On the Location of the Chapman-Jouguet Surface in Gaseous Detonations Close to the Limit of Propagation

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Abstract

The location of the sonic surface x_S in a cellular detonation is measured by the use of time-resolved schlieren photography for stoichiometric oxy-hydrogen mixture (diluted with 40 % argon and pure) and for stoichiometric oxy-acetylen. This is done by fixing a thin blade in the middle of a detonation tube, whose edge faces the incoming detonation front. A weak shock wave forms at the edge of the blade as soon as it is engulfed by the front. This weak shock separates from the edge when the absolute gas velocity has decreased from its highly supersonic value (directly behind the front) to the speed of sound. After separation the absolute velocity of the shock is low and becomes nearly constant. This is explained as an indication of the proximity of the sonic surface and the CJ-surface. Furthermore it is shown, that the ratio of x_S and the cell size λ rises with pressure, and the influence of the proximity of λ to the tube diameter is small. In addition a diagonal-mode detonation was observed with λ equal to the diagonal Δ of the utilised tube with square cross-section. This mode was defined by Hanana et al. (1999).

Introduction

The location of the CJ-surface x_{CJ} has been used occasionally to predict the velocity deficit of near-limit detonations (Fay, 1959) (Ishii et al., 2000) by calculating the expansion effect that is caused by the wall boundary layer. The value obtained is almost a linear function of x_{CJ}, but data about this value is not commonly available and its determination is a problem of measurement and definition. It was intended to localise the plane by Vasiliev (1972) using optical methods and by Edwards (1976) measuring the decay of pressure fluctuations behind the front. Vasiliev measured the velocity deficits in a thin, retreating cellophane tube and calculated the necessary expansion ratio $\Delta r/r$ from the front to the CJ-surface. With this value he measured x_{CJ} from instantaneous frames of the exhaust-gas luminosity taken at 1 Mfps. The method yielded values of x_{CJ}/λ ranging from 3.6 to 10. Regarding the very low values of the expansion ratios ($\leq$ 1%) and the given uncertainty of the velocity measurement (~ 2%), the significance of the numbers seems low. With another method, which is the origin of the one used here, he studied x_S as a lower limit for x_{CJ}. He plotted the values of x_S/λ ranging from 1 to 3 over the ratio of the tube diameter of his tube to the cell size d/λ and obtained a positive correlation. He drew the conclusion that this correlation is "unique for the various mixtures", which might be understood as if there was an influence of the tube diameter, even though d/λ was $\geq$ 4, which is far from the limits. Edwards estimated roughly similar values of 2 to 4. Aside from enlarging the database on x_{CJ}, it is intended to answer two questions in the present study:

1. Is x_S/λ and thereby x_{CJ}/λ a function of the initial pressure?

2. From which value on does a decreasing ratio d/λ assert a non-negligible influence on x_{CJ}/λ?

Experimental set-up

Experiments are performed in a 9 m long shock tube with 6 m low-pressure section, that has a square cross section with side length d = 54 mm, which equals the hydraulic diameter of a rectangular duct defined as $d_h = 2\ a\ b\ /\ (a+b)$, with a = b = d. Detonation is ignited with a spark plug at the end of the hp-section, which is filled with turbulence promoting spirals and not separated by a diaphragm. For the initiation, a small amount of highly explosive gas mixture (~10% of tube volume) is filled in next to the spark plug just before experiment. Thereby minimum ignition pressure was decreased down to 2.5 kPa. Calculation of diffusion yields that traces of the initiation mixture in the test-section are negligible. Detonation velocities in the lp-section are measured by pressure gauges mounted 6000, 788, 288, and 38 mm in front of the blade position. They are constant except for the typical fluctuation at λ > d. Cell sizes, measured with sooted plates in front of the test-section (Fig. 1), fit well to values of the detonation database. The initial conditions of the experiments are summarised in Fig. 2 and compared to CJ-calculations. As expected, the velocity deficits increase close to the propagation limits.

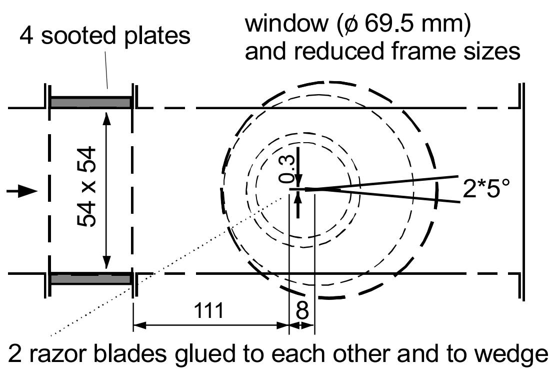

Fig. 1: Test-section

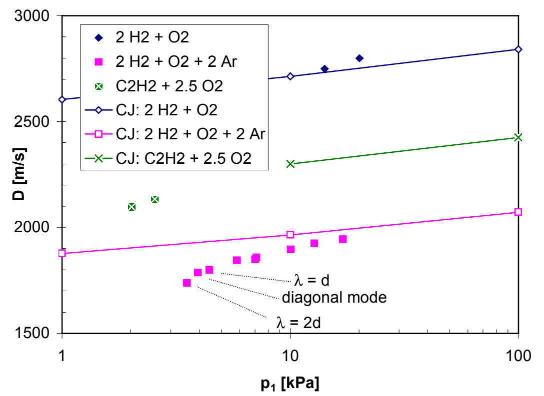

Fig. 2: Measured detonation velocities D compared to CJ-calculation

The optical system with ruby laser stroboscope and rotating mirror camera (described in Weber et al., 1998) was used at time steps of 2.5, 3, and 5 µs depending on λ. The vertical schlieren edge cuts the light deflected by density gradients rising in the direction of detonation propagation, to be most sensitive for the separating weak shock (dark). The focus of the adjustment laser is set directly next to the schlieren edge. The front shocks are visualised by a semi-circular knife edge of 13 mm in diameter surrounding the focus on the other hand side (dark as well). In experiments at large λ and low pressure, the front shocks appear white (Figs. 4, 5). This is probably caused by the large focus of the ruby laser flashes, which lies partially on the vertical edge and is let through completely by the weak deflection in the front. Diffraction fringes have a distance of 0.4 mm in vertical direction and at maximum 0.3 mm in the important horizontal direction (Fig. 3). Accuracy of optics is therefore +/- 0.15 mm. The film is scanned at a resolution of 2700 dpi, yielding about 18 pixels per test-section mm. That means the accuracy of the schlieren system corresponds to +/- 3 pixels. Images are rotated to the horizontal direction with Anti-Alias function and arranged in a column with 1 pixel accuracy, yielding an overall error of the measurement system of +/- 0.2 mm or 4 Pixel. The path measurement for the separating weak shock is indicated in Fig. 6.

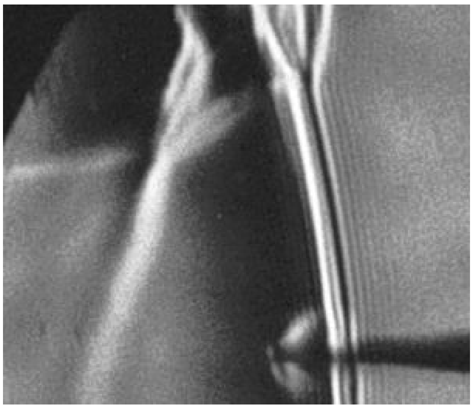

Fig. 3: Maximum observed fringe distance in front of the detonation front: 0.3 mm
$2H_2 + O_2 + 2Ar$
initial pressure 5.8 kPa
cell size λ 40.8 mm
original section width 16.8 mm

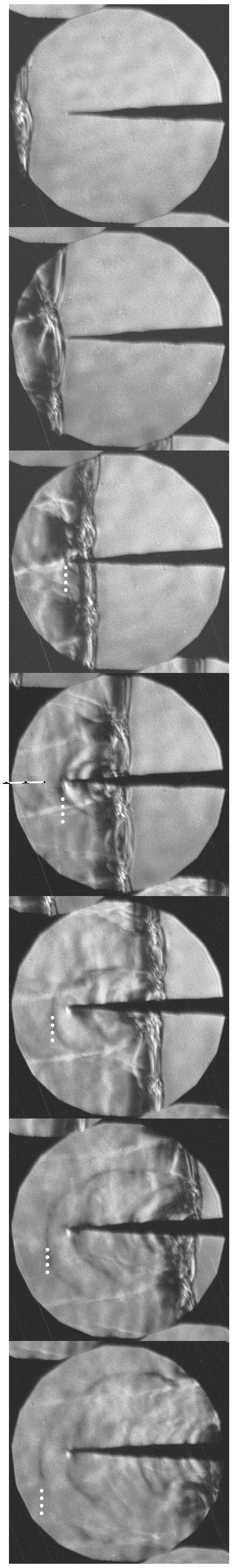

Fig. 6: Determination of shock position (indicated approx. as white dots under it)
$2H_2 + O_2 + 2Ar$, 12.8 kPa
cell size 12.6 mm
frame size 33.7 mm
time step 3 µs

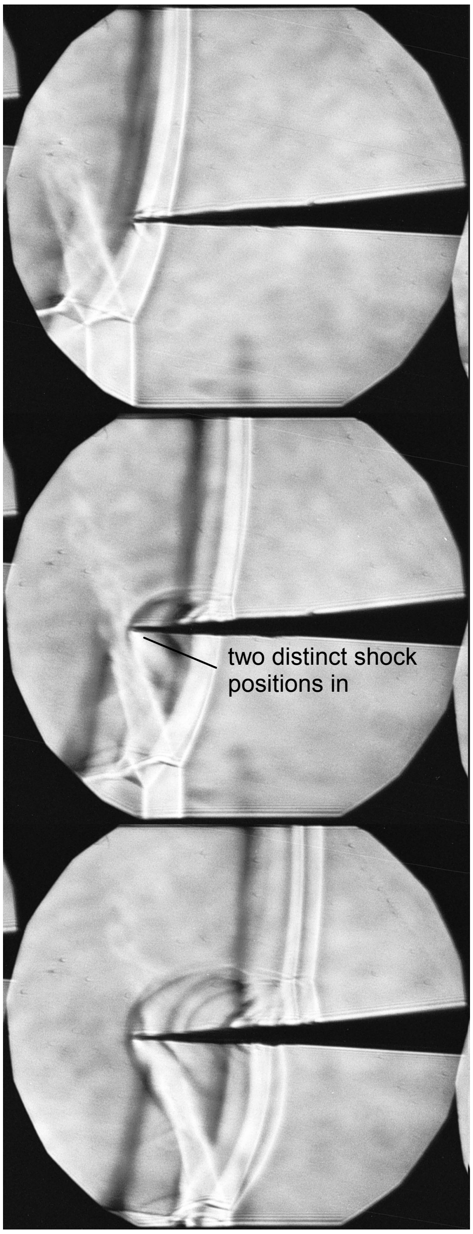

Fig. 4: Details at $\lambda = 2$ d ($\Delta t = 5$ µs)

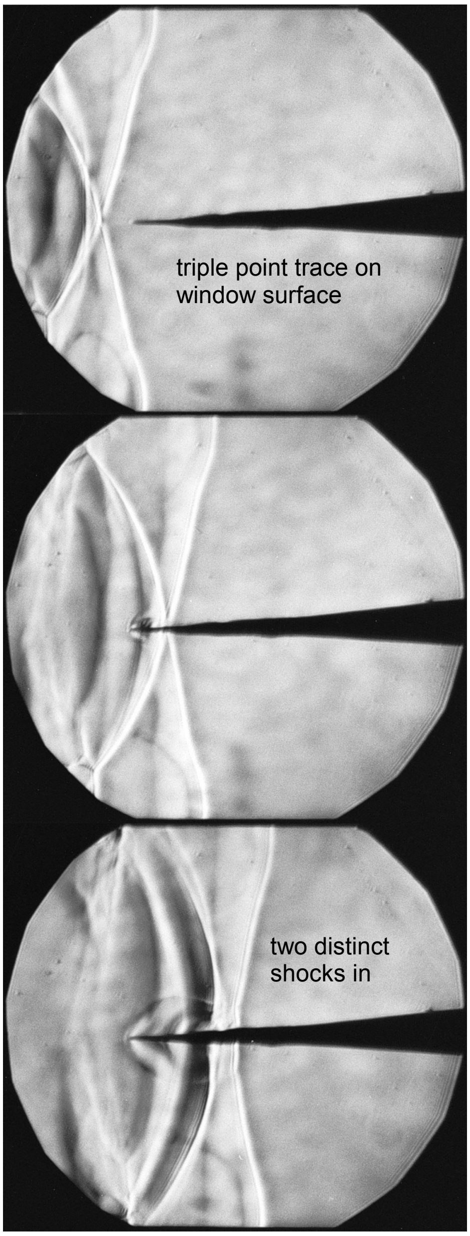

Fig. 5: Diagonal-mode at $\lambda = 1.4$ d

Determination of separation time and results

For each experiment 6 to 12 frames are analysed - 1 or 2 of them before engulfing. The engulfing time t_0 is calculated from the maximum and the minimum front positions of three frames around t_0 with a linear fitted curve. For transverse wave spacings $\lambda > 0.5$ d three front positions on the centerline of the blade are taken for the evaluation. The position of the separated shock varies due to 3D-effects along the optical integration line. Additionally it becomes weakened quickly. For both reasons the observed schlieren effect can reach extensions of up to 2 mm, which is not measurement inaccuracy but physical effect. The shock position x_R is determined in the middle of the schlieren effect. If the local flow direction at the moment of engulfing is oblique to the blade a stronger reflection occurs and leads to a pre-separation. At lower pressures occasionally two different shock positions just in front of the blade could be distinguished (Fig. 4-6). Their mean position is shown in Fig. 7 together with error indicators.

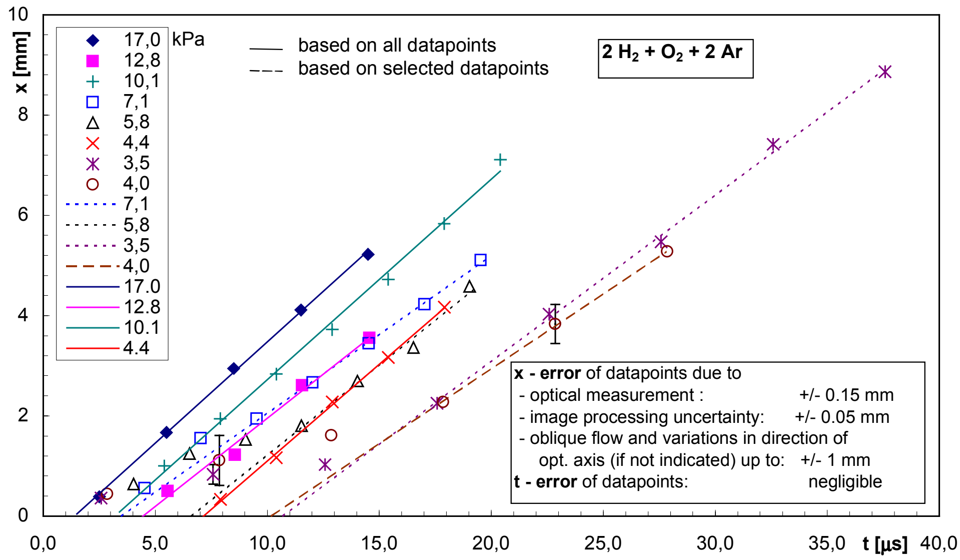

Fig. 7: Paths of separating shock waves for $2H_2 + O_2 + 2Ar$

The separated shock reaches nearly constant velocity - after initial fluctuations. At higher pressures, i.e. small cells, short times, and short ways, initial fluctuations could not be observed. For these experiments a linear fitted curve was calculated for all data points, while for the other experiments the last (3-5) - apparently linear - data points were selected for the approximation. The time of separation t_S is determined from these curves, even though separation occurs locally earlier. The location of the sonic surface is determined with D:

$$x_S = t_S * D$$

The same is also valid for the four experiments in the pure mixtures. Figure 8 compares the results of this work with those of Vasiliev. The error bars indicate the influence of the framing accuracy on the exact determination of the blade edge position. It is obviously smaller for larger cell sizes, while in contrast these will spread more, due the instantaneous front assemblage. Further experiments will be performed to account for the spread. The relative local front velocity at engulfing is given as reference.

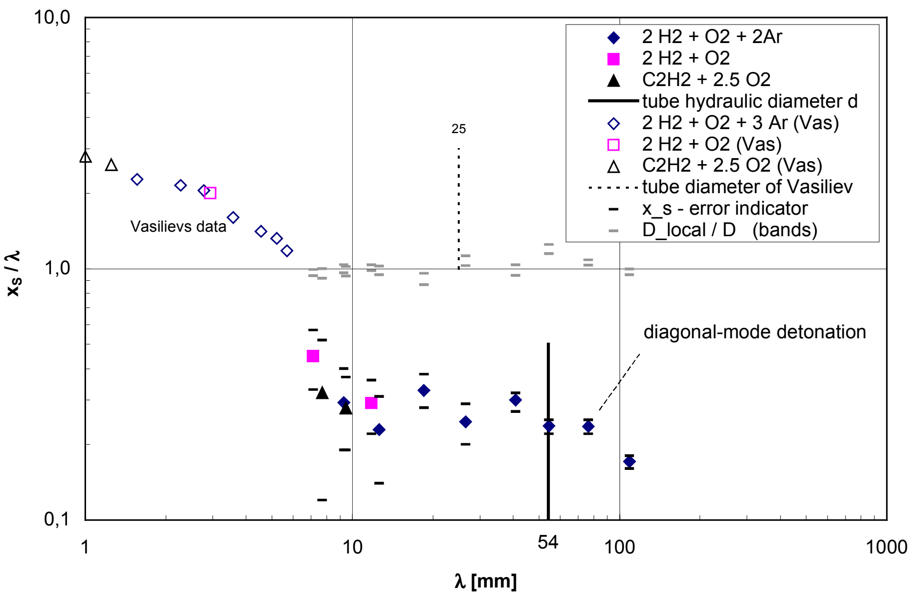

Fig. 8: Location of the sonic surface

Conclusion

Regarding the overall tendency, it can be stated that the ratio x_S/λ decreases with λ - or increases with pressure. Considering especially the low slope between 10 to 54 mm, it becomes obvious, that it is not the proximity of λ to the tube diameter that lowers x_S/λ. We cannot yet explain the step between the results of Vasiliev and ours. An influence of details of the determination method is possible, but Vasiliev did not report them in his article.

Outlook

As the framing frequency ultimately could be risen up to 700 kfps (probably even 1 Mfps), experiments at higher pressures, which demand a high temporal resolution, will facilitate better comparison to Vasilievs results. Measurements at the end of a flat duct with $d_h << d$ will provide additional information about the influence of the hydraulic diameter of the tube. The velocity of the separating wave will be correlated to the speed of sound and the absolute velocity in the CJ-state. The x_S/λ decrease will be compared to ZND calculations.

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