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Fig. 1

Figure 1: Fig. 1

Abstract

Full Text

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PHYSICS

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ON THE QUESTION OF THE SMOOTHNESS OF THE DETONATION FRONT IN A LIQUID EXPLOSIVE

In ([1]), by the optical method ([2]), the smoothness of the detonation front in a liquid explosive (L.E.)—a mixture of nitric acid with dichloroethane—was investigated. At a definite initial temperature and composition, experiment shows that there is specular reflection of light from the detonation front, the intensity (reflection coefficient R) of which, however, is substantially smaller than that calculated from the expected change of the refractive index in the wave front. This result cannot be understood within the framework of geometrical optics. Below we give a semi-quantitative description of such a picture, taking into account the wave theory of reflection of light. The analysis shows that the results obtained are explained by the presence, on the shock-wave front of the detonating substance, of relatively small roughnesses.

Fig. 1

Let us suppose that on the detonation front there exist inhomogeneities (roughnesses) comparable with the wavelength of light λ, and let us consider the reflection of light from such a front using wave theory. First consider the reflection of a coherent beam of light of diameter S (see Fig. 1), incident on the detonation front at an angle α_0. In wave theory each element of the surface reflects at any angle; equality of the angle of incidence and the angle of reflection for a smooth surface is obtained only after considering the summation (interference) of the amplitudes of the waves from all elements. It is easy to show that, for light reflected in the direction α_0, a rise of the reflecting surface by z changes the path length by $2z\cos\alpha_0$. Consequently, the phase of the wave changes by $2kz\cos\alpha_0$.

In reflection from a smooth surface all its portions act in the same phase

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$$A_{\text{refl}}^{\text{spec}} = \int_M a_{\text{refl}} e^0 \, dM = a_{\text{refl}} M, \qquad M = \frac{S}{\cos\alpha_0};$$

in the case of a rough surface

$$A_{\text{refl}}^{\text{rough}} = \left| \int_H a_{\text{refl}} \exp(2ikz\cos\alpha_0) \, dM \right|.$$

For small roughness

$$\exp(2ikz\cos\alpha_0) = \left[1 + 2ik(z-\bar{z})\cos\alpha_0 - 2k^2(z-\bar{z})^2\cos^2\alpha_0\right]\exp(2ik\bar{z}\cos\alpha_0),$$

and in this case

$$A_{\text{refl}}^{\text{rough}} = a_{\text{refl}} M \left[1 - 2k^2\,\overline{(z-\bar{z})^2}\cos^2\alpha_0\right].$$

Accordingly, the attenuation of the intensity of specular reflection in the presence of roughness
$\left(\overline{(z-\bar{z})^2}\right)^{1/2} = (\overline{\Delta z^2})^{1/2}$ is

$$I_{\text{rough}} = I_{\text{spec}}\left[1 - 4k^2\overline{\Delta z^2}\cos^2\alpha_0\right]. \tag{1}$$

The decrease in specular reflection is accompanied by the appearance of diffuse reflection (reflection at angles α different from α_0). In Fig. 2, K_0 is the projection onto the plane of reflection of the wave vector $\mathbf{K}$ of the incident light; K_0' and K_1' are the projections of the wave vector $\mathbf{K}'$ of the light reflected specularly and diffusely, respectively. The change in the direction of the wave vector of the reflected light, or of its projection onto the plane of reflection (the frequency does not change upon reflection, $|\mathbf{K}| = |\mathbf{K}'| = K$), occurs at the expense of the Fourier component of the surface perturbation with the corresponding plane wave vector $\vec{\chi}$. These conditions make it possible to express the scattering angle (α, φ) in terms of $\vec{\chi}$. In this case the amplitude of the light scattered in the direction α, φ (φ is the meridional scattering angle) is

$$A_{\text{diff}}(\alpha, \varphi) = \text{const} \cdot a_{\text{refl}} b(\vec{\chi}),$$

where

$$b(\chi) = \int z e^{-i\chi r} \, d^2 r,$$

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r is a vector in the plane of the wave. The scattering intensity over all angles (solid-angle element $d\omega$) is, obviously,

$$\int I_{\text{diff}}\, d\omega = \text{const}\cdot a_{\text{refl}}^2 \int |b(\vec{\chi})|^2\, d^2\vec{\chi},$$

and, by the completeness theorem,

$$\int b(\vec{\chi})^2\, d^2\vec{\chi} = \int (z-\bar{z})^2\, dM$$

and

$$\int I_{\text{diff}}\, d\omega = \text{const}\cdot I_{\text{spec}}\overline{\Delta z^2}. \tag{2}$$

Comparing (1) and (2), we see that the expressions for specular and diffuse reflection are consistent; their sum does not change in the presence of small roughness.

If $(\overline{\Delta z^2})^{1/2}$ becomes large, then for a random character of z we expect

$$I_{\text{rough}} = I_{\text{spec}} \exp\left(-4k^2\overline{\Delta z^2}\cos^2\alpha_0\right),$$

which in the limit of small $(\overline{\Delta z^2})^{1/2}$ returns to what was written above. Specular reflection formally always exists; it is only exponentially small when $(\overline{\Delta z^2})^{1/2} \gg \lambda$.

Depending on the degree of roughness, the character of the reflection of light and its intensity change.

1. $(\overline{\Delta z^2})^{1/2} \ll \lambda/4\pi$—we have a smooth surface reflecting according to Fresnel.
2. $(\overline{\Delta z^2})^{1/2} \sim \lambda/4\pi$—diffuse reflection appears alongside specular reflection; the intensity of the specular reflection is less than the Fresnel value.
3. $(\overline{\Delta z^2})^{1/2} \gg \lambda/4\pi$—for a random character of z, specular reflection is exponentially small; the reflection is practically entirely diffuse.

For an incoherent light source (as, for example, in ([1]), where the source is a shock front in argon), we represent it as a set of point coherent sources and consider the reflection of such sources, mutually incoherent, for each of which the dependences obtained above are valid. In this case specular reflec-

···light (although attenuated) gives a spot whose linear size is of order $(\lambda l)^{1/2}$, where l is the distance from the light source to the reflecting surface.

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When $(\Delta\bar{z}^2)^{1/2} \sim \lambda/4\pi$, it is easy to show that the characteristic scattering angle $\overline{\delta\alpha} = \alpha - \alpha_0$* will correspond to the mean period $\bar{h}$ of the disturbances along the reflecting surface

$$\chi = k\cos\alpha_0\delta\alpha \qquad (\varphi = 0);$$

$$\bar{h} = \lambda/\overline{\delta\alpha}\cos\alpha_0. \tag{3}$$

Thus, in principle, measurement of the intensity I_{spec} and of the dependence of I_{dif} on the angle gives a complete characterization of the disturbances on the reflecting surface.

In determining the size of inhomogeneities on the detonation front in a mixture of nitric acid with dichloroethane, the intensity of specular reflection from the rough front I_{spec} was determined experimentally analogously to (2), while the intensity of specular reflection from a smooth surface I_{spec} was calculated analogously to (1).

Fig. 3. Microphotometric section of a photochronogram (for the experimental scheme and a typical photochronogram see (1)) at the instant of detonation of a liquid explosive mixture. $1, 3, 4, 5, 6$ are the experiment numbers according to Table 1. I_{II} is the intensity of light reflected from the reference boundary glass TF-5/liquid explosive; $I(x)$ is the intensity of light reflected from the detonation front; $I_{\text{dif}}(x)$ is the intensity of diffusely reflected light; $I_{\text{spec}} = I(x)_{\max} - I_{\text{dif}}(x)_{\max}$; $I_{\text{spec}} = \text{const}\, I_{\text{II}}$; I_{ϕ} is the background intensity.

The mean period of roughnesses $\bar{h}$ was determined from the obtained pattern of diffuse reflection** (see Fig. 3)

$$\bar{x} = \int_0^{x_0} I_{\text{dif}}(x)\, x\, dx \Big/ \int_0^{x_0} I_{\text{dif}}(x)\, dx, \qquad \bar{x} = \text{const}\,\overline{\delta\alpha},$$

where the proportionality coefficient is determined by the optical parameters of the recording system.

The obtained results are presented in Table 1. The adopted notation is: L/d is the ratio of the length of the liquid-explosive charge to its diameter; t_0 is the initial temperature of the mixture; p_x is the pressure in the chemiquette; $U_{\text{p}}/U_{\text{J}}$ is the piston velocity relative to the velocity of the explosion products at the Jouguet point in overcompressed detonation—the degree of overcompression.

Thus, a detonation process in a liquid explosive with very small inhomogeneities on the detonation···

* In (1), rays reflected at the specular-reflection angle α_0 are recorded (the aperture angle of the optical system, $\sim 15'$, may be neglected), and in this case α is the angle of incidence of light on the detonation front.

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** The intrinsic glow of detonation hinders detection of light scattered through large angles; therefore it is possible that the obtained values of $\bar{h}$ may be somewhat overestimated.

front*, and the picture of detonation with such inhomogeneities on the front is stationary (whereas much larger perturbations on the shock front are rapidly smoothed out).

In light of the results obtained, it cannot be ruled out that in the experiments [1] with a slightly overcompressed detonation wave (Table 1, experiment 1) there was a roughness with $(\overline{\Delta z^2})^{1/2} \ll 0.02\,\mu$, which cannot be detected even by the optical method, from a decrease in the reflection intensity.

Table 1

Experiment no.	Mixture composition	Initiating charge, its composition, diameter (mm) and length (mm)	d, mm	$\frac{L}{d}$	Screen	t, °C	D, km/sec	p_x, kbar	$\frac{U_P}{U_{Zh}}$	$\frac{I_{rough}}{I_{mirror}}$	$(\overline{\Delta z^2})^{1/2}$, μ	$\bar{h}$, μ
1	60/40 *	TG50/50; 120, 220	100	0.15	Aluminum 10 mm	−9	6.2	230	1.3	1	< 0.02 ***	$\gg (\overline{\Delta z^2})^{1/2}$
2	60/40 **	120, 220	100	0.15	Same	−3	6.2	230	1.3	0.3	0.062	5.6
3	60/40	120, 220	100	0.15	Same	−20	6.2	230	1.3	0.08	0.09	5.7
4	60/40	TG50/50; 120, 30	60	6	Glass 5 mm	+5	6.2	220	1	0.06	0.095	5.0
5	30/70	TG50/50; 120, 220	100	0.15	Aluminum 10 mm	+15	5.6	170		0.27	0.065	6.5
6	75/25	120, 220	100	0.15	Same	+8	5.8	200		< 0.01	> 0.12	10.5

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* Stoichiometric mixture—60 wt.% HNO_3.
** 10 wt.% water added (the curve in Fig. 3 is not shown).
*** The resolving power of the method makes it possible to record inhomogeneities $> 0.02\,\mu$.

The analysis of the experimental data made it possible to establish that the front of the shock wave in the detonating liquid is not ideally specular. However, the resolving power of the experiment does not make it possible to determine whether, among the set of angles $\alpha = (\overline{\Delta z^2})^{1/2} / {}^1\!/_2 \bar{h} \sim 1^\circ$, there are any that could lead to hot spots, i.e., to pulsating detonation.

At present two interpretations of the experiments are possible:

1. Either we are dealing with a picture that is in principle analogous to that previously observed for gas detonation [(3)], where in a mixture of $C_2H_2 + 2.5\,O_2$ the minimum scale was (along the front) $\sim 10^{-2}$ cm. Taking this scale to be inversely proportional to density, we obtain $\sim 10^{-5}$ cm for condensed high explosives, i.e., even less than in our experiments.

Similar inhomogeneities on the detonation front in condensed high explosives could not have been detected by the photographic-chronograph method [(4)] because of its low resolving power.

2. Or else the inhomogeneities arise in the chemical-reaction zone and cause inhomogeneity of the shock-wave front (owing to the subsonic velocity in the region between the wave and the reaction zone). But this inhomogeneity of the front has no appreciable feedback effect on the reaction.

In conclusion, let us note that, in order to obtain more complete information on the profile of the detonation surface, it is proposed to use an OKG as the light source. The periodic structure of the inhomogeneities will appear especially sharply in the case of monochromatic coherent light; a narrow-band light filter will make it possible to eliminate interference associated with the wave' s own luminosity.

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* It is interesting to note that such inhomogeneities—roughnesses on the detonation front—correspond to class 11 (out of 14) of surface-finish purity according

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to GOST 2789-59.

Note: Figure translations are in progress. See original paper for figures.

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