Do Weak Detonation Waves Exist?

Tim G. Adams*
Ford Motor Company, Dearborn, Mich.

The interaction of a detonation wave with a boundary gas results in a lateral shock wave moving into the boundary. Certain explosive-boundary gas combinations produce a detached shock wave with a detonation velocity about one-half of the Chapman-Jouguet velocity. The existence of this "detonation wave" gave rise to speculation that a weak detonation wave might exist. To investigate this possibility, a series of experiments were conducted using explosive-boundary gas combinations that formed a detached shock, thus a sub-Chapman-Jouguet wave. Results using H_2-O_2 mixtures bounded by H_2 or He showed a wave traveling at a velocity approximately 83% of the Chapman-Jouguet velocity. Experiments with a CH_4-O_2 mixture bounded by He resulted in a wave traveling at approximately 44% of the Chapman-Jouguet velocity. Although the evidence is not conclusive, it is believed that the sub-Chapman-Jouguet wave is a quenched detonation wave decaying to a quasisteady value corresponding to the sound speed in the boundary gas.

Introduction

IT has been postulated[1] that weak and slow-moving detonation waves might exist. Indeed, Voitsekhovskii[2] reported a detonation wave that propagated at one-half the Chapman-Jouguet velocity, while being maintained in an annulus with side relief. Subsequently, Dabora et al.[3] investigated the velocity decrement of a gaseous detonation wave propagating through a channel bounded by a compressible nonreacting gas. Their preliminary experiments indicated the reaction zone would propagate at about half the theoretical Chapman-Jouguet velocity when the detonation wave was bounded by hydrogen or helium. It was also noted that there was some uncertainty as to whether the wave was steady (continuing to propagate at this lower velocity) or was quenched, thereby exhibiting this velocity only in the transient state of decaying to a deflagration.

Several years later, while investigating H_2-CO-O_2 reactions, Lu[4] made a limited effort to determine whether or not these sub-Chapman-Jouguet waves were steady. Using an explosive mixture composed of 75% H_2 and 25% O_2 by volume, and hydrogen or helium as a boundary gas, he found that the velocities measured from streak schlieren pictures were considerably lower than predicted by the Chapman-Jouguet theory. The wave speeds when bounded by hydrogen were 60-70% of the predicted velocity, while the propagation velocity was 50-60% of the theoretical value when bounded by helium. The wave speeds apparently were steady.

The results of these studies indicate the possible existence of a form of detonation which has a propagation velocity less than the Chapman-Jouguet velocity. If this is true, then it would certainly be a significant factor in the design of a gaseous fuel-powered rotating detonation wave rocket engine, such as the one described in a feasibility study by Nicholls and Cullen[5] or on the performance of the continuous detonation wave reaction engine patented by Lange et al.[6]

Although Sichel[7] was successful in providing a hydrodynamic theory for the interaction of a gaseous detonation wave with a compressible boundary, it was applicable only for cases in which the sound speed was less in the inert than in the explosive. For the case considered here, the acoustic velocity was greater in the boundary than in the explosive. The interface flow was more complex due to shock detachment and resulting refracted and/or reflected shocks in the explosive mixture. This produced a very complex flow pattern and did not lend itself to the construction of an analytical model. Therefore, the purpose of this study was to examine experimentally the interaction between a gaseous detonation wave and a low-density boundary gas. The results of the previous studies have been extended in order to determine if a steady sub-Chapman-Jouguet wave does exist.

Experimental Arrangement

The experimental apparatus consisted mainly of a detonation tube and a test section through which a premixed explosive was allowed to flow. Ignition occurred well ahead of the test section, to allow the detonation wave to form and become fully developed before reaching the test section where it was photographed using a spark schlieren system.

The detonation tube was a stainless steel welded assembly with 0.64-cm walls and a rectangular cross section 0.91 cm deep × 1.27 cm wide. The 49-cm long test section, shown in Fig. 1, was mounted on one end of the detonation tube and originally included two 1.27-cm-thick glass plates which served as the front and back walls. Each glass plate had two grooves machined into it to allow nitrocellulose film holders to slide into place. Thin nitrocellulose films were used to reduce diffusion between the gases, yet not affect the interaction between the detonation wave and the boundary gas. Details on the requirements for film thickness and the making of the films are given in Ref. 3. When the film holders containing the thin films were inserted into the test section from the top and slid into position, they formed two identical channels. The inner channel (the one next to the solid wall of the test section) formed a continuation of the detonation tube. The outer channel contained the inert boundary gas. The region beyond the outermost thin film was open to the atmosphere so as to provide minimum confinement of the detonation to avoid breaking the glass. The cross-sectional area selected for the channels was a compromise between the size necessary to avoid quenching due to channel size and the size necessary to avoid the hazard posed by a large volume of explosive gas. Even so, several sets of glass plates were quickly broken and were replaced with 1.27-cm-thick Plexiglas II, UVA. This significantly reduced the breakage.

The explosive mixture was prepared by the partial pressure method using high-pressure, research-grade bottled gases. The premixed explosive, which was at atmospheric pressure in the detonation tube, was allowed to flow upwards through the test section as was the boundary gas. This was done to reduce diffusion through the nitrocellulose film. Ignition of the explosive mixture was initiated by momentary closure of a

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*Principal Research Engineer, Induction, Emissions, and Combustion Research Department.

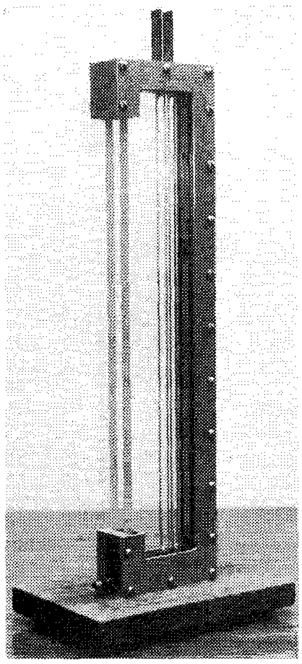


Fig. 1 Test section.

switch which put 6 V across the filament of a 1.5 V glo-plug. The wave speed through the detonation tube was monitored using ionization probes in conjunction with a μs counter. This was done to insure that a fully developed, steady wave had formed.

Two pressure transducers were used for this study. A blast pressure transducer was located in the detonation tube halfway between the ionization probes. It was used to trigger the start channel of the time interval counter. The other transducer was installed in the test section to generate a pulse to stop the time interval counter on the arrival of a shock or detonation wave. The test section was machined so this transducer could be positioned at one of five locations to detect velocity changes which might occur as the detonation wave experienced side relief. The other four positions were normally fitted with screws which were flush with the sidewall.

The velocity of the detonation wave when subjected to side relief can vary depending upon the degree of confinement provided by the boundary gas. For this reason, the determination of the velocity through the test section was made by noting the time of arrival at the five different positions in the test section and plotting the data as distance vs time. Since only one transducer was available for use in the test section, several runs were made at each location to insure repeatability. Then the transducer was moved to a different location and the process repeated. The average velocity was determined at any point within the test section by computing the slope of the line on the time-distance plot.

Experimental Results and Discussion

The usual interaction between a detonation wave and an inert boundary gas causes an oblique shock to be induced into the boundary. For some explosive-boundary combinations, an oblique shock solution does not exist and a detached shock will form.[8] This is caused by the shock in the low-density boundary gas running out ahead of the detonation wave. A detached shock configuration existed in each case where an apparently steady sub-Chapman-Jouguet wave was observed. Therefore, the explosive-boundary gas combinations used for these experiments were selected so a detached shock would form.

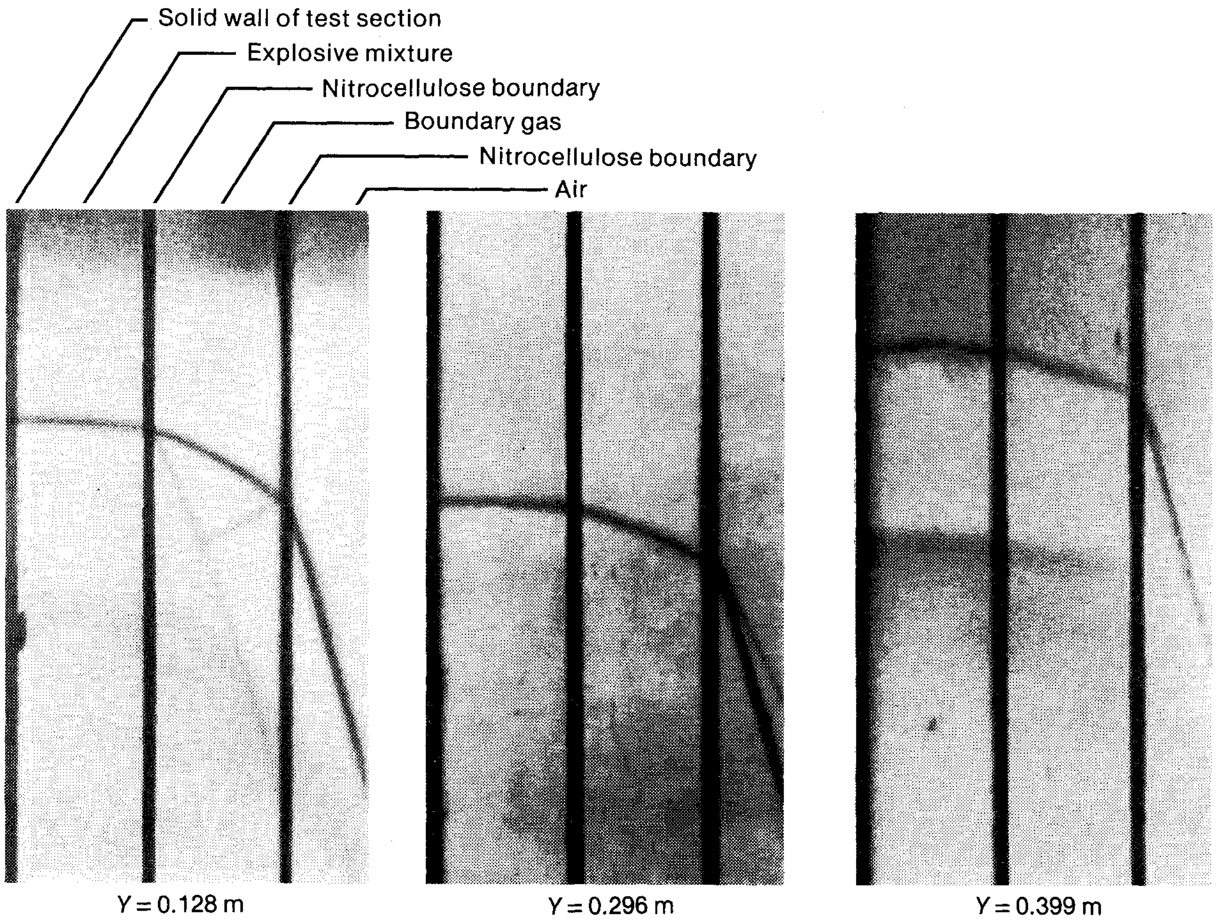


Fig. 2 Schlieren photographs of a detonation wave in a 50% hydrogen-50% oxygen mixture with a helium boundary.

Figure 2 shows a sequence of photographs for the propagation of a detonation wave through a 50% H_2-50% O_2 mixture with a helium boundary. Although it was determined that there is no oblique shock solution for this explosive-boundary combination, a detached shock did not occur. An examination of the sequence of photographs shows that the shock in the inert gas is essentially a normal shock at the explosive-boundary interface and the trailing portion of the oblique shock in the boundary gas is gradually overtaking the detonation wave.

A series of runs were also made using hydrogen as the boundary gas for the 50% H_2-50%O_2 mixture. It was conceivable that the use of hydrogen as the boundary gas would produce more definitive results, since the acoustic impedance

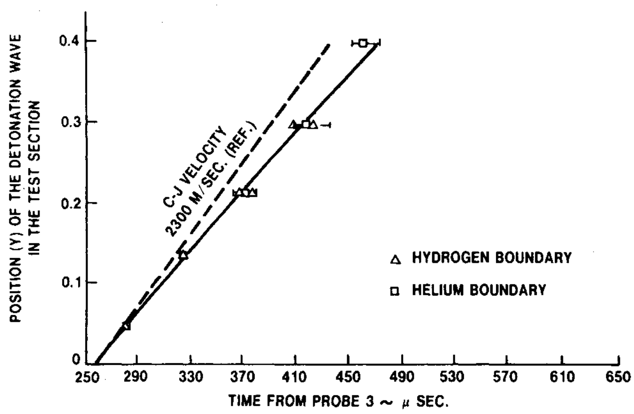


Fig. 3 Position vs time of a detonation wave in a 50% hydrogen-50% oxygen mixture with side relief.

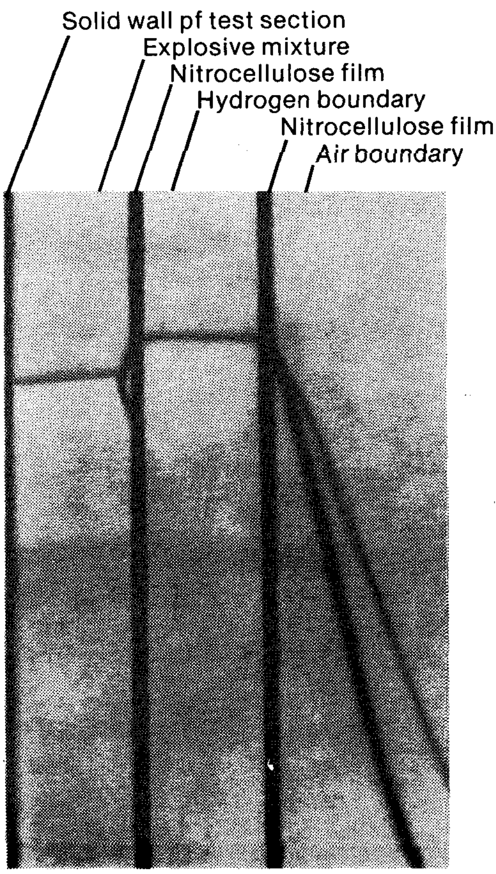


Fig. 4 Schlieren photograph of a detonation wave in a 50% hydrogen-50% oxygen mixture showing an oblique shock in the explosive resulting from a leading shock in the hydrogen boundary ($Y = 0.296$ m).

ratio across the interface is much less for hydrogen than for helium. The results, however, were surprisingly the same as when helium was used as the boundary. The data from these sequences of runs are plotted in Fig. 3, which compares the velocity of the detonation wave in the 50% H_2-50% O_2 mixture with a hydrogen or helium boundary to the velocity of the detonation wave through the same explosive mixture confined by a solid boundary. The detonation wave velocity has decreased as a result of the low-density boundary; the slope of the line indicates a velocity that is approximately 83% of the Chapman-Jouguet velocity.

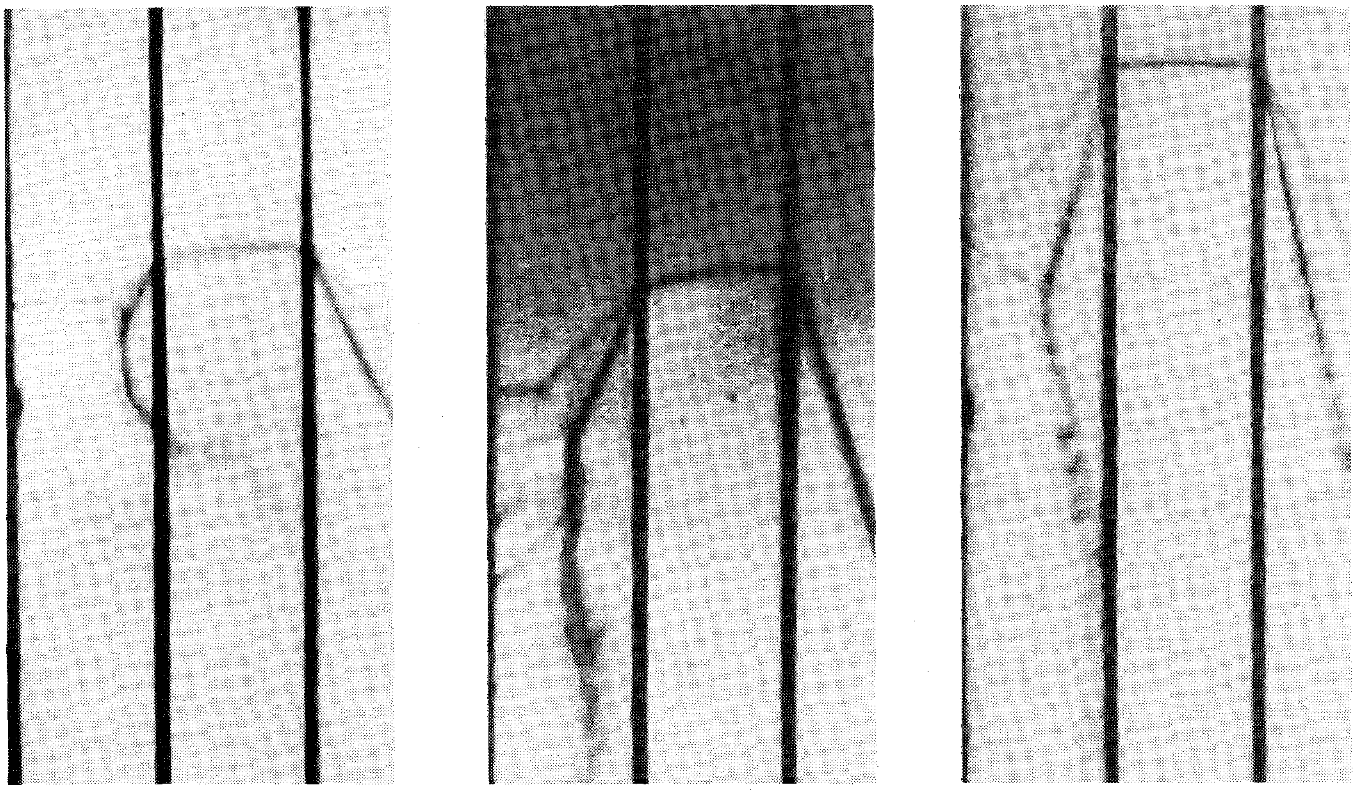
Although the detonation wave velocity through the hydrogen-oxygen mixture did not change with the acoustic impedance of the boundary gas, there was photographic evidence that the use of hydrogen as the boundary gas did effect the interaction. There was no noticeable difference in the photographs taken of the detonation wave in the lower part of the test section. However, as the wave progressed further into the test section, a detached shock did occur in in the hydrogen boundary gas and moved ahead of the detonation wave. Figure 4 shows that even with the detached shock out in front of the detonation wave, the reaction zone is still thin and quenching was not apparent.

A second feature that can be seen in Fig. 4 is that the detonation wave has a very slight upward tilt toward the explosive-boundary interface. This is indicative of a slight diffusion of the hydrogen into the explosive mixture. This diffusion through the thin film into the explosive mixture would increase the hydrogen content of the explosive mixture near the interface and thereby increase the detonation velocity. Although diffusion is obvious at the interface, it is still small and does not appear to be a significant factor in the interaction of a detonation wave with a boundary gas.

When the explosive H_2-O_2 mixture was "confined" by a much lower density boundary gas, it was found that the velocity decreased only about 17% within the confines of the test section. This value is greater than the 8-10% that Dabora et al. had concluded would result in the quenching of a detonation wave in a H_2-O_2 mixture and its deterioration to a shock. If this is a detonation wave that is quenching, then it should be noted that the propagation velocity decreases rather slowly for the H_2-O_2 mixture and therefore the quenching process itself must be rather slow. Support for this conclusion can be found in the work of Lu who made soot track records of detonations with side relief. He observed that the quenching process of a detonation wave, unlike the abrupt onset of detonation, is a gradual process.

The results of the runs made with the H_2-O_2 mixtures led to the decision to use a methane-oxygen mixture bounded by helium. The acoustic impedance ratio across the interface for this combination is much less than for the H_2-O_2 mixtures bounded by hydrogen or helium and, therefore, reduced the degree of confinement. Figure 5 shows the development of the detached shock when a detonation wave propagates through an explosive mixture composed of 30% CH_4-70% O_2 with a helium boundary. It can be seen from this sequence of photographs that over approximately 38 cm of the test section through which the interaction has occurred, a steady-state condition has not been reached. This observation is based on the fact that the distance between the shock front at the solid wall and the leading shock in the boundary gas has continued to increase.

A minimµm of five runs were made at each of the five available probe positions in the test section. From the data recorded, it was possible to plot the position of the detonation wave vs the elapsed time from a fixed reference point (Fig. 6). Based upon what was considered to be the best line drawn from the point at which the detonation wave exited from the tube through the mean of the other five points, it was found that the detonation wave exhibited a marked change in velocity within the first 3 cm of travel after experiencing side relief.



Y = 0.128 m Y = 0.296 m Y = 0.399 m

Fig. 5 Schlieren photographs of the development of a detached wave (30% methane-70% oxygen, helium boundary).

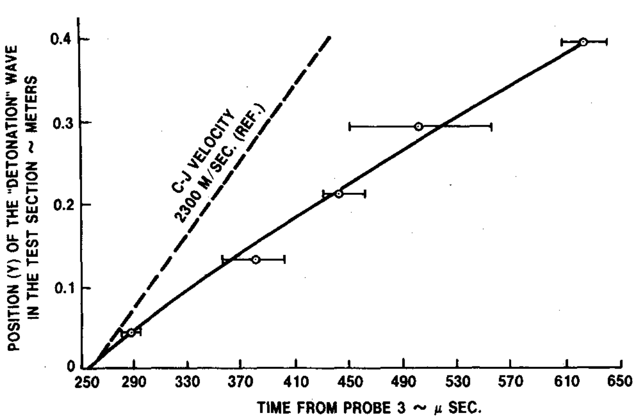


Fig. 6 Position vs time of a detonation wave in a 30% methane-70% oxygen mixture with a helium boundary.

Another interesting feature was found when the average slope of the line of Fig. 6 was determined for the first 20 cm of wave travel in the test section. Using the slope, the wave velocity was found to be approximately one-half the velocity exhibited by the detonation wave when confined by the solid tube. The indication is that the wave velocity decreases rapidly over a length of approximately 3 cm when confined by an inert gas with a much lower acoustic impedance. It appears to travel for approximately the next 17 cm at an average velocity of half the Chapman-Jouguet velocity, the result first reported by Voitsekhovskii and noted by Dabora et al. and Lu. It might be concluded that the wave velocity was constant at this point had not the data from the additional length of test section been available. As the detonation wave continued to propagate, however, the velocity decreased slightly until it reached a seemingly constant velocity for the last 10 cm of measured travel. The velocity over this range corresponded to a value that was approximately 44% of the Chapman-Jouguet velocity.

Since the position of the line drawn through the data scatter of Fig. 6 is subject to individual judgment, a further evaluation of the data seemed appropriate. Using the data of Fig. 6, the equation corresponding to the least-square parabola was calculated to be:

$$Y = -1.83 \times 10^{-2} + 1194.82 \times 10^{-6} t - 233.78 \times 10^{-9} t^2$$

where Y is the displacement in meters and t is the time in microseconds. The curve corresponding to this equation (Fig. 7) shows some curvature for small values of t, but appears to become fairly linear for large volumes of t.

The questions that remained were: 1) Is this wave that propagates at a low velocity a true detonation wave?, and 2) Why did the velocity appear constant over portions of the test sections? To determine the possibility of the existence of a sub-Chapman-Jouguet detonation wave, it is necessary to examine several conditions that would lead to the required end state.

For the detonation wave to propagate steadily at the low-velocity commensurate with a weak detonation wave, it must be continually supplied with energy by the trailing exothermic chemical reaction. The criterion for the maintenance of a gaseous detonation wave propagating at the Chapman-Jouguet velocity is that the reaction zone is relatively short, e.g., 0.3-1.9 cm (Ref. 9), and is attached to the shock front.[10-12] If the reaction zone begins to thicken, i.e., the distance over which the chemical reaction takes place increases, then the energy released by the combustion process cannot continue to drive the detonation wave. Based on the current level of understanding of gaseous detonation waves, it appears that a weak detonation achieved through side relief would have basically the same configuration as a Chapman-Jouguet wave. The length of the reaction zone would probably show a slight increase if the wave was to steadily propagate at a reduced pressure and an increased specific volume. The increase in length would result from the lower velocity of the detonation wave and consequently a lower local temperature immediately behind the shock wave with a corresponding increase in induction time. It should be noted, however, that the increase in length of the reaction zone would be small, since it has been experimentally observed that a marked increased in reaction zone length coupled with a separation from the shock are indicative of a quenched detonation or deflagration wave.

The condition then for the existence of a weak detonation wave resulting from side relief is for the reaction zone to remain relatively thin. A close examination of Fig. 5 indicates this is not the case for the methane-oxygen detonation wave interaction. The reaction zone appears to thicken considerably. Based on this observation and the results of previous studies,[3,7,13] it appears that insufficient energy could be released to support a weak detonation wave. Thus, it is concluded that even the apparent steady state noted in Figs. 6 and 7 is a transient condition. This conclusion supports the previous observation regarding Fig. 5, that a steady-state condition had not been reached.

It was possible to determine the velocity of the shock in the boundary gas by measuring the oblique shock and interface angles induced into the explosive mixture. Using the supersonic flow over a wedge analogue, the propagation Mach number and, consequently, the velocity of the shock wave in the boundary gas were determined at several positions within the test section. The sequence of photographs shown in Fig. 5 were used to obtain the data points at $Y=0.128$, 0.296, and 0.399. The results are shown in Fig. 8 and indicate a velocity decrease from a condition corresponding to an overdriven

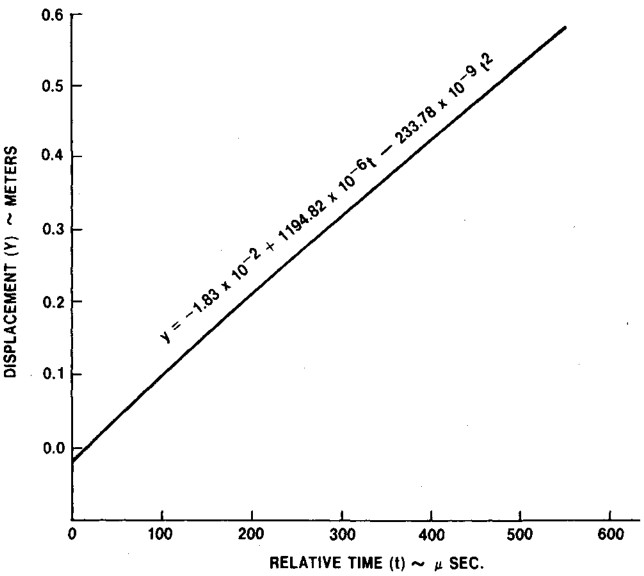


Fig. 7 Least-squares curve fit of the data obtained from a detonation wave in a 30% methane-70% oxygen mixture with a helium boundary.

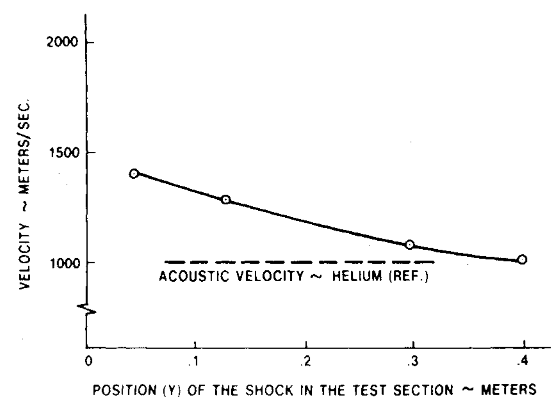


Fig. 8 Shock wave velocity in the helium boundary with a detonation wave in a 30% methane-70% oxygen mixture.

shock wave to a velocity of approximately 1006 m/s, the sound speed in the helium boundary. The speed found for the shock wave in the boundary gas near the top of the test section is the same apparently steady speed determined from the slope of the "best line" drawn through the data scatter of Fig. 6. Thus, it appears that the detonation wave degenerates into a weak deflagration wave and a quasisteady shock wave. This is typical of the quenching of a detonation wave.

Further Considerations

There are several other factors regarding the propagation of a detonation wave through an explosive mixture, bounded by a much lower density inert gas, that bear consideration. The first of these is the possibility of the leading detached shock in the boundary gas inducing an oblique shock into the explosive mixture and forming a Mach stem at the wall. This would provide a high local temperature which might sustain a detonation. It would seem, however, since the detonation wave is quenched at this point, that if a high local temperature was achieved behind the Mach stem, the detonation wave might be re-established. However, there was no indication of a Mach stem forming at the wall.

A factor which might be partially responsible for the apparent constant velocity of the hydrogen-oxygen mixture is the configuration of the shock in the boundary gas. Although the shock angle in the boundary gas is approximately 90 deg at the interface, which is greater than the value of θ max. predicted by the oblique angle calculations and is, therefore, classified as a detached shock, it does not show the leading shock characteristics that occurred with the heavier methane-oxygen mixtures. This is a result of the still relatively high propagation velocity of the detonation wave in the mixture. It is possible that the normal shock in the inert at the explosive-boundary interface produces a sufficient increase in the acoustic impedance of the boundary gas that the detonation wave is more confined. This would mean a lower deflection angle for the interface streamline, a smaller area increase and, therefore, a smaller change in velocity. This would result in very slow quenching. The same increase in the acoustic impedance of the helium, when used as boundary for methane-oxygen mixture, is not sufficient to offer suitable confinement for the reaction and the detonation appears to quench.

Another argument can be given for the relatively small velocity decrement shown by the detonation wave propagating through the hydrogen-oxygen mixture. A comparison of the minimum spark ignition energies of hydrogen-oxygen mixtures with methane-oxygen mixtures reveals that much less energy is required for ignition of the hydrogen mixture.[14] Less energy would also be required for ignition achieved through an adiabatic compression as would occur across a normal shock. This would mean that the hydrogen-oxygen mixture is able to sustain itself better than any other explosive mixture and therefore is less susceptible to the sudden lateral expansion and corresponding velocity decay exhibited by a hydrocarbon mixture.

Conclusions

No supporting evidence was found in this study for suppositions relative to the existence of a weak detonation wave. It was found that a quenched detonation wave "confined" by a much lighter inert boundary gas would exhibit a transient velocity corresponding to 50% of the Chapman-Jouguet velocity. Since this velocity occurred in the first 20 cm of the test section, which was longer than the test section used by Dabora et al. and approximately equal to the length of the longest interaction observed by Lu, it is concluded that this condition is the "apparently steady" velocity they observed. As the interaction progressed, the velocity of the shock wave was observed to decay to a quasisteady value corresponding to the acoustical velocity in the inert boundary gas.

Insufficient information is given in the results of the studies by Voitsekhovskii so that a determination can be made as to why a detonation velocity was observed corresponding to half the Chapman-Jouguet velocity or why the detonation was maintained for only 1-1.5 s. The results of the present research indicate that probably a slow-quenching detonation wave was observed.

Although the results of this research do not disprove the existence of weak detonation waves, it appears unlikely that a sub-Chapman Jouguet wave occurred in the present study. The results are not as conclusive as desired because of the relatively long times for large changes to occur in some of the detonation configurations and because a major criterion for quenching is rather qualitative, i.e., thickening of the reaction zone. It is evident that considerable effort and care are required to determine the existence and nature of steady-state detonation wave configurations with compressible side relief.

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