

On critical conditions of the flow within the cellular detonation structure

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1 Introduction

The cell size is an important scale factor responsible for the wave stability at diffraction and transient detonation phenomena [1-3]. The formation of cells is the result of the strong coupling and interaction between chemical and gasdynamic processes that proceed in a post-shock flow of the propagating detonation. This interaction occasionally generates necessary conditions across the flow field for the next cell re-initiations in time and in space. When these conditions are not reached the decoupling results in both the disintegration of a detonation structure and the subsequent transition into the low-velocity propagation mode. The knowledge of critical gas parameters released along the cells required for the decoupling is important for both practice and theory, because they determine a stability of the detonation. This work addresses to systematic measurements of shock wave and reactive flow parameters released along the marginal and normal detonation structures of different regularity with objectives to establish critical flow conditions required for completion and reinitiation of the cell cycle [4,5].

2 Experimental setup

Experiments were performed in a smooth tube with inner diameter of 50 mm. The aspect ratio L/d of the tube was more than 200 to ensure an adequate travel for the observation of stable detonations. A 100 mm driver section containing a $C_2H_2+2.5O_2$ mixture was used to provide the initiation. The pressure of a driver gas was usually made higher than that of a test mixture in order to initially overdrive the detonation. For stable regimes of the wave propagation in the measuring part of the tube a minimum pressure ratio between driver and working gases was maintained prior to detonation initiation. Irregular stoichiometric C_2H_2 – air and regular lean 3.5% $C_2H_2+26.5\% O_2+70\% Ar$ mixtures [6] at different initial pressures and ambient temperature were used in these studies.

Spinning and two-cell marginal and three-cell normal detonation structures in a round tube [7] were tested. Ion and pressure sensors measured detonation velocity and pressure, and smoked foils recorded a cellular structure. 105 cm- and 24cm-long sections of the tube were equipped with 28 and 9 ports to measure reaction flow velocity during the detonation traveling. The distances between ports were equal to the quarter (39 mm) and eighth-length (19.5 mm) of the spin pitch πd , where d is the tube diameter. Each port consisted of four ion sensors. Thus, the velocity evolution and bulk structure of a reaction front has been carefully studied over the length of 105 cm before the detonation transmission into the 24-cm end section applied for simultaneous smoked-foil, ion current and pressure observations. Figure 1 illustrates the arrangement of ion and pressure gauges relative to smoked foils of spinning and two-cell detonations in 24-cm end section of the tube. The axial distance of 19.5 mm between sensor locations was much less than a length of the detonation cell and determined

the spatial resolution of the method. As is seen in the figure, an ion gauge technique can provide precise reaction flow measurements for spinning detonation waves (the spin pitch is 150 mm) and ensures acceptable spatial and temporal resolutions for two- (length is ≈ 90 mm) and three-cell (length ≈ 70 –80 mm) detonations.

Only those experimental runs were selected for a further analysis in which the orientation of pressure and ion sensors coincided with the centerline of the detonation cell (Fig. 1b). For spinning detonations, this requirement was fulfilled automatically. The data were collected from different runs performed at identical initial pressures and showing the same type and symmetry of cell pattern.

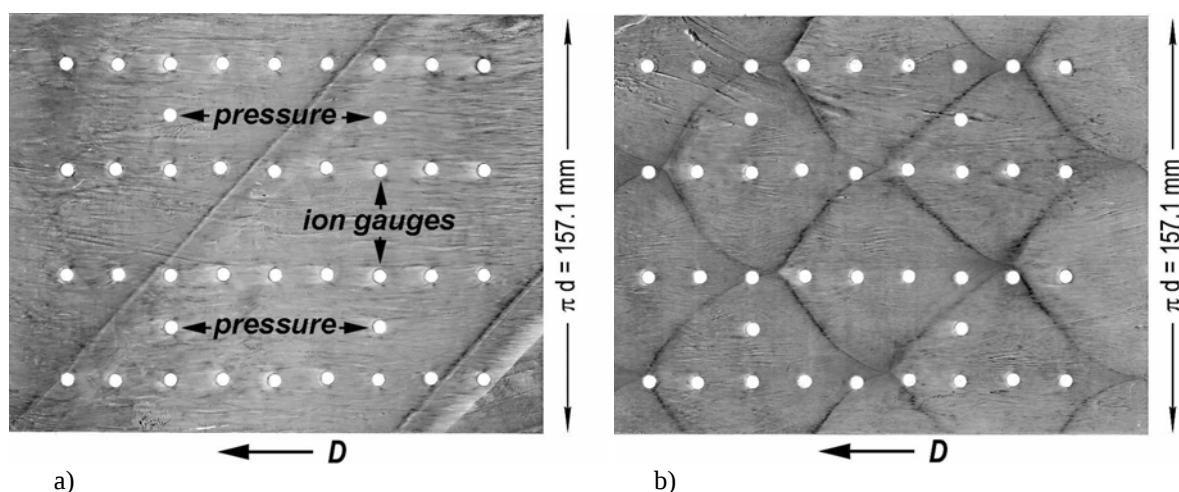


Fig. 1. Soot imprints of the detonation propagation along the end part of the tube and positions of ion and pressure sensors relative to smoked foils of spinning (a) and two-cell (b) marginal detonations. Mixture 3.5% $C_2H_2 + 26.5\% O_2 + 70\% Ar$

3 Results

For regular and irregular mixtures, Figure 2a shows measured velocities of the reaction front as a function of distance along the structure of a spinning detonation. The entire scale of the x-axes in the plots corresponds to the spin pitch. As is seen in the figure, the velocity data were distributed in two characteristic domains. The velocity measurements provide reasonable values only for domain I (Fig. 2a). In domain II, the transverse wave (TR) propagating along the detachment zone between leading shock and reaction fronts and having a size of $1.1 R \approx 27.5$ mm [8] can transverse almost instantaneously a space between neighboring ion gauges and the local reaction front velocity becomes discontinuous [9, 10]. Thus, for distances exceeding 100 mm along the spin pitch longitudinal velocities of the reaction front obtained from local ion current measurements are overestimated significantly (Fig. 2a, domain II). In addition, the concept of mean velocity has no sense in domain II due to the flow discontinuity.

Minimum and maximum velocities of the reaction front along the cell were established using the linear approximation of experimental points at the beginning and at the end of the domain I (Fig. 2a). For spinning, two- and three-cell detonation structures, minimum velocities of reaction front were realized at the end of domain I. For spinning detonations in regular and irregular mixtures within the scatter of experimental data, minimum velocities of reaction flow conformed well to isobaric sound speeds of combustion products a_{isobar} . Peak velocities of reaction front along the tube were detected after cell reinitiation at the beginning of the detonation cell. These maximum values were by a factor of 2.02–2.1 larger than those of the isobaric sound speed of combustion products. Thus, the experiments evidence that for spinning detonations the critical condition in reacting flow required for the local completion and reinitiation of a detonation cycle along the tube is the flow choking. In addition, the choking distance corresponding to the path traversed by reaction front during a decay time from peak to sound velocity should be directly proportional to the cell length of the mixture.

Figures 2b shows pressure records at selected locations within the structure of spinning detonations (Fig. 1a). Measurements of the pressure differential P/P_0 across the front of leading shock wave obtained from experimental observations provides a tool for estimation of shock wave and post-shock gas velocities using a shock adiabatic curve. For irregular acetylene/air mixture the dynamics of reaction flow exhibit the stronger level of coupling between the leading shock wave and the reaction zone. The decay rate of a shock wave velocity is approximately the same as for the reaction front due to a lower specific heat capacity of the gas. This results in the smaller detachment zone between the leading shock wave and the flame front in comparison with argon diluted mixture (and, consequently, in a weaker intensity of the transverse detonation. For regular mixture, a high specific heat capacity of the gas caused by a significant argon additions leads to a fast grow of a detachment zone, which weakens the coupling between the leading shock wave and the reaction zone and results in a stronger transverse detonation (Fig. 2a).

For two- and three-cell detonations, main features of the flow evolution along the cellular structure were very similar to those in spinning detonation case. Taking into account the worse spatial resolution of the ion gauge technique that averages the measurement results over the distance of 19.5 mm the minimal velocity of the

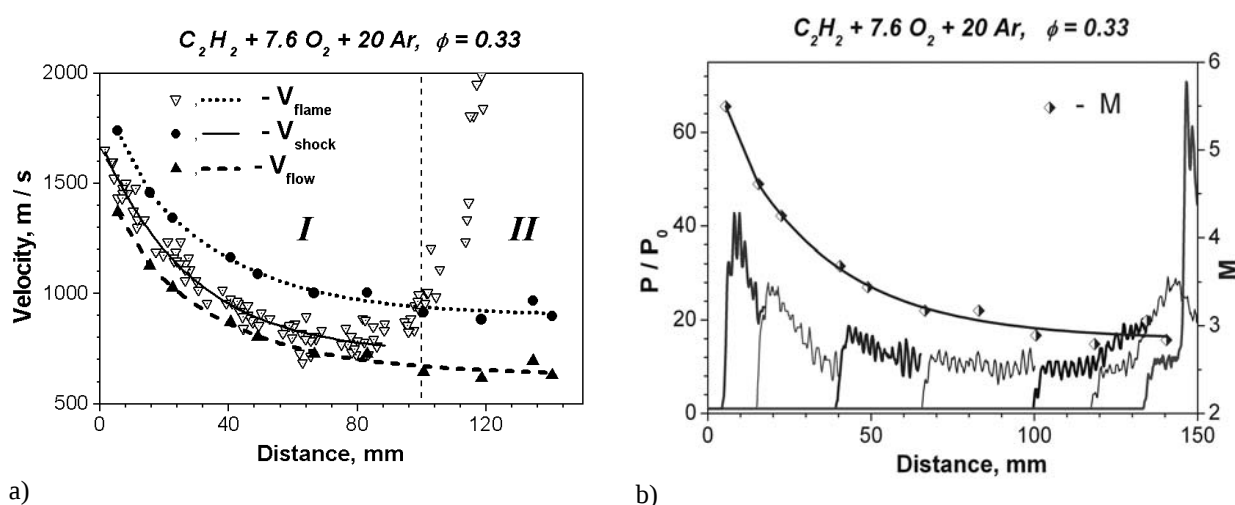


Fig. 2. Distribution of flow parameters along the structure of spinning detonation in regular 3.5% C_2H_2 +26.5% O_2 +70% Ar mixture: shock wave, flow and reaction front velocities (a) and Mach number, pressures (b) vs. distance along the spin pitch.

reaction flow exhibits a good correlation with isobaric sound speeds of combustion products a_{isobar} . Besides, the averaging overestimate slightly the minimal velocity of a reaction flow in comparison with its local value and this should improve the coincidence with a_{isobar} too. As for the case of spinning detonation, the choking distance corresponding to the traveling path of reaction front from peak to sound velocity is directly proportional to the detonation cell length.

Similarly, the peak velocity along the tube was released after reinitiation at the beginning of the detonation cell. This maximum value was by a factor of 2.17 larger than the sound speed of combustion products.

4 Conclusions

One can definitely say that for both marginal and normal detonations the cells are re-initiated when within the scatter of experimental data a local flame velocity decays to the some critical value, which is very close to the isobaric sound speed of burnt mixture. It was established that the rate of velocity decay from peak to critical

value determines the length of the detonation cell. Because of it, a distance of decay could be used as the proper length scale for diffraction and transient detonation phenomena instead of the cell size.

It was shown that the flow dynamics within the structures of irregular detonation provides a stronger level of coupling between the leading shock and reaction fronts. This results in a smaller detachment zone and a weaker transverse detonation in comparison with regular argon-diluted mixtures.

Acknowledgements

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