UM 026030-4-P

Annual Report

TWO PHASE DETONATION STUDIES CONDUCTED IN 1972

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prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

March 1973

Grant NGL 23-005-336

NASA Lewis Research Center
Cleveland, Ohio

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FOREWORD

This report covers the progress made in the year 1 February 1972 to 1 February 1973 on NASA Grant NGL 23-005-336. The study was under the direction of Professor J. A. Nicholls, Department of Aerospace Engineering. Dr. R. J. Priem, NASA Lewis Research Center, was technical monitor.

The phases of research discussed herein and the personnel active in those phases are as follows:

Phase A: Passage of a Shock Wave over a Burning Drop
H. Miyajima - Visiting Researcher from Japan
Rajshekhar Oza - Graduate Student

Phase B: Energy Release Patterns
T. H. Pierce - Post Doctoral
Prabhakar Patil - Graduate Student

Phase C: Acoustic Liner Studies
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ABSTRACT

This report briefly describes the research conducted in the past year on this grant. In those cases where the findings are already available in the literature, the material is merely referenced. The research discussed herein includes the passage of a shock wave over a burning drop, the energy release pattern in a two phase detonation, detonation of a liquid fuel-liquid oxidizer-inert gas, and the attenuation of shock waves and detonation waves by an acoustic liner or by porous walls.

I. INTRODUCTION

The research covered by this annual progress report represents a continuation of our study of detonation waves in two phase (liquid-gas) systems. The motivation for the work is associated with liquid propellant rocket motor combustion instability although certainly the studies are also applicable to internal combustion engines, jet propulsion engines, safety aspects of spilled liquid fuel, coal mine explosions, and weaponry. The research is divided into phases and three of these phases are described herein. A fourth phase has been concerned with liquid film detonations. The work on this has been completed and a NASA contractors report is being prepared which will summarize the entire phase. A fifth phase, devoted to an analytical treatment of a rotating detonation wave in a rocket motor, is essentially completed as a contractors report and will be published in the near future.

The progress made on the three phases will now be described.

II. RESEARCH RESULTS

Phase A - Passage of a Shock Wave Over a Burning Drop

In last year's annual progress report the experimental technique for injecting, and igniting when desired, a single liquid fuel drop into the test section of the horizontal shock tube was described. Image converter camera photographs of the drop injection, ignition, and needle retraction process were shown. During the past year a number of experiments were conducted wherein shock waves of various strengths were passed over burning and non-burning drops. Shock Mach numbers in the range 1.5-2.5 were used and image converter photographs were taken. The fuel was diethylcyclohexane and various initial pressures of pure oxygen were used. Qualitatively it was observed that in the case of ignited drops the flame front was approximately spherically symmetric about the parent drop before shock wave interaction. Upon passage of the shock, in some cases the flame was stabilized and confined in the wake region of the drop and in other cases the flame blew off. In the interest of determining the boundary between "wake flame" and "blow-off", a series of experiments was conducted with initial oxygen pressure and shock strength as the variables and for a constant drop size. In general it was found that higher initial pressures of oxygen were required as the shock Mach number increased. In these experiments a photocell was used to determine whether the flame had been blown off or not.

The image converter photographs revealed a marked distinction in the deformation of the drop in the 2 cases. Immediately after shock passage the drop diameter increases with time in a direction transverse to the flow. In the case of non-ignited or flame blow-off drops, the diameter increases to a maximum of about 3.5 times the initial diameter before it starts to decrease. In the wake-flame case the diameter increases much more rapidly and goes to a maximum value of at least 6 times the initial diameter. Presumably this should affect the rate of combustion.

Streak photography was also employed in some of the foregoing experiments. From the data obtained, the breakup time of the drops and the drag coefficient were determined. There appeared to be little difference in breakup time for the 3 cases of non-ignited, flame blow-off, and wake flame. There were indicated differences in the drag coefficient but the trend is not definitely established at this point.

An abstract for a paper based on the foregoing preliminary investigation has been accepted for presentation at the Third International Symposium on Combustion Processes, Polish Academy of Sciences, Kajimierz, Poland, September 1973. The full paper is in process of preparation.

The investigation described so far suffered from 2 limitations. First, the drops produced were not perfectly spherical and tended to have a "tadpole" shape. This resulted in some abiguity in regard to drop burning, deformation, breakup, etc. Accordingly, effort was devoted to redesigning the drop suspension capillary and readjusting the position of the electrodes. This has resulted in a much improved drop shape. The second limitation arose from the fact that the shock Mach number range was too narrow and weaker as well as stronger shock waves were desired. The difficulty arose in synchronizing the firing of the shock tube with injection of the burning drop. It was found that at higher Mach number the shock arrived in the test section before retraction of the needle was complete, thus resulting in damage to the needle and electrodes. A new technique has been developed which uses an exploding wire sandwiched between 2 mylar diaphragms. Thus, firing of a capacitor rapidly explodes the wire and breaks the diaphragm and yields a dependable time signal for drop injection. This system has produced good results.

The improved experimental technique is now ready and more controlled experiments are about to commence.

Phase B - Energy Release Patterns

Theoretical

The first order, time dependent numerical model for the reaction zone structure in monodisperse two-phase spray detonations was completed. This model was described briefly in Ref. 1. A more complete but succinct presentation is given in Ref. 2, while a thorough discussion of all facets of the model is provided in Ref. 3. This model was described at the 14th International Symposium on Combustion at Pennsylvania State University in August 1972, and at the 9th JANNAF Combustion Meeting at Monterey, California, in September 1972. In order to allow for ready re-implementation of the extended computer program (over 3000 lines in FORTRAN IV) which was used for the theoretical computations, a complete documentation of that program was prepared.

The mechanism involved in the ignition of single fuel droplets following their impulsive exposure to high-speed convective oxidizing gas flows is still unsettled, and so additional efforts have been addressed to that area of the research. The pertinent experimental information has been carefully re-examined, and through assessing the possible mechanisms which could account for the observed induction period characteristics, a new ignition theory has evolved. The final details of this theory have not been completed; hence, only a conceptual summary will be offered here.

When a liquid droplet is suddenly subjected to a high-speed gas flow, it immediately begins to contract in the axial direction (direction of gas motion) and elongate in the lateral direction. Once the induced boundary layer in the droplet has grown to a thickness and mass velocity which will permit a rearward-moving annulus of that thickness to overcome the restraining force of surface tension (thickness of less than a micron), "boundary-layer stripping" commences. With time, the boundary layer thickness increases, the size of the stripped annulus increases, and the mass rate of stripping correspondingly accelerates.

These stripped annuli break up into droplets of commensurate diameter, which move, initially, at a velocity which is much less than the convective flow velocity. This velocity is also lower than the rate of lateral expansion of the parent drop, and lower than the rate at which any point on the surface of the wake recirculation zone (which grows in length as the parent drop grows) moves rearward in the axial direction.

In addition, it is noted that photographs, taken during the portion of the droplet induction period in which the drop is growing in frontal diameter, show well-defined conical recirculation zones. Hence, from these observations, it appears that, while the parent drop is growing, the mass which is stripped from it (microspray drops) enters the recirculation zone and remains "trapped" there.

Except for convective gases containing low oxygen concentrations, the recirculation zone remains fuel lean during this period. The accumulated fuel vapor produced there by microspray evaporation is not large, and also, the recirculation zone grows in volume during this period, and in doing so entrains fresh oxidizer which further dilutes the mixture. In those cases for which little enough oxygen exists in the convective gases so that reactive mixture ratios are formed in the recirculation zone, reaction there probably occurs, but the energy release rate is in any event bounded by the evaporation rate, which is too slow to allow for explosion. In any event, only 2-20% of the mass stripped during this period evaporates, cumulatively. This would also explain the observation that, when ignition does occur, the recirculation zone does not take part.

Lateral expansion of the parent drop terminates at about $\overline{T} = 1.31$, where $\overline{T} = (u_2 t^*/D_0) \sqrt{\rho_2/\rho_\ell}$. Here, u_2 is the convective flow velocity, ρ_2 is its density, D_0 is the initial liquid drop diameter, and t^* is time[4]. It is interesting that this also approximates the time for the liquid boundary layer to grow to the center of the drop[5].

Once the parent drop begins to shrink in frontal diameter ($t > t^*$), additional shed microspray does not enter the recirculation zone, but rather becomes exposed to the convective flow. Moreover, microspray that was entrained in the recirculation zone is gradually re-exposed to the convective flow velocity, but does so through sufficiently high Weber's numbers that in the process, the accelerating microspray is itself stripped. Evaporation times for the second generation microspray drops are negligible.

Thus, after $t = t^*$, additional stripping of the parent drop and re-exposure of recirculation zone microspray drops produces a shroud of fuel vapor which moves rearward at the convective flow velocity. The shroud is in the wake of the parent drop, and so the turbulence there mixes the fuel vapor with the gases comprising the convective flow.

The first and second generation microspray is assumed heated to the liquid boiling temperature during the stripping processes. As the second generation microspray evaporates, it absorbs heat from the surrounding gases. Subsequently, upon mixing with the convective flow, the gases in the shroud region equilibrate to a temperature intermediate between the liquid boiling temperature and T_2. The cooling is substantial; shroud temperatures at this point are 600-900°R lower than T_2, the convective flow temperature, while $1700 < T_2 < 2200$ °R, approximately.

The shroud mixtures are quite fuel rich, and at the equilibration temperatures, chemical reaction rates are very slow. However, thermal conduction from the hot external gases (temperature T_2), which move with the shroud, raises the shroud temperature to temperature T_ν in time τ_c, which is the thermal conduction component of the overall ignition delay time.

Then, beginning at time $t = t^* + \tau_c$, and at the temperature T_ν, the combustible mixture in the shroud reacts. The self-heating of the shroud by this reaction accelerates the reaction rates; the process is unstable, and after a chemical induction time τ, the rate of increase in shroud pressure (at constant volume) becomes suddenly very large. This is identified as the moment of explosion. The total ignition time is therefore given by $t_{ig} = t^* + \tau_c + \tau$. Computations of t_{ig} are in progress and a paper will be submitted to an appropriate source upon their completion.

Experimental

An experimental program to investigate self-oxidizing, bi-liquid (SOBL) spray detonations, in which the charge gas is inert, has been initiated. Sprays consisting of kerosene and concentrated hydrogen peroxide have been chosen for the initial studies. Hydrogen peroxide (50%) is a strong oxidizer which presents difficult storage and handling problems in connection with use in a drop generating system such as that described in Ref. 6.

Extensive equipment modifications to accommodate two different liquids simultaneously in the drop generator have been nearly completed. Problems with the H_2O_2 segment of the plumbing have impeded progress; certain essential elements of the plumbing have not yet been successfully passivated so as to avoid H_2O_2 dissociation. Such dissociation cannot be tolerated since it both presents a safety hazard and also upsets the requisite hydraulic character of the drop generator plumbing.

A dimensional analysis was carried out on the parameters which characterize a SOBL spray detonation, and from the many groupings which result, it was decided to begin the study on the basis of three: the global equivalence ratio, ϕ; the ratio of the diameter of fuel drops to that of the oxidizer drops, ψ; and the ratio of the maximum "interaction distance" to the hydraulic radius of the duct in which the detonation is confined, λ.

It is to be noted that in SOBL detonations, a fixed value of ϕ can be realized with sprays of any total number density, as opposed to ordinary two-phase detonations. Nevertheless, ϕ fixes the relative proportions of fuel and oxidizer in the spray mixture, and is expected to be an important parameter.

The parameter ψ is also expected to influence the character of the detonations. If $\psi \ll 1$ or $\psi \gg 1$, a detonation similar to pure two-phase detonations is expected, since the smaller drops will break up and their vapor will mix with the convective flow long before the induction period of the larger drops; i.e., the system would behave (except for mass loading) as though the smaller drops had been in the form of vapor initially. On the other hand, if $\psi \approx 1$, a true SOBL detonation should result, in which both species drops must break up, vaporize, and mix with each other in the convective flow before energy can be released.

The "interaction distance," R_i, is the length of a side of the icosahedron whose volume, when centered on a given species i drop contains the proper number of species j drops to complete the intended stoichiometry (specified by ϕ) with that drop. That is, R_i represents a maximum average distance over which vapor from either species must migrate in order to react with the other species. To the extent that the reaction zone length should be a function of R_i, and the reaction zone length compared to the hydraulic radius r_H of the confining duct determines the velocity deficit of the detonation, $\lambda = \max (R_i/r_H)$ is expected to be an important parameter.

Calculations of drop generator settings for which ϕ and ψ are held constant while λ is varied have been completed for kerosene-H_2O_2. As soon as the problems with the equipment have been overcome, this experimental program will be implemented.

Phase C - Acoustic Liner Studies

The principal aim of this phase of our work has been the study of the effectiveness of acoustic liners as attenuating devices for two-phase detonation waves. In this connection the following aspects have been considered:

1. Experimental and analytical study of the interaction of a shock wave with an array of Helmholtz resonator type cavities lining the walls of a shock tube,
2. Effect of gas mass bleed behind the leading shock of a steady state propagating two-phase detonation under laboratory and rocket motor conditions,
3. Effect of gas mass bleed behind a blast wave originating from the combustion zone of a two-phase detonation wave,
4. Qualitative analysis of the effect of small disturbances on the two-phase detonation wave, employing an approximate structure for the wave using the available models for the drop breakup and ignition schemes.

A succinct summary of our efforts is presented below.

Recognizing that a fully developed two-phase detonation would be practically impossible to quench, attention has concentrated on damping out the compression waves generated by the rapidly burning drops, thereby precluding development of the combustion front into a detonation.

Thus the study of the effectiveness of acoustic liners in a shock tube in attenuating a shock wave of comparable strength was initially taken up. The interaction of a planar shock wave with a single narrow slit and an array of Helmholtz resonator type cavities lining the walls of a shock tube was investigated experimentally via schlieren photography. The characteristic features of the interaction of the shock wave and the cavities was elucidated from these experiments. The flow of high pressure shocked gas into the cavities generates a series of expansion waves at the side walls. These expansion waves overtake the leading shock and gradually weaken it. The leading shock is diffracted through the cavity openings. The diffracted shock in its collision and then reflection inside the cavity opening create secondary shock waves which are dissipated in strength inside the cavities and in the duct by multiple reflections from the duct walls. These observations led to the use of mass efflux into the cavities and the energy dissipation through the secondary shocks as the mechanisms acting for the attenuation of the leading shock. Approximate analysis using isentropic relations for the mass efflux and complete dissipation of the kinetic energy of the inflow in the cavities was employed as the model in the analytical studies. Experimental measurements of the cavity pressure compared well with the theoretical predictions. The net reduction in velocity obtainable in distances comparable to the reaction zone lengths was seen to be small. An idealized case of a perforated wall for the shock interaction was treated analytically. The perforated tube case removes the difficulties of back flow from the cavities into the duct and makes possible a parametric study of the size of the cavity spacings and the cavity openings. The conclusion was reached that the velocity reductions obtainable by the cavities of typical rocket motor acoustic liners is small and the process is slow. The time and distance needed to obtain a 50% reduction in the dynamic pressure of the convective flow behind the shock has often been used in our analysis as a measure of the effectiveness of the liner.

Analytical study of tangential mode combustion instability for an annular combustion chamber has been successfully completed in Phase E of our two phase detonation studies. That analysis concerns the effects of those parameters used in the design of liquid rocket motors on the strong limit of the tangential mode rotating detonation wave. The results of the analysis compare favorably with the experiments and the correct dependency of the parametric effects is predicted. As a prelude to the motor case, the effect of gas mass bleed behind a steady state two-phase detonation wave propagating in a tube has been studied parametrically. Jump conditions for a two phase mixture of burned gases and unburned fuel and oxidizer droplets with different incoming velocities were developed. An analysis was carried out to yield the relations for the properties of a C-J detonation with mass bleed. To obtain any appreciable velocity reduction for the wave the gas bleed fraction was found to be large. This study was then extended to the annular motor case, thereby bringing in the effects of motor operating parameters. Also this provided ways of correlating engine conditions and the laboratory test conditions. The drop breakup dynamics and different wall porosity values were included to estimate the bleed fraction possible and the possible steady state velocity reduction for the wave in the presence of bleed. The conclusions reached for typical liner values of open-area ratios and drop sizes are that for a steady propagating wave in the motor case; it is not possible to obtain significant reductions in the propagation veloc ity of the wave and consequently the intensity of the wave remains high. This is mainly attributed to two factors: (i) the available reaction zone length is small and (ii) the effective open area ratio is small.

The next step taken was to inquire into the effect of gas mass bleed behind the blast waves originating from the drop combustion zone and moving towards the leading shock front. Using one-dimensional time-dependent finite difference techniques the motion of the blast wave was observed for selected leading shock strengths and drop sizes and wall porosity values. It has been seen that for conditions corresponding to fully developed detonation the blast wave strength is not appreciably reduced in the time it moves through the reaction zone. Extensive calculations have not been done for the different motor and laboratory conditions. Detailed correlations between the two situations need be established for the case of a blast wave attenuation.

So far the studies conducted have considered the nature of detonation wave attenuation in two ways: one, the steady state reductions possible by gas mass bleed through the liner wall, and two, the gas mass bleed to cause a slowing down of a shock wave or blast wave of the combustion zone, thus decoupling the leading shock from the combustion front. Both these are for fully developed two-phase detonation waves for which the characteristics can be predicted and also experimental correlations are available. The available information on drop breakup has been used to elucidate the drop size effects. The indications have always pointed to the fact that once the two-phase detonation is fully developed the gas mass bleed alone does not appreciably effect the wave. No useable model has been available for a developing two-phase detonation wave and the effect of mass bleed has not been considered explicitly in that regard. However, it is parametrically possible to see the effect of mass bleed on the wave considering different fractions of energy release, while the relationship of reaction zone lengths in these cases remains unknown.

In a rocket motor case of the two-phase detonation wave the tangential mode of instability appears as a strong discontinuity. In a manner analogous to the case of gaseous detonation waves, by modelling the wave as a shock followed by reaction and using the hydrodynamic jump conditions connecting the end states to include the effect of mass bleed, drop breakup, micromist sizes, and ignition schemes, it is possible to inquire whether small disturbances introduced into the wave would grow or subside. This can be done qualitatively to establish the relevant parameters. This has been done using changes in dynamic pressure of the convective flow. The controlling mechanism of drop breakup is not fast enough, that is, very large changes in dynamic pressure are needed to bring about significant changes in the micromist produced in order to obtain an ignition collapse, particularly in case of drops of 100 microns size and less. In order to find out analytically conditions under which small disturbances would grow rapidly, it is necessary to conduct a stability analysis. It is felt that not enough information is known to provide confidence in such an analysis. However, limit studies such as whether a sudden collapse of combustion would reignite and develop into a detonation again can be studied if only qualitatively.

The detailed write-ups for all the above mentioned phases of acoustic liner studies have been written up and are currently being reviewed for initiating specific action in the coming months.

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