AMPLIFICATION OF WEAK SHOCKS IN A BURNING TWO-PHASE LIQUID-GAS SYSTEM

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So far there has been practically no systematic investigation of the propagation of compression waves through reacting two-phase (gas-liquid) mixtures. Only Webber [1] has published certain preliminary qualitative results. The detonation of two-phase (droplet-gas) fuel mixtures has received much more attention [2, 3], though the study of heterogeneous detonation is of greater scientific interest, since detonation is a consequence of a certain transient process in the system leading to intensification of the starting disturbances that appear during combustion.

It has proved possible to show that breakup of the droplets has an important influence on the process of mass and heat transfer in the combustion zone behind the wave front.

In what follows we examine some features of the interaction of weak shocks with liquid fuel (kerosene) droplets burning in an atmosphere of oxygen gas. The experimental results are discussed in relation to the known laws of the process of droplet fragmentation.

1. Experimental Apparatus and Procedure. The interaction of weak shocks and a burning gas-liquid mixture was investigated on the apparatus shown schematically in Fig. 1. The principal component of the apparatus was a shock tube with a low-pressure chamber (LPC) 1 and high-pressure chamber (HPC) 2. The inside diameter of the tube was 50 mm. The LPC had two sections: a vertical section of length l = 1300 mm and a horizontal L-shaped section of length l = 1500 mm. To the upper end of the vertical section we attached an atomizer 3, to which liquid was supplied from a tank 4 following a sudden increase in pressure in vessel 5 resulting from the inflow of compressed gas from chamber 6. The diaphragm 7 at the end of chamber 6 was ruptured by a plunger 8 driven by compressed gas admitted by electropneumatic valve (EPV) 9. Diaphragm 10 in the shock tube was ruptured by plunger 11 controlled by EPV 12.

The two-phase mixture in the LPC was ignited by a hot wire 13 introduced into the tube at a distance l = 1300 mm from the atomizer.

The pressure in the shock waves was measured by means of five piezoelectric pressure transducers 14 (transducer frequency f = 50 kHz). The arrangement of the pressure transducers will be clear from

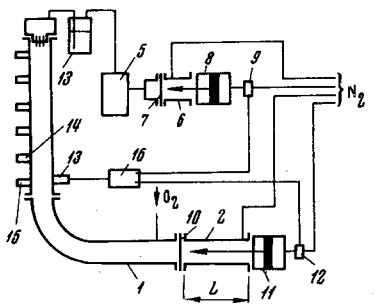

Fig. 1

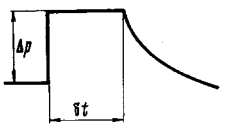

Fig. 2

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TABLE 1

M	Δp	u_2	ρ_2 / ρ_1	$R \cdot 10^{-4}$	$W \cdot 10^{-3}$	δt_1	δt_2
1.07	0.18	42.5	1.12	0.70	1.25	2.08	0.204
1.11	0.26	57.5	1.18	0.84	3.38	1.72	0.175
1.14	0.31	71.3	1.22	1.10	6.50	1.62	0.150
1.16	0.40	85	1.27	1.22	8.75	1.56	0.125
1.20	0.50	107	1.35	1.93	15.50	1.50	0.115
1.30	0.80	150	1.51	3	32.80	1.42	0.018

Fig. 1. The five-beam Sl-33 recording oscillograph was triggered by pressure transducer 15 opposite the ignition source. The main systems controlling the supply of liquid fuel to the LPC, the ignition of the two-phase mixture, and the rupture of diaphragm 10 were automatically triggered in a predetermined sequence by programmer 16.

As the working gas in the liquid supply system and the driver gas we used nitrogen (N_2). The liquid fuel (kerosene) was injected through nine holes 0.6 mm in diameter. The liquid was supplied under a heat ensuring a droplet flow regime. The spray thus formed was monodisperse with droplets 2 mm in diameter. The LPC was filled with oxygen gas (O_2) at a pressure p = 1 atm abs. The mixture composition averaged over the volume of the vertical section corresponded to an oxidizer/fuel ratio $\alpha = 2$. The mixture composition in experimental apparatus with accelerated motion of the droplets varies along the length of the tube. In the case in question the mixture composition corresponded to $\alpha = 1$ at a distance $l = 100$ mm from the atomizer and to $\alpha = 3$ at $l = 1300$ mm.

In all the experiments the sequence of operations was as follows:

1) increase the pressure in vessel 5 at the same time supplying voltage to the ignition source 13;

2) after igniting all the two-phase fuel mixtures in the vertical section of the LPC, rupture diaphragm 10, allowing a shock wave to enter the LPC.

The time intervals between the individual stages of the process were predetermined. The inside surfaces of the tube walls were wiped carefully before each experiment to remove contamination from the previous experiment.

The principal variables were:

1) the intensity of the shock wave (as a result of variation of the pressure drop across diaphragm 10);

2) the duration of the positive phase of compression in the wave (as a result of variation of the length of the HPC).

The measured values of the pressure drop at the shock front $\Delta p = p_2 - p_1$ and the Mach number M of the shock wave before interaction with the burning droplets are presented in Table 1. The Mach number was determined from the velocity of the shock wave and the speed of sound in oxygen at $p_1 = 1$ atm abs and

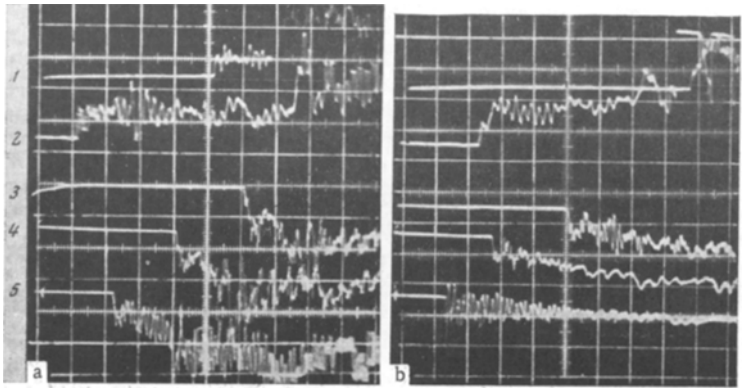

Fig. 3 a,b

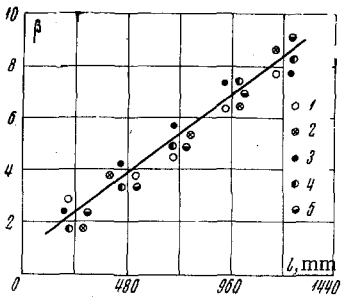

Fig. 4

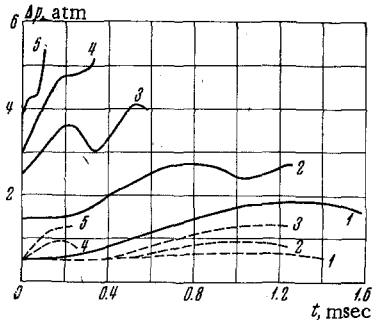

Fig. 5

$T_1 = 293°$ K. The parameters with subscript 1 relate to the state of the medium ahead of the shock front and those with subscript 2 to the state of the medium behind it. At $p_1 = 1$ atm abs the quantity Δp is numerically equal to the shock-wave intensity $\delta p = p_2 - p_1/p_1$.

Table 1 presents values, calculated from shock-tube theory [4], of the gas velocity behind the wave u_2 in m/sec, the density ratio p_2/ξ_1, and the Reynolds and Webber numbers

$$R = \rho_2 u_2 d\mu^{-1}, \qquad W = \rho_2 u_2^2 d\psi^{-1} .$$

Here ψ is the surface tension of the liquid, μ the coefficient of dynamic viscosity of the gas. The values of ψ and μ were taken at the temperature $T_1 = 293°$ K. Reducing the length of the HPC led to shortening of the duration of flow at constant parameters behind the shock front. The shape of the pressure wave in front of the inlet to the kerosene-oxygen mixture combustion zone is shown in Fig. 2. The quantity δt in Fig. 2 represents the time interval between the successive moments of arrival of the shock front and the head of the reflected expansion wave at a given point of the LPC [4]. Values of δt_1 in msec for a HPC length L = 400 mm and δt_2 in msec for L = 100 mm are also presented in Table 1.

2. Results of the Experiments. In the absence of droplets the propagation of the shock waves through the LPC at $\delta t = (1.42\text{-}2.08) \cdot 10^{-3}$ sec was stationary. At $\delta t < 10^{-4}$ sec attenuation of waves having a velocity $M > 1.2$ was observed. Finally, at $\delta t < 0.5 \cdot 10^{-4}$ sec all the waves were damped. The photographs in Fig. 3 show the pressure records obtained for the interaction of the shock wave and burning kerosene droplets at $M = 1.16$, $\delta t = 1.56 \cdot 10^{-3}$ sec (Fig. 3a) and at $M = 1.16$, $\delta t = 0.125 \cdot 10^{-3}$ sec (Fig. 3b). Traces 1, 2, 3, 4, 5 were obtained from each of the five pressure transducers 14 at distances $l = 1200$, 960, 720, 480, 240 mm from the triggering transducer 15, respectively.

The time scale in Fig. 3a, b is 100 μsec for traces 1 and 2, and 250 μsec per division of the horizontal scale for traces 3, 4, and 5.

In Fig. 3a the pressure scale for traces 1 and 2 (positive deflection upwards) and 3, 4, and 5 (positive deflection downwards) is equal to 5.8, 4.0, 2.08. 1.29 and 0.8 atm, respectively, while in Fig. 3b the pressure scale for the same traces is equal to 0.8, 0.63, 0.83, 0.80 and 0.77 atm per division of the vertical scale, respectively.

In the first case we noted an increase in the intensity of the shock wave (from $\delta p = 0.4$ to $\delta p = 3.2$) and its velocity (from 380-400 to 570-600 m/sec) as the wave moved along the LPC. Immediately behind the shock front intense secondary pressure vibrations, absent when the same waves traveled through a nonreacting two-phase mixture, developed. The frequency of the secondary vibrations was close to $f = 50$ kHz. The amplitude of the secondary vibrations increased as the shock front moved away from the ignition source. At a distance $l = 240$ mm the double amplitude of the vibrations was $2A = 0.8$ atm, and at a distance $l = 1200$ mm it was $2A = 1.5$ atm. As the shock-wave velocity increased, starting from $M > 1.1$, the amplitude of the secondary vibrations also grew at the initial measuring point, i.e., at $l = 240$ mm, where for waves with $M = 1.16$ the amplitude $2A = 0.8$ atm, while for waves with $M = 1.3\text{-}2.4 = 1.8$ atm. For waves with $M < 1.1$ the amplitude of the secondary vibrations did not increase with increase in the distance l. The shock waves with $M < 1.1$ themselves were either propagated uniformly ($\delta t = 1.72 \cdot 10^{-3}$ sec) or were damped ($\delta t < 0.17 \cdot 10^{-3}$ sec).

The results of the interaction of shock waves and a burning two-phase mixture accompanied by an increase in shock-wave intensity are presented in Fig. 4. In the graph the relative intensity $\beta = \delta p/\delta p_0$,

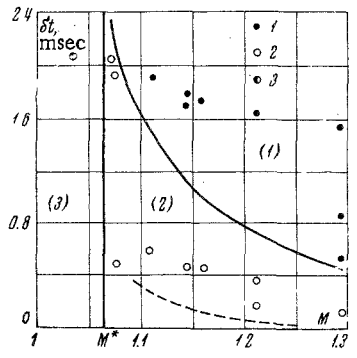

Fig. 6

where δp_0 is the intensity of the shock wave in a nonreacting kerosene-oxygen two-phase mixture, and δp the variable shock wave intensity, is plotted as a function of the path length traversed by the shock wave in the LPC. The points 1, 2, 3, 4, 5 in Fig. 4 corresponds to the passage of shock waves with Mach numbers M = 1.11, 1.14, 1.16, 1.2, 1.3 through the burning two-phase mixture.

As may be seen from Fig. 4, all the cases of amplification can be described by a common linear dependence of the quantity β on the path traversed by the wave.

In the second case of interaction (Fig. 3b), which differs from Fig. 3a only with respect to the value of δt, there is no increase in shock-front intensity as the wave moves through the combustion zone. The secondary pressure vibrations behind the wave front are damped. The pressure jump on trace 2, which appears 800 μsec after the trace is triggered, corresponds to the moment of arrival of the reflected pressure wave.

We will consider the variation of the mean pressure (center line of the secondary vibrations) behind the shock front in the course of interaction with kerosene droplets burning in oxygen. The mean pressure profile for all the transducers, whose position is determined by the value of l (Fig. 1), is plotted in Fig. 5. Curves 1, 2, 3, 4, 5 show the variation of the pressure behind the wave front at positions l = 240, 480, 720, 960 and 1200 mm. At all these points the reference time coincides with the arrival of the shock front at the corresponding transducer. It is clear from Fig. 5 that the mean pressure behind the wave front increases, i.e., a compression wave is formed. At the beginning of the interaction (l = 240 mm) the pressure in the compression wave is small, but as the distance l increases, it grows continuously. In the upper part of the LPC behind the main shock front a secondary shock front is formed. The case described is typical of all the experiments in which $\delta t \geq 1.4 \cdot 10^{-3}$ sec, and $M \geq 1.1$. If it is assumed that the increase in the mean pressure in the compression wave behind the shock at the point l = 240 mm depends linearly on time, then $dp/dt = 0.6 \cdot 10^3$ atm/sec on the interval M = 1.16-1.3 and $dp/dt = 0.1 \cdot 10^3$ atm/sec on the interval M = 1.07-1.11. At $\delta t = 0.125 \cdot 10^{-3}$ sec the character of the variation of the mean pressure behind the shock front changed (dashed line in Fig. 5). In the combustion zone behind the wave a very weak compression wave is formed. In this wave the rate of growth of pressure varies slowly, and the intensity of the shock wave, i.e., δp (t = 0), does not increase. Only at the end of the interval investigated does the compression wave begin to overtake the shock front.

3. Discussion of the Results and Conclusions. The duration of flow at constant parameters behind the shock front δt (Fig. 2 and Table 1) may be regarded as the residence time of the droplets in that flow zone. In fact, the change in droplet velocity can be found from the relation

$$dw / dt = 0.75\ c\rho\ (u - w)^2\ (\rho_f d)^{-1}\ .$$

Here w is the droplet velocity, $c \approx 1$ the resistance coefficient, ρ_f the density of the liquid, and ρ the density of the gas. Taking $\rho = \rho_2$ and assuming that $u - w \approx u_2$, we obtain

$$u_2^{-1} \Delta w = 0.75\ c\rho_2 u_2\ (\rho_f d)^{-1} \delta t\ .$$

Here Δw is the change in the velocity of the droplets in time δt. Hence it follows that even for waves with M = 1.3 under the conditions considered the quantity $u_2^{-1}\Delta w \leq 10\%$. This makes it possible to assume that the liquid droplets are at rest during time δt.

In evaluating the possibility of shock-wave amplification it is necessary to take at least two factors into account. Firstly, the effect of the pressure disturbance on the heat release process should lead to a rise in the rate of energy release above the stationary level that more than compensates for the energy losses in the wave. As shown below, it is apparently this effect that causes breakup of the droplets by separation of a surface layer of liquid [5]. The essence of this breakup mechanism consists in wavelike disturbances being formed on the surface of the droplet which, however, still retains its integrity.

The amplitude of the disturbances is increased by the high-velocity gas flow over the droplets. During passage of the perturbation wave from the point of formation (usually at the center of the windward side of the droplet) to the equitorial section the wave amplitude is able to reach a value at which the surface

Table 2

M	τ	t_1	δl	r	T
1.07	2.10	101	36.70	92	12.50
1.11	1.70	42	15.50	61	5.50
1.14	1.40	19	7	40	2.14
1.16	1.25	16	6.60	37.5	1.87
1.20	0.82	6.01	2.04	23.6	0.84
1.30	0.45	1.86	0.87	12	0.22

tension forces no longer suffice to overcome the aerodynamic forces. Finally, a toroidal layer of liquid, whose cross section depends on the amplitude and length of the waves on the droplet, while the diameter depends on the size of the droplet [6], separates from the droplets.

As a result of fragmentation of the droplets by the removal of a surface layer a large number of droplets, very small as compared with the starting droplet [5], is formed and the combustion surface increases, as does the mass velocity of the combustion process. As shown in [5], the removal of a surface layer from the droplets begins when the condition $WR^{-0.5} \geq 1$ is satisfied.

The second requirement for shock-wave amplification is analogous to the Rayleigh criterion. It consists in most of the mass and energy release behind the shock front taking place in a time not greater than the duration of the positive-pressure phase, i.e., in the case in question in a time $\delta t^* \leq \delta t$. As the time parameter characterizing droplet breakup we will take the breakup time τ. According to the data of [7, 8], in which breakup was studied under conditions comparable to our own,

$$\tau = 2d\rho_f^{0.5}u_2^{-1}\rho_2^{-0.5}.$$

Then from Fig. 5 we see that an increase in shock front intensity occurred at $\tau \leq \delta t$, whereas at $\tau > \delta t$ the shock-front intensity did not increase. On the basis of these relations in Fig. 6 we have plotted the stability limit of shock waves interacting with a liquid fuel burning in a gaseous oxidizer atmosphere. The principle used in plotting the stability limit consisted in finding on the plane (δt – M) the locus of the points at which the equation $\delta t(M) = \tau(M)$ is satisfied. Above the limit $\delta t > \tau$ (region 1) and, in accordance with our assumption, all cases in which shock-wave amplification was observed should be found here. On the left the region of possible regimes of interaction between shock waves and the combustion zone of two-phase mixtures is bounded by the vertical straight line M = M*. The value M = M* is obtained from the condition $W(M^*)\,R^{0.5}(M^*) = 1$. The straight line separates the region of shock waves in which droplet breakup proceeds according to the surface-layer stripping mechanism (to the right of the straight line M = M*). The curve $\tau(M) = \delta t(M)$ asymptotically approaches the straight line M = M*, which it reaches only at very large values of δt.

The distribution of the experimental points relative to the stability limit in Fig. 6 indicates the correctness of our assumptions concerning the parameters controlling the conditions of shock-wave amplification. In the case of shock waves with parameters corresponding to points 1 in region 1 we observed an increase in wave intensity. In the case of waves with parameters corresponding to points 2 in region 2 the quantity δp was nonincreasing on the length l = 1200 mm, but in the zone behind the wave front a weak compression wave that gradually overtook the leading front developed. To the left of the straight line M = M* (region 3) there should be no signs of shock-wave amplification in the burning two-phase mixture owing to the impossibility of droplet breakup. In order to confirm the validity of this we conducted a series of additional experiments. In these experiments (points 3) we studied the behavior of shock waves with M = 1.03-1.07 and $\delta t = 3.4 \cdot 10^{-3}$ sec. Waves having a velocity M = 1.03-1.07 passed through the heterogeneous burning mixture as if it were a neutral medium.

Webber [1], in investigating the interaction of shock waves and kerosene droplets burning in an oxygen atmosphere, always observed the amplification of weak (M > 1.1) shock waves irrespective of the length of the zone of constant flow parameters behind the shock front. From the standpoint of the ideas developed here, this may be explained as follows. To inject the kerosene Webber used a high pressure drop $\Delta p \approx 7$ atm, which led to the formation of a large number of fine droplets. Cramer [2], having evaluated the spray spectrum, demonstrated the presence of droplets with diameter d = 100-200 μ. If in Fig. 6 we plot the stability limit of shock waves in a mixture with droplets of this diameter (dashed line), the practical impossibility of detecting in such sprays an effect of the time characteristics of the shock waves on their amplification becomes clear.

The hypothesis of fragmentation as the leading mechanism of the process of shock-wave amplification in a two-phase burning mixture makes it possible to clarify a series of characteristics of the process. Droplet breakup is known to begin at a certain distance from the shock front after an induction period t_1, which according to Mayer's theory [9] can be estimated from the equation

$$t_1 = 45\,(\rho_f \psi^2 \mu_f)^{0.33}\,(\rho_2 u_2^2)^{-1.33}.$$

The distance from the wave front to the point at which breakup begins is $\delta l = t_1 u_2$. The mean size of the droplets separated from the starting droplets is calculated, according to Mayer, from the equation

$$r = 9\pi 16^{0.33}\,(\mu_f \psi^{0.5} \rho_f^{-0.5})^{0.66}\,(\rho_2 u_2^2)^{-0.66}.$$

The total evaporation time for droplets of radius r and hence their total combustion time is estimated from the equation $T = (2r)^2 k^{-1}$, where k is the evaporation constant of the burning kerosene droplets.

The quantity T will serve as a measure of the microdroplet burning rate. Values of the breakup time τ in msec, the induction period t_1 in μsec, the distance δl in mm, the size of the microdroplets r in μ, and their evaporation time T in msec can be found in Table 2.

A comparison of the values presented in Table 2 shows that for the weakest waves (M = 1.07-1.16) the process of evaporation of the microdroplets behind the shock front is protracted, and the beginning of the zone of rapid combustion is further from the leading wave front. These factors together determine the low rate of growth of mean pressure downstream from the shock wave. In shock waves of greater intensity the mass velocity of the combustion process increases in the immediate neighborhood of the wave front and to a greater degree than in weak waves. The occurrence of secondary vibrations is evidently associated with the ignition of local, almost homogeneous mixture volumes formed after the mixing of fuel microdroplets and oxidizer. Consequently, the amplitude of the secondary vibrations should increase with the initial velocity of the pressure wave for reasons already indicated above. The damping of the secondary vibrations at small values of δt is associated with the entry of the droplets into the region of the expansion wave, where the gas velocity is reduced. The secondary vibrations should disappear at the instant at which the gas velocity passes through the value at which droplet breakup is no longer possible.

The detected characteristics of the interactions of shock waves and burning two-phase mixtures are evidently associated with the fact that:

1) The number of droplets in the mixture is small, so that large distances between individual droplets prevent neighboring droplets from interacting. In our case the total number of droplets was about $n \approx 144$, i.e., on average there was 17 cm^3 of gas for each droplet.

2) The droplet sizes are such that there is no change in droplet velocity during the period of action of the positive-pressure phase in the shock wave and the droplets are not entrained behind the wave, which minimizes the residence time of the droplets in the region of constant parameters behind the shock front.

In two-phase mixtures with fine droplets and the same mixture composition the propagation of weak shocks may have a number of features that require additional investigation.

On the basis of these experiments it has been established that:

1) The amplification of weak shocks with M = 1.1-1.3 in a reacting two-phase liquid droplet-gas mixture takes place as a result of a sharp increase in the mass burning rate of the mixture owing to fragmentation of the droplets.

2) The increase in mass burning rate behind the shock front leads to an increase in heat release and the formation of a compression wave that overtakes the leading front.

3) On the range of shock intensities and wavelengths investigated it is always possible to find values at which the wave is propagated through the reacting two-phase mixture either without amplification or with damping.

4) Irrespective of their time parameters the shock waves will propagate through the reacting two-phase mixture as if it were a neutral medium, if the wave intensity is insufficient to initiate droplet fragmentation in accordance with the surface-layer stripping mechanism.

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