AMPLIFICATION OF TRIANGULAR SHOCK WAVES IN A FLAMMABLE TWO-PHASE MEDIUM

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In [1, 2] values are established for the parameters of a compression wave with a triangular pressure variation such that when the wave interacts with a two-phase gas—liquid medium it can produce nonstationary combustion. More complicated to study, but of greater practical interest, is the interaction of longitudinal compression waves with a burning two-phase medium.

It is best to consider first the interaction between flammable heterogeneous mixtures and shock waves which have a triangular pressure profile behind the leading edge.

1. Experimental Method. The study of the interaction between a shock wave which has varying parameters (pressure and velocity) behind the shock front and flammable heterogeneous systems was carried out by the method already described in [1, 2]. The triangular pressure profile was achieved by shortening the length of the section of driving gas in the shock tube to C = 1, 2.5, 4.5, and 7 cm. Photographs of the pressure variation in a shock wave traveling through a nonburning two-phase mixture of kerosene + 0.5 N_2 + 0.5 O_2 are shown in Fig. 1a. The Mach number on entry into the aerosol was M = 1.15 and at 500 mm away was M = 1.05; i.e., triangular shock waves are attenuated in a nonburning mixture. The time scale on all the oscilloscope traces is 250 μsec per division. The pressure scales are 0.52, 0.85, 0.66, 1, and 0.66 atm on beams 1, 2, 3, 4, and 5, respectively. The five pressure recorders were at distances of 300, 540, 780, 1020, and 1260 mm from the point where the shock front met the lower boundary of the aerosol. Figure 1 shows an outline of the pressure profile with the main parameters labeled. The quantity $\Delta p = p_2 - p_1$ is the difference between the pressure of the undisturbed gas p_1 and of the compressed gas p_2. The length of the positive pressure phase is denoted by δt. The strength of the wave is denoted by the ratio $\delta p = \Delta p p_1^{-1}$. We give below values of δt_1, δt_2, δt_3, and δt_4 in msec for the various high pressure lengths l = 1, 2.5, 4.5, and 7 cm at three Mach numbers:

M	δt_1	δt_2	δt_3	δt_4
1.1	0.8	1	1.2	1.5
1.15	1	1.35	2	2.1
1.2	1.2	2	2.2	—

Experiments were carried out with an equimolar mixture of nitrogen and oxygen at a pressure of p_1 = 1 atm and an initial temperature T_1 = 293°K. The value of the component ratio averaged over the volume of the vertical part of the low-pressure chamber (l = 1300 mm) was α = 1. Ignition of the two-phase mixture was brought about as in [1, 2] from a heated oxidizer source near the lower boundary of the system by burning a nichrome spiral.

The measurement error in the pressure, time, and drop size did not exceed 10, 5, and 10%, respectively.

2. Experimental Results. Figures 1b and 1c show photographic recordings of the pressure read by piezoelectric transducers (with a natural frequency above 30 kHz) during the interaction of a triangular pressure wave with an aerosol (drop diameter d = 1 mm). The time and pressure scales are the same as in Fig. 1a. The initial waves had values of δp = 0.36 (M = 1.15) and δt = 1.45 msec for Fig. 1b, and δp = 0.36 and δt = 1.55 msec for Fig. 1c. With the given value of δp, it is observed that the wave is attenuated inside the two-phase mixture when δt < 1.4 msec. When δt = 1.45 msec, the attenuation is no longer observed, but

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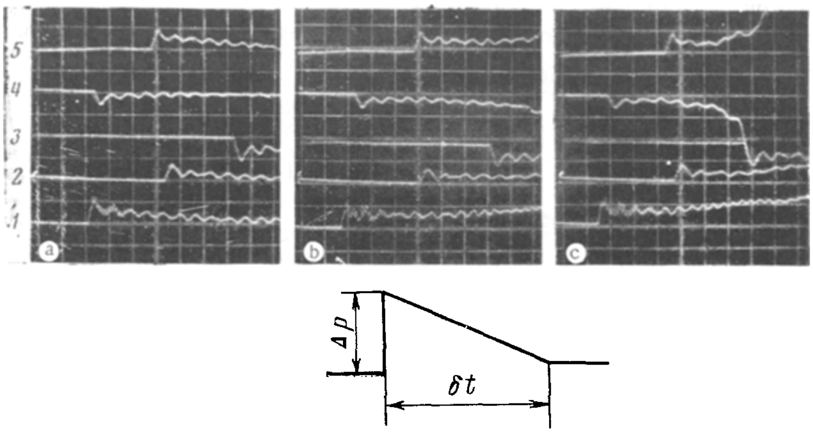

Fig. 1

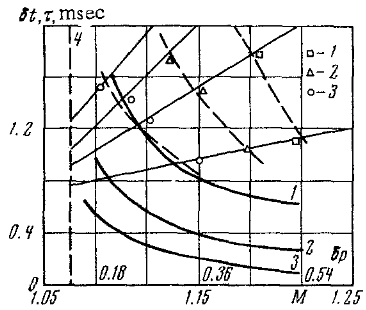

Fig. 2

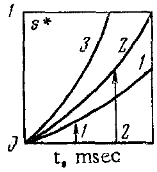

Fig. 3

there is a transformation of the initial wave onto a square wave, and even a weak compression wave appears after $t \approx 1$ msec.

The process involved here is an interaction between a pressure wave and a flammable two-phase medium which brings about a slowly-increasing nonstationary combustion effect. Eventually, in the wave with $\delta p = 0.36$ and $\delta t = 1.55$ msec, a high-intensity pressure wave is produced which catches up gradually on the original wavefront. If the strength of the original wave is kept constant but the length of the compression phase is increased, the nonstationary combustion process ends in the detonation of the heterogeneous mixture.

It can be seen from these results that only a small change in the parameters of the compression wave is needed to excite nonstationary combustion. The transition or critical value of the pressure change may be taken as that for which the triangular wave is transformed into a square wave (as in Fig. 1b, for example).

Figure 2 shows generalized experimental data on the critical parameters of different strength shock waves interacting with sprays of various dispersions.

The background grid gives the shock wave parameters, M, δp, and δt, for various values of the driving gas cross section (thin lines). The dashed lines show the boundaries of the nonstationary interaction regions (above the curves) for systems with drop sizes of $d = 2$, 1, and 0.65 mm (points 1, 2, and 3). For the sake of comparison the graphs also show curves of the breakup times $\tau = 2d\rho_f^{0.5}(\rho_1 u_1^2)^{-0.5}$, where u_1 is the gas velocity and ρ_f is the liquid density. Lines 1, 2, and 3 correspond to the same drop sizes as above.

3. Discussion. We can compare the present results with the critical pressure values given in [1, 2]. It was found in these references that the strength of the critical disturbance was determined by the condition that a breakup process should occur and that the length of the disturbance was equal to the breakup time τ. We can see from Fig. 2 that for a given wave intensity δp (M), the critical length for a square profile is shorter than that for a triangular profile. In the former case the critical value of the pressure change when allowance is made for the pressure drop in the rarefication wave is

$$I^* \approx 1.5\delta p\tau c\,(2d)^{-1} = 1.5\ M_1^{-1}\delta p\ (\rho_f\rho_1^{-1})^{0.5}$$

where M_1 is the Mach number calculated from the relative velocity between the gas and a drop u_1, and the speed of sound in the undisturbed medium c. In triangular waves the critical pressure change is

$$I_1^* \approx 0.5\delta p \delta t^* c\,(2d)^{-1} \approx I^*$$

since the experiment showed that $\delta t^* \approx 3\tau$. Here δp_1 is the size of the leading edge of the wave.

We now examine the trend of the boundary curves $\delta t^* = f(M)$ as the Mach number of the incident wave is reduced. The change in the values of δt^* with decreasing wave strength differs from the change in τ because of the large slope of the δt^* curve. We can thus tentatively conclude that for a triangular compression wave there will be a rise in the limiting strengths which form the boundary in Fig. 2 to the left of the nonstationary regions (ordinate 4 for drops of $d = 0.65$ mm). It has not proved possible to produce pressure changes with $\delta t > 2.1$ msec in the shock tube.

An increase in the length of the driving gas section to $l > 0.1$ m led to the appearance of square waves. Thus for drops $d > 1$ mm it was not possible to establish the value of limiting value of δp^* for which no change in δt produces nonstationary combustion. In a two-phase system with $d = 0.65$ mm the value of δp^* was about 0.18, which is almost 1.5 times greater than the value for square waves calculated from the relationship $W = R^{0.5}$. Here $W = \rho_1 u_1^2 d\sigma^{-1}$, $R = \rho_1 u_1 d\mu^{-1}$ are the Weber and Reynolds numbers, and σ and μ are the surface tension of the liquid and dynamic viscosity of the gas behind the shock front.

It seems that the increase in the limiting disturbance may be related to the change in the nature of the breakup process due to the variation in gas pressure behind the wave. In fact, if δp_1 in a triangular wave is such that $W(\delta p_1) = R^{0.5}(\delta p_1)$, then immediately after the gas begins to flow round a drop it is seen that $W(\delta p) < R^{0.5}(\delta p)$, where δp is the actual value of the change in pressure. Drop breakup can only be of the parachute type [3, 4] where the original drop breaks into several large parts. Owing to their inertia, these parts take some time to achieve the velocity of the gas. Because of the high gas speeds, it is not possible to ignite large particles. (The critical speed at which the flame is carried away from a drop is 1-4 m/sec [5].)

We now consider the breakup process for a kerosene drop of diameter $d = 0.65$ mm in triangular pressure waves with $\delta t = 1$ msec and various strengths.

Figure 3 shows graphs of the dimensionless displacement in the exposed surface of drops $s^* = 2sd^{-1}$, calculated from the simplified model suggested in [6]. Curves 1, 2, and 3 correspond to waves with $\delta p_1 =$ 0.24, 0.36, and 0.48. The critical stage in the deformation of a drop occurs when $s^* \approx 1.8$-1.9. The arrows in Fig. 3 show the values of the ordinate corresponding to the moments in time t^* at which the flow parameters behind the wave are such that $W(\delta p) = R^{0.5}(\delta p)$. At this instant there is a change in the way the drop breaks up. In a wave with $\delta p_1 = 0.24$, the drops are hardly deformed at all before the time when $W = R^{0.5}$. Then parachute breakup occurs.

In the intermediate case, such as $\delta p_1 = 0.36$, the drop is already noticeably deformed. Since the induction period for a thin layer of liquid to start to break off from drops with $W \geq R^{0.5}$ is close to $\tau_i \approx 0.5\tau$, we can see that in the second case $\tau_i \approx 170$ msec and that after a time t^*, a considerable fraction of the original mass has managed to tear off from the drop.

The breakup in this phase is very fine (the size of the microdrops $d \approx 10$-50μ) and so the droplets rapidly attain the gas velocity and can ignite in the positive pressure region. However, because of the negligible mass, the ignition of these droplets causes only a small increase in pressure, sufficient merely to convert the triangular wave into a square wave. When $\delta p_1 = 0.48$, the critical stage in deformation is reached long before the time t^*. There is now a more complete breakup of the original drops. The greatest amount of flammable liquid is involved in the formation of regions of almost homogeneous mixture of microdrops and gas ready for combustion. The ignition of this mixture produces a compression wave behind the incident wavefront, and an amplification of the original disturbance is observed up to the point where heterogeneous detonation is excited.

This amplification of a triangular compression wave can occur if the strength is greater than the critical value

$$\delta p^* = (\gamma\sigma)^{0.66} (c p_1 d\mu)^{-0.33}$$

and the dimensionless pressure change

$$I^* \geqslant 1.5\delta p^* \delta t^* c\,(2d)^{-1} = 1.5\,(\gamma\sigma)^{0.66} (c p_1 d\mu)^{-0.33} (\rho_l \rho_1^{-1} M_1^{-2})^{0.5}$$

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