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Simulation of Condensed-Explosive Detonation Phenomena with Gases

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The detonation of a condensed explosive within a solid container and the detonation of a gaseous explosive within an inert-gas boundary are found to be hydrodynamically similar situations. Experiments with hydrogen, methane, ethane, and propane-oxygen mixtures confined by air or helium boundaries show that, as with condensed explosives, the properties of the boundary strongly influence the detonation characteristics of the explosive. Schlieren photographs of the interaction process between a gaseous detonation wave and an inert-compressible-gas boundary show that the detonation wave becomes curved, and in some cases is quenched, the quenching process being initiated at the compressible boundary. Either oblique or detached shocks are found to occur in the boundary. These observations parallel those made from experiments in which condensed explosives were confined by solid boundaries. With the use of an idealized-flow model, the acoustic-impedance ratio of the gaseous boundary to the explosive is determined to be the parameter which characterizes the confining ability of the boundary. Application of these results to condensed-explosive detonations provides an understanding of some experimentally observed phenomena

INTRODUCTION

THE detonation pressures of most condensed (i.e., liquid or solid) explosives are of the order of 10^5 atm. At these pressures any presently known materials become plastic or, in essence, compressible.[1,2] The confinement of a condensed-explosive detonation wave is therefore never "perfect" since any container a condensed explosive is detonated within yields under the influence of the detonation pressure and thereby allows the detonation process to depart from one dimensionality. Since an interaction process takes place between the boundary and detonation wave, it follows that the detonation properties of condensed explosives are observed to be strongly dependent upon the nature of the container.[3,4] The curvature of condensed-explosive detonation fronts has also been observed experimentally.[5]

The concept of a solid boundary becoming compressible under explosive attack suggested to the authors that some understanding of the manner in which various containers influence the detonation characteristics of condensed explosives could be obtained by studying the effect of confining gaseous explosives with inert gaseous boundaries. The detonation of a gaseous explosive under these conditions provides circumstances analogous to those experienced by a condensed explosive detonated within a solid container. Setting aside for a moment the question of the validity of the suggested analogy, the advantages of such a simulation process are self-evident. In experimental work with condensed explosives one must contend with their awesome destructive power, while theoretical endeavors are beset with fundamental problems relating to their thermodynamic properties and equations of state.[6,7] The study of gaseous explosives imposes none of these problems.

Some of the most enlightening experiments performed to determine the influence of the container on condensed explosives were those of Campbell *et al.*[3] They found that at room temperature the liquid explosive nitromethane would detonate in brass tubes of 3-mm i.d. and 1.6-mm wall thickness, and in Dural tubes of 4.8-mm i.d. and 1.6-mm wall thickness, but would fail in glass tubes below 17-mm i.d. They also found that lining a glass tube with a 2-mil-thick layer of aluminum foil reduced the "failure diameter" of the glass toward that corresponding to a tube made entirely of Dural. Further evidence of the container's influence was provided by lining a glass tube, whose diameter was smaller than the failure diameter, with thin platinum foil. The tube was lined for several inches

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[1] R. W. Goranson, D. Bancroft, B. L. Burton, T. Blechar, E. E. Houston, E. F. Glittings, and S. A. Landeen, J. Appl. Phys. **28**, 1472 (1955).

[2] M. H. Rice, R. G. McQueen, and J. M. Walsh, in *Solid State Physics*, edited by F. Seitz and D. Turnbull (Academic Press Inc., New York, 1958), Vol. 6, Part I.

[3] A. W. Campbell, M. E. Malin, and T. E. Holland, Second ONR Symposium on Detonation (1955).

[4] L. Medard, Mém. des poudres **39**, 47 (1957).

[5] M. A. Cook, *The Science of High Explosives* (Reinhold Publishing Corporation, New York, 1958), p. 100.

[6] S. J. Jacobs, ARS J. **30**, 151 (1960).

[7] S. Paterson, Tek.-Vetenskap. Forsk. **29**, 109 (1958).

with 1-mil-thick platinum foil, for the next several inches with $\frac{1}{2}$ mil foil, and for several more inches with $\frac{1}{5}$-mil foil. Investigation showed that a detonation in nitromethane would propagate through the two regions having the thicker foil but quench in that lined with only $\frac{1}{5}$ mil of platinum. In addition, the failure process experienced by a detonation wave was observed in all cases to proceed from the boundary inward toward the tube center. Experiments by these same investigators eliminated chemical seeding, catalytic action, or surface smoothness as possible explanations for the results.

With the hope that understanding of condensed-explosive detonation phenomena might be obtained, a theoretical and experimental study of the interaction between gaseous detonation waves and inert gaseous boundaries was performed.[8] The portions of that study which relate to the suggested analogy are described herein.

EXPERIMENTAL INVESTIGATION

In order to study experimentally the influence of a compressible boundary on a gaseous detonation wave, it appeared desirable to impose the compressible boundary only on fully formed Chapman-Jouguet detonations. A Chapman-Jouguet detonation is one which satisfies the unique condition that, relative to the wave, the combustion products leave the wave at the local speed of sound, i.e., at Mach 1. (This rather oversimplified model of a Chapman-Jouguet detonation was used throughout for convenience and because it was consonant with the qualitative nature of the calculations. Recent modifications to this model have been proposed, however, and are noted in reference 9.) This is the type of detonation process which results from igniting a quiescent, detonable mixture in a constant-area pipe, for example, and allowing sufficient distance for the detonation to stabilize. In the absence of any disturbing influences, e.g., imperfect confinement, the supersonic shock wave and the chemical-reaction zone of the detonation will become coupled, such that the reaction supplies just the energy required for the continued propagation of the shock. Once formed, this process is normally quite stable. By subjecting only fully formed Chapman-Jouguet detonations to the compressible boundary, any alterations in the detonation wave's characteristics could be attributed to the compressible boundary and comparisons made between waves under perfect and imperfect confinement.

Experiments were conducted in vertically mounted detonation tubes so as to take advantage of stabilizing buoyant forces on some of the low-molecular-weight explosive mixtures used. The gases making up the explosive were introduced into the tube base through sonic orifices which faced each other, mixed, and allowed to flow upward through an approximately 5-ft-long tube, exiting at the top through the test section. The explosive was ignited at the tube base by a hot wire and Chapman-Jouguet detonations formed by natural transition from deflagrations. Explosive mixtures were formed of oxygen and fuels; the fuels used included hydrogen, methane, propane, and ethane. Most of the experiments were conducted in a rectangular detonation tube measuring $\frac{3}{8} \times \frac{1}{2}$ in. internally, although a few initial experiments were performed using a round pipe 0.3-in. i.d. Further details of the experimental setup are given in reference 8.

Instrumentation consisted of an electronic means of measuring the detonation velocity in the tube, accurate to within 0.5%, and an automatic time-delay unit for sequencing a spark-schlieren system. The spark-schlieren system was utilized to record the effects of the compressible boundary on the detonation wave. Because only one photograph was taken of each experiment, emphasis was placed on making the experiments highly repeatable. Proof of the repeatability of the experiments is evident in the data plotted in Fig. 5. It was generally found that the variation in detonation velocity among the test points for a given explosive mixture, was less than 1%.

The first experiments performed used the round detonation tube mentioned earlier. In these experiments a stable jet of 80% hydrogen–20% oxygen (all mixtures given on volumetric basis) was established at the exit of the tube. The velocity of the jet was in this, as in all other cases, so low as to be negligible compared to the Chapman-Jouguet velocity of the explosive (it never exceeded 0.3% of the Chapman-Jouguet velocity). The test section in this instance was merely the air around the tube exit. The jet of explosive in the air provided a compressibly confined column of explosive. Although some striking schlieren photographs were obtained, such as shown in Fig. 1, it was found that the detonation would not continue up the column of explosive any observable distance. In fact, this arrangement provided an excellent means of quenching the wave.

Figure 1 was taken using the knife edge parallel to the jet axis. The end of the detonation tube is

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[8] W. P. Sommers, Ph.D. thesis, University of Michigan, 1961.

visible at the bottom of the picture. Note that the jet can be seen ahead of the shock, which confirms that little mixing of the jet and air occurred. The "blunt body" trailing the shock front by a small distance is the gas interface between the air and the hydrogen-oxygen mixture. Although the detonation wave left the tube exit at just under 11 000 ft/sec, at the instant the photograph was taken the detonation had been extinguished and the shock speed had deteriorated to roughly 3000 ft/sec. At this point, the shock front is approximately seven tube diameters from the tube exit.

Following the experiments using a round detonation tube, two-dimensional experiments were performed. In this instance the test section was mounted on top of the rectangular tube described earlier and consisted of a 10-in.-long section of three-sided shock tube. One side was supporting metal structure and the two parallel sides were plate glass. The fourth side consisted of a two-dimensional jet of the inert gas used as the boundary. The glass walls of the test section served to maintain the two dimensionality of the experiment. The metal wall was effectively the centerline of a two-dimensional section, twice as wide as the one used, since any boundary-layer effects in the slow moving jet would have negligible influence on the rapidly advancing detonation front.

Both helium and air were used as boundary gases. The two adjacent two-dimensional jets satisfied the requirement of containing a gaseous explosive by an inert gas. Mixing and diffusion effects between the explosive and boundary were minimized satisfactorily by maintaining laminar jets and approximately equal flow velocities.

Schlieren photographs were taken of the interaction process between the detonation waves and the gas boundaries. Figures 2 and 3 are examples of the photographs taken. Figure 4 is an idealized schematic sketch in which the various flow features are labeled. In both Figs. 2 and 3 the detonation front is moving upward (in the x direction) while producing a shock wave in the boundary which trails or follows along with the detonation. In Fig. 2 the interface between the combustion products and the boundary gas through which the oblique shock wave has passed, is evident as a dark line which forms tangent to the oblique shock and diverges from it gradually, making a smaller angle with respect to the vertical direction than the shock (see Fig. 4). The edge of the explosive jet ahead of the detonation wave, although not visible in Fig. 2, is quite prominent in Fig. 3. In both photographs the detonation wave front is normal to the supporting wall to the left, suggesting that the Chapman-Jouguet condition must be satisfied at this point. Velocity plots of these waves confirmed this fact. Further explanation of the flow processes pictured in Figs. 2, 3, and 4 is given in Fig. 8 and its attendant discussion.

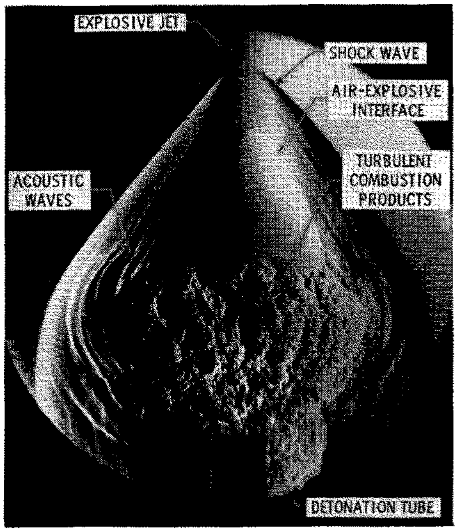

FIG. 1. Detonation failing to propagate up unconfined column of 80% hydrogen–20% oxygen within air boundary.

It is noted in both Figs. 2 and 3 that the detonation wave front is curved. To a lesser or greater extent, this was observed to be true of all cases in which a

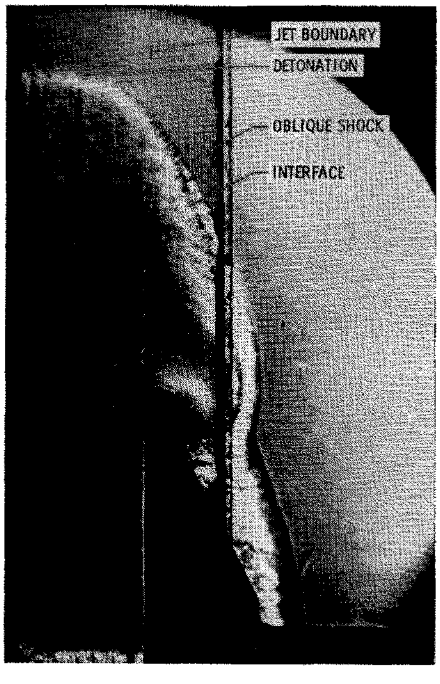

FIG. 2. Detonation of 50% hydrogen–50% oxygen mixture next to an air boundary.

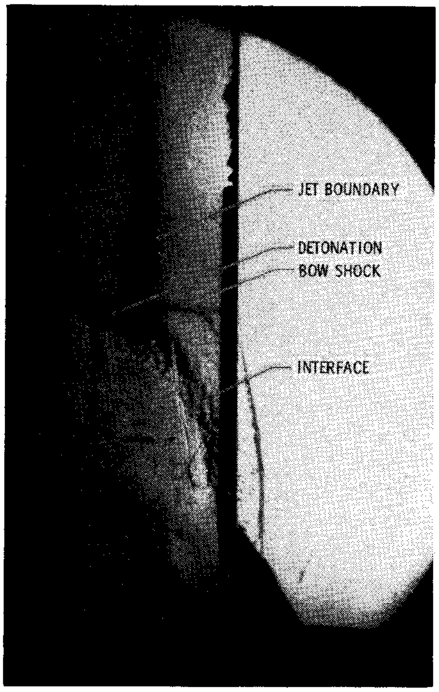

FIG. 3. Detonation of 35% hydrogen–65% oxygen mixture next to helium boundary.

gaseous explosive was bounded by a gas. A theoretical analysis of the diffusion and mixing processes between the explosive and boundary showed that neither effect could account for the curvature observed. In fact, dilution of hydrogen-oxygen mixtures with helium causes the detonation velocity to increase, rather than decrease, which would have caused the detonation to curve in the direction opposite to that it has in Fig. 3. The curvature was therefore concluded to be due to the compressible boundary permitting a departure from one-dimensional detonation,[9] the same reason curvature occurs in condensed explosive detonation waves.[10]

The shock in the air in Fig. 2 is a weak oblique shock, while that in the helium boundary in Fig. 3 is a detached shock. (The presence of a small metal strip at the glass edge caused the detached shock to acquire a lambda shock configuration at the edge.) It has been shown theoretically by Erkman that explosively induced shocks in solid materials can also be of either the oblique or detached variety.[11]

A most important objective of the experimental program was to learn whether a detonation wave would quench or continue propagating upon reaching the compressible boundary region. To determine this the wave position as a function of time was recorded. This necessitated performing many experiments under identical conditions and taking a photograph of each, the photographs being sequenced such that a complete history of a wave's travel could be pieced together from individual photographs. Figure 5 is a plot of wave position vs time for two mixtures of hydrogen and oxygen with an air boundary. The dimensionless distance is the distance the wave has traveled in the x direction divided by twice the tube width, or 1.0 in. (see Fig. 4). The time scale is in microseconds and represents the time elapsed between the wave passing a specific fixed point in the detonation tube and arriving at the position at which the photograph was taken. Negative dimensionless distances correspond to photographs taken of the wave front prior to reaching the end of the nozzle fairing which is the tube exit. The electronically measured detonation velocity of the 50% hydrogen–50% oxygen mixture prior to reaching the test section was 7570 ft/sec, the same as the velocity computed from the slope of the appropriate data in Fig. 5. The electronically measured detonation velocity of the 35% hydrogen–65% oxygen mixture was 6350 ft/sec, and equals that computed from the straight portion of the corresponding curve in Fig. 5.

Distance vs time plots of the type shown demonstrated that some gaseous detonation waves continued to move at Chapman-Jouguet velocity in

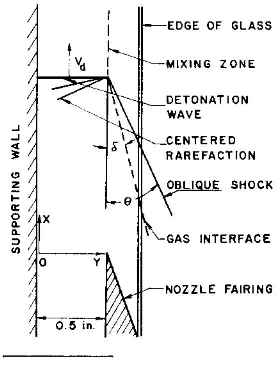

FIG. 4. Explanatory sketch of Figs. 2 and 3 using an idealized flow model.

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[9] Research on other forms of the departure of detonations from the ideal, one-dimensional flow model have been reported recently by J. A. Fay [J. Chem. Phys. **29**, 955 (1958)], D. R. White, [Phys. Fluids **4**, 465 (1961)], and Yu. N. Denisov, Ya. K. Trashin, and K. I. Shchelkin, [Bull. Acad. Sci. U.S.S.R., Div. Tech. Sci., Power and Automation, No. 6, 79 (1959)]. The research reported in these articles was concerned with detonation in one-dimensional passages. However, because of second-order effects usually neglected analytically such as turbulence, combustion instability in the reaction zone, and boundary-layer growth within the reaction zone, detonation under these conditions is not one dimensional. In the present study gross departure from one dimensionality is caused by the inherently two-dimensional nature of the confinement provided by the compressible boundary. Any second-order effects are considered to be negligible relative to the compressible boundary effect.

[10] H. Eyring, R. E. Powell, G. H. Duffey, and R. B. Parlin, Chem. Revs. **45**, 69 (1949).

[11] J. O. Erkman, Phys. Fluids **1**, 535 (1958).

spite of the presence of a compressible boundary. In these cases the wave became curved, the curvature process beginning at the compressible boundary and proceeding inward as the wave progressed in the x direction. However, after some distance the wave front appeared to achieve an equilibrium shape and propagated unchanged from then on. The mixture of 50% hydrogen–50% oxygen next to air plotted in Fig. 5 is an example of this.

In other cases, such as a mixture of 35% hydrogen–65% oxygen next to air, the curvature process again started at the compressible boundary, but in propagating inward resulted in the detonation being quenched. The quenching process was clearly observed by the shock gradually being separated from the reaction zone. While the same process must have occurred in the axisymmetric experiments attempted first, it was not observed. In the two-dimensional experiments the quenching process was plainly evident.

The success of the two-dimensional experiments over the axisymmetric ones in being able to propagate a stable gaseous detonation wave adjacent to a compressible boundary is undoubtedly due to two effects. First, a two-dimensional shock of the same Mach number as a three-dimensional shock is dissipated less rapidly, thus providing a higher-pressure field behind it. This fact would favor the two-dimensional experiments as the pressure ratio across the shock in the boundary will be seen shortly to determine the confining ability of the boundary. Second, since the two-dimensional jet of explosive was confined on only one side by the boundary gas, the metal wall became analogous to the centerline of a test section twice as wide. This means the tube of explosive was effectively increased in size from 0.3-in. diameter to 1.0-in. wide when the change from the axisymmetric to the two-dimensional arrangement was made. Since a size effect undoubtedly is present, this change may have been sufficient to insure operating above the failure diameter.

Some rather interesting similarities between the gaseous experiments performed and condensed detonation phenomena are now apparent. In both cases curved, rather than one-dimensional, detonation fronts occur. When a detonation is quenched, the quenching process begins at the boundary and progresses inward. And finally, the boundary shock is observed to have either an oblique or detached form.

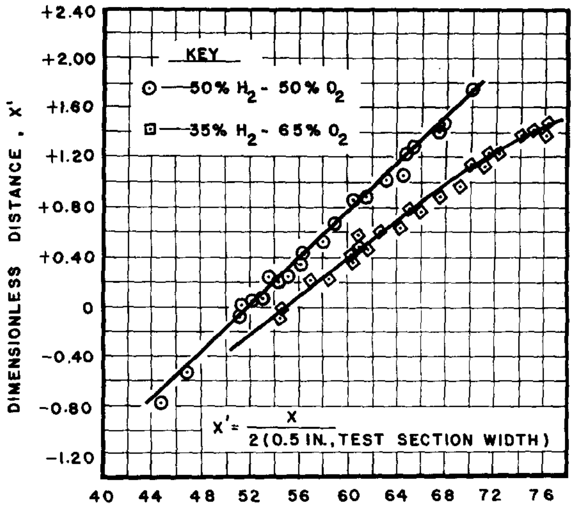

Fig. 5. Dimensionless distance of wave front from tube exit vs time delay for hydrogen-oxygen mixtures next to an air boundary.

THEORETICAL ANALYSIS

A theoretical analysis was performed of the idealized-flow model illustrated in Fig. 4 from which the shock angle θ and the interface angle δ were computed. Both the shock and detonation wave were considered to be vanishingly thin discontinuities. Initially it was also assumed that neither the detonation nor the shock wave had any curvature. Although it has already been seen in the photographs presented that this is not the case, it is a satisfactory first approximation which allows virtually all aspects of the interaction process to be explained. Some of the restrictions placed on the problem were subsequently relaxed in order to determine their influence on the solution.

If the coordinates of Fig. 4 are transformed such that both the explosive and the inert gas flow into the wave front at a velocity equal to the Chapman-Jouguet velocity of the explosive, the detonation and shock configuration become fixed in space.[12] Assuming ideal gases, the following relations can be written and utilized in a trial-and-error procedure to calculate θ and δ.

The interface angle and the shock angle are related by the equation[13]

$$\tan \delta = 2 \cot \theta \frac{M_{i1}^2 \sin^2 \theta - 1}{M_{i1}^2(\gamma_{i1} + \cos 2\theta) + 2}, \tag{1}$$

where M_{i1} is the Mach number of the inert-gas flow

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[12] Although the two gases have the same flow velocity they do not in general have the same Mach number. It was found that for virtually any combination of explosive and boundary gas, the Mach numbers of both flows were greater than one, meaning a shock wave must exist in the boundary. The same was found to be true for condensed explosives and solid boundaries.

[13] H. W. Liepmann and A. Roshko, *Elements of Gasdynamics* (John Wiley & Sons, Inc., New York, 1957), Chaps. 3 and 4.

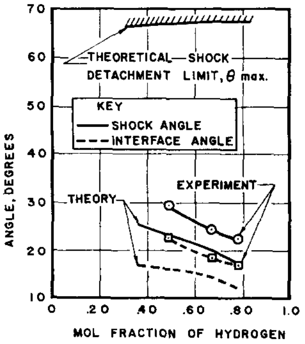

FIG. 6. Comparison of theoretical and experimental shock and interface angles for oxygen-hydrogen mixtures with an air boundary.

ahead of the boundary shock; i.e. $M_{i1} = V_d/A_{i1}$, V_d being the Chapman-Jouguet detonation velocity and A_{i1} the speed of sound of the inert gas. γ_{i1} is the ratio of specific heats of the boundary gas.

Assuming that the expansion of the detonation reaction products is isentropic, the Prandtl-Meyer relation can be used to compute the flow through the centered rarefaction. Since the flow is at a Mach number of 1 at the rear of a Chapman-Jouguet detonation, the Prandtl-Meyer angle ν must equal the interface angle δ.

$$\nu = \left(\frac{\gamma_{e2}+1}{\gamma_{e2}-1}\right)^{\frac{1}{2}} \operatorname{arc\,tan} \left[\frac{\gamma_{e2}-1}{\gamma_{e2}+1}(M_{e3}^2-1)\right]^{\frac{1}{2}} - \operatorname{arc\,tan}(M_{e3}^2-1)^{\frac{1}{2}}. \qquad (2)$$

γ_{e2} is the ratio of specific heats of the reaction products and M_{e3} is the Mach number of the reaction products following the Prandtl-Meyer expansion, i.e., M_{e3} is the local velocity of the reaction products following the expansion process, divided by the local speed of sound.

The static pressure ratio across the shock wave P_{i2}/P_{i1} is given by the expression

$$P_{i2}/P_{i1} = 1 + [2\gamma_{i1}/(\gamma_{i1}+1)](M_{i1}^2 \sin^2\theta - 1). \qquad (3)$$

The static pressure ratio across a Chapman-Jouguet detonation wave, P_{e2}/P_{e1}, is written

$$P_{e2}/P_{e1} = (1 + \gamma_{e1}M_{e1}^2)/(1+\gamma_{e2}), \qquad (4)$$

where γ_{e1} and M_{e1} are, respectively, the ratio of specific heats and the entering Mach number of the undetonated explosive; $M_{e1} = V_d/A_{e1}$, A_{e1} being the speed of sound of the undetonated explosive.

For a specific gaseous explosive and boundary, Eqs. (1)–(4) can be solved by an iterative procedure to determine θ and δ. This solution makes use of the additional condition that the flow direction on both sides of the gas interface must be identical, as must the two pressures P_{e3} and P_{i2}.

The computation procedure outlined above was used to determine θ and δ for a large number of gas combinations. These results were found to be in surprisingly good agreement with shock and interface angles measured from the schlieren photographs. In addition, this same simplified theory correctly predicted the conditions under which the shock in the boundary would become detached. Figure 6 is an example of the agreement obtained. Additional calculations showed that accounting for the detonation front curvature in even an approximate fashion, using small straight-line wave segments, would produce still better numerical agreement.[8]

Since the idealized theory includes the salient features of the interaction process and gave qualitative, if not quantitative, agreement with experimental values, it was found convenient to employ it further. In order to isolate the parameters which determine the degree of confinement offered by a boundary, it is convenient to eliminate the necessity of making trial-and-error solutions. To facilitate this the above equations were all specialized to those for high Mach numbers, i.e., small values of θ and δ. This was done by employing trigonometric estimations and infinite series expansions wherever appropriate. As an example, employing this procedure, Eq. (1) above reduces to the following[13]:

$$\theta \approx \tfrac{1}{2}(\gamma_{i1}+1)\delta. \qquad (5)$$

Expanding the arc tangent terms in the Prandtl-Meyer relation, Eq. (2), using the infinite series

$$\operatorname{arc\,tan} x = x - \tfrac{1}{3}x^3 + \tfrac{1}{5}x^5 \cdots,$$

the equation can be written

$$\nu \approx \tfrac{2}{3}(M_{e3}^2 - 1)^{\frac{3}{2}}/(\gamma_{e2}+1). \qquad (6)$$

Continuing with this procedure an expression for the pressure ratio across the boundary shock P_{i2}/P_{i1} is finally obtained directly in terms of the initial conditions, without the need of a trial-and-error analysis.

$$\frac{P_{i2}}{P_{i1}} \approx \frac{1+BZ_{e1}}{1+\gamma_{e2}(1+\{[\frac{3}{2}(\gamma_{e2}+1)/CZ_{i1}](P_{i2}/P_{i1}-1)\}^{\frac{2}{3}})}. \qquad (7)$$

B is defined as $V_d^2/P_{e1}A_{e1}$ and C as V_d/P_{i1}. The initial gas pressures must be equal, i.e., $P_{e1} = P_{i1}$. Z_{e1} is the acoustic impedance (density times the speed of sound) of the undetonated explosive and Z_{i1} is the acoustic impedance of the inert-gas boundary. Since γ_{e2} is roughly equal to 1.2 for all explosive mixtures, Eq. (7) expresses the pressure ratio across the shock in terms of two constants, B and C, which are fixed by the initial conditions and the explosive chosen, and the two acoustic impedances Z_{e1} and Z_{i1} which describe the acoustic properties of the explosive and boundary, respectively. The pressure ratio across the shock, which shall be seen shortly to be the prime characteristic of a boundary's ability to "confine," is virtually a function of only the acoustic properties of the boundary for any given explosive.

Pressure ratios calculated using Eq. (7) are compared in Fig. 7 with those computed from Eqs. (1)-(4). As predicted by Eq. (7), the shock-pressure ratio is virtually independent of any variable other than the acoustic impedance ratio. Since the detonation wave was found to "reflect" back into the detonation products as a rarefaction in all of the cases considered,[14] the shock-pressure ratio is asymptotic to the detonation-wave-pressure ratio, P_{e2}/P_{e1}. Points along the curves corresponding to specific boundary gases are labeled.

DISCUSSION OF RESULTS

A highly simplified theoretical model was chosen above and utilized to predict theoretical shock and interface angles. The reasonably good agreement found between experimental and theoretical results encourages one to accept the idealized model as at least grossly correct. It is now necessary to consider what the implications would be due to considering the detonation wave as having a finite thickness, which is equivalent to recognizing that any explosive has a measurable reaction time.

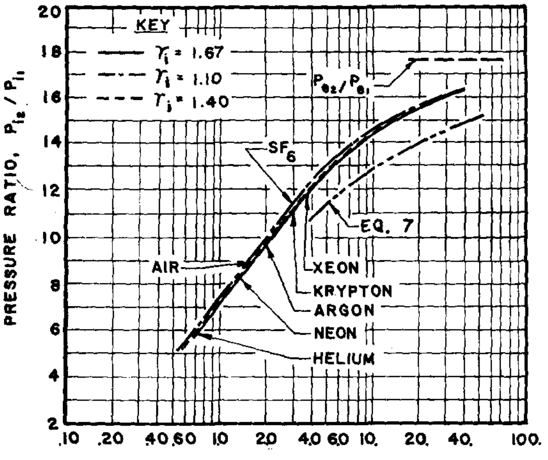

FIG. 7. Pressure ratio across oblique shock vs acoustic-impedance ratio for stoichiometric hydrogen-oxygen and various gas boundaries.

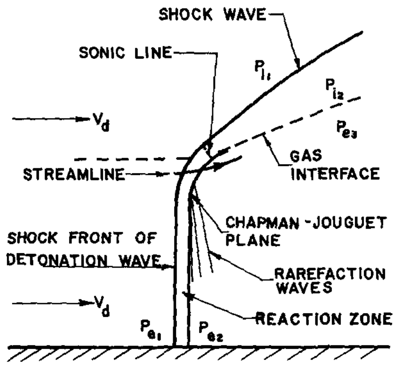

FIG. 8. Schematic of actual detonation wave-boundary interaction.

Figure 8 is a sketch of the flow model which results for a two-dimensional system. The rigid wall shown is equivalent to the centerline of an explosive confined on both sides by a compressible boundary. It is apparent in Fig. 8 that since a finite time is required for a chemical reaction to occur, lateral pressure relief, such as caused by a compressible boundary, lowers the pressure and thereby the temperature of the reacting fluid below that which it would have had if perfect confinement had been provided. Thus, for a given explosive, the boundary material which causes the highest pressure ratio across the shock in the boundary is the "best" container. For gases, the pressure ratio across the shock in the boundary was easily determined from the foregoing theoretical analysis, Fig. 7 being an example of the results. If the proposed analogy between condensed and gaseous detonation phenomena is meaningful, the acoustic-impedance ratio should also be the major factor in determining the confining ability of solid materials for condensed explosives.

A portion of the conclusions drawn by Campbell *et al.*, following their experiments with nitromethane, were as follows[3]:

TABLE I. Ratio of acoustic impedance of various boundary materials to that of nitromethane.

Nitromethane density = 1.13 g/cm^3
Nitromethane acoustic velocity = 1331.5 m/sec

Boundary	Density g/cm^3	Acoustic Velocity m/sec	Z_{i1}/Z_{e1}
Tungsten	18.6	4300	53.3
Platinum	21.37	2690	38.2
Steel	7.83	5000	26.1
Brass	8.56	3500	20.0
Lead	11.34	1227	9.6
Aluminum	2.7	5100	9.2
Glass	2.4-2.8	5000-6000	8.0-11.1

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[14] The interaction of a detonation with a gas boundary is similar in some respects to the collision of a shock wave with a slip plane. In both cases the use of simplifications, such as either very weak or very strong shocks, can lead to closed solutions, but in general a trial-and-error solution must be pursued. The shock wave-slip plane interaction problem is discussed by A. H. Shapiro [*The Dynamics and Thermodynamics of Compressible Fluid Flow* (The Ronald Press Company, New York, 1953), Vol. I, Chap. 16] and W. D. Hayes and R. F. Probstein [*Hypersonic Flow Theory* (Academic Press Inc., New York, 1959), Chap. 7].

"Additional experiments suggested that for a given foil thickness, steel was more effective a confining material than aluminum, and tungsten was more effective than steel. The effectiveness was evidenced by the minimum diameter glass tube in which propagation [of the detonation wave] was made possible by the presence of the foil."

Table I gives the ratio of acoustic impedance of the materials rated by Campbell *et al.* to that of nitromethane, plus some additional materials which are included for comparison. The velocity of sound and density information for the solids were taken from the *Handbook of Chemistry and Physics*[15] and that for nitromethane from a report by Butt.[16]

The order of the three materials rated by Campbell *et al.* as to confining effectiveness is identical with the order of the acoustic-impedance ratios. While not constituting conclusive proof, these results along with the phenomenological similarities noted earlier, suggest strongly that the proposed analogy is valid.

It will be recalled that while experimenting with nitromethane, Campbell and his associates noted that very small changes in the thickness of platinum foil caused marked changes in the ability of the detonation wave to propagate.[3] The reason for this is also believed to depend upon the consideration of the thickness of the detonation wave. It is reasoned that all a container need do, regardless of how thin, is to result in a sufficiently high pressure behind the shock in the boundary that the detonation wave will not be too adversely affected by the decreased temperature and pressure at the boundary. However, if the foil is thin enough that the shock passing through it can reflect off the next interface and return in time to encounter the reaction zone, the foil's properties alone may not be the decisive factor. The shock might, for instance, be reflected as a rarefaction which, if strong enough, will quench the detonation. It is interesting to note that the pressure-volume relationships of platinum and glass are such that a shock passed through platinum will be reflected back through the platinum as a rarefaction for all except extraordinarily strong shocks.[2,15]

Cotter measured the reaction-zone thickness of a nitromethane detonation wave and found it to be approximately 0.007 in.[17] Assuming for instance that the shock angle θ in platinum is 30° and that the reflected disturbance returns at an angle of 30° (measured with respect to the foil-explosive interface), the foil would only have to be roughly 2-mil thick to appear "infinitely" thick to the explosive. This is of the same order of magnitude of the foil used in the experiments cited. It would be interesting to see the result of backing the thin platinum foil with a material which would force the wave reflected back into the nitromethane to be a shock.

CONCLUSIONS

The detonation of a gaseous explosive bounded by an inert gas is found to be hydrodynamically similar to the detonation of a condensed explosive within a solid container. Experiments with hydrogen-, methane-, ethane-, and propane-oxygen mixtures next to air or helium show that, as with condensed explosives, the properties of the boundary influence the detonation characteristics of the explosive. In either the condensed or gaseous explosive case, the presence of a compressible boundary causes the detonation wave to become curved and in some cases to quench, the quenching process beginning at the compressible boundary. In addition, similar shock configurations are found to be present in the solid boundaries confining condensed explosives and in the gaseous boundaries confining gaseous explosives.

For gases, it is found theoretically that the acoustic-impedance ratio of the boundary to the explosive is the determining parameter which characterizes the confining capability of the boundary. Experiments with gases verify this conclusion. Utilization of this same acoustic-impedance ratio as a correlating parameter for condensed-explosive experimental results provides an explanation for some rather interesting phenomena and thereby adds support to the proposed analogy.

A major task remaining to be performed is the rigorous analysis of the flow field depicted in Fig. 8. The analytical description of the process experienced by the explosive will be rather difficult as, in succession, the explosive passes through regions having subsonic, sonic, and supersonic flow. In addition, while passing through the subsonic region it is simultaneously reacting chemically and being subjected to an expansion process. The simultaneous solution of the chemical kinetic and hydrodynamic relationships describing these processes will be greatly facilitated by the use of ideal gas assumptions and equations. Because of the success shown through use of the gaseous analogy it appears expedient to make the first attempt at solving this problem using the suggested model for gases, and only later attempt to extend the method to condensed explosives.

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[15] *Handbook of Chemistry and Physics* (Chemical Rubber Publishing Company, Cleveland, Ohio, 1958), 40th ed.

[16] E. P. Butt, British Ministry of Supply Rept. No. 3/R/58, (1958).

[17] T. P. Cotter, Ph.D. thesis, Cornell University (1953).