Experimental Aspects on Detonation Cells : Past, Present and Future.

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Abstract

The multidimensional character of all detonation waves has been established experimentally about 40 years ago. The pioneering work of the russian schools of Moscow and Novosibirsk have been seminal in that respect. They demonstrate that the front shock was never planar as assumed by previous authors irrespective to the fact the detonation propagates close to the composition limits or not. In 1958, Denisov and Troshin (1) were stating that the scant amount of available information about the intrinsic nature of detonation waves is still the major hindrance to the development of a complete detonation theory. But, at the same time, they develop a new tracer method based upon the use of the imprint left over by the detonation in a soot layer deposited either on the walls of the tube, or on glass plates located inside the detonation chamber.The technique was used then extensively by Shchelkin and Troshin (2) to prove that any kinds of detonation (in tubes, in divergent ducts, or in spherical containers) were exhibiting the same type of behaviour, i.e. "irregularities" in the front shock. The size of these irregularities were sensitive to the initial pressure. For a given pressure of the combustible mixture the irregularities, as measured by the trace method and by the photoscanning method coincide in size within the limits of the measurements accuracy. All those detonations were named "pulsating" in contrast with the so- called spinning detonations observed close to the limits. These authors have also shown that for readily detonable mixtures the size of the irregularities became very small, of the order of .1 mm in a stoichiometric mixture of acetylene and oxygen at atmospheric pressure. Another technique to visualize the irregular detonation front was also used: imprints on a very thin lead foil mounted on a soft cushion exhibit the same type of irregularities.
Furthermore, with the use of the motion-compensation method to record the luminous structure of the front wave, Voytsekhovskiy, Mitrofanov and Topchian (3) were able to demonstrate also the multidimensional character of the leading front of a detonation. They called that structure a "multifront" detonation, but it is totally equivalent to the "pulsating" type. From a combination of a sequence of stroboscopic laser shadow photographs obtained with a smoke film deposited on one of the glass wall of the detonation tube, Oppenheim's group (4) was able to show how these traces were recording the multiheaded wave front. At last, it should be mentioned that interferometry is also a valuable tool to record the irregularities of the detonation front, as it was demonstrated by D. White (5), but that technique is less straightforward to be applied in a quantitative manner.

Later on, the soot track method has been used extensively by several research teams among others: Edwards, Knystautas, Lee, Manson , Oppenheim, Strehlow, Wagner and myself. That method became, thus a standard technique to visualize the front structure of a detonation wave and has been applied in a variety of experimental conditions which will be reviewed briefly later.

It is appropriate here to mention the extensive studies of Strehlow's group about transverse wave spacings or its equivalent definition i.e. cell sizes. That group has investigated in the early seventies the nature (6) and the strength (7) of the transverse waves in detonation, as well as the transient phenomena (8), and the role of the chemical nature of the explosive mixture on the detonation structure (9,10). When the structure is observed to be extremely regular the detonation is called an equilibrium configuration detonation. These equilibrium configuration detonations have the property that their structure is exactly repeatable at equal time intervals of distance down the length of the tube. Stoichiometric hydrogen-oxygen mixtures that contain more than 50 per cent of an inert monoatomic gas such as argon or helium propagate in rectangular tubes as equilibrium configuration detonations. From studies (8) in rectangular tube in which the detonation passed from one mixture into another with different properties without any diaphragm , Strehlow's group has been able to determine which waves are to fail and which are to continue propagating. Waves were never observed to disappear by merging with one another . But, the spacing which is smaller than the preferred transverse wave spacing for specific incident conditions causes a very rapid decay of a specific transverse wave. Furthermore, in these experiments the failure was always rapid once it began. On the contrary, experiments of detonation transiting into an inert gas show that the natural rate of decay is much slower. They have observed also a complex process for the formation of new waves in which each original wave of the system spontaneously forms two new waves. It appears from the

record that this formation process may have a three dimensional nature because the waves originate in a region where the orthogonal minor mode waves are interacting with the major mode waves.

Although the detonation structure revealed by the soot imprints is the mere consequence of the gasdynamics of the triple shock configurations and interactions, they are very sensitive to the composition of the fresh gaseous mixture as shown already by Shchelkin (2) and Strehlow (6). Dove and Wagner (11) have shown the influence of hydrogen content in carbon monoxide-oxygen mixture on the mechanism of spinning detonation by using photographic method. It has been demonstrated (12) how very slight changes of the chemical process caused by promoting or inhibiting species added in traces to the original mixture can modify the detonation cell size at the same initial pressure and at an equivalent energy content of the fresh gases mixture. The influence of chlorofluorinated hydrocarbons on the detonations propagating in carbon monoxide-hydrogen-oxygen-argon mixtures is quite clear in that respect. The addition of similar bromo compounds is still more efficient to modify the heat release rate in the reaction zone of the detonation (13). Typical soot records of the same benchmark mixture where 1.87% of five different additives are present are shown on figure 1. The cell sizes are drastically different according to the nature of the additive.

Erratic structures have been noticed in mixtures containing methane (6) or nitrogen oxides (14), they can be related to the reduced activation energy (E/RT_{VN}) of the overall heat release process as indicated by Manzhalei (15), or to the high activation energy (E) of the decomposition reaction required to sustain the chemical phenomena (14). A very unusual behaviour of detonation in nitromethane and nitromethane-oxygen mixtures has been observed by Presles et al. (16) a double scale cellular structure, it seems to be related to the two stage reaction mechanism of those systems. Large scale experiments on cell size have been performed on hydrogen-air-water mixtures to investigate their detonation sensitivity (17). Decomposition of explosive molecules such as hydrogen azide and chlorine dioxide exhibits also detonation structure, but the reliability of the soot imprints method reaches here its limit of application due to the non-negligible reactivity of those substances with the soot itself (18).

Besides the chemical influence on the cell size of detonation waves, recent developments (19) have indicated also the occurrence of different types of matching conditions of the detonation with the acoustic modes of a square cross-section tube. Two fundamental types were observed (figure 2): a rectangular and a diagonal structure. In the first case, the waves are orthogonal to the pairs of side walls of the square tube and they travel independently from each other, providing so the usual slapping waves corresponding to the reflection of the triple points line on the walls. In the second type where no slapping waves are visible, the triple points line are canted at 45 degrees to the walls. A better sustainance mechanism of the front shock is achieved in that configuration. By no means, that type of structure cannot be confused with the so-called planar detonation. That type of coupling between the front shock and the heat release zone is more efficient and achieve a better self-sustained detonation. The diagonal type which is easily reproducible is sensitive to the way the detonation is initiated. That problem is developed in another session of this colloquium. The various gas detonation mechanisms actually available and connected to the structure have been reviewed by Mitrofanov (20) it stresses out, once more, the essential 3D character of all stable detonation phenomena.

In conclusion, we can predict that the future work on detonation structure will require to consider both the accurate chemical description of the heat release process and the precise gasdynamics of the transverse waves interactions to achieve a clear understanding of the self-sustainance mechanism of gas detonation to be able to harness their formidable power for practical applications.

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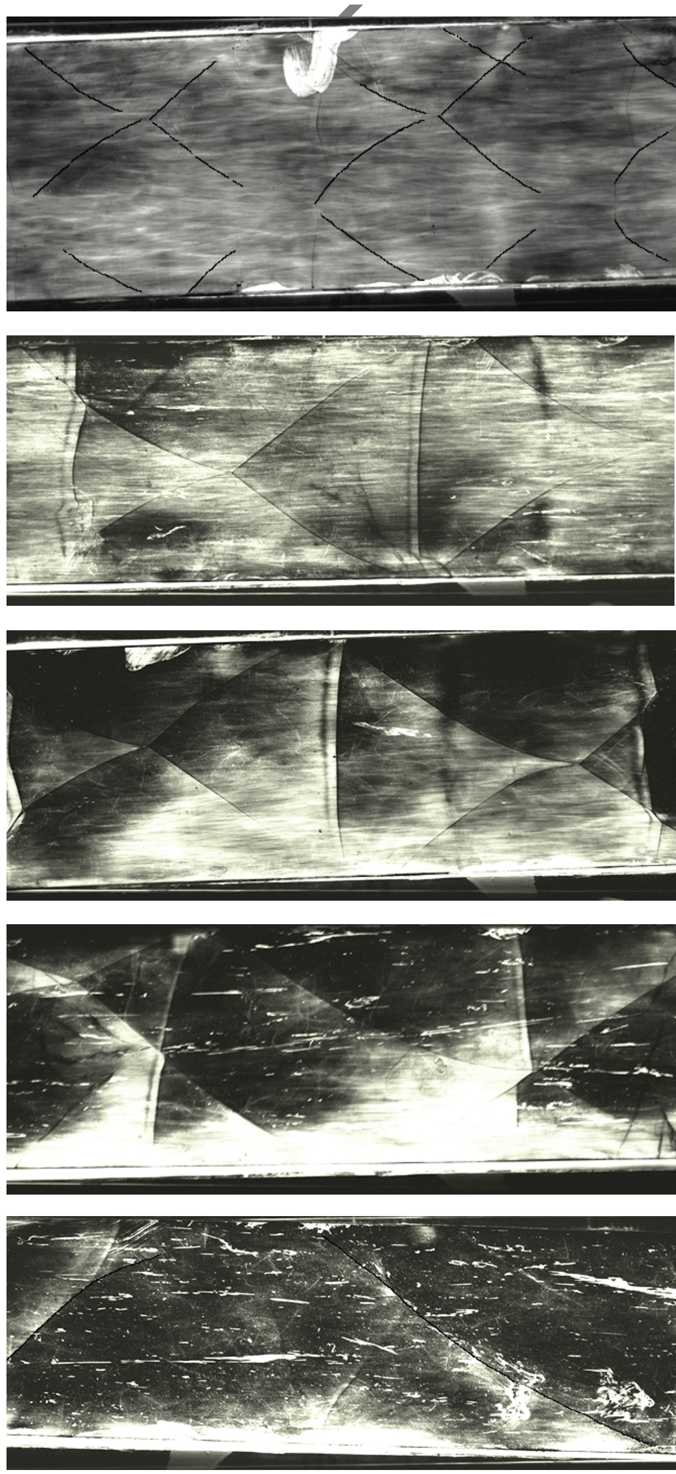
Mixture #5

H_2 - CO - O_2 - Ar - Inh. / 2.3 - 44.3 - 23.3 - 28.13 - 1.87 (%)
P = 100 Torr



$C_2F_4H_2$

C_2F_5H

C_2F_4HCl

CF_2HBr

CF_3Br

Figure 1:Comparison of soot records of selected experiments: reference mixture #5 containing 1.87% of (a) C2F4H2-mode 3, (b) C2F5H-mode 2, (c) C2F4HCl-mode 2, (d) CF2HBr-mode 2/1) and (e) CF3Br-mode 1. Some triple shock paths are enhanced.

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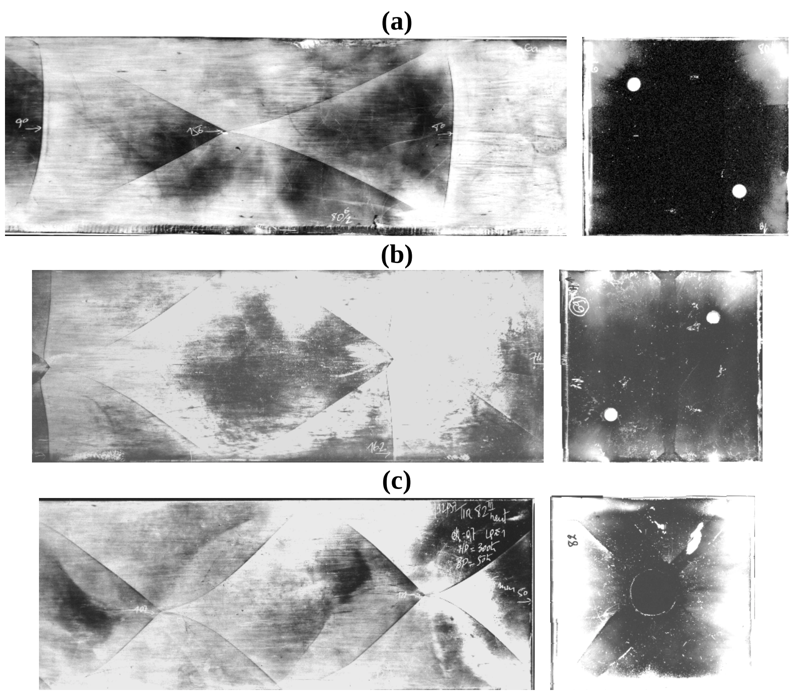

Figure 2: Types of multidimensional structures recorded on soot plates.for the same explosive mixture: (a) and (b) rectangular types with slapping waves, (c) diagonal type without slapping wave. Records on the left column are end-plates for the same run.