Visualizing Detonation Waves

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Abstract

Visualization has played an essential role in the development of our understanding of the complex unsteady flows associated with the initiation, propagation, and extinction of detonation waves. These methods and application to various aspects of detonation are illustrated by results obtained in my laboratory, particularly using combinations of the PLIF technique with other methods. Examples shown will include detonation initiation by projectiles, diffraction over ramps and steps, diffraction out of tubes, detonation implosion, and the cellular structure of detonation waves.

A variety of visualization methods have been used over the past five decades and each reveals different aspects of detonation behavior. Most importantly, these visualizations, together with theoretical and numerical analyses, provide important clues to the physical and chemical basis for understanding and simulating detonations.

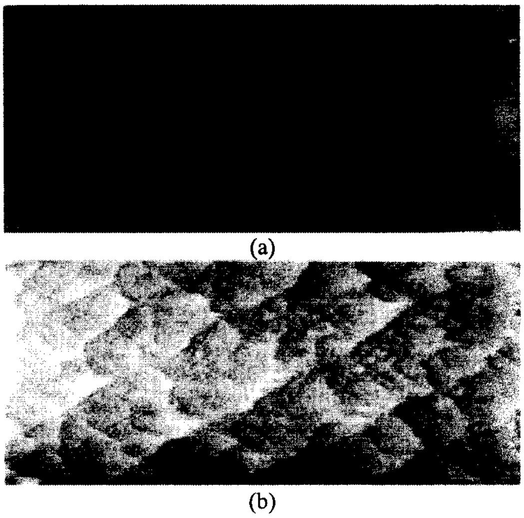


Figure 1. Examples of soot foil recordings for two types of detonation in a rectangular channel. (a) Stoichiometric hydrogen-oxygen highly diluted with argon. (b) Stoichiometric ethylene-oxygen diluted with nitrogen. (Khokhlov et al 2004).

The simplest techniques for visualizing detonations are the soot foil (Strehlow 1969) or open shutter photography. Examples of the result of the soot foil method applied to two different types of detonations are shown in Fig. 1. Although soot foils continue to be extensively used in detonation research, the interpretation is subjective, and the relationship between the soot tracks and the actual fluid dynamics of the detonation front is complex and poorly understood (Pintgen and Shepherd 2002, Inaba et al 2005). For this reason, optical methods like interferometry, shadow, or schlieren photography (Fig. 2) provide much more useful information about the detonation front.

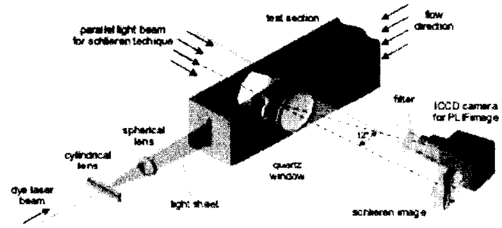
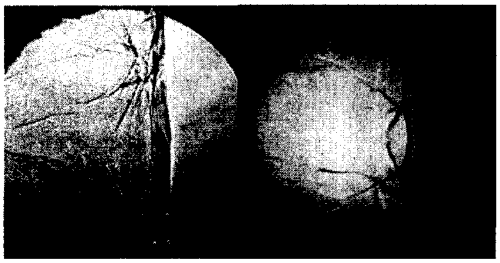


Figure 2. Arrangement for simultaneous schlieren and PLIF imaging. (Pintgen 2000)

Unfortunately, the instability of the detonation front and the following turbulent flow make it difficult to interpret these images in many situations (Fig. 3a). By using narrow channels and mixtures highly diluted with argon (Fig. 3b), nearly laminar, two-dimensional flow can be produced and a great deal can be learned (Strehlow 1969) from the combination of soot foils and images.



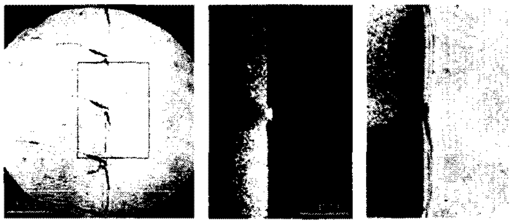
(a) (b)

Figure 3. Cellular structure of detonation wave (a) laser shadowgraph integrated through 150 mm wide test section (Akbar 1997) (b) frame from schlieren movie of nearly two-dimensional wave in 18 mm wide section (Austin 2003).

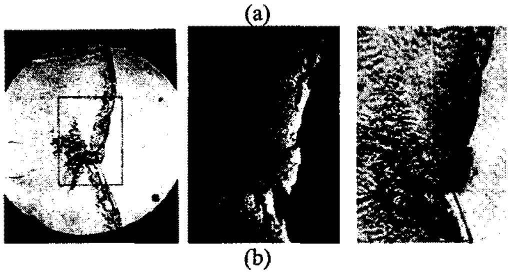
Although enormous progress has been made using schlieren and shadowgraph photography, these methods can only reveal density gradients and tell us nothing about chemical activity within the detonation. In order to visualize chemical features, we applied the method of planar laser induced fluorescence to detonations (Pintgen 2000). The technique is simple in concept (Fig. 2) but requires careful choice of the mixture and optical path to obtain clear images. The easiest mixtures for which this is possible are dilute hydrogen-oxygen, Fig. 4, which has very low luminosity and therefore a good signal-to-noise ratio. The fluctuations in the leading shock front velocity produce the characteristic keystone shapes of weak instability in the detonation front (Fig. 4 and 5a).

Figure 4. False color OH PLIF image (a), schlieren image (b) and superposition of PLIF and schlieren (c). Detonation in stoichiometric hydrogen-oxygen with 85% argon dilution in 150 mm wide channel. (Pintgen 2000, Pintgen et al 2003.).

Laminar detonations with weak instability waves appear to be the exception rather than the rule. The highly turbulent detonations characteristic of hydrocarbon fuel-air mixtures are much more interesting for both practical applications and scientific study. The cellular structures have a wide range of spatial scales (Fig. 1), the flow is turbulent behind the shock front (Fig.5b), the chemical activity is distributed over a region and the species concentration fronts are highly irregular (Fig. 5b).



(a)



(b)

Figure 5. Simultaneous laser shadowgraph and OH PLIF images of detonations propagating in a narrow (18 mm width) channel (a) regular front characteristic of mixtures highly diluted with argon (b) irregular front characteristic of hydrocarbon fuel-air mixtures (Austin 2003, Austin et al 205).

The appearance of the front is linked to the instability of the coupling between chemical reaction and the leading shock front (Austin 2003, Austin et al 2005).

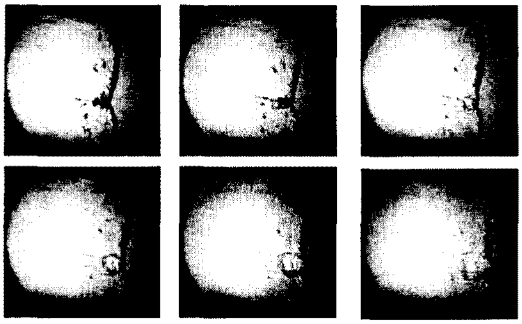


Figure 6 . Frames from a schlieren movie showing the development of a localized explosion within a detonation front propagating in a propane-air mixture in a narrow (18 mm width) channel (Austin et al 2005, Austin 2003).

Mixtures with very high effective activation energy show very fine-scale turbulence behind the front (Fig. 5b and Fig. 6) and the spontaneous development of explosions within the front (Fig. 6).

PLIF images can be used to learn about many other aspects of the detonation front. For example, PLIF images taken parallel to and very close to a soot foil reveal the soot tracks and the keystone points are not quite coincident but are closely correlated.

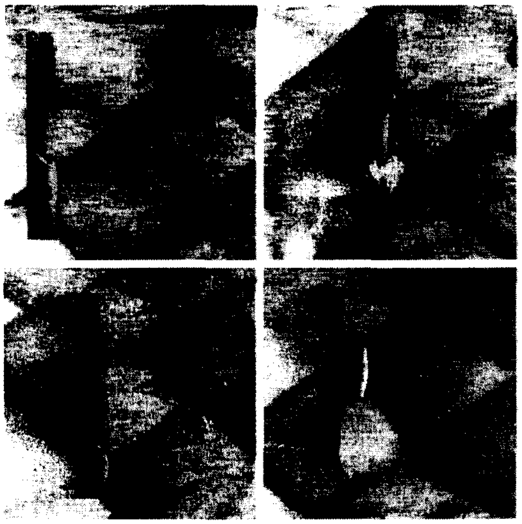


Figure 7. Examples of PLIF images overlaid on sidewall soot foils showing the correspondence of keystone structures to transverse wave locations (Pintgen and Shepherd 2003).

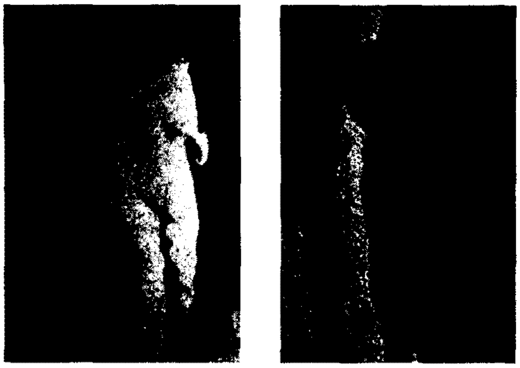


Figure 8. Shear layers observed using OH PLIF in stoichiometric hydrogen-oxygen mixtures diluted with nitrogen. Kelvin-Helmholtz instability is clearly seen at the interface of reacted and unreacted material (Pintgen et al 2003).

Another feature that can be clearly observed within the reaction zone are the vortex structures (rollers) characteristic of Kelvin-Helmholtz instability developing on the shear layers (Fig. 8) originating at the triple points where the transverse waves intersect the main shock front. The roles of these shear layers and the extent of chemical reaction due to mixing created by the instabilities is an active area of research.

In addition to the examples discussed above, these visualization methods have been applied to a wide variety of situations such as projectile initiation of detonation, diffraction of detonations through apertures and gradients, and the initiation of detonations using implosions. From a scientific point of view, the features revealed by these visualizations have been important in leading to new areas of research, particularly the role of unsteadiness and mixing in the propagation mechanism of detonation waves.

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