Instabilities and Soot Formation in High Pressure Explosion Flames

R.D. Lockett and R. Morishima
School of Engineering & Mathematical Sciences, The City University, London EC1V 0HB, United Kingdom.

Flame instabilities, cellular structures and soot formed in high pressure, rich, spherically expanding iso-octane-air flames have been studied experimentally using high speed Schlieren cinematography, OH fluorescence, and laser induced incandescence. Cellular structures with two wavelength ranges developed on the flame surface. In rich flames with equivalence ratio $\phi > 1.8$, soot was formed in a honeycomb-like structure behind flame cracks associated with the large wavelength cellular structure.

Introduction

If a deformation occurs in the surface of a spherically expanding laminar flame during its early development, any potential instabilities (hydrodynamic, thermal-diffusive) will be stabilised by the flame stretch until a critical Peclet number is reached. After this critical point, the flame may become unstable to surface perturbations, which can grow on the flame surface through the development of propagating cracks or cellular fission [1].

If the Lewis number for the deficient reactant in the fuel-air mixture is below a critical value, then in general, a perturbation in the expanding flame front is unstable. However, if the Lewis number for the deficient reactant in the fuel-air mixture is above a critical value, then the flame front is stable to perturbations on the surface. Generally, this means that for fuel-air mixtures where the molecular mass of the fuel is considerably smaller than the molecular mass of air, lean flames are unstable to surface perturbations. The converse is also true for rich flames. This kind of flame instability is known as a thermal-diffusive instability [1 – 3].

The second type of flame instability examined here is hydrodynamic in origin. Flame surface perturbations cause local pressure and density variations ahead of the advancing flame front, which can accelerate surface cracking. Hydrodynamic instabilities can be distinguished from thermal-diffusive instabilities through the identification of the different wavelengths associated with the two mechanisms. Furthermore, pressure oscillations ahead of the advancing flame front identify the presence of hydrodynamic instabilities. In practice, initial perturbations in a spherically expanding flame surface occur as a consequence of the mode of ignition, whether by a spark plug, or laser, or other means [1 – 3].

Experimental

Cracking in spherically expanding laminar flames was investigated using Schlieren cinematography, and hydroxyl Planar Laser Induced Fluorescence (PLIF). The flames were generated in the fan stirred bomb at Leeds University. The bomb is a spherical vessel of volume 31 litres, with six 190 mm diameter optically accessible windows, and four tetrahedrally oriented fans.

Soot formed during explosions of rich iso-octane-air mixtures at high pressure was investigated using laser induced incandescence (LII) in the optically accessible bomb at Shell, Thornton. Details of the experiments can be obtained from Tait [4] and Lockett et al [5].

Schlieren cinematography was employed to investigate the evolution of the long wavelength cellular structure on the surface of the expanding flames, induced by the hydrodynamic instability.

The OH PLIF measurements were conducted in the Leeds bomb using a Lambda Physik EMG 150 MSC excimer laser, operating in narrow band tunable mode at 308.24nm. The fluorescence from the excited OH was imaged onto a lens coupled intensified CCD camera.

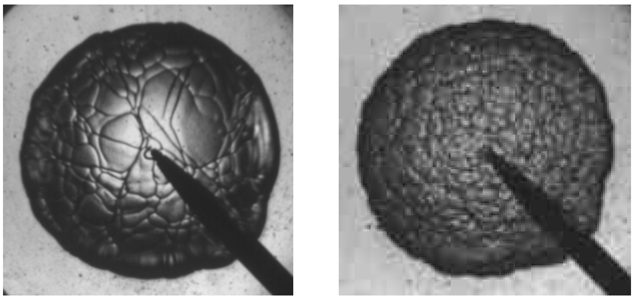
The flames were initiated from the centre of the bomb using single kernel spark plug ignition. Cracking in spherically expanding laminar flames was investigated for stoichiometric iso-octane-air flames and equivalence ratio $\phi = 1.4$ iso-octane-air flames at 5 bar pressure,

LII scattering measurements in the Shell high pressure bomb were conducted using a Spectra Physics GCR-270 laser operating at 532nm. The LII emission from soot structures generated in the flame was imaged through a window using a Princeton Instruments ICCD camera and a Nikon f1.2 50 mm lens.

Results

Figure 1 (a) shows a Schlieren image of a stoichiometric iso-octane-air spherical explosion flame obtained in the Leeds bomb at 5 bar pressure [3]. The flame radius is approximately 60 mm (Peclet no. ˜ 600). Surface wrinkling with a length-scale of approximately 5 mm to 1 cm is observable, with a smooth surface between the wrinkle lines.

Figure 1 (b) shows a Schlieren image of a $f = 1.4$ iso-octane-air spherical explosion flame obtained in the Leeds bomb at 5 bar pressure [3]. The flame diameter is approximately 60 mm (Peclet no. ˜ 600).



(a) **(b)**

Figure 1: Schlieren Images of 5 bar, (a) $f = 1.0$, and (b) $f = 1.4$, Iso-octane-Air Explosion Flames [3]. (Flame radii ˜ 60 mm, courtesy of R. Woolley, Univ. of Leeds).

Surface wrinkling with a length-scale range of approximately 5 mm to 1 cm is observable as before. In addition, there is a fine structure superimposed on the larger surface wrinkles.

Figure 2 shows processed LII images obtained from soot formed behind $f = 1.8$ iso-octane-air explosion flames obtained from the Shell bomb with an initial pressure of 5 bar [3, 5]. The soot formed behind the flame forms a honeycomb-like structure. A characteristic length-scale defining the soot cell size is observed to be of the order of 5 mm to 1 cm in length.

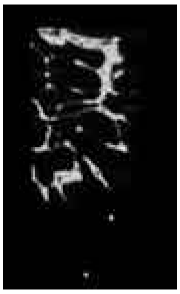


Figure 2: LII Signal from a 5 bar, $f = 1.8$ Iso-octane-Air Explosion Flame [3, 5] (Flame radius ˜ 60mm)

This corresponds with the larger cellular length-scale observed in Figures 1(a) and 1(b) above, determined by the hydrodynamic instability.

The images presented in Figures 1 and 2 have been subjected to a detailed analysis, which demonstrates the quantitative relationship between the length-scales observable in Figure 2 and the large length-scales identified in Figure 1 (a) and (b). This analysis will be presented at the conference.

Conclusions

1. Two distinct length-scales associated with flame cracking have been observed from the Schlieren images.
2. In highly enriched, high pressure explosion flames ($f > 1.8$), soot was observed to be formed in a honeycomb-like structure behind the flame.
3. The soot cell size was observed to be of the order of 5 mm to 1 cm, which corresponded with the larger length-scale cellularity.

References

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