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THE INTERACTION OF AN INCIDENT SHOCK WAVE WITH LIQUID FUEL DROPS

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Abstract

Additional information concerning an experimental study which examines the results of the interaction of an incident shock wave with a fuel drop in oxidizing and inert atmospheres is described. For conditions under which spontaneous ignition occurs the combustion process may be *described as a shock wave followed by a region of intense* combustion. The two fuels examined, diethylcyclohexane and n-hexadecane, show similar combustion characteristics, and an ignition mechanism is postulated. The aerodynamic shattering behavior of the fuel drops is examined and a comparison is made with the shattering characteristics of water drops. The surface tension and/or the viscosity of the liquid may be important parameters with regard to the aerodynamic shattering, and the results of the acceleration wave theory of aerodynamic shattering are apparently not *applicable to the conditions encountered in this study.*

I. Introduction

Although gaseous detonations have been known and studied for almost a century, the occurrence of a two-phase detonation (gaseous oxidizer and liquid fuel) has been recognized only in the last decade. This phenomena was apparently first investigated by Webber[1] who noted that ". . . a spray of fairly coarse fuel may be burned rapidly enough, under the influence of a pressure wave, to sustain and amplify the pressure wave. It is apparently not necessary that the fuel be vaporized or partially burned before the arrival of the wave." This investigation was continued and expanded upon by Cramer[2]. Additional research was carried out in the area of two-phase detonation by Dabora, Ragland, and Nicholls[3] who were motivated by the belief that this mode of combustion was associated with the severe transverse pressure waves that were observed in liquid propellant rocket engines[4]. They also pointed out that the time required for the aerodynamic shattering of the fuel drops was in approximate agreement with the induction time for the two-phase detonation. In subsequent works[5, 6] they devoted much effort to the study of the details of the processes occurring in the reaction zone. Because it was thought that drop shattering by the aerodynamic forces was an important mechanism in the two-phase detonation, and indeed it had been shown by Williams[7] that fuel drop vaporization could only play a limited role, an extensive investigation of aerodynamic drop shattering under conditions applicable to two-phase detonations was undertaken by Ranger and Nicholls[8]. Subsequently, Borisov, Gelfand, Gubin, Kogarko and Podgrebenkov[9] examined the effect of drop shattering on the structure of the reaction zone of the two-phase detonation. In essence, they considered the effect of different drop shattering models on the energy *release rates. A study of the induction processes* that occur upon the interaction of a shock wave and a fuel drop in an oxidizing atmosphere was evidently first made by Kauffman and Nicholls[10] who examined the ignition and combustion characteristics of a stream of individual fuel drops falling transverse to the flow direction in a shock tube. They observed that under certain conditions a fuel drop in an oxidizing atmosphere could indeed be ignited by an incident shock wave and that the wake initiated combustion process occurred after a delay period that was satisfactorily described by an *Arrhenius type rate law. Recently Borisov, et al*[11] expanded their initial work in an attempt to examine the induction zone of the two-phase detonation. They observed that the transition from the nonsteady combustion regime to detonation occurred only when; 1) a finite amplitude pressure disturbance was present which could cause sufficient drop shattering, and 2) when hot gas was present that was capable of igniting the mixture of shattered fuel drop and surrounding oxidizer.

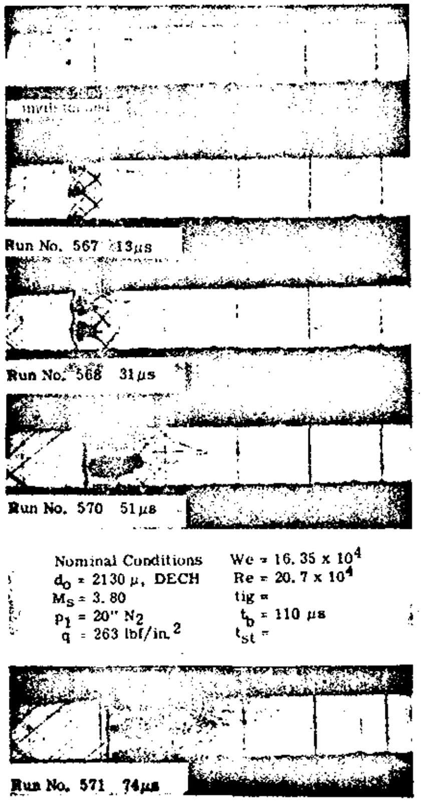
Since it was evident that the induction processes occurring in two-phase detonations were not yet fully understood, additional research in this area was undertaken. It was desired to compare the effects of different liquids on the combustion and breakup process and to attempt a description of the fundamental processes that occur upon interaction. The experimental conditions considered in this investigation involve incident shock waves having a Mach number of from 3 to 5 interacting with drops of diethylcyclohexane, n-hexadecane, and water in oxygen and nitrogen atmospheres. The test conditions are such that the Weber and Reynolds numbers are sufficiently large to ensure that the drop breakup will not be of the bag type.

II. Experimental Apparatus

The experimental arrangement used in this investigation, which is described in detail elsewhere[10], consists of a helium driven shock tube with a test section in which the ambient conditions can be closely controlled. A stream of monodisperse drops is produced by the Rayleigh capillary instability technique and allowed to fall vertically through the test section. Heat transfer and pressure histories are monitored at various stations along the driven section. *The shock wave/drop* interaction has been observed photographically using streak and spark recording techniques in conjunction with the usual shadowgraph system.

III. Experimental Results and Discussion

In order to establish a baseline so that the effects of combustion on the dynamics of drop shattering can later be noted the interaction of a shock wave with diethylcyclohexane (DECH) drops in an inert atmosphere was first examined. This interaction is shown in the series of spark shadowgraphs presented in Figure 1. It should be noted that each photograph corresponds to a different run—with identical run conditions—and that this is not a sequence of photographs from the same run. The stream of undisturbed fuel drops falling through the test section is shown in the first photograph. *The vertical lines on the photograph are reference* marks on the test section window and are spaced one inch apart. In the second photograph of the sequence the incident shock wave moving from left to right has passed by the stream of fuel drops with 13μs elapsing since the interaction occurred. One may recognize from the photograph, in addition to the incident shock wave, the bow and wake shocks associated with each drop. The distortion of the drop from its original spherical shape can be noted as well as the mass which is entrained in the drop wake. This is material that has been shed from the parent drop *through boundary layer stripping*[8]. The photograph at 31μs shows the continued



Nominal Conditions
d_o = 2130 μ, DECH
M_s = 3.80
p_1 = 20" N_2
q = 263 lbf/in.^{2}
We = 16.35 x 10^4
Re = 20.7 x 10^4
tig =
t_b = 110 μs
t_{st} =

Figure 1. Non-reacting 2130μ DECH Drops.

Nominal Conditions
d_o = 2130 μ, DECH
M_s = 3.75
p_1 = 20" O_2
q = 255 lbf/in.^{2}
We = 15.91 x 10^4
Re = 18.28 x 10^4
tig = 70 μs
t_b = 128 μs
t_{st}

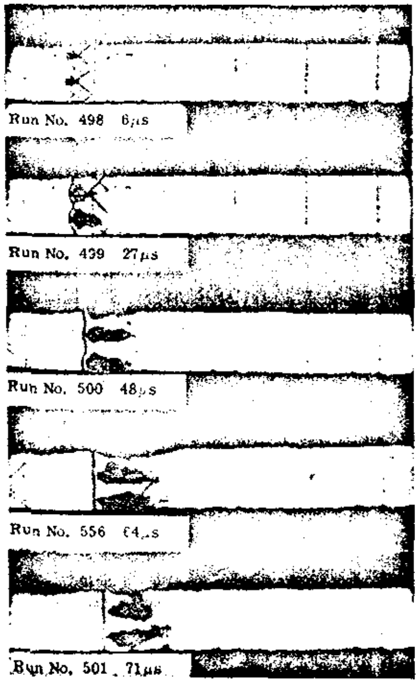


Figure 2. Reacting 2130μ DECH Drops.

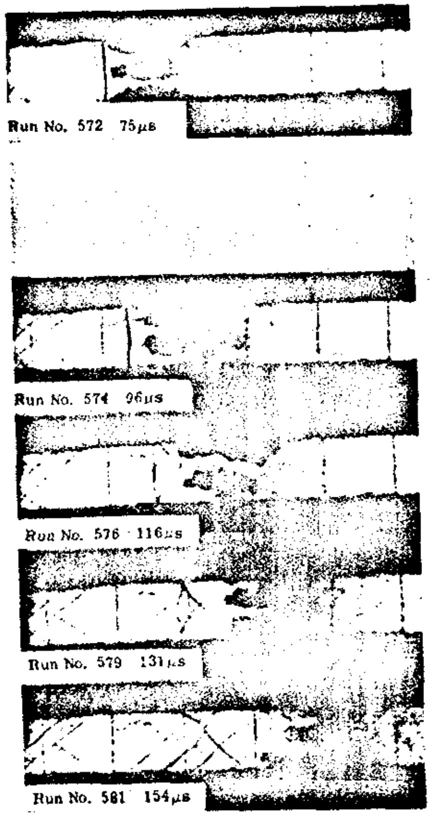


Figure 1 (cont.). Non-reacting 2130µ DECH Drops.

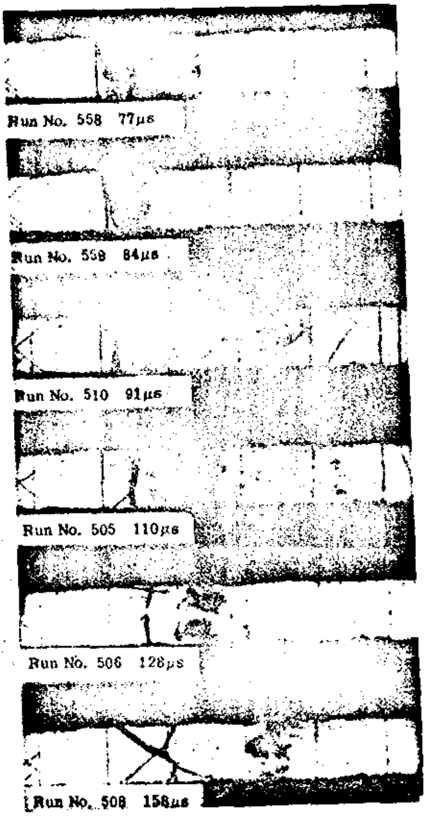


Figure 2 (cont.). Reacting 2130µ DECH Drops.

distortion of the fuel drop due to the pressure and shear forces as well as an accelerated mass removal from the drop. As the period of time after interaction increases it should be noted that the original spherical drop assumes a more amorphous shape and that the original drop mass is spread out over an increasingly larger volume. Also, we can note the increasing downstream displacement of the disintegrating drop as it is accelerated to the convective flow velocity. Based upon the acceleration of the drop to 60% of the convective flow velocity the drop is considered to have been shattered at 110µs. As Run No. 576 shows, the original drop mass is quite diffuse at this time. The last photograph of the sequence shows that at 154µs after the interaction the original drops are reduced to a diffuse cloud of spray moving at the convective flow velocity. It should be noted that in a qualitative sense the shattering of a fuel drop in an inert atmosphere is identical to the water drop shattering investigated by Ranger[8].

The sequence of shadowgraphs appearing in Figure 2 shows the interaction of the fuel drop and the shock wave under conditions identical to those in Figure 1 with the exception that oxygen has replaced nitrogen as the ambient gas in the test section of the shock tube. A pinhole in the optical system excludes any light emitted by the combustion process. One may observe the similarities of the initial phase of the shattering process in both atmospheres as we again note the presence of bow and wake shocks, the distortion of the original drop, the shedding of the micromist from the parent drop, and the acceleration of the parent drop. However, it is noted that the similarity abruptly ceases at somewhere between 71µs and 77µs. At this time the appearance of additional shock waves is recognized and the wake area is noted to be significantly different. Spontaneous ignition of the micromist shed by the parent drop which is entrained in the wake region has occurred. The shock wave generated by the initiation of the combustion process propagates both in the upstream and in the downstream directions. At 91µs after the original interaction the wake region as well as the region between the drops gives the typical mottled appearance of a flame shadowgraph. It is also noted at this time that the bow shock wave has been significantly thickened by interaction with the blast wave originating from the combustion process and that the incident shock wave has been overtaken by the portion of this blast wave which propagates downstream. The continuing combustion process can be observed in Runs No. 505, 506 and 508 along with the continuing acceleration and destruction of the original drops. It should be observed that there is much less drop mass remaining in Run No. 508 where combustion is present as compared to approximately the same time after interaction in Run No. 581 where combustion is absent. This, of course, is due to the consumption of the drop mass by the combustion process.

The spontaneous ignition of a n-hexadecane drop is shown in the streak shadowgraph of Figure 3. The time scale is vertical with time increasing upward and the distance scale is horizontal where the vertical lines are the reference markers on the test section window of the shock tube. The incident shock wave passes from left to right across the photograph. Again a pinhole is used to mask the emitted radiation from the combustion process. It is seen that the convective flow field leads to the acceleration of the drop in the downstream direction as well as to the stripping of mass from the drop. After a period of time, the ignition delay time, the appearance of a strong shock wave is noted in the wake of the shattering drop. Intense luminosity is also observed to be present in this region when the pinhole is not used. This is the region which contains the material that was stripped from the parent drop by the aerodynamic forces. It should be recognized that the combustion does not originate in the mass that is first removed from the drop, but it has its origin in that mass which is shed at a later time, the mass stripping time. It is observed that as in the previous figure the blast wave propagates both in the upstream and the downstream directions. Because the emitted light has been removed one can clearly observe the interaction of the blast wave with the drop. At any given time before the appearance of this wave the drop exhibited a fairly uniform density but after its appearance the mass seems to be more concentrated towards the front of the drop. This effect could be due to the blast wave "squashing" the drop from the rear and causing the mass to move forward and/or by the removal of mass through the combustion process.

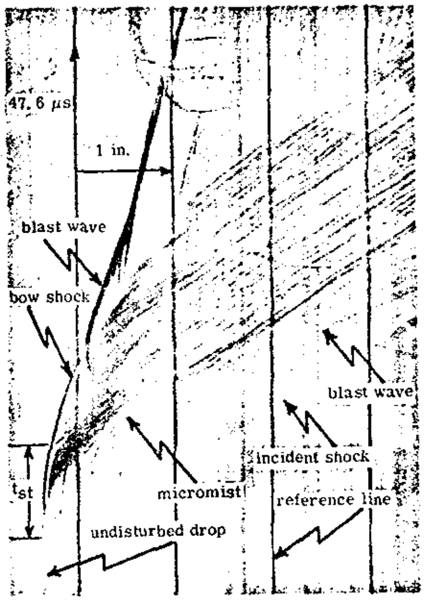


Figure 3. Reacting 930µ N-Hexadecane Drops - Emitted Light Removed.

The propagation velocity of this blast wave has been measured and the results are presented in Figure 4. It is seen that the time dependence of the wave velocity is adequately described by the predictions of blast wave theory with a cylindrical blast wave giving the best agreement. It has been found that the DECH data may also be correlated with the blast wave theory. For the DECH drops it has been observed that after the blast wave separates from the flame front its Mach number, based upon the free stream static temperature, remains approximately constant. Its magnitude does, however, show a slight dependence upon the initial drop

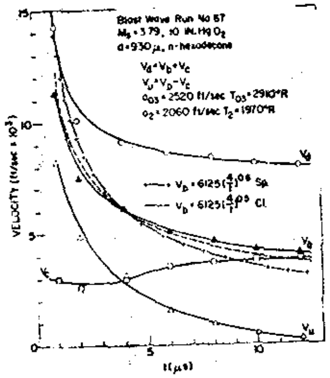


Figure 4. Blast Wave Velocity-930μ N-Hexadecane Drops.

diameter and the Mach number of the incident shock wave. Typical values of the blast wave Mach number range between 2.7 to 3.2 which is only slightly less than the strength of the incident shock wave. It should be noted that it is propagating through a gas that has been heated and compressed initially by the incident shock wave.

A slightly different representation of the combustion process is shown in the streak photograph of Figure 5. Here the light emitted by the combustion process has not been removed and the optical system has been focused on the drop—this essentially negates any shadowgraph effect. The behavior here is identical to that represented in Figure 3 except that now there is a sudden appearance of luminosity in the drop wake instead of a shock wave. A superposition of these two figures will show that the shock wave and the luminosity appear at the same time. It is seen that the flame propagates both in the upstream and downstream directions presumably until it reaches a point where there is no longer a combustible mixture present. After the initial appearance of combustion it is seen that the intensity of the flame diminishes and that the flame assumes a rather "stringy" appearance with periodic fluctuations in intensity.

The combustion process for n-hexadecane drops was observed over a range of shock Mach numbers for various initial pressures of oxygen in the test section. The ignition delay time was measured for each case in which combustion occurred. It was assumed that the n-hexadecane data could be correlated using an Arrhenius type rate law as had been done in the case of the ignition data for the DECH drops[10]. A least squares fit to the data was made on this basis and the results for the 930μ drops are shown in Figure 6. The general trend of the data is quite similar to that previously reported for the DECH. It is noted from the figure that the ignition delay time can be decreased by either increasing the Mach number of the incident shock wave or by increasing the initial pressure of the oxygen in the test section. Although incident shock waves having Mach numbers of 3 and 3.25 were also used repeatable spontaneous ignition was not attainable under these marginal conditions.

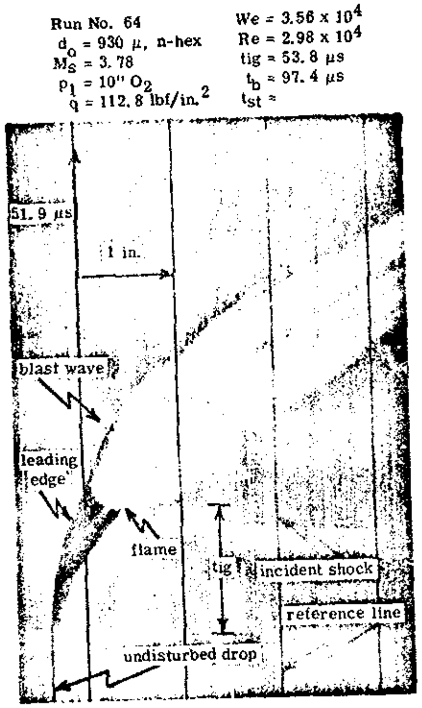


Figure 5. Reacting 930μ N-Hexadecane Drops.

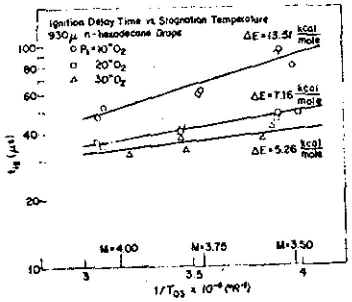


Figure 6. Ignition Delay Time - 930μ N-Hexadecane Drops.

For a convenient comparison the activation energies for the DECH as computed from the Arrhenius rate law fit of the data is shown in Figure 7. The temperature dependence of the rate law is again based on the stagnation temperature behind the bow shock. The use of the flow static temperature results in a small decrease, approximately 20%, in the activation energy.

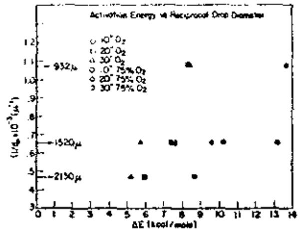


Figure 7. Activation Energy - DECH Drops.

Based upon the data that has been collected to date, an ignition mechanism for the spontaneous ignition of a fuel drop by a shock wave in an oxidizing atmosphere has been hypothesized. As was previously mentioned it has been observed that ignition does not occur in the micromist which is first stripped from the parent drop even though this fuel has been exposed to the high temperature environment for the longest period of time. The failure of this shed material to ignite is clearly noted on the streak photographs where mass is seen to be swept downstream well past the location of the origin of the flame. And, once the flame appears, it propagates in the downstream direction consuming this earlier shed mass. It is believed that the small size of the microspray droplets (~10μ) precludes the establishment of the usual diffusion type flame and that the small droplets simply vaporize much along the lines reported by Faeth[12] and Wood and Rosser[13]. The vaporization of this microspray would lead to the accumulation of a gaseous fuel/oxidizer mixture in the wake of the drops. The resultant intense initial blast upon ignition could well be a detonation of this premixed gaseous mass. It is recognized on the photographs that the intense combustion which accompanies the ignition does not propagate upstream completely to the leading edge of the parent drop, and that it does not persist for a long period of time after the ignition. This is believed to be due to the absence of sufficient combustibles in the gaseous state.

The period of time between the initial interaction and the shedding of the microspray that is first ignited, t_{st}, has been measured for all of the cases in which ignition of the DECH drop occurred. The dimensionless value of this quantity, $\overline{T}_{st}$, for the 2130μ drops is presented in Figure 8. The effect of this non-dimensionalization is to normalize the effects of the dynamic pressure on the breakup. Here it is noted that as the value of the free stream Mach number increases the value of $\overline{T}_{st}$ becomes smaller. This implies that for higher Mach numbers, and therefore higher post-shock temperatures of the ambient gas, the drop is less shattered when ignition occurs, i. e., there is less stripped micromist in the region behind the parent drop. Also, from similar plots for drops having different initial diameters it has been found that as the diameter of the drop decreases the entire curve tends to move upwards. That is, a smaller initial drop diameter implies in general a larger $\overline{T}_{st}$. Thus the smaller drops are more completely shattered when ignition occurs. This behavior would seem to imply that a certain amount of the fuel from the parent drop must be present in the wake before ignition will occur under the ambient conditions, i. e., a certain equivalence ratio must be reached at a given ambient temperature for ignition to occur. The larger drops can provide this necessary amount of fuel with less stripping and a higher post-shock temperature requires the presence of less fuel in order to obtain the critical fuel-lean mixture ratio required for ignition.

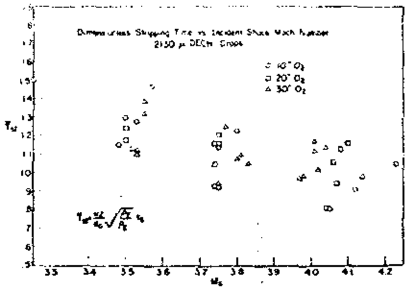


Figure 8. Dimensionless Stripping Time - 2130μ DECH Drops.

The implications of this proposed ignition process are that for very small drops ignition of individual drops may not be possible because the required mass density of microspray may not be reached even upon complete shattering of the drop. And, for very large drops the required mass density, or equivalence ratio, could always be reached. Extrapolating these results to a spray where we have a collection of individual drops this would imply the existence of a certain number density whose joint shattering would provide the necessary mass of fuel microspray which is required for ignition. This of course would imply the existence of a certain minimum overall equivalence ratio for ignition of the spray. It may be, however, that as post-shock temperatures and oxidizer concentrations increase, the individual droplets in the microspray may be able to sustain a normal diffusion type flame.

It is thought that the activation energy shows an initial drop diameter dependence because if boundary layer stripping properly describes the removal of mass from the parent drop, the size of the shed micromist should be related to the fluid boundary layer thickness. Therefore because of the Reynolds number dependence of the fluid boundary layer thickness, the larger size drops should produce a larger size micromist. These different micromist sizes would, of course, lead to different evaporative characteristics.

It thus appears that the ignition process which occurs when a shock wave interacts with a fuel drop is quite similar to the ignition process which occurs in a diesel engine. The micromist produced by the droplet shattering seems quite analogous to the spray produced by the fuel injector, and the shock heated ambient atmosphere is similar to the adiabatically compressed cylinder air.

Once combustion has initiated it is believed that the parent drop simply acts as a fuel supply for the flame present. The shed micromist is immediately ignited and this flows downstream producing the "stringy" appearance of the flame.

In order to better understand the shattering characteristics of the drops, which are apparently so important in the ignition process, a comparison was made between the shattering behavior of the two different fuels, DECH and n-hexadecane, as well as water. The physical characteristics of these fluids are given in Table I. It may be recognized that the properties are quite similar except for the surface tension of the water and the larger viscosity of the n-hexadecane. A streak photograph showing the shattering of a water drop is presented in Figure 9. The behavior is typical of a drop shattering in the absence of combustion. One should note, however, the darkness of the wake region which contains the stripped micromist. Essentially, most of the light from the shadowgraph light source has been removed through scattering by the micromist. In comparison, Figure 10 shows the shattering of a DECH drop under identical conditions. Again the behavior is typical of a non-reacting drop, but the intense light scattering by the micromist in the wake region is absent. A quantitative comparison of these two cases is given in Figure 11 which is a microdensitometer scan of the original negatives. The scans were made horizontally across the film at a constant time. The breakup time was chosen since it was felt that this would represent equal shattering of the drops. It is readily seen that the micromist produced by the water drop shattering is much more effective as compared with the DECH micromist at scattering the light from the shadowgraph light source.

Run No. 451
$d_o = 2060\ \mu$, H_2O
$M_s = 3.30$
$p_1 = 20''\ N_2$
$q = 176\ \text{lbf/in.}^2$
$We = 4.01 \times 10^4$
$Re = 18.07 \times 10^4$
$t_{ig} =$
$t_b = 196\ \mu s$
$t_{st} =$

Figure 9. Non-reacting 2060µ Water Drop.

If it is assumed that at $t = t_b$ an equal volume of fluid has been removed from both the DECH and the water drops through aerodynamic stripping (this does not seem unreasonable in view of their similar viscosities and densities) and that this stripped micromist has been distributed over equal wake volumes, then it may be shown from basic light scattering considerations[14] that the diameter of the droplets of the water micromist must be less than the diameter of the droplets in the DECH micromist. This also implies a greater number density for the water micromist.

Run No. 346
$d_o = 2130\ \mu$, DECH
$M_s = 3.30$
$p_1 = 20''\ N_2$
$q = 176\ \text{lbf/in.}^2$
$We = 11.08 \times 10^4$
$Re = 18.83 \times 10^4$
$t_{ig} =$
$t_b = 170\ \mu s$
$t_{st} =$

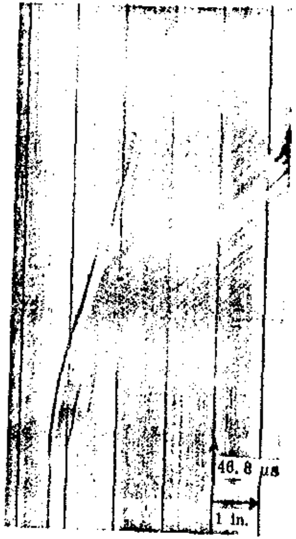


Figure 10. Non-reacting 2130µ DECH Drop.

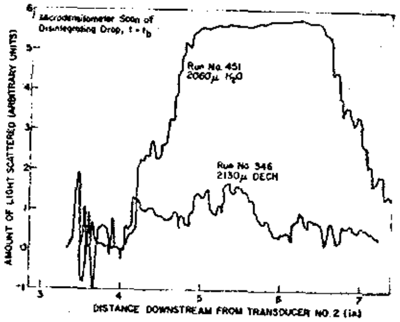


Figure 11. Microdensitometer Scans - 2060µ Water Drop and 2130µ DECH Drop.

In the case of the aerodynamic destruction of liquid jets injected into supersonic airstreams two of the mechanisms that have been proposed for their destruction are the capillary wave theory and the acceleration wave theory[15]. Both of these mechanisms predict that the mean size of the shed micromist is proportional to the one third power of the surface tension. That is, the size of the droplets in the micromist should increase with increasing surface tension. Noting that the surface tension of water is approximately three times greater than that of DECH these theoretical predictions appear to be contrary to the findings reported here. It would therefore seem that under the conditions reported in the present drop shattering studies that the capillary wave theory and the acceleration wave theory of shattering are not applicable.

Property at 20°C	DECH	N-Hex	Water
Composition	$C_{10}H_{20}$	$C_{16}H_{34}$	H_2O
Density (gms/cc)	.80	.777	.998
Surface Tension(dyne/cm)	27.5	20.38	72.75
Viscosity (poise)	0.0114	0.0241	0.0100
Index of refraction	1.5		1.33

TABLE I. Physical Properties of Drop Liquids.

A comparison of the gross breakup characteristics is given in Figure 12 which shows the breakup times, based on the acceleration of the shattering drop to 60% of the convective flow velocity, for DECH, n-hexadecane, and water drops (water data from Ref. 16) in a non-reacting situation. One can readily recognize that it takes longer for the water drops to shatter than it does for either DECH or

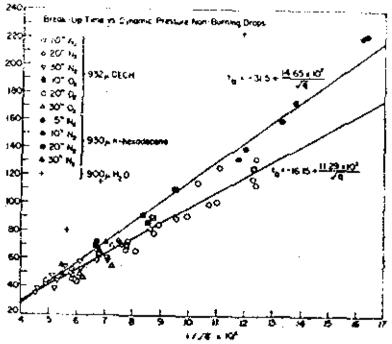


Figure 12. Breakup Time - Non-reacting Drops.

n-hexadecane drops whose breakup times are quite similar. This is believed to be caused by the higher surface tension of the water which more effectively resists the aerodynamic forces, perhaps by maintaining a lower drag coefficient for the drop, even though the Weber numbers are quite large.

A comparison of the breakup times for reacting DECH and n-hexadecane drops is made in Figure 13. Again it is seen that the n-hexadecane and DECH are in close agreement although comparison with the non-reacting case shows that the breakup time has increased slightly.

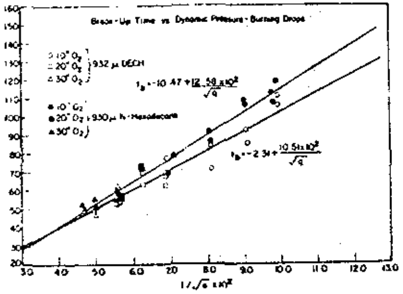


Figure 13. Breakup Time - Reacting Drops.

Another comparison of the difference in the breakup behavior between the water and DECH drops is shown in Figure 14. Here the dimensionless breakup time is presented as a function of the convective flow Mach number. This nondimensionalization essentially removes the effects of the dynamic pressure and of the initial drop diameter on the breakup time. It is again recognized that for these larger size drops that the water drops take longer to shatter, and in addition that there is a slight dependence of the nondimensional breakup time on the convective flow Mach number for both drops.

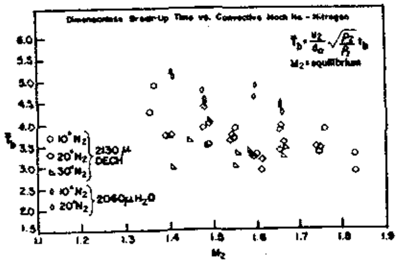


Figure 14. Dimensionless Breakup Time - Non-reacting Drops.

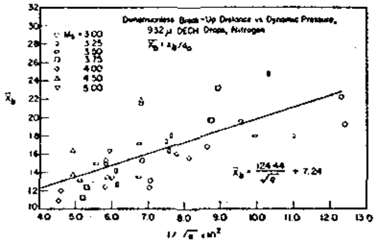


Figure 15. Dimensionless Breakup Distance - 932μ DECH Drops.

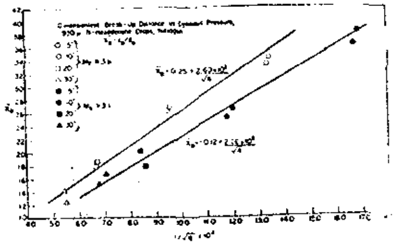


Figure 16. Dimensionless Breakup Distance - 932μ N-Hexadecane Drops.

The data presented in Figures 15 and 16 shows the dimensionless breakup distance for DECH and n-hexadecane drops. It is seen that this quantity is both a function of the dynamic pressure and of the convective flow Mach number. It was reported by Ranger[16] that for water drops $\bar{X}_b$ was approximately a constant having a value of approximately twenty-five. Although the dynamic pressures for the water data was not reported it is seen that the values of $\bar{X}_b$ for the DECH and the n-hexadecane drops can either exceed or be less than the value reported for water.

IV. Conclusions

The combustion behavior exhibited by a shock wave ignited fuel drop surrounded by an oxidizing atmosphere is similar for the two fuels, diethylcyclohexane and n-hexadecane. The occurrence of ignition whose delay time is adequately described by an Arrhenius rate law is apparently governed by the establishment of a combustible mixture ratio in the wake of the shattering fuel drop. The combustion process appears to be a flame front which closely follows a strong shock wave whose behavior may be described by point explosion theory. The drop combustion depends strongly on the strength of the incident shock wave, the fuel drop diameter, and the initial oxidizer pressure.

A substantial difference exists with regard to the aerodynamic shattering characteristics exhibited by the fuel drops and water drops. The water drops require both a larger time and in general a larger distance for breakup to occur as compared to that required for the fuel drop destruction. The dimensionless breakup distance has been found to be a function of the dynamic pressure for both the water and the fuel drops, and the microspray produced by the water drop shattering is smaller in size than that produced by the fuel drop shattering. The latter finding is contrary to the predictions of the acceleration and capillary wave theories of aerodynamic breakup.

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Nomenclature

a = velocity of sound
d = drop diameter
ΔE = global activation energy
M = Mach number
p = pressure
q = $1/2\, \rho_2 U_2^2$ = dynamic pressure
Re = $\rho_2 U_2 d_o/\mu_2$ = Reynolds number
t = dimensional time
T = temperature
$\bar{T}$ = $U_2(\rho_2/\rho_l)^{1/2}\, t/d_o$ = dimensionless time
U = flow velocity
V_{bl} = *propagation velocity of blast wave*
V_c = "convective" flow velocity around drop
V_d = downstream velocity of blast wave
V_u = upstream velocity of blast wave
We = $q\, d_o/\sigma$ = Weber number
X = dimensional distance
$\bar{X}$ = X/d_o = dimensionless distance

μ = viscosity
ρ = density
σ = surface tension

Subscripts

o = stagnation condition, initial condition
1 = gas before incident shock wave
2 = gas behind incident shock wave
3 = gas behind bow shock wave
b = breakup (based on $0.6\, U_2$ criteria)
ig = ignition
l = liquid
s = shock wave
st = mass stripping

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