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Final Report

THE INTERACTION PROCESS BETWEEN GASEOUS DETONATION WAVES AND INERT GASEOUS BOUNDARIES

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FOREWORD

This report constitutes the final report on Grant DA-ARO(D)-31-124-G345 by the U. S. Army Research Office. It contains only a statement of the problem and a summary of the results obtained since detailed results are covered by previous reports. A list of publications and technical reports and a list of all personnel who worked on this grant are also included.

All personnel involved would like to acknowledge the support of ARO.

STATEMENT OF THE PROBLEM AND SUMMARY OF RESULTS

The properties of gaseous detonation waves when subjected to a compressible (gaseous) inert boundary are investigated both theoretically and experimentally. Properties of interest are the propagation velocity, the reaction length, the quenching conditions and the shape of the wave. The zeroth order analytical solution of the hydrodynamic equations involved, an assessment of several quenching criteria, a description of the experimental setup, and the experimental results are presented in detail in (1)*. As a summary of this work, the abstract and the conclusions of (2) are quoted below:

> "The velocity decrement of a gaseous detonation propagating through a channel with a compressible, nonreacting boundary is investigated experimentally and theoretically. The decrement depends on the width of the channel, the reaction length of the gaseous explosive, and the ratio of the explosive to inert-gas densities.
>
> In the experiments, the gaseous explosive was separated from the boundary gas by a very thin film (~ 250 Å) to eliminate any diffusion effect. Extensive experimental results for H_2-O_2 mixtures bounded by nitrogen, and some results on stoichiometric CH_4-O_2, show a general agreement with theory. In the case of H_2-O_2 mixtures, minimum channel width at which the wave continues to propagate is determined. It is found that a velocity decrement beyond 8%-10% leads to quenching, which appears to be best predicted by Belles' explosion-limit criterion. Using velocity decrement data, the reaction lengths of the stoichiometric mixtures of H_2-O_2 and

*( ) refers to list of publication.

CH_4-O_2 are found to be 0.11 in. and 0.26 in., respectively.

Experimental results on the deflection angle of the interface and the shock induced by the detonation wave into the inert gas, are also presented. They show good agreement with a theory based on a shock-tube analogy."

"1. The velocity decrement of gaseous detonations bounded by a nonreacting gas is approximately proportional to the reaction length and the inverse of the channel width, and is dependent of the density ratio of the confining medium and the explosive gas. The higher the ratio, the lower the velocity decrement.

2. Velocity-decrement data can be used to measure the reaction length in the gaseous explosive. The value obtained for the stoichiometric H_2-O_2 is in good agreement with that reported in the literature.

3. For H_2-O_2 mixtures, a velocity decrement beyond 8%-10% results in quenching of the detonation wave and its deterioration into a shock. Quenching data can best be predicted by Belles explosion-limit criterion.

4. Near the quenching limit, the detonation wave propagates like a spinning wave so common at composition limit.

5. Because of the intimate connection between quenching and the chemistry in the reaction zone, it is believed that the experimental technique could be used as a tool in elucidating or checking the reactions involved in detonable gaseous mixtures other than H_2-O_2."

The first order solution of the hydrodynamic equation which effectively predicts the shape of the wave is presented in (3) and (4) and again as a summary the abstract and the discussion are quoted here:

"Detonations through an explosive of finite width are curved and propagate at a lower velocity than an ideal one-dimensional plane wave. A theory relating the velocity decrement and curvature of a gaseous detonation to the conditions at the explosive inert interface is developed. A two-dimensional detonation bounded on one side by a solid wall and on the other by an inert gas is considered. Approximate reaction zone equations are derived by expanding the flow variables in powers of a small parameter proportional to the ratio of reaction zone thickness to radius of curvature. Locally the reaction zone equations are the same as for one-dimensional flow with increasing area and heat addition, the rate of increase depending on the local wave curvature and the density variation through a plane detonation. Using Fay's result that the relative detonation velocity decrease is proportional to the fractional increase in the reaction zone streamtube area, an ordinary differential equation for variation of the wave angle is developed. Approximate solutions of the above equation yielded velocity decrements which agreed with experimental results."

"The first order theory developed above provides a relationship between the explosive-inert interface conditions and the velocity decrement and detonation curvature. The theory is essentially a hydrodynamic one without detailed consideration of chemical effects. Analysis of the problem of detonation stability and quenching limits, which is not considered in this paper, can undoubtedly be coupled to the present theory.

Laminar flow within the reaction zone has been assumed, though it is well known* that the structure of many C-J detonations is turbulent and that the wave surfaces may be non-uniform or crinkled. If it is reasonable to use temporal averages within distances of the order of the reaction zone thickness the theory developed here may still be applicable.

The agreement between the approximate calculations and Dabora's experimental results is reassuring; however, further verification would be desirable. In particular more precise values of $\rho^{(0)}/\rho_\infty$ and the pressure variation, should be used in the computation of Λ and α_i. Calculated values of α_i and wave curvature should be compared with values taken from Schlieren photographs, and the comparison of theory and experiment should be extended to wider ranges of mixture ratio. It should be possible to use the present theory to obtain chemical-kinetic information from Schlieren photographs and velocity decrement data from gaseous detonations with side relief.

Only the case in which the speed of sound in the inert is less than in the explosive was considered in the treatment of the interface flow. The curved front theory above should remain valid

*White, D. R., "Turbulent Structure of Gaseous Detonation," The Phys. of Fluids, v. 4, n. 4, April 1961.

even in the case of higher sound speed in the inert gas. The chief difficulty in this more complex case lies in the calculation of the detailed interface flow.

The nature of the C-J condition requires further study, especially the nature of the transition from the plane to the curved front case."

Finally the effects of small amounts of water-vapor added to H_2-O_2 mixtures, on the onset of quenching as well as the reaction length are assessed experimentally in (5). The abstract and the conclusions of this paper are included here:

"Gaseous detonation waves were slowed below their usual Chapman-Jouguet detonation Mach number by exposing one side of the wave to an inert gaseous boundary. The minimum Mach number of propagation, below which detonative combustion is not expected, is given by Belles' explosion limit criterion. Belles' criterion predicts that the addition of 2% of water vapor (by volume) to stoichiometric hydrogen-oxygen mixtures will increase the minimum required Mach number of detonation by 3%. Experiments which verify this prediction are described in this report. It is also found that the addition of 2% water vapor to the stoichiometric mixtures decreased the reaction length (distance from the leading shock to the Chapman-Jouguet plane) by approximately 50%. The experimental work of Kistiakowsky and Kydd was found to support the latter finding."

"It has been experimentally verified that, for 66 2/3% H_2 + 33 1/3% O_2 mixtures, the addition of water vapor increases the minimum required Mach number of propagation. This finding is in agreement with the explosion limit criterion given by Belles. Specifically, the high efficiency of water vapor as a third body in the chain breaking reaction, . . . , has been verified for detonative combustion. In addition, it was found that the addition of water vapor to 66 2/3% H_2 + 33 1/3% O_2 mixtures acted to reduce the Mach number decrement due to the compressible boundary. According to Dabora's analysis, this reduction in Mach number decrement is explained by postulating a reduction in reaction length. The experimental work of Kistiakowsky and Kydd was found to give further support to this conclusion."

The work in (5) was partly done on contract DA-31-124-ARO(D)-299, therefore a detailed version will be issued soon under that contract.

LIST OF PUBLICATIONS AND TECHNICAL REPORTS

1. Dabora, E. K., "The Influence of a Compressible Boundary on the Propagation of Gaseous Detonations," Report No. 05170-1-T, Univ. of Mich., December 1963. Also Ph. D. thesis, 1963.

2. Dabora, E. K., Nicholls, J. A., and Morrison, R. B., "The Influence of a Compressible Boundary on the Propagation of Gaseous Detonations," Tenth Symposium (International) on Combustion, 1965, to be published.

3. Sichel, M., "A Hydrodynamic Theory for the Interaction of a Gaseous Detonation with a Compressible Boundary," Report No. 05170-2-T, Univ. of Mich., February 1965.

4. Sichel, M.,"A Hydrodynamic Theory for the Interaction of a Gaseous Detonation with a Compressible Boundary," paper presented at Second A. I. A. A. meeting in January 1965 and submitted for publication in the A. I. A. A. Journal.

5. Kerkam, B. F., "The Influence of Water Vapor Addition on the Interaction of Hydrogen-Oxygen Detonations with a Compressible Boundary," paper presented at A. I. A. A. Student Conference, Great Lakes Region held at the Univ. of Cincinnati, Cincinnati, Ohio on May 15, 1965 (paper won second prize in graduate division).

LIST OF PERSONNEL

J. A. Nicholls, Professor in the Department of Aeronautical and Astronautical Engineering, Project Supervisor.

E. K. Dabora, Research Engineer (Ph. D. earned while working on grant).

M. Sichel, Associate Professor in the Department of Aeronautical and Astronautical Engineering.

J. McComb, Assistant in Research.

B. F. Kerkam, Assistant in Research (M. S. earned while working on grant).