DISTRIBUTION OF SPHERICAL SHOCK WAVES IN A TWO-PHASE FUEL MIXTURE

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A study has been made of the distribution of spherical shock waves in a two-phase fuel mixture. It is shown that interaction with the liquid fuel droplets increases the wave intensity. Conditions for spherical shock wave amplification in a two-phase fuel mixture are marked out.

The interaction between planar shock waves and gas–liquid fuel mixtures has been throughly studied. The pressure perturbations observed in actual explosion chambers are usually similar to those found in spherical shock or compression waves. There has been little study of the distribution of spherical pressure waves in two-phase fuel systems. A distinguishing feature of the spherical shock wave is the fact that its parameters vary in both time and space, losses during shock front propagation resulting in a continuous diminution of wave amplitude and an accompanying alteration of the length of the positive compression phase. On this basis, it could be anticipated that planar pressure wave interaction with a fuel mixture might be considerably different from spherical pressure wave interaction with the same mixture. For example, the conditions under which nonstationary perturbation amplification or spherical heterogeneous detonation can be observed will differ considerably, depending on whether one is working with a planar or a spherical shock wave.

1. Apparatus and Experimental Procedures. Spherical shock wave interaction with a two-phase fuel mixture was studied in the system shown schematically in Fig. 1. The principal component of this system was a thick-walled cylindrical chamber 1 of 400 mm length and 280 mm internal diameter. The upper portion of this chamber carried a droplet generator 2, which had been bored for 250 openings, each 0.6 mm in diameter. These openings were uniformly distributed over the bottom of the generator, being located at the corners of squares 10 mm on a side. Pressurized nitrogen in tank 4 was used to force the liquid fuel (kerosene) out of container 3. The chamber was first filled with an equimolar nitrogen–oxygen mixture at 293°K and 1 atm pressure, and a monodispersed fog of fuel droplets, 1 or 2 mm in diameter, then formed in it. The kerosene–nitrogen–oxygen mixture was close to stoichiometric composition.

Spherical shock waves were generated in the chamber by detonating hexogen charges weighing from 0.3 to 4 g. Detonation was by means of a percussion detonator containing 0.3 g of explosive. In what follows, the total weight of detonator and hexogen will be given for explosive charges in excess of 0.3 g. The charge 7 was so suspended in the chamber as to be surrounded by two pressure sensors 5 and a synchronizer sensor 6. The distance from the bottom of the droplet generator to the sensor plane was 170 mm. The arrangement of the sensors on the chamber wall is indicated in Fig. 1. The distance between the detonator charge and sensor 6 was 110 mm; between the charge and the first of the sensors 5, 180 mm, and between the charge and the second of the sensors 5, 145 mm. The sensor characteristic frequencies were in excess of 30 kHz. Signals from the pressure sensors were recorded with the aid of a S1-33 oscilloscope. The pressure measurements were accurate to within 10-15%, the time measurements to within ~7%.

2. Experimental Results. The photographs of Fig. 2a, b are pressure–time relations in waves initiated by 1.3 g charges detonated in neutral (a), and in combustible (b), mixtures. Trace 1 gives the out-

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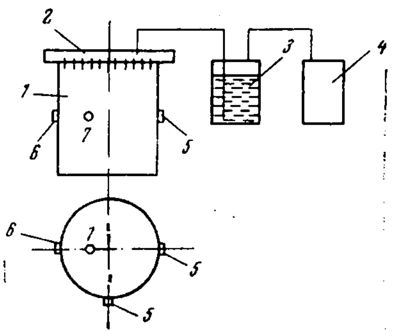


Fig. 1

put from the first sensor, and trace 2 the output from the second. The unit of time measurement on the horizontal axis was 50 μsec; the unit of pressure measurement on the vertical axis 17 atm.

For charge detonation in the inert 1-mm droplet kerosene–nitrogen mixture, sensor 5 fixed the arrival time of the incident wave and the change of pressure resulting from wave front reflection at the wall. Damping was observed as the wave continued its movement through the chamber, the sensor reading falling off markedly with each successive wave reflection from the chamber walls. The wave velocity in the neighborhood of the chamber wall could be estimated from the difference of wave front-arrival times indicated by the measuring sensor. For the case of Fig. 2a, the Mach number M of the incident wave was ~ 1.7. Here the Mach number is defined in the usual manner as the ratio of shock wave velocity u_s to the velocity of sound in the unperturbed medium.

In the fuel mixture, spherical waves of the same intensity showed higher values of such parameters as the wave velocity, leading shock front intensity, and duration of the positive compression phase. For example, the first sensor indicated essentially a twofold greater pressure drop over the front, while the wave velocity was almost Mach 2. Pressure readings during subsequent movement of the wave through the chamber indicated that there was no wave damping, at least over the 500-700 μsec interval following charge detonation. There was, however, a rapid, nonstationary rise in the mean chamber pressure, the rate of the increase being $\sim 10^4$ atm/sec. This increase in mean pressure was accompanied by numerous pressure surges, the latter resulting from rapid ignition of local centers in the body of the chamber mixture. Prime interest attaches here, however, to amplification of the leading front of the shock wave.

The curves of Fig. 3 show values of the amplification coefficient of the incident shock wave for various values of the detonating charge, g. The amplification coefficient k is defined as the ratio of incident wave amplitudes in the fuel mixture Δp and, with the same charge, in the neutral two-phase system Δp_0. Incident wave amplitudes were determined from the pressure readings in the following manner. A table showing reflected wave amplitudes as a function of incident wave Mach numbers was constructed. Having determined the reflected wave amplitude from the sensor reading, the table could then be used to find the incident wave amplitude. It is a well-known fact that the increase in pressure accompanying wave reflection is closely dependent on the incident wave intensity. Thus if the ratio of incident wave intensities is k, the ratio of reflected wave intensities k_1 will be greater than k.

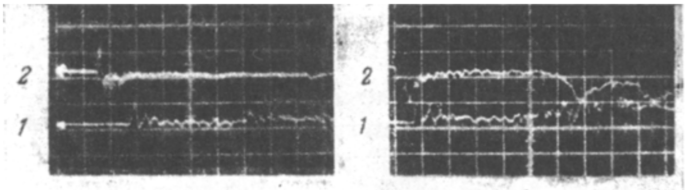
Curves 1 and 2 of Fig. 3 were constructed from data on 1- and 2-mm droplet mixtures, respectively, using first-sensor data. The form of these curves is such as to indicate incident shock wave amplification over the 185-mm path. Curve 3 of this same figure, applying to a 1-mm droplet mixture, shows incident wave amplification over the 145-mm path.

The results obtained here made it clear that shock wave amplification could be attained in our system with detonation charges of the indicated magnitude. The charge range in question was limited on both the low (g_1) and the high (g_2) sides. Within the $g_1 \leq g \leq g_2$ range, there could always be found a single charge g_3 which would, on detonation, generate a pressure wave with maximum amplification coefficient. The amplification coefficient of the wave generated by fixed detonation charge was found to increase as the droplet diameter diminished.

The range of shock waves capable of amplification was found to contract as the detonation charge was moved closer to the pressure sensor. The contraction of the g_1-g_2 interval was largely the result of a displacement of g_2 toward lower values.

3. Discussion of Results. Spherical shock wave amplification during propagation through a two-phase fuel mixture requires that there be a flow of energy into the pressure wave. This energy flow can be realized only if the two-phase mixture is burning rapidly behind the spherical wave front. Conditions behind this front must, therefore, be such as to favor the formation and ignition of a rapidly burning, combustible mixture. The time required for pressure rise and fall in the spherical shock wave is no more than 1 μsec [1, 2]. Thus it is impossible that a combustible mixture be formed by large droplet vaporization during the positive pressure phase of the wave [3].

The only way to attain the rates of combustible mixture formation required here is for liquid droplet breakdown behind the shock wave front to proceed through removal of a thin liquid film from the surfaces



a b

Fig. 2

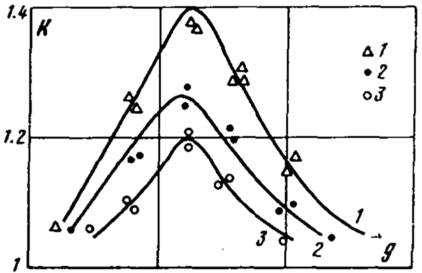


Fig. 3

of each droplet. No other type of droplet fragmentation behind the wave front could produce a quasi-homogeneous, explosive mixture of minute coarse-droplet fragments, gaseous oxidizing agent, and fuel vapors. It is clear that ignition of such a mixture must occur explosively, generating a secondary wave which, in turn, amplifies the leading front.

It has been shown [4, 5] that ignition of the two-phase gas–droplet mixture is retarded to the extent $t = \tau_i + \tau_c$ relative to the wave front, τ_i being the induction period for fragmentation and τ_c the chemical retardation for ignition. The temperature behind the wave front being high and the chemical retardation for ignition low, it follows that $t \approx \tau_i$ for high-intensity incident shock waves with Mach number $M \geq 3$. Measurements of the parameters of detonation generated shock waves [1] indicate that incident waves with Mach numbers in excess of 3 can be set up within a sphere of radius $r_t \approx 25r_0$, r_0 being the charge radius. Within such a sphere, the characteristics of the droplet fragmentation process will completely determine the course of two-phase fuel ignition in the wave. Expanding the path for spherical wave front propagation from $25r_0$ to $30r_0$ reduces the wave velocity from $M \geq 3$ to $M \approx 2$. This reduces the gas temperature and increases the chemical retardation of ignition to such an extent that the fuel mixture can no longer ignite during the positive pressure phase. The result is that that part of the combustible mixture which has been formed by droplet disintegration at distances from the detonation center in excess of $30r_0$ must be fired by the products from local center combustion. The mean pressure in the chamber rises in the course of this combustion, but this clearly has no effect on the initial perturbation which is being propagated throughout the chamber at supersonic velocity.

Complete two-phase burning may not, however, be attained over a spherical region of $25r_0$ radius, even under conditions favorable to fragmentation and ignition. The point is that shock wave front propagation is controlled by the expansion of the cloud of chemically neutral products arising from charge detonation. Burning of the two-phase mixture will then be confined to the region of shock-compressed oxidizer which lies between the shock front and the surface of contact with the detonation products. Let the width of this region be designated by δ, and suppose droplet fragmentation to begin at a distance δ_i from the shock front. If $\delta_i > \delta$, droplet fragmentation will begin behind the contact surface, in the detonation products. The width of the shock-compressed oxidizer will vary with r_s, the shock wave radius. At a certain value of r_s, namely r_{si}, δ_i will become equal to δ, the result being that droplet fragmentation then occurs in the compressed oxidizer and burning becomes possible if $r_s > r_{si}$.

The data of [1] indicate that the width of region of shock-compressed oxidizer is given by the equation $\delta^* = 0.045\,(r_s^{*\,1.4} - 1)$, with $1 < r_s^* < 35$. Here $\delta^* = \delta r_0^{-1}$, $r_s^* = r_s r_0^{-1}$. The value of δ_1 is determined by the product $u_s t_1$, u_s being the shock wave velocity and t_1 the time at which droplet fragmentation begins in the strong shock wave. According to the data of [6], $t_1 \approx \alpha \rho_f^{0.5} (\rho_1 u_1^2)^{-0.5}$. Here u_1 and ρ_1 are the respective velocity and density of the gas behind the shock wave front, and ρ_f is the liquid density. Since $u_s u_1^{-1} \approx 1$, in strong shock waves, while $\rho_1 \approx 6\text{–}8$, it follows that $\delta_1^* > \delta^*$ when $r_{si} \leq 44d^{*0.7}$. Here $d^* = d r_0^{-1}$. Values of r_{si}^* for 1 mm ($i=1$) and 2 mm ($i=2$) droplet mixtures are given below. The first two lines of Table 1 show the detonation charge in g and the charge radius, in mm. It is clear that the region of droplet fragmentation in the combustion products contracts with diminishing droplet radius. The displacement of the droplet behind the wave front during time t_1 being less than the droplet diameter, this factor has no effect on the calculations in question here. The conclusion is that the spherical shock wave radius must exceed r_{si}^* if mixture burning in the shock-compressed oxidizer is to begin behind the wave front.

TABLE 1

g	0.3	1.2	3
r_0	3.5	5.6	7.9
r_{s1}^*	17	13	11
r_{s2}^*	27	21	17
L^*	35	40	62

There is one additional limitation imposed on the combustion process by the mechanism of drop fragmentation behind the wave front. There comes a time during propagation of the spherical wave front through the inert gas at which the dynamic impact of the gas has fallen off to such an extent that intensive drop fragmentation comes to an end. It is a well-known fact [7] that amplification of a one-dimensional shock wave with triangular pressure and gas velocity profiles is possible only if flow parameter values satisfying the inequality $W > R^{0.5}$ are maintained over the time interval $\tau = 2d\rho f^{0.5} (\rho_1 u_1^2)^{-0.5}$. Here $W = 0.5\,\rho_1 u_1^2 d\psi^{-1}$ is the Weber number, $R = \rho_1 u_1 d\mu^{-1}$ the Reynolds number, ψ the surface tension, and μ the gas viscosity. Let it be assumed that intensive drop fragmentation in the spherical wave is possible only if the inequality $W > R^{0.5}$ is satisfied at time τ. We will now develop an expression for L^*, the distance between wave front and detonation center over which this condition is fulfilled. When $r_s^* < L^*$, intensive droplet fragmentation can occur behind the wave front. The process of droplet fragmentation in the wave alters completely over the range $r_s^* > L^*$, the droplet breaking down into still smaller particles as soon as it passes out of the compression zone. The shock wave parameters are then given by the following equation, due to M. A. Sadovskii,

$$\Delta p = 0.85\, g^{0.33} r_s^{-1} + 3 g^{0.66} r_s^{-2} + 8 g r_s^{-3}$$

Here g is the detonating charge in kg, r_s is the distance from the detonating center in m, and Δp is the pressure drop on the front in atm.

The positive phase period is given by the expression $\Delta t = 1.2 g^{0.16} r_s^{0.5}$, where Δt being in sec. The pressure drop behind the wave front is determined by the conditions

$$\delta p = \delta p_0 (1 - t\Delta t^{-1}) \quad (\delta p_0 = \Delta p_0 p_0^{-1},\ \delta p = \Delta p\,(t)\, p_0^{-1})$$

The dynamic impact of the gas is related to δp through the equation $\rho u^2 = \rho_0 c_0^2 \delta p^2 \{\gamma\,[1 - (0.5\gamma)^{-1} (\gamma - 1)\delta p\}^{-1}$ c_0 being the velocity of sound in the original medium. The value of δp_i can be found from the known value of the induction time τ, and then used to obtain the distance L^* at which $W(\delta p_i) = R^{0.5}(\delta p_i)$. Table 1 gives values of $L^* = L r_0^{-1}$ at several values of the detonating charge, for initial radius r_0. A comparison of the dimensions of the region over which the temperature is optimal for ignition, $r_t \approx 25\, r_0$, with the dimensions of the region over which intensive drop fragmentation can be expected, makes it clear that $r_t < L$. From this it can be concluded that autoignition and combustion in the positive compression phase are possible only within a spherical shell of radii $r = r_t$ and $r = r_{si}$. The mass of droplets actually involved in shock wave feed is given by $m = f m_1 n_0 (r_t^3 - r_{si}^3)$. Here, f is a proportionality coefficient, m_1 the mass of the individual droplet, and n_0 the number of droplets per unit volume. This droplet mass has available energy E, of which only a fraction β can be transferred to the pressure wave. Any reduction in the parameter m will result in a reduction of the amplification coefficient. A reduction in m can be brought about by reducing the detonating charge or increasing the droplet diameter.

The system geometry may, in some cases, be such that the operating dimensions are less than r_t or r_{si}. Droplet ignition during the compression phase will not occur if $D > r_{si}$, and there will then be no wave amplification. If $r_t \geq D \geq r_{si}$, the mass of liquid fuel involved in wave feed will be such that $m_1 \sim D^3 - r_{si}^3$. If r_{si} is assumed to be negligably small, the mass of droplet fuel involved in wave amplification will be reduced by the factor $D^3 r_t^{-3}$. Geometric factors proved to be controlling in fixing both the reduction in wave amplification coefficient resulting from sensor movement toward the detonation center, from the 180 to 145 mm position, and the reduction resulting from an increase in the detonator charge at $l = 180$ mm. The optimal charge for a system of diameter D should be that for which $D = r_t = 25 r_0$. For our system $r_0 \approx 6$ mm, from which it would follow that $D \approx 145$-180 mm, in conformity with experiment.

It was determined experimentally that the degree of damping falls off as the shock wave is propagated through the unignited fuel mixture, the extent of the decrease depending on the dispersion of the medium and the parameters of the initial perturbation. The amount of energy required for maintaining the spherical shock wave is determined by the conditions of two-phase fuel mixture ignition within the wave itself. The portion of the mixture which failed to ignite during the positive compression phase will begin to burn once contact is made with combustion products from the burning of earlier portions of the fuel. A compression wave radiates out of the shock wave during combustion of the two-phase fuel mixture, and slowly overtakes the original initial perturbation front. The compression wave originating at the 180-mm position has, however, no effect on the intensity of the primary shock wave intensity.

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