Simultaneous Soot Foil and PLIF Imaging of Propagating Detonations

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Soot foils placed on the side and end walls of a detonation tube are the standard experimental technique for the determination of cell size, regularity, and shock wave configuration of multifront detonations. While it is clear that soot gets redistributed or removed by the passing detonation, the physical principle behind the soot foil technique is not yet completely understood. It is commonly supposed that the soot tracks coincide with the triple point on the detonation front simultaneous schlieren and soot foil measurements [1] show that the soot tracks appear to closely follow the triple points but the mechanism of track formation or exact correspondence to the wave features has not been shown. The experiment described in this paper uses Planar Laser Induced Fluorescence (PLIF) of the OH radical to visualize the reaction front close to the wall, deducing the approximate position of shear layer, triple point, and leading shocks of the detonation front structure. Simultaneously obtained soot foils allow for an overlay of the obtained soot foil and PLIF image. We report on experiments with stoichiometric H_2-O_2 mixture diluted with 85% Ar at initial conditions of 0.2 bar and 294 K.

The experiments were carried out in a 7.3 m long, 280 mm diameter detonation tube [2]. The detonation is initiated by an exploding wire together with a short length of acetylene-oxygen. The propagating detonation is cut at the end of the tube by four plates with sharp edges, which form a 152 mm square cross-section, and transitions into the 1.8 m long, 152 mm square section of the facility. One 150 mm diameter quartz window, through which the PLIF signal is detected, is located 0.5 m from the end plate in the side wall. The $Q_2(8)$ and $Q_1(9)$ transition lines close to 284 nm are used to excite the OH radicals with an Excimer pumped dye laser (6.5 mJ/pulse) in a planar light sheet of height 70 mm and thickness 0.3 mm. Soot foils, 630 by 150 mm, are placed on the side wall opposite to the camera. The distance between the light sheet and soot foil is approximately 1 mm.

Overlay images of the PLIF and soot foil images are shown in Fig. 1. The distinct OH concentration front seen on the PLIF images corresponds to the sharp rise in OH concentration at the end of the induction zone, in which chain breaking processes are taking place. Since the induction zone length increases sharply with decreasing shock velocity, keystone-shaped regions of lower fluorescence are observed behind the low-velocity portions of the front, termed “incident” wave, and keystone-shaped regions of higher fluorescence appear

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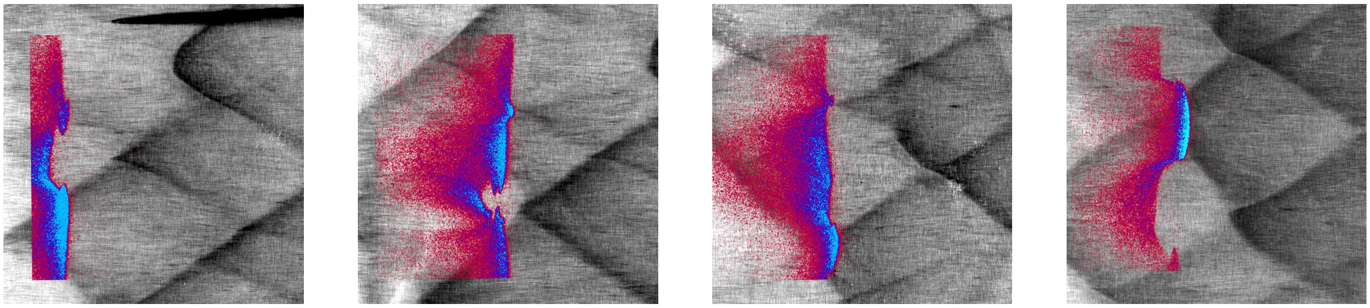
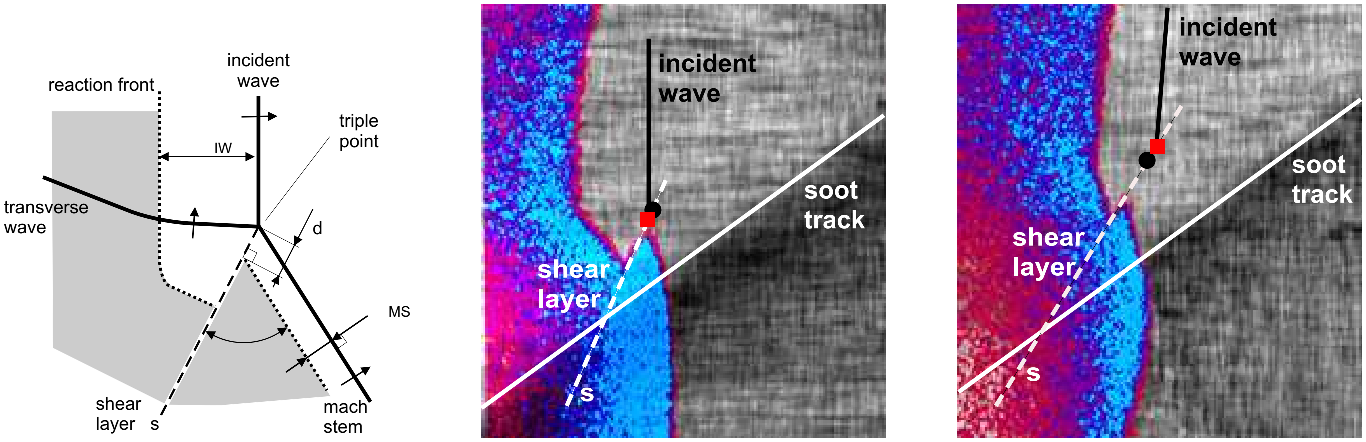


(a) Shot 1651 (b) Shot 1652 (c) Shot 1653 (d) Shot 1654

Figure 1: Overlay of soot foils and PLIF-Images. Image height: 85 mm ; $17Ar+2H_2+1O_2$; Initial conditions: 0.2 bar, 294 K.

behind the high-velocity portions of the front, termed Mach stem. The keystones of lower fluorescence are bounded front and back by the incident wave and the end of the induction zone, and on the sides by the shear layers. This shear layer is the dividing line between particles which have passed through the Mach stem and particles which have passed through the incident and transverse wave. The soot foils show tracks, with the expected regular structure, a track angle of approximately 33°, and a cell size of 46 mm. The soot tracks appear as a dividing line between brighter and darker regions on the soot foil. The keystones of lower fluorescence correlate well with the "closing" portion of cell patterns, keystones of higher fluorescence with the "opening" portions of the cell patterns. Note that the keystone corner of higher fluorescence is located on the side of the incident shock with respect to the soot track.

Using an idealized configuration of the triple point configuration Fig. 2 a, the location of the triple point can be found to lie on the extension of the shear layer at a certain distance d from the keystone corner. According to a two-dimensional simulation for a similar mixture [3] the normalized velocity, U/U_{CJ}, on the center line of the leading shock wave decreases from 1.3 to 0.9 in a cellular cycle. We have analyzed Fig. 2a and c to estimate the location of the incident wave and Mach stem and used the numerical simulation to find the wave speeds. The corresponding induction zone lengths, Δ_σ, were computed using a one-dimensional ZND-simulation. The induction zone length is here defined as the distance from the shock front to the maximum temperature gradient location, which corresponds to the location of the maximum OH-production. The location of the triple point can be derived in two ways. First, from the induction zone length behind the incident wave, $\Delta_{\sigma IW}$, the location of the incident wave parallel to the reaction front can be estimated. The location of the triple point is the point of intersection of the extended shear layer line s and the assumed incident wave, shown as a red square in Fig. 2b and c. Second, the distance d is estimated directly from the Mach stem induction zone length, $\Delta_{\sigma MS}$, and the angle θ between the shear layer and the Mach stem. The angle θ is taken to be constant at 46°, which corresponds to a track angle of 33° and incident wave velocity of 0.98 U_{CJ}. These values agree with the observations on soot foils and PLIF images



(a) (b) (c)

Figure 2: a): Schematic of simplified triple point constellation; b) and c): Derived triple point location for Shot 1651 (U_{MS}/U_{CJ}=0.97; $\Delta_{\sigma\,MS}$=2 mm; U_{IW}/U_{CJ}=0.91; $\Delta_{\sigma\,IW}$=3.6 mm) and Shot 1653 (U_{MS}/U_{CJ}=1.1; $\Delta_{\sigma\,MS}$=0.8 mm; U_{IW}/U_{CJ}=0.92; $\Delta_{\sigma\,IW}$=3.3 mm).

[4]. Neglecting the curvature of the Mach stem, the velocity in the vicinity of the triple point is taken to be the numerically simulated [3] value on the cell centerline. The triple point location computed in this fashion is indicated by a black dot.

The two images shown in Fig. 2b and c have been processed to exaggerate the sharpness of the reaction front. Any three-dimensional effects of the detonation caused by the shock wave system are neglected, so the triple line, which is attached to the triple point being considered, is assumed to be perpendicular to the soot foil. If the angle between the triple line and the soot foil is small, the PLIF image would not show distinct keystone features but vertical coherence. The error introduced by the possible non-orthogonal wave system is minimized by choosing a distance of 1 mm between the soot foil and the light sheet. All possible triple point locations derived from this consideration are located on the side of the incident shock wave with respect to the soot track. Neglecting the curvature of the shock wave at the wall, this indicates that the soot track is not caused by the triple point directly, but subsequently created on the Mach stem side.

To investigate the influence of the boundary layer on the experimental results, a non-reacting similarity solution behind a shock wave traveling with CJ-velocity (1415 m/s) was obtained by numerically solving the equations of motion. For simplicity, the Prandtl number Pr, the pressure, and the specific heat capacity at constant pressure c_p are taken as constant and the kinematic viscosity μ is taken to be proportional to the temperature T. The viscosities are calculated by the Sutherland law. The post shock velocity, U_{ps}, of the free stream is 1087 m/s. The velocity component U, which is parallel to the wall in the lab fixed coordinate system, is plotted (Fig. 3) against the distance y to the wall for several distances x, from the distance to the shock front. Also shown is the location of the light sheet and the induction zone length at U_{shock}=U_{CJ}

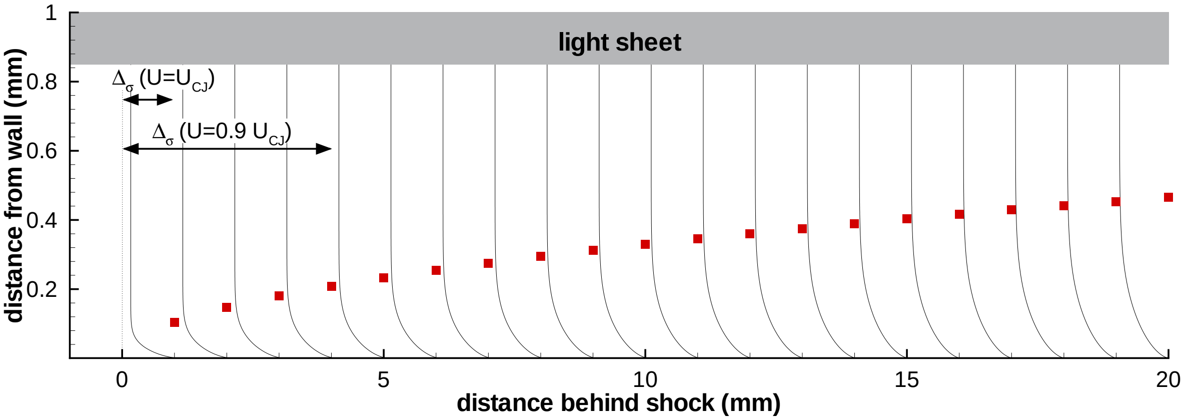


Figure 3: Calculated wall parallel velocity profiles behind a shock wave traveling with CJ-velocity; Location of U=0.99 U_{ps}.

and at U_{shock}= $0.9\,U_{CJ}$. This calculation assumes laminar flow. At $Re \approx 3.5\ 10^5$ to 10^6, the boundary layer transitions to turbulent, which corresponds to a distance of 10 to 28 mm behind the shock front. Neglecting the influence of transverse waves, the boundary layer is laminar in the induction zone. The location of the distinct OH front seen on the PLIF images is, therefore, not influenced by the boundary layer.

The simultaneous soot foils and PLIF visualization technique on detonations near the CJ-state in an Ar-diluted stoichiometric H_2-O_2 mixture, has been successfully applied. The keystone-shaped discontinuities of the front seen on the PLIF images correlate well with the cellular structure observed on the soot foils; keystones of lower fluorescence appear in the image overlay on the closing half of the cell and vice versa. The location of the triple point, as derived from two simplified models, is displaced from the soot foil tracks. The triple point in these preliminary results is consistently located on the incident shock side of the soot foil track. Simplified similarity calculations of the boundary layer indicate that the PLIF images are taken outside the boundary layer. More experiments will be carried out.

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