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Abstract

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ON THE INSTABILITY OF THE SURFACE OF A LIQUID WHEN DETONATION AND SHOCK WAVES SLIDE OVER IT

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The problems of interaction of shock and detonation waves with the surface of a liquid have become especially interesting in connection with questions of safety engineering in the transportation of air, explosive mixtures, and gases through pipelines ([1–3]).

In light of this, the study of all stages of the interaction of detonation and shock waves with a liquid surface when a wave slides along the surface acquires great importance, and especially the question of the stability of the free surface after the wave has passed over it.

Since, when a detonation or shock wave moves over the surface of a liquid layer, for any regimes $D > C$ and $D < C$ (D is the wave velocity, C is the speed of sound in the liquid), the occurrence of microdisturbances on the liquid surface is always possible owing to multiple reflection of compression and rarefaction waves in the liquid layer, it is necessary to investigate the stability of this surface in a gravitational field with allowance for surface-tension forces.

Landau ([4]) investigated the stability of a tangential discontinuity of two liquids (one at rest, the other moving) in a gravitational field with allowance for surface tension. The stability criterion

$$U_0^4 \leqslant \frac{4\alpha g\rho}{\rho_1^2},$$

where α is the coefficient of surface tension, g is the acceleration of free fall, ρ is the density of the liquid, and ρ_1 is the density of the gas behind the wave above the liquid, as applied to our case of the boundary between liquid and gas gives the minimum velocity of the gas over the liquid surface, U_0, at which this surface is stable. In real cases the gas velocity behind the front of a shock or detonation wave is always greater than U_0. Thus, the free surface of the liquid is unstable after a shock or detonation wave has passed over it.

For experimental verification of the picture of the interaction of shock and detonation waves with a liquid surface, an installation of the shock-tube type was used, the observation section of which was viewed by means of an IAB-451 shadowgraph setup combined with an SFR high-speed photorecorder operating in the time-loupe mode. Experiments carried out with various liquids and viscous materials (of the type of technical petroleum jelly) and with shock and detonation waves of various intensities showed that the liquid surface is unstable when a detonation or shock wave slides over it. Figure 1 shows the temporal development of disturbances on the surface of glycerin after the passage of a detonation wave in the mixture $2H_2 + O_2$. The mean velocity of rise of the liquid surface during the development of the disturbances is of the order of 20 m/sec. At the crests that arise when the waves bulge out, particles of liquid are torn off by the gas stream and are broken up in the stream into the finest particles.

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Fig. 1. Development of instability on the surface of glycerin after the passage of a detonation wave in a mixture of $2H_2 + O_2$ at a pressure of 1 atm. Time between frames: 95 μsec. 1—gas, 2—liquid. The detonation wave traveled from left to right.

Fig. 2. Development of instability on a thin film of technical vaseline (thickness on the order of 0.1 mm) after the passage of a detonation wave in a mixture of $CH_4 + 2O_2$ at a pressure of 1 atm. Time between frames: 95 μsec. 1—gas, 2—thin vaseline film.

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Fig. 4. X-ray pattern of an alloy crystallized at $v_{\text{cool}} > 10^6$ deg/sec.
a—Al + 36.0%Mg, VRS camera, $d = 114$ mm, back-reflection photography; Cu radiation.
b—pure aluminum.

A dense mist is formed from glycerin droplets suspended in the gas. This mist gradually settles in the gas after it has come to rest. From the settling time of the liquid particles in the gravitational field, one can estimate the average size of the glycerin droplets formed, $R = 0.5\,\mu$. In time, the process of formation of a glycerin spray proceeds through four conventional stages: 1) formation of disturbances on the liquid surface behind the front of a running detonation or shock wave (these are microdisturbances) $-t_1 = 300 \div 400\,\mu$sec; 2) appearance and development of (noticeable) disturbances on the liquid surface $-t_2 = 500\,\mu$sec; 3) stripping and spraying of liquid droplets from the crests of the waves that have arisen $-t_3 = 500\,\mu$sec; 4) settling of the resulting mist in the quiescent gas $-t_4 = 3 \div 4$ min. Similar experiments carried out with other liquids, for example mercury and viscous materials (such as technical vaseline), give a similar picture of spray formation both behind detonation and behind shock waves (Fig. 2). Even when a detonation wave slid over the surface of such a solid material as paraffin, the formation of a weak spray consisting of comparatively large droplets, which quickly settle, was observed.

The interaction of a wave with a small drop of liquid lying on the surface of the chamber develops somewhat differently. At first the usual shearing of part of the liquid from the surface by the gas flow is observed, and then ejections from the surface occur, analogous to the ejections in the case of large liquid surfaces. And again a mist of the finest liquid droplets is formed.

Preliminary experiments were carried out on the ignition of the resulting heterogeneous mixtures of a mist of combustible liquid (kerosene, cetane $C_{16}H_{34}$) and oxygen in shock waves at an initial pressure of 100 mm Hg. For this purpose a shock tube and the apparatus described in work (^{5}) were used. During spray formation, the resulting micron-sized droplets of combustible liquid are very rapidly heated ($t_1 = 1\,\mu$sec) and evaporate ($t_2 = 10\,\mu$sec) in the hot oxygen behind the shock wave. The possibility of ignition of the heterogeneous mixtures of oxygen with cetane and kerosene formed as a result of spraying has been shown experimentally, beginning at certain Mach numbers in the shock wave. For example, for oxygen with cetane the limiting Mach number is 2.1; for air with cetane the limiting Mach number is 2.6. Ignition was observed in reflected shock waves. The determining factor in the formation of a combustible mixture in these experiments is the instability of the liquid surface and the occurrence of a fine spray of micron-sized droplets, which ensures very rapid evaporation of the fuel.

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