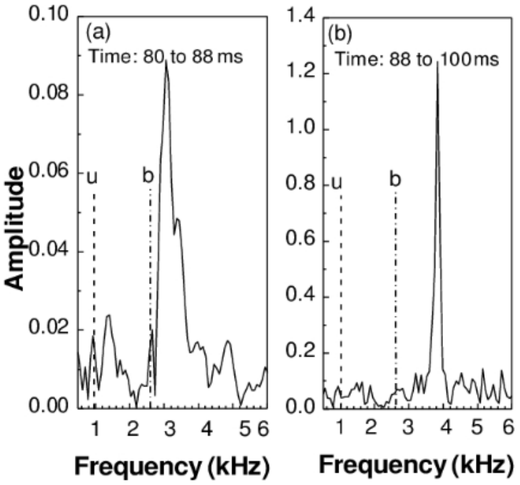

Fig. 5. Fourier analyses spectra over different times. Conditions of Fig. 2.

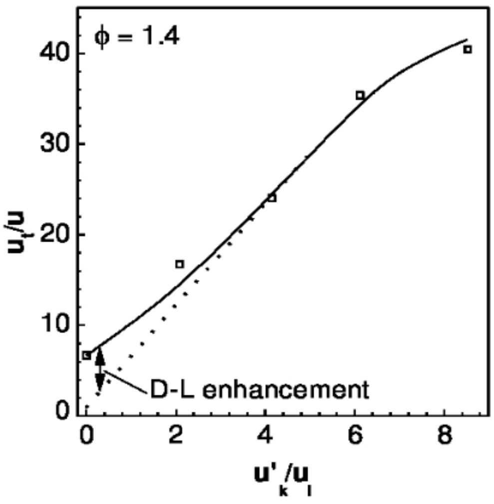

Fig. 6. Variation of u_t/ u_l with u'_k/u_l for ϕ =1.4, 2.0 MPa, 428 K.

V. 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 caused additional enhancement in the burning rate. In turbulent flames no obvious Taylor instabilities were detected and the D-L instabilities seemed to disappear at fairly low levels of turbulence.

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NOMENCLATURE

A	flame area
Λ_s	wave number for a localized cell
L	Markstein length
Ma	Markstein number
m_b	mass of burned gas
m_u	mass of unburned gas
P	Pressure
p_e	end pressure
Pe	Peclet number
Pe_{cl}	second (cellular) critical Peclet number
Pe_{cr}	first critical Peclet number
p_o	initial pressure
R	explosion vessel radius

R	mean radius
r_1	bottom flame radius
r_2	tope flame radius
T	time from ignition
T_o	initial temperature
T_u	unburned gas temperature
u'	r.m.s turbulent velocity
u'_k	effective r.m.s turbulent burning velocity
u_l	laminar burning velocity
u_n	stretched laminar burning velocity
u_t	turbulent burning velocity
δ_ℓ	laminar flame thickness
ϕ	equivalence ratio
ρ_b	burned gas density
ρ_u	unburned gas density