Study of Detonation in Condensed Explosives by One-Dimensional Channel Flow

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The detonation of mixtures of 80/20 ammonium nitrate/trinitrotoluene was studied using pseudo one-dimensional channel flow. A layer of explosive was confined symmetrically by two relatively massive metal plates whose shock velocity was higher than the detonation velocity of any of the explosive mixtures studied, thus producing a close approximation to a steady-state two dimensional detonation. From measurements of the plate velocity the flow could be analyzed as a pseudo one-dimensional channel flow. The quantity $(dP/d\rho)^{\frac{1}{2}}$ was found to have a maximum which served as an approximate experimental measure of the location of the Chapman–Jouguet point. The observed dynamic quantities were in substantial agreement with the Zeldovich–von Neumann–Doering model. Variation of the particle size of the ammonium nitrate produced a complex effect on reaction time, which could be adequately interpreted in terms of the three reaction steps in the detonation. Flash radiography provided a check on the one-dimensionality of the flow and allowed a rough estimate of the density profile behind the front, which was compared with the optical results.

INTRODUCTION

THE description of a detonation wave as a reaction initiated by a shock wave was put forward by Zeldovich[1] in 1940, and independently by von Neumann[2] and Doering[3]. The description was simplified by these idealizations: The system was assumed to be one-dimensional, and the detonation wave was assumed to consist of three separate parts—a shock wave, a steady reaction zone in which the reaction proceeds to completion, and finally a rarefaction wave which satisfies the rear boundary conditions. If a granular solid explosive is being treated as a continuous medium, the shock front must extend over a distance equal to several times the particle diameter. For fast reaction rates, the overlap of reaction zone and shock front could be important. The rarefaction may be eliminated by sustaining the detonation by a piston or in principle by supplying a suitable starting transient to form the steady reaction zone and to place the leading edge of the rarefaction wave far enough behind the shock front to allow essentially complete reaction, but only if one-dimensionality can be maintained through the steady zone.

In practice a rarefaction wave due both to lateral expansion and to the effect of the rear boundary generally overlaps the reaction zone, thus increasing the difficulties encountered in studying the reaction zone of detonations in condensed explosives. Part of the difficulty in studying the reaction zone is due to the fact that when the detonation closely approaches the one-dimensional steady-state Zeldovich–von Neumann–Deoring model, the measuring devices used to detect the reaction zone introduce transient or three-dimensional effects. In previous measurements of this type[4] involving end-on impact of the detonation against a metal plate the impedance of the metal was not exactly equal to that of the reacting explosive, and a wave was reflected from the interface back into the detonation products. Despite the disturbance by the reflected wave, this and similar measurements of the reaction zone length have been the most reliable ones available for condensed explosives. Measurements made on long columns of explosive by x-ray transmission, optical interference, or wall pressure gages all suffer to some extent from deviations from one-dimensionality. In detonations in long columns of solid or liquid explosives, a close approach to a steady state may be attained, but an appreciable deviation from one-dimensionality is caused by lateral expansion, which is appreciable even for charges confined by heavy metal walls. For unconfined or lightly confined solid explosives, the effects of lateral expansion are quite large.

Most of the experimental determinations of the reaction zone length in condensed explosives have been indirect. The experimental data comprise values of detonation velocity as a function of charge size, with the explosive either unconfined or confined by

[1] Y. B. Zeldovich, Zh. Eksperim. i Teor. Fiz. 10, 542 (1940).
[2] J. von Neumann, Office of Scientific Research and Development Report No. 549 (1942).
[3] W. Doering, Ann. Physik 43, 421 (1943).
[4] R. E. Duff and E. Houston, J. Chem. Phys. 23, 1268 (1955).

walls of different impedance. A number of approximate theories[5–7] have been developed to relate data on the detonation velocity versus diameter to the reaction zone length. In most cases, and especially for unconfined charges, the system is extremely complex, consisting of a collection of stream tubes which differ widely in character. The situation is further complicated by the fact that the rate of chemical reaction depends strongly on the variables (e.g., temperature and pressure) which are influenced by the flow, and in turn the flow is strongly influenced by the energy released by chemical reaction.

To attempt a separation of the interacting effects of lateral expansion and chemical reaction, it is desirable, and perhaps even necessary, to observe the behavior of a single stream tube. The experimental difficulties in measuring the properties of an internal stream tube can be avoided if a system can be selected in which the flow is nearly the same throughout the cross section of the explosive, i.e., a system in which all the explosive lies in a single stream tube. Such a system can be analyzed as a pseudo one-dimensional channel flow with varying cross-sectional area. The requirements to be met are that the area must change gradually and the walls must be free of sharp changes in angle. The gradual area change can be insured by confining the explosive in realtively massive walls of high impedance material. A sharp angle will, however, occur at the line of contact of the detonation front with the wall if the detonation velocity appreciably exceeds the weak shock velocity (or plastic sound velocity) of the wall material. In this case, the wall will be deflected by an oblique shock attached to the detonation front. On the other hand, if the detonation velocity is less than the sonic velocity of the wall material, the steady-state flow configuration will exhibit no shock waves in the wall, and the boundary of the explosive will have no discontinuities in angle. For example, with stainless-steel walls the detonation velocity must not exceed 4.5 mm/μsec, so that military explosives at high density cannot be studied in this way. Most explosives at densities less than 1.0 g/cc, and many commercial explosives of somewhat higher density, have sufficiently low detonation velocities to be studied.

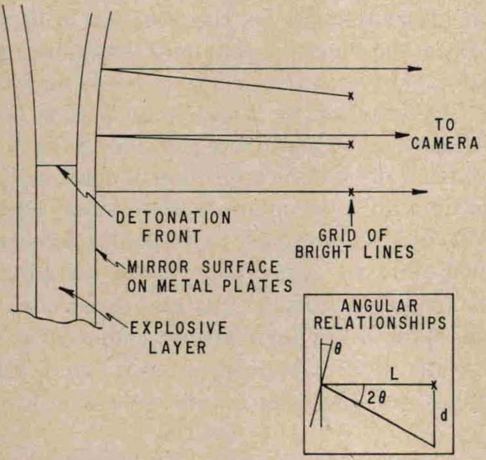

FIG. 1. Method of measurement of plate angle by the reflection of the image of a grid from the outside surface of the confining plate assembly.

[5] H. Eyring, R. E. Powell, G. H. Duffy, and R. B. Parlin, Chem. Rev. 45, 69 (1949).
[6] H. Jones, Proc. Roy. Soc. (London) A189, 415 (1947).
[7] M. A. Cook, *The Science of High Explosives* (Reinhold Publishing Corporation, New York, 1958), pp. 125–128.

EXPERIMENTAL

Experimental Method

The system chosen to meet the requirements for the application of a one-dimensional channel flow treatment consisted of a symmetrical sandwich of two parallel flat metal plates containing a layer of explosive, as shown schematically in Fig. 1. The explosive was initiated along the top edge by a line–wave generator. The length and width of the explosive and plates were much greater than the thickness. Observations of plate motion were made as described below in a region half way between the lateral edges and near the end (bottom) away from the initiation end. The edges were confined by heavy steel bars. A typical assembly was 8 in. wide × 12 in. high with a $\frac{1}{2}$-in.-thick layer of explosive confined between two Type 304 stainless-steel plates each $\frac{1}{4}$ in. thick. Stainless steel was a reasonable compromise for the requirements of high density, high sonic velocity, and relatively low elastic strength.

A direct measurement of the velocity of the plate as a function of distance behind the detonation front during passage of the detonation enabled the determination of the width of the channel occupied by the reacting and expanding explosive and of the pressure exerted by the explosive against the plate. Since the plate configuration was a steady one moving along the plate at the detonation velocity D, a measurement of the angle θ by which the surface of the plate was deflected gave a direct measure of the velocity of the plate as a function of distance y behind the detonation front. The deflection of the plates was obtained by observing the displacement of the image of a grid reflected in the polished outside surface of one of the plates. This method has the sensitivity required to determine the pressure in the region immediately behind the detonation