Direct Observations of Reaction Zone Structure in Propagating Detonations

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We report experimental observations on the reaction zone structure of self-sustaining, "cellular" detonations propagating near the CJ state in hydrogen-oxygen-argon mixtures. Two-dimensional crosssections perpendicular to the propagation direction were imaged using the technique of Planar Laser Induced Fluorescence (PLIF) and in some cases, compared to simultaneous pulsed-laser schlieren imaging. For the first time, images are obtained which clearly show the nature of the disturbances in an intermediate chemical species (OH) created by the variations in the strength of the leading shock front associated with the transverse wave instablity of a propagating detonation. The images are compared to two-dimensional, unsteady simulations with a reduced but realistic model of the chemical reaction processes in the hydrogen-oxygen-argon system. We interpret the experimental and numerical images using simple models of the detonation front structure based on the "weak" version of the flow near the triple point. Both the unsteady simulations and the triple point considerations are consistent with the creation of keystone shaped regions of low reactivity behind the incident shock near the end of the oscillation cycle within the "cell" created by two counterpropagating transverse waves.

Introduction

Previous experimental studies of detonation waves have been primarily limited to point measurements of pressure, visualizations of the density field using schlieren or shadowgraph methods which integrate through the flowfield, or soot foil records. These techniques are poorly suited to revealing the true structure of the detonation front. Further, the quantities of greatest interest, the concentrations of the chemical species, can at best be only indirectly inferred from such measurements. Recognizing these limitations, Andersen et al. (1992) applied the method of planar laser induced predissociated fluorescence (LIPF) in an effort to visualize a crosssection of the OH concentration behind a detonation front in a hydrogen-oxygen-argon mixture. Although OH images were obtained, there not sufficient spatial resolution to obtain any information other than the average spatial period of the oscillations in OH emission. One major difficulty that this study identified was the substantial amount of natural fluorescence that occurs in detonations and importance of careful attention to reducing this in the final image in order to obtain high signal-to-noise ratios. Rayleigh scattering from a planar laser sheet was used by Anderson and Dabora (1992) to image a cross section of the density field behind detonations propagating in hydrogen-oxygen-argon mixtures. Shock front shapes and quasi-periodic spatial fluctuations in density were observed that correlated with previous numerical and experimental studies. These results confirmed the density variations inferred from previous optical images and predicted by simulation. However, there was no insight provided into the chemical processes taking place in the reaction zone A more promising technique is non-resonant LIF which has had success in elucidating the reaction zone structure of turbulent flames and shock-induced combustion. By carefully choosing the parameters of the detonation and LIF system, we felt that it would be possible to oversome previous difficulties and image the details of the reaction zone structure.

Experimental Setup

The experiments were carried out using a 8-m long, 280-mm diameter detonation tube (Akbar, 1997), attached with a "cookie-cutter" to the 150-mm square test section described in Kaneshige (1999). The detonation reaction zone has been visualized by exciting OH fluorescence at about 284 nm with a planar light sheet and imaging the emitted light with a intensified charged-coupled device camera. Simultaneous observations with laser shadowgraph have also been used in some tests. The UV light for excitation of the OH molecules is produced by frequency doubling the output of a excimer-pumped dye laser. The energy after exiting the frequency doubler was about 6.5 mJ. The frequency of the dye laser was tuned to 284.008 nm, which is located half-way between two OH transitions: a) $A^2\Sigma^+$–$X^2\Pi_i(1,0)$ $Q_2(8)$ at 284.009 nm; 2) $A^2\Sigma^+$–$X^2\Pi_i(1,0)$ $Q_1(9)$ at 284.007 nm. The induced fluorescence was imaged through a bandpass filter onto a slow-scan CCD camera. The detected radiation is expected to be primarily due to (1,1) transitions (Dyer and Crosley, 1982) near 315 nm. For simultaneous schlieren and PLIF images, the Q-switched, flash-lamp pumped ruby laser described by Akbar (1997) was used to create a short pulse at 693 nm.

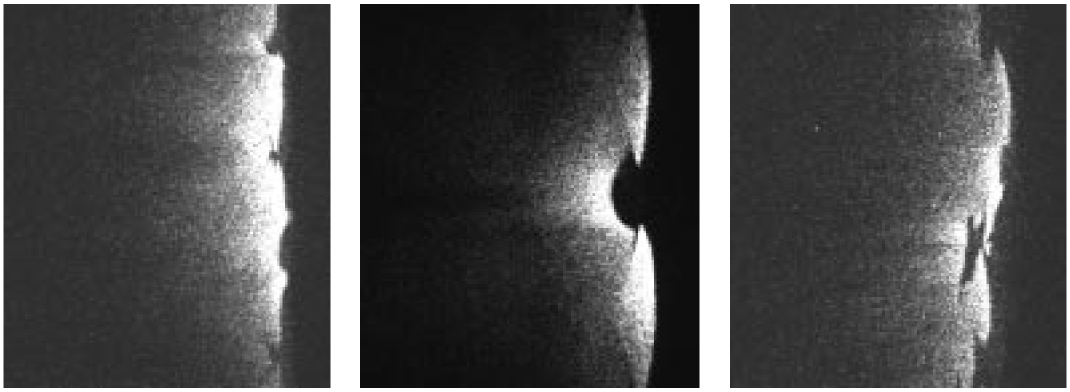
Experimental Results

One OH image is obtained for each experiment. A selection of these images are shown in Fig. 1; the image is identified by the test number. The height of each image is approximately 80 mm and the detonation wave is traveling from left to right in all images. It is important to note that these images are qualitative rather than quantitative since we have not corrected for the effect of the laser beam nonuniformity or molecular effects such as quenching or time-dependence of the excited state population. The main value of the present results is in revealing the geometry of the OH fronts and enabling an interpretation in terms of gas dynamics and chemical reactions.

A distinct OH concentration front is visible in all cases. Simulations of the reaction zone behind the shock front, discussed subsequently, indicate that the origin of the front is due to the sharp rise in the OH concentration at the end of the induction zone or region of radical chain reaction behind the main shock front. In Fig. 1, the shock location is not known but it can be inferred from the simulations and simultaneous schlieren and plif images to be just to the right of the OH emission front. We anticipate that the distance from the shock to the concentration front will be a strong function of shock strength and the clearly visible sudden changes or jumps in the location of the front must be associated with the instability of the detonation wave.

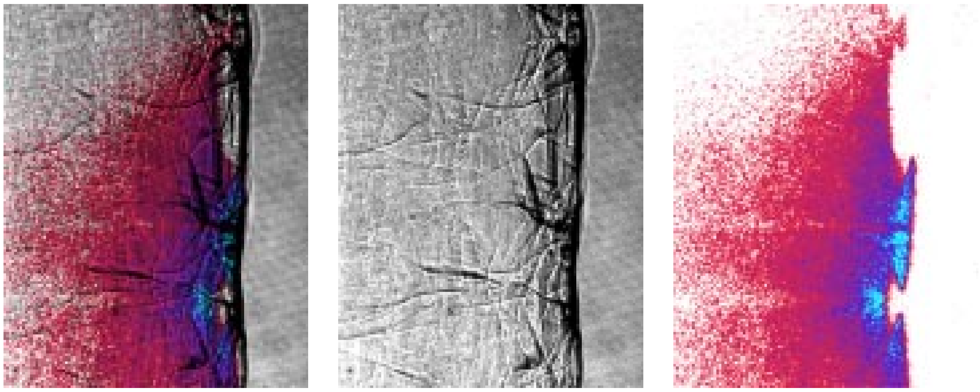
This is confirmed by the simultaneous schlieren and OH PLIF images shown in Fig. 2. Despite the masking effect of the three-dimensional nature of the transverse waves, it is clear that the changes in the OH concentration front location can be correlated directly with the density field changes visualized by the schlieren images. The variation in the OH concentration front location with shock velocity is confirmed by numerical simulations described subsequently.

The geometry of the OH front is striking and some common features stand out. A single and particularly pronounced feature in seen in shot 1419.



a) Shot 1416 b) Shot 1419 c) Shot 1426

Figure 1: Images of OH fluorescence behind detonation fronts in stoichiometric H_2-O_2 mixtures diluted with a) 80% Ar, b) 85% Ar, and c) 60% N_2.



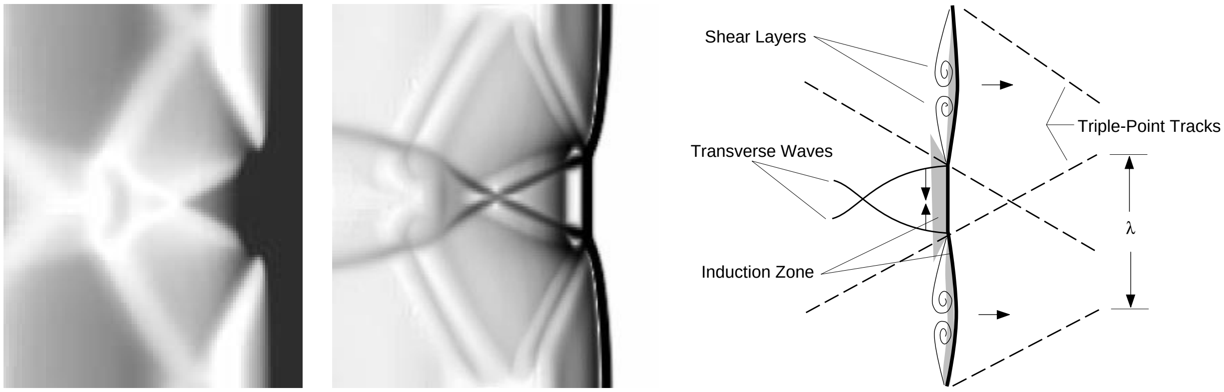
Overlay Schlieren Shot 1433 PLIF

Figure 2: Simultaneous schlieren and OH fluorescence images behind detonation fronts in stoichiometric H_2-O_2 mixture diluted with 85% Ar.

Numerical Simulation

Numerical simulations of two-dimensional detonations traveling at the Chapman-Jouguet velocity in $2H_2$+O_2+7Ar mixtures at an initial pressure of 6.7 kPa have been carried out by Eckett (2000). These simulations used a realistic reaction model and thermochemistry based on a detailed reaction mechanism and systematically reduced using the ILDM method.

Simulated schlieren and OH mass fraction images are shown in Fig. 3. Several features can be observed in the OH mass fraction image. First, there are the obvious OH fronts closely following curved portions (Mach stems) of the leading shock wave. Second, on the centerline between the two Mach stems, there is a keystone-like feature which is bounded by the lead shock, the shear layer and the OH front behind incident wave. Third, the decrease in mass fraction along the downstream edge of slip lines can also be seen. There is a striking qualitative similarity between the overall appearance of the numerical simulation of OH mass fraction and the experimental images presented in Fig. 1.



(a) (b) (c)

Figure 3: Results of numerical simulation of Chapman-Jouguet detonation in stoichiometric H_2-O_2 mixture diluted with 70% Ar, initial pressure 6.7 kPa: (a) OH mass fraction (b) Density (c) Schematic of detonation front features.

Triple Point Analysis

A shock and detonation polar calculation was carried out to analyze the triple point configuration at various locations throughout the cell. The analysis assumes the flow is quasi-steady in the frame of the triple point and the waves are locally straight. The incident shock Mach number at each location was estimated from centerline pressure profiles calculated by Eckett (2000) and the incident flow angle was measured from sooted foils mounted on the walls of the test section and assumed to be constant throughout the cell. It was determined that under these conditions, a detonation solution involving a single triple point was not possible. A single nonreactive slip-stream balance was found to be in reasonable agreement with numerical schlieren images in the immediate vicinity of the triple point to within the resolution of the calculation. Other more complex polar constructions are being considered in view of other numerical simulations Oran et al. (1998). ZND calculations are being carried out to determine the OH mass fraction profiles behind the incident wave and Mach stem. Preliminary results show reasonable agreement with OH fluorescence images

Acknowledgements

We thank Raza Akbar, Mike Kaneshige, Eric Schultz, and Pavel Svitek for their contributions to the development of the detonation facility and imaging experiments. The simulations were carried out with James Quirk's Amrita computational system. Portions of this work were supported by the ONR and the DOE.

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