Shock-Wave Ignition of Liquid Fuel Drops

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An experimental investigation of the ignition of an individual fuel drop in an oxidizing atmosphere by an incident shock wave has been made. The general characteristics of the combustion process have been observed and ignition criteria have been established. The appearance of combustion is not instantaneous but occurs at some period of time after the shock wave has interacted with the fuel drop. The combustion process is initiated in the micromist which has been stripped from the parent drop and which is entrained in the wake of the parent drop. The resulting flame propagates both upstream to the stagnation point of the drop and downstream in the wake. The combustion is not uniform but appears as a series of discrete explosions with the resulting shock waves strongly interacting with the bow and incident shock waves. Although the combustion process involves several delay times—stripping, micromist evaporation, and chemical—the entire process scales well with an Arrhenius type rate law where the activation energy is a function of the drop diameter. It is shown that the combustion process has a small but definite effect on the drop breakup and shattering. Data given include ignition delay times, breakup times, and activation energies for diethylcyclohexane drops.

Nomenclature

a = velocity of sound
d = drop diameter
ΔE = global activation energy
M = Mach number
p = pressure
q = $\frac{1}{2}\rho_2 u_2^2$ = dynamic pressure
R = universal gas constant
Re = $\rho_2 u_2 d/\mu_2$ = Reynolds number
t_b = breakup time (based on $0.6u_2$ criteria)
t_{ig} = ignition delay time
T = temperature
$\bar{T}$ = $u_2(\rho_2/\rho_l)^{1/2}t/d_0$ = dimensionless time
u = flow velocity
V_c = "convective" flow velocity around drop
V_d = downstream velocity of luminous front
V_f = propagation velocity of luminous front
V_u = upstream velocity of luminous front
We = qd/σ = Weber number
X = mole fraction
μ = viscosity
ρ = density
σ = surface tension

Subscripts

0 = stagnation condition, initial condition
1 = gas before incident shock wave
2 = gas behind incident shock wave
3 = gas behind bow shock wave
l = liquid
s = shock wave

I. Introduction

In recent years a considerable research effort has been sustained with the hope of obtaining a better understanding of the complex problem of rocket motor combustion instability. The numerous investigations into this problem have considered both the linear regime and the nonlinear case. However, one item common to both types of combustion instability is the coupling between the gas dynamic perturbations and the combustion process that provides the driving force for the instability. This paper does not propose to treat rocket combustion instability per se. However, it is hoped that this study will provide a better understanding of the events that occur when a shock wave and a fuel drop interact in an oxidizing atmosphere, since it is thought that this interaction may well be the driving mechanism in the nonlinear type of combustion instability.

It was with regard to establishing a better understanding of the nonlinear combustion instability that the examination of the two-phase detonation phenomena was undertaken. In this case it was found that a detonation or detonation-like wave could propagate through a mixture of fuel drops and a gaseous oxidizer. In the systematic experiments of Ragland, Dabora, and Nicholls,[1] two important observations were made concerning the nature of two-phase detonations. The first was that the combustion process was not smooth but was accompanied by numerous pressure peaks or overpressures. Evidently the fuel drops were not burning in a controlled manner but literally exploding. Secondly, it was found that the two-phase detonation had a very long induction time as compared with the usual gaseous detonation. The long delay was evidently due to difficulty in producing a combustible mixture ratio since all of the fuel was in the form of liquid drops. Thus fuel drop shattering or breakup time was found to be an important parameter in determining the length of the induction zone. To obtain more information on the aerodynamic destruction of liquid drops—which may greatly enhance the burning rate—an extensive study was undertaken by Ranger and Nicholls.[2] The results of this work established the conditions for the destruction of water drops and its mechanism at large Weber and Reynolds numbers over a wide range of dynamic pressures and incident shock wave Mach numbers.

In view of the two investigations mentioned above it was thought desirable to examine the effects of drop combustion on drop shattering and to examine the details by which an individual fuel drop could be ignited by a shock wave. It should be emphasized that this is not the case of suddenly exposing a fuel drop to a high temperature quiescent environment as has been treated in the past by numerous investigators.[3,4] An additional effect is present in that the drop is

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exposed to a high convective flow velocity which will cause the drop to break up. The case of the interaction of a shock wave with an initially burning drop has been considered by Rabin, Schallenmuller, and Lawhead[5] as well as by Jaarsma and Derksen.[6] Neither of these investigations, however, considered auto-ignition of the fuel drop by the shock wave.

The experimental conditions in this investigation involve shock waves having a Mach number of 3–5 interacting with drops having a diameter of 932μ, 1520μ, and 2130μ in atmospheres of oxygen, nitrogen, and mixtures of these two gases at pressures of 10, 20, and 30 in. of mercury. The Weber and Reynolds numbers are sufficiently large to ensure that the drop breakup will not be of the bag type. In the following discussion the effects of these variables on the shock ignition of fuel drops and their breakup is shown.

II. Experimental Apparatus

The experimental arrangement used in this investigation is shown schematically in Fig. 1. A helium driven shock tube is used to produce uniform strength shock waves. The driven section of the shock tube may be evacuated and filled with an arbitrary gas. The firing of the tube is accomplished through the use of the double diaphragm technique. The fuel drops with which the shock wave interacts are produced by causing a small jet to oscillate at the Rayleigh instability frequency.[7] This stream of drops then falls vertically through the shock tube and into a catch system which contains a flame suppressor.

The data concerning the fuel drop/shock wave interaction are recorded in the following manner. The velocity of the shock wave is measured by employing two Kistler transducers and a microsecond counter. Transducer No. 1 also triggers a dual beam Tektronix oscilloscope and the xenon flash tube used in the photographic system after appropriate time delays. The outputs of transducers No. 2 and No. 3 as well as the outputs of heat-transfer gages No. 1 and No. 2 are monitored on the oscilloscope. This allows one to monitor the character of the incident shock wave, the testing time, and the pressure and temperature history associated with the combustion process. The photographic data collection is achieved by using a streak shadowgraph system (which has the disadvantage of recording self-luminous events occurring in the test section in a manner such that they are not focused at the film plane) which employs a modified Beckman Whitley Dynafax as the drum camera. The path of the film travel is orthogonal to the flow direction in the shock tube. A slit is placed in the shock tube window to ensure that only one drop will be visible during the test.

In an experimental run the following sequence of events occurs; the driven section is evacuated and filled with the desired gas to a given pressure, a stream of fuel drops is established, the driver is filled, the intermediate pressure section of the diaphragm section is vented, and the shock wave passes transducer No. 1 triggering all data recording equipment.

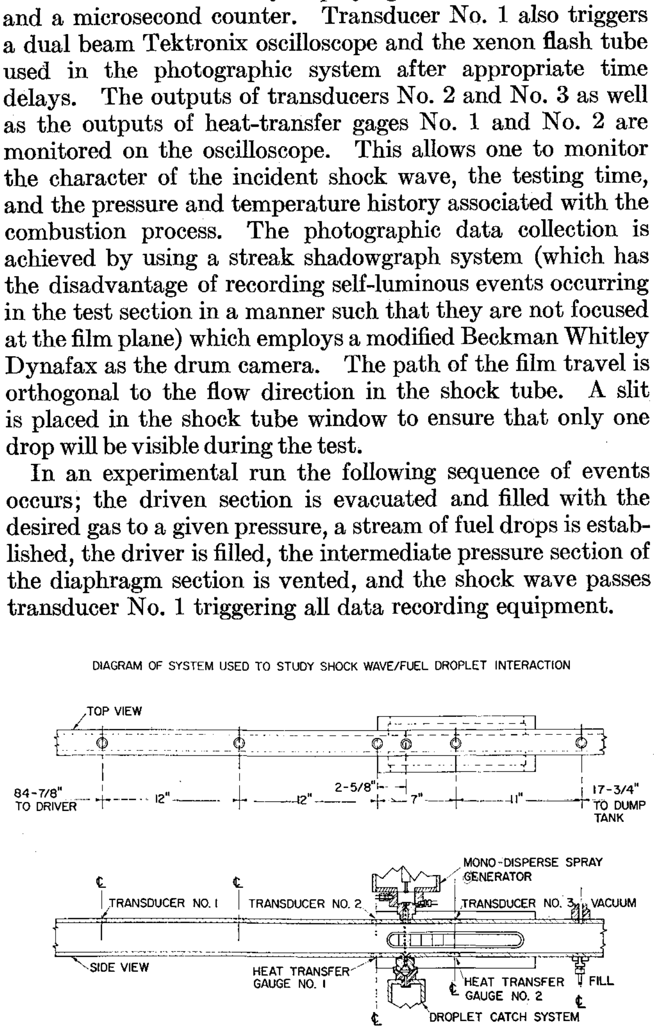

Fig. 1 Experimental apparatus.

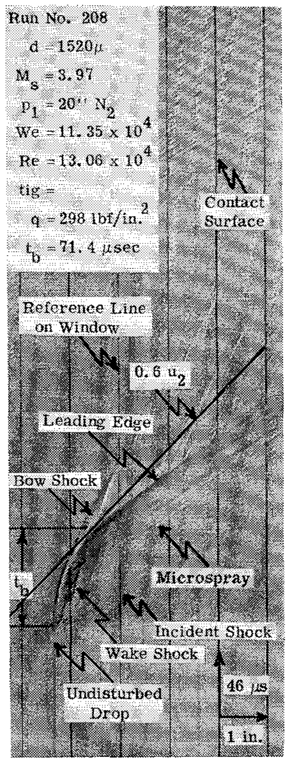

Fig. 2 Nonreacting drop.

III. Experimental Results and Discussion

The results given below are considered representative of the extensive data that were collected. Certain specific data had been selected for presentation because they clearly emphasize given features. The fuel used in all experiments was diethylcyclohexane (DECH). This was chosen because it is a pure chemical compound that closely resembles kerosene and because it has a relatively low vapor pressure.

The first experimental studies made were concerned with the interaction of a fuel drop and a shock wave in an inert atmosphere. This case was considered since it was necessary to establish a reference for the drop shattering process so that later the effects of combustion on this process could be delineated. Figure 2 shows a typical shock wave/fuel drop interaction in an inert atmosphere. The time scale is vertical and the distance scale is horizontal. Several features of this photograph should be noted. The six vertical lines which appear in the photograph are the reference lines on the windows of the optical section of the shock tube. The undisturbed fuel drop is seen to remain at the same position in space until it is struck by the incident shock wave which is traveling from left to right across the photograph. Because of the finite width of the slit employed the shock wave has finite width on the photographs, and hence the time base is uncertain within the width of this slit. At the time of interaction several events of interest occur. It is seen that a bow shock wave is formed ahead of the leading edge of the drop and that this later decays into a Mach wave. The drop is accelerated in the downstream direction due to the convective flowfield which has been established by the incident shock wave. It is also noted that after contact with the shock wave the drop image begins to widen due to the aerodynamic shattering of the drop. The mass shed by the deforming drop due to boundary-layer stripping[2] is clearly visible in the wake. The period of time between the initial shock wave/drop interaction and when the leading edge of the original, although disintegrating, drop reaches 60% of the convective flow velocity is designated the drop breakup time t_b. Well before this time, however, mass removal from the drop has been initiated. One can also recognize in the photograph the recompression shock in the wake and the contact surface.

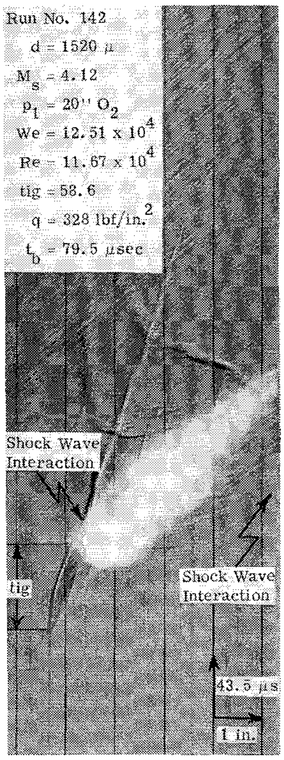

Fig. 3 Reacting drop.

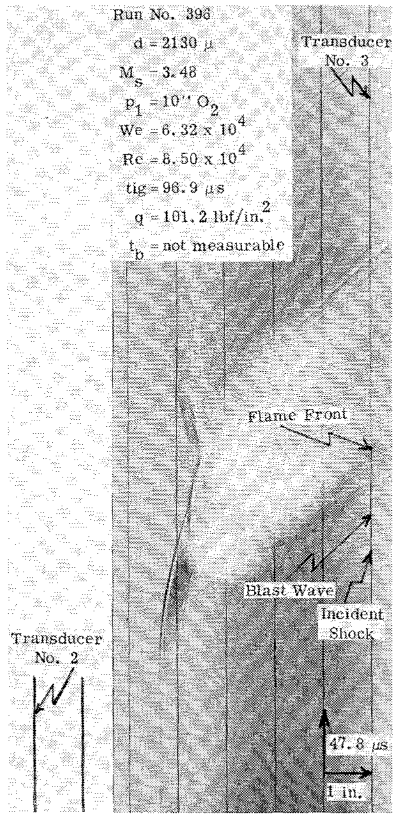

Fig. 5 Reacting drop—low dynamic pressure.

Similar phenomena occur in an oxygen environment when the shock is not strong enough to ignite the drop.

Figure 3 shows the history of a typical shock/drop interaction in which combustion occurs. Again, we have all of the features of the nonburning case plus several additional items of interest. The presence of combustion is indicated by an intense region of luminosity and strong shock waves or blast waves which first appear in the wake of the fuel drop. It is this region which contains the micromist which has been stripped from the parent fuel drop. The time interval between the interaction of the shock wave with the drop and the appearance of the strong shock wave is designated the ignition delay time t_{ig}. Because of the distortion of the emitted light by the shadowgraph it appears as if light emission occurs before the occurrence of the blast wave. This is not the case however, as the use of a schlieren system has shown that the emission of light is simultaneous with the appearance of the blast wave. It is noted that the flame propagates both upstream to the stagnation point of the parent drop and downstream in the wake until presumably the fuel/oxidizer mixture will no longer support combustion.

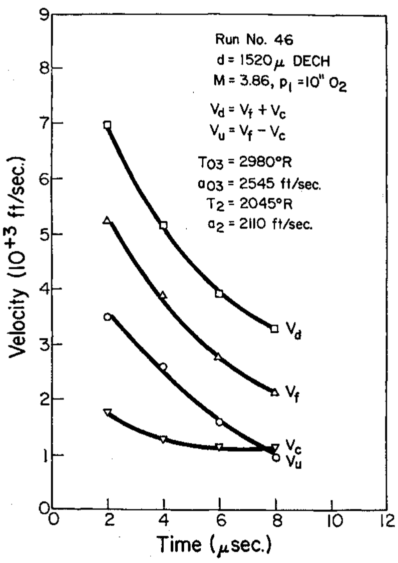

Fig. 4 Luminous front velocity.

It is seen that the emitted blast waves interact strongly with the bow shock wave of the drop and with the incident shock wave. It should also be noted that the combustion is not uniform but appears in discrete "spurts" each of which is accompanied by these strong secondary shock waves. This nonuniformity of combustion is clearly shown on self-luminous photographs. Also the self-luminous photographs that were taken show the complete absence of combustion in the stagnation point region. Under all of the conditions considered in these experiments the combustion was definitely initiated in the wake. In shadowgraphs taken which excluded the light emitted by the combustion process, an absence of mass, as indicated by decreased light scattering, is noted in the regions where the intense luminosity is normally present.

The propagation velocity of the luminous front, as measured from a schlieren photograph, is shown in Fig. 4. The maximum velocity which occurs is at the initiation of combustion and is 5250 fps. The minimum velocity occurs as the flame reaches the point of its maximum travel from the point of initiation and is 2150 fps. This minimum value seems to be quite close to an acoustic velocity based on the static temperature of the gas.

An example of drop combustion under the condition of low freestream dynamic pressure and lower stagnation temperature is shown in Fig. 5. Again the combustion is wake ini-

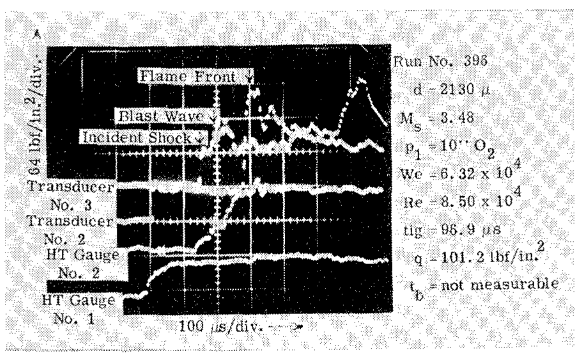

Fig. 6 Heat transfer and pressure history.

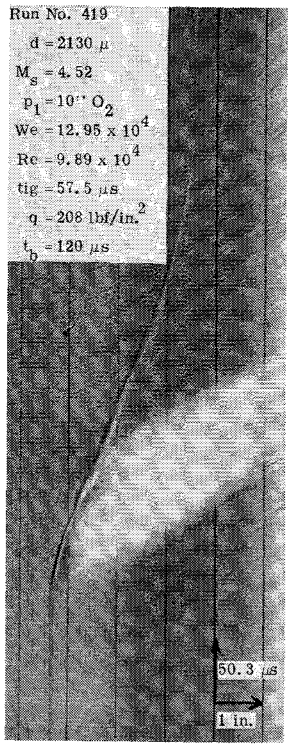

Fig. 7 Reacting drop—high Mach number.

tiated, and it is accompanied by strong blast waves. It is seen that these blast waves strongly interact with the deforming drop, perhaps aiding in its destruction. The interaction is so strong in fact that it is not possible to measure the breakup time. As was indicated in Sec. II, two pressure transducers are located in the test section (see Fig. 5) such that it is possible to obtain a pressure history of the combustion process. This history is shown in Fig. 6. It is noted that both the upstream and downstream sensors show the passage of the incident shock wave. However, the downstream pressure transducer shows in addition the arrival of the blast wave produced by the combustion process. This wave almost doubles the ambient pressure level, increasing it from 68.5 lbf/in^2 to 128 lbf/in.^{2}. The heat-transfer gage

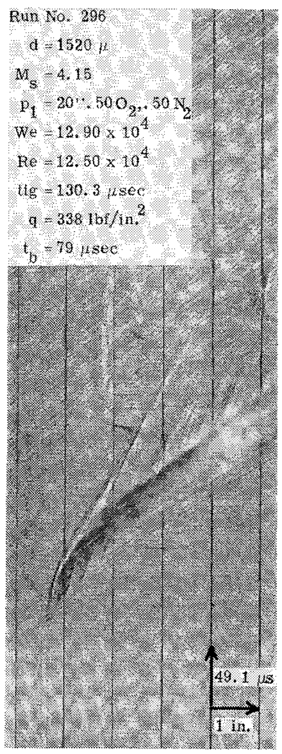

Fig. 8 Reacting drop—diluted oxidizer.

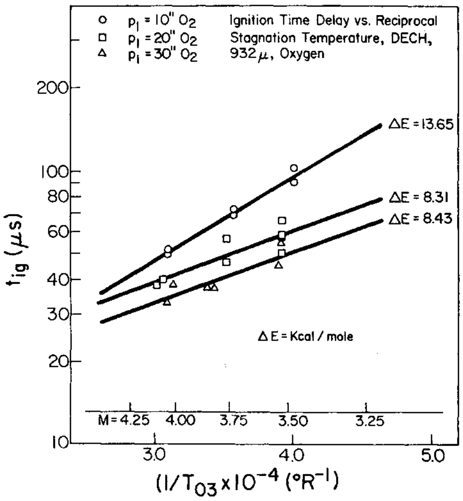

Fig. 9 Ignition delay time—932μ drops.

also shows a response to the blast wave and the subsequent passage of the flame front.

An example of drop combustion at a relatively high Mach number is shown in Fig. 7. In this case we note again that the combustion is accompanied by strong shock waves. However the series of explosions is now absent and only a single blast wave may be detected. Combustion is again initiated in the wake region although it is difficult to ascertain exactly when. The ignition delay period is estimated using the data presented in Fig. 10.

The shock/drop interaction shown in Fig. 8 illustrates how sufficient dilution of the pure oxygen atmosphere may significantly affect the combustion process. It was necessary to add 50% mole fraction of nitrogen in order to achieve this result. In this case there is an absence of the strong secondary shock waves which normally accompany the combustion, and only the presence of Mach waves may be detected. This has been designated as a deflagrative mode of shock initiated combustion as opposed to the detonative mode which has been previously discussed.

The combustion process was observed over a range of shock Mach numbers for various densities and compositions of the gas surrounding the various size fuel drops. The ignition delay time was measured for each case in which combustion occurred. It was assumed that these data could be correlated using an Arrhenius type of rate law where the temperature dependence was represented by the stagnation temperature in the region behind the bow shock. A least squares fit to the data was made on this basis. The results for the 932 μ

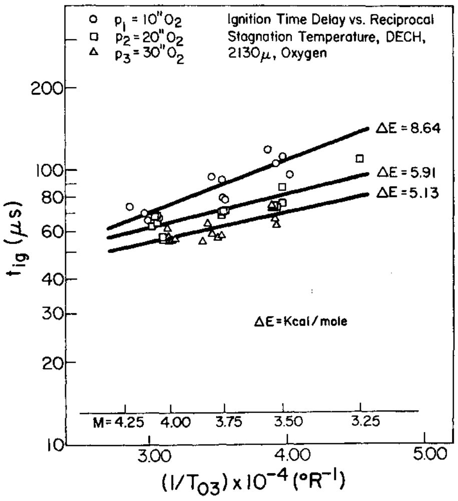

Fig. 10 Ignition delay time—2130μ drops.

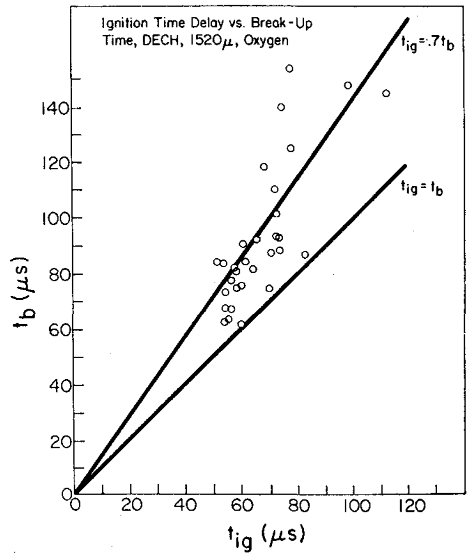

Fig. 11 Breakup and ignition times.

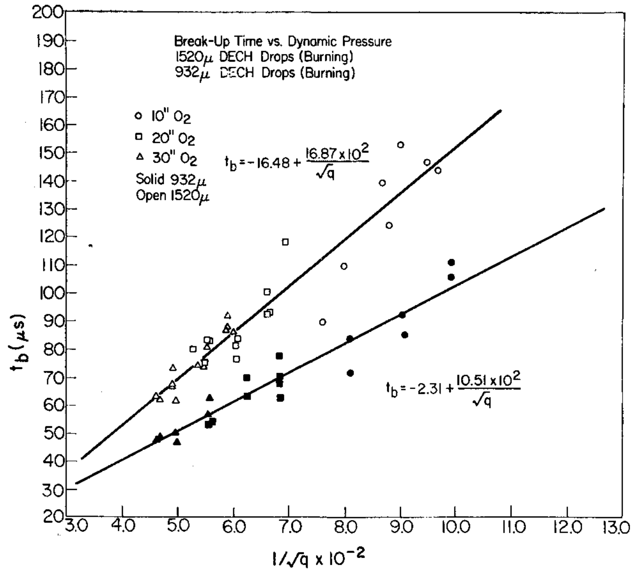

Fig. 13 Breakup time—burning.

drops are shown in Fig. 9. Although incident shock waves having a Mach number of 3 and 3.25 were used repeatable spontaneous ignition of the fuel drops was not obtainable under these conditions, i.e., a minimum incident shock wave Mach number is required. In this particular case it is between $M_s = 3.25$ and $M_s = 3.50$. For the 1520 μ drops this threshold was determined to be $M_s = 3.30$ at $p_1 = 30$ in. Hg of oxygen. From the figure it is noted that at a given initial pressure an increase in the incident shock wave Mach number will decrease the ignition delay time and that at a given shock wave Mach number an increase in the initial pressure will also decrease the ignition delay time. A least squares fit of the data was used to calculate the noted activation energies.

Similar ignition delay time data for the 2130 μ drops are presented in Fig. 10. Again the same trends were noted. However, it is obvious that the slope of the data points is much less for the 2130 μ drops. The least squares fit again gives the activation energies listed on the figure.

The effect of diluting the ambient atmosphere with nitrogen was also examined as was previously indicated. If the dilution was not large enough to change the mode of combustion from the detonative type to the deflagrative type the effect was simply to increase the ignition delay time by a constant amount. The activation energy remained approximately equal with that of the undiluted case. Hence, it seems reasonable to conclude that the ignition delay time may be predicted by

$$t_{ig}^{-1} \sim [\text{oxidizer concentration}] \exp(-\Delta E/RT_{03})$$

where judging from the experimental data of Fig. 9 and 10

$$\Delta E = f(d_0)$$

However, the ignition delay time does not only consist of a chemical delay time but also includes a stripping delay time—the time for material to be removed from the parent drop and to be carried to the wake—and a micromist evaporation delay time. It is realized that the Arrhenius rate law is not being applied in the most rigorous sense, but it does seem to give satisfactory results. It has been used in a similar manner in other analogous situations.[8]

The effects of drop combustion on the dynamics of drop destruction were next examined where drop breakup is based on the acceleration of the disintegrating drop to 60% of the post shock convective flow velocity. As Fig. 11 shows, combustion is initiated in most cases well before drop breakup. Hence the combustion process does have an opportunity to affect the aerodynamic destruction process. The results of other tests indicate that this relationship between t_b and t_{ig} is dependent on drop size with $t_{ig} = 0.8\, t_b$ for the 932 μ drops.

Breakup data for nonreacting drops are given in Fig. 12. Here the effects of the dynamic pressure and the drop size

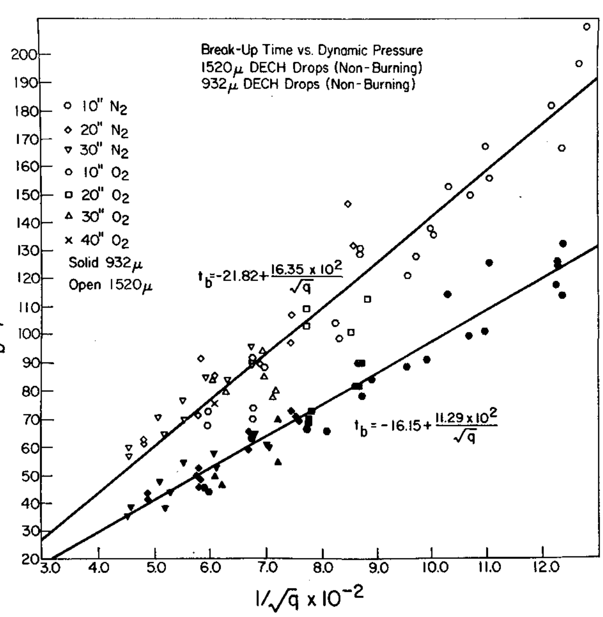

Fig. 12 Breakup time—nonburning.

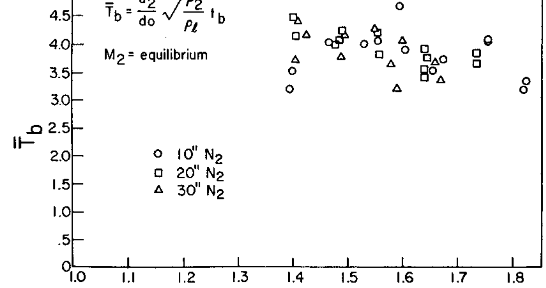

Fig. 14 Dimensionless breakup time—nitrogen.

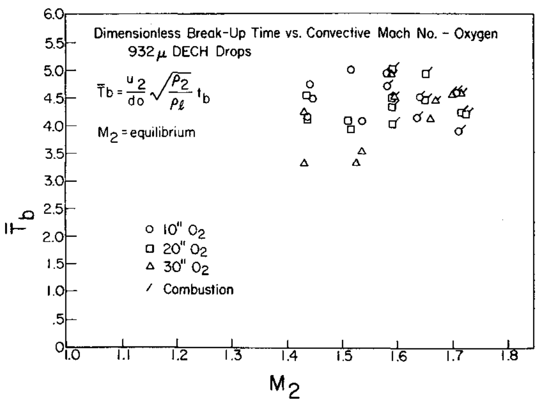

Fig. 15 Dimensionless breakup time—oxygen.

are noted. A least-squares fit of the data yields a relationship which was first proposed by Clark.[9] That is,

$$t_b \sim dq^{-1/2}$$

Figure 13 shows the breakup data for drops that are experiencing combustion. It is clear that the above functional relationship between t_b and q is still valid, but it is noted that the combustion process has increased the breakup time. This is not surprising since the combustion is accompanied by large pressure pulses, which may significantly affect the pressure and velocity distribution about the drop.

The nondimensional breakup time $\bar{T}_b$ is presented in Fig. 14 as a function of the convective flow Mach number M_2, for drops in a nitrogen atmosphere. The Mach number is based on equilibrium chemistry. It is noticed that there is a general decrease in $\bar{T}_b$ with increasing M_2 (when $M_2 > 1.0$) in much the same manner as the data reported for water drops.[2]

In Fig. 15 the nondimensional breakup time is presented for drops in an oxygen atmosphere, some of which are reacting. In comparing these data with those of Fig. 14 it is recognized that in cases where combustion is present the nondimensional breakup time tends to be larger for the same convective flow Mach number. Hence, it is again clear that the combustion process tends to delay drop breakup, at least when destruction is based upon the 0.6 u_2 criteria.

IV. Conclusions

A fuel drop which is surrounded by an oxidizing atmosphere may be ignited by an incident shock wave as long as the strength of the shock wave exceeds a certain minimum value. The combustion process initiates in the wake of the partially shattered drop after an ignition delay period which is satisfactorily correlated by an Arrhenius type rate law where the global activation energy is a function of the drop size. The combustion is accompanied by intense blast waves which interact strongly with the drop and the incident shock wave. The breakup time is increased slightly by the combustion process, but it still remains inversely proportional to the square root of the dynamic pressure.

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