SLIDING OF DETONATION AND SHOCK WAVES OVER LIQUID SURFACES

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The interaction of detonation and shock waves, propagating in a gaseous medium, with liquid surfaces over which they slide has recently attracted much attention. This interest has been aroused primarily by problems of the safe transportation of air and explosive mixtures through pipelines [1—3]. The interaction of a detonation wave with the surface of an inert gas has been thoroughly studied [4, 5].

The object of our work was to study all the stages of interaction between detonation and shock waves and liquid surfaces over which they slide.

INTRODUCTION

We shall consider the interaction of a detonation wave with a liquid surface in the presence of sliding. Almost all the results obtained are also applicable to shock waves. When a detonation wave passes over a liquid surface two interaction regimes are possible depending on the relation between the detonation wave velocity D and the speed of sound in the liquid c_1.
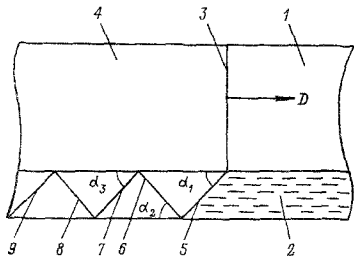

Fig. 1. Diagram illustrating interaction of detonation wave and liquid for $D > c_1$. 1) Explosive mixture, 2) liquid, 3) detonation front, 4) detonation products, 5) attached shock, 6) reflected shock, 7) primary reflected rarefaction wave, 8) reflected rarefaction wave, 9) secondary reflected shock.

1. The first regime corresponds to $D > c_1$ (Fig. 1). Interaction between detonation wave and liquid results in the formation of an attached shock, 5, (in the gas, a rarefaction wave), oriented at an angle α_1 to the surface of the liquid. Analysis of the interaction in terms of the diagram of pressure vs. flow rotation angle (p, χ) (Fig. 2) shows that shock 5 and all subsequent waves in the liquid are acoustic. If the layer of liquid is bounded by a pipe wall made of elastic material, then reflected shock 6 (Fig. 1) develops

with twice the pressure amplitude and angle of reflection $\alpha_2 = \alpha_1$. Subsequently, there is a whole series of reflections from the wall and the free surface of the liquid with the formation of a system of shock waves and rarefaction waves in the liquid.
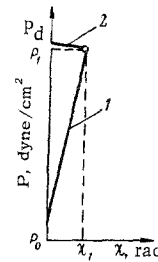

Fig. 2. Diagram illustrating the case of interaction between a detonation wave and a liquid surface for $D > c_1$.
p_0 — initial pressure of mixture,
p_d — pressure in detonation wave,
p_1 and χ_1 — pressure and flow rotation angle after interaction.

For the specific mixture $2H_2 + O_2$ and water at an initial pressure $p_0 = 1$ abs. atm we get the equation of straight line 1 (see Fig. 2):

$$p_1 - p_0 = 5 \cdot 10^{10} \chi_1$$

and the equation of curve 2:

$$p_1/p_g = 1 - 1 \cdot 4\chi_1^{2/3}.$$

Solving this system for p_1 and χ_1, we get

$$\chi_1 = 3.4 \cdot 10^{-4} \, \text{rad}, \quad p_1 = 0.9995 p_g, \quad \text{т. e.} \quad p_1 \simeq p_g.$$

The pressure in wave 6, $p_2 = 2p_1$, in wave 7, $p_3 = p_1$, in wave 8, $p_4 = p_0$, in wave 9, $p_5 = p_1$, and so on. This wave packet, moving in the liquid behind the detonation wave, may be characterized by a certain effective wavelength λ_0. If the depth of the liquid layer is h_0, then

$$\lambda_0 = 4h_0 (D^2/c_1^2 - 1)^{1/2}.$$

In a layer of liquid of finite length there is an interaction between the wave packet and the end of the pipe or free surface. In this case a new system of waves is reflected either in phase (rigid wall) or in antiphase (free surface). Interfering with the tail of the incident packet, the new packet produces a system

of the standing wave type. The distance between nodes or antinodes in this system is equal to λ_1, where $\lambda_1 = \lambda_0/2 = 2h_0(D^2/c_1^2 - 1)^{1/2}$.
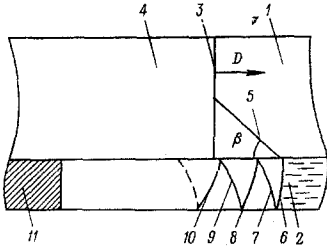
Fig. 3. Diagram illustrating interaction of detonation wave and liquid for $D < c_1$. 1) Explosive mixture, 2) liquid, 3) detonation front, 4) detonation products, 5) lateral shock, 6) refracted shock, 7) reflected shock, 8) primary reflected rarefaction wave, 9) reflected rarefaction wave, 10) secondary reflected wave, 11) insert.

2. The second interaction regime corresponds to $D < c_1$ (Fig. 3). At the moment detonation wave 3 strikes the surface, a refracted cylindrical shock wave 6 develops in the liquid. It moves away from the point of origin at a velocity c_1 and overtakes the detonation wave 3, since $D < c_1$. This generates a lateral shock 5, which travels through the detonation mixture ahead of the detonation front. The angle of inclination of the lateral shock to the liquid surface $\beta = \arcsin c_2/c_1$, where c_2 is the speed of sound in the explosive mixture. The pattern of motion is non-stationary; one end of the lateral wave moves upward along the detonation front. The refracted shock 6, on being reflected from the pipe wall, generates a system of shock waves and rarefaction waves similar to that

previously described under case 1. In case 2 all the waves are cylindrical except lateral wave 5, the wave system is acoustic and rapidly attenuates.

To clarify the subsequent behavior of the liquid we shall investigate the stability of the resulting tangential discontinuity (almost still liquid—moving gas) with allowance for the gravitational field and surface tension forces. For this purpose we shall employ Landau's stability criterion [6]:

$$u_0^4 \leqslant \frac{4\alpha g\,(\rho - \rho_1)\,(\rho + \rho_1)^2}{\rho^2\,\rho_1^2},$$

where u_0 is the maximum gas velocity under stable conditions, α is the surface tension coefficient, g is the free-fall acceleration, ρ is the density of the liquid, and ρ_1 is the density of the detonation products. For $\rho \gg \rho_1$ we get the following expression for the stability criterion:

$$u_0^4 \leqslant \frac{4\alpha g\,\rho}{\rho_1^2}.$$

For the case of detonation of a mixture of $2H_2 + O_2$ over a glycerin surface $u_0 \leq 8$ m/sec. The velocity of the detonation products is almost everywhere greater than u_0; therefore the surface of the liquid is in an unstable state and the wave systems considered above naturally lead to the appearance and subsequent development of perturbations of the liquid surface. Particles of liquid are then entrained by the flow of gas and broken up into very fine droplets [7].

An estimate of the amount of liquid that could be evaporated from the surface behind the wave during the characteristic time of the atomization process, 500 μsec, based on calculations of the heat flow in a shock tube from the gas to the walls [8, 9], gives 5×10^{-8} g of water per cm^2 of liquid surface. The
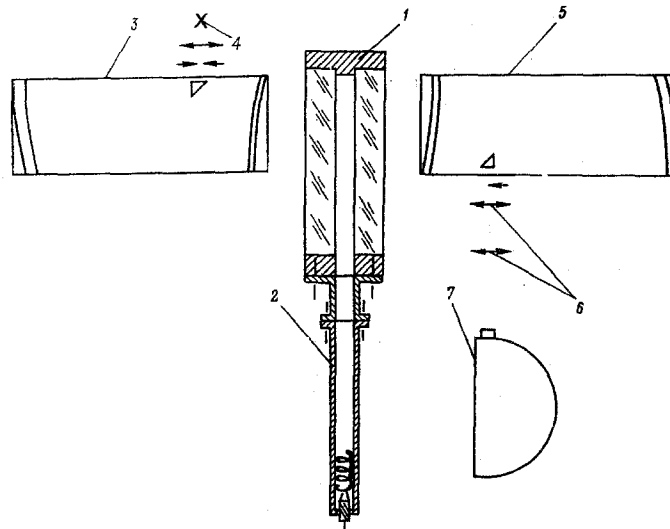
Fig. 4. Experimental setup — schematic. 1) Observation chamber, 2) detonation tube, 3) and 5) half-shade polarimeter, 4) flash lamp, 6) transition lens system, 7) SFR photorecorder.

effect due to evaporation from a smooth surface is
very small. Taking viscosity into account also gives
a very small result for a characteristic time of
500 μsec.

RESULTS OF THE EXPERIMENTS

The experimental setup is illustrated in Fig. 4. A
chamber with two transparent side walls, rectangular
in cross section with sides 27 × 28 mm and 37 cm
long, was connected with a detonation tube (diam.
15 mm, length 50 cm). The detonation wave was
initiated in the tube by an electric spark. A spiral
was inserted in the tube to reduce the predetonation
period. The interaction processes were investigated
using a half-shade polarimeter combined with a SFR
photorecorder or a SKS motion-picture camera [10].
In observing the interaction pattern the device was
tuned either to the liquid or the gas.

The following were studied: explosive mixtures—
$2H_2 + nO_2$, $CH_4 + 2O_2$; gases—oxygen and air; five
different liquids—water, glycerin, mercury, kerosene,
and cetane. These liquids were chosen because of the
range of properties they represent. Kerosene and
cetane (hexadecane $C_{16}H_{34}$) were chosen as liquid
fuels with low vapor pressure. We also used such
materials as commercial petrolatum and paraffin.
The paraffin was deposited on the bottom of the
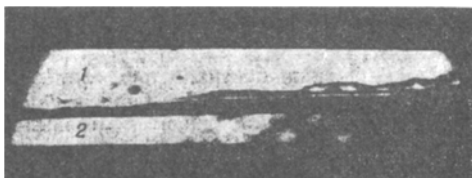chamber in molten form and cooled to form a solid
layer.

Fig. 5. Wave system in glycerin following
interaction of a detonation wave in a $2H_2 +$
$+ O_2$ mixture with the glycerin surface,
$p_0 = 1$ abs. atm. Detonation wave travels
from left to right. 1) Gas, 2) liquid.

A small number of experiments with kerosene and
cetane were made using a large shock tube of the type
described in [11, 12]. The ignition of the resulting
mixtures of kerosene or cetane and oxygen of air in
the shock waves was investigated.

Experiments with an explosive mixture of $2H_2 +$
$+ nO_2$ (by varying n from 1 to 6 it is possible to vary
the detonation wave velocity from 2820 m/sec to
1700 m/sec) and selected liquids together with com-
mercial petrolatum and paraffin confirmed the as-
sumed results of the interaction of detonation waves
and liquid surfaces. Passage of a detonation or shock
wave was followed by instability of the liquid surface.
The instability develops differently for the different
liquids and materials selected.

Experiments with glycerin ($D > c_l$). Glycerin is a
useful test substance in that it makes it possible to

observe the results of interaction both in the liquid
and in the gas. In this case the interaction may be
arbitrarily divided into four stages.

The first stage lasts about 300μsec (Fig. 5), be-
ginning from the moment the detonation wave reaches
the liquid surface. A wave system $\alpha_{1t} = 44°$; $\alpha_{1e} =$
$= 45° \pm 3°$, $\alpha_2 = \alpha_1$, etc. is visible in the glycerin. In
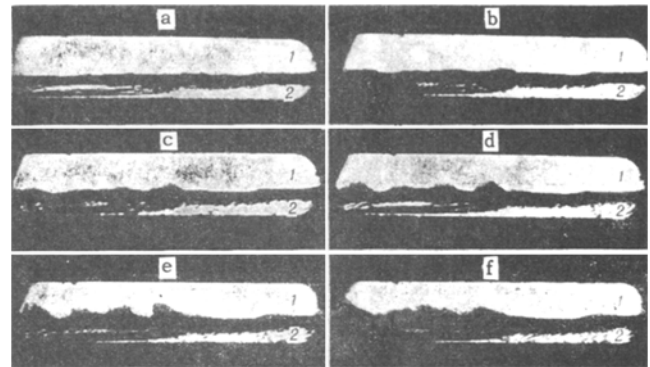this stage the surface of the liquid remains smooth.

Fig. 6. Atomization of glycerin after passage of
detonation wave in a $2H_2 + O_2$ mixture. The det-
onation wave traveled from left to right. Time
between frames 95 μsec. 1) Gas, 2) liquid.

By varying the depth of the glycerin layer h_0 it is
possible to change the characteristic wavelength λ_0
of the wave packet.

The second stage begins with the visible perturba-
tion of the liquid surface and continues until it be-
comes quite rough. This phase lasts about 500 μsec
(Fig. 6). The mean upward velocity of the liquid is
about 20 m/sec, which is in good agreement with the
estimated results. The disturbance of the surface has
a certain periodicity. The wavelength following from
this periodicity (λ_{1e}) is equated with λ_{1t} obtained in
the introduction (Fig. 7). The good agreement be-
tween these quantities indicates the correctness of
our assumption concerning the causes of the phe-
nomenon. In the third stage the liquid detached from
the surface is broken down into fine droplets by the
gas flow and fills the entire chamber with a dense
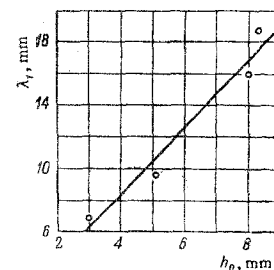mist. This stage continues for about 400 μsec.

Fig. 7. Variation of distance
between antinodes λ_1 with
depth of layer h_0 for glycer-
in. The straight line is theor-
etical.

The fourth stage is associated with settling of the mist in the still gas in the gravitational field and makes it possible to measure the mean diameter of the glycerin drops. Settling lasts about 4 min, which gives a droplet radius $R \simeq 0.5$ micron. The atomization is very fine.
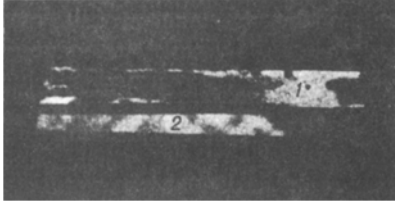

Fig. 8. Wave system in water following interaction of detonation wave in a $2H_2 + O_2$ mixture with the water surface, $p_0 = 1$ abs. atm. Detonation wave travels from left to right. 1) Gas, 2) liquid.

Experiments with glycerin $(D < c_1)$. In this case the wave system is very weak and rapidly damped. The method employed does not make it possible to observe this system in glycerin. However, the subsequent course of the interaction process coincides with that for $D > c_1$. Part of the glycerin is atomized forming a mist.

Experiments with water and mercury $(D > c_1)$. In experiments with water it is possible to observe the interaction pattern only in the liquid; vapor settling on the glass obscures what takes place in the gas. In the first stage the interaction pattern coincides with that assumed above (Fig. 8). A wave system with $\alpha_{1e} = 30° \pm 3°$, $\alpha_{1t} = 29°$ is clearly visible. The result is a dense mist.

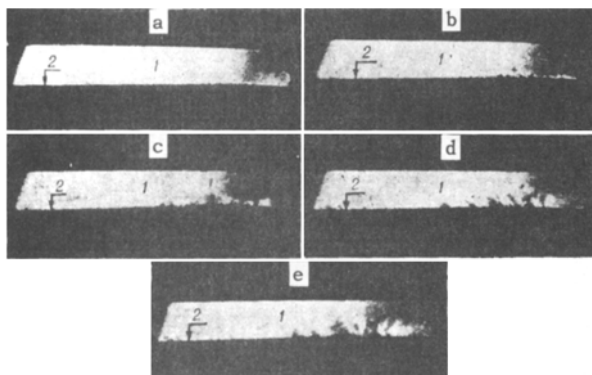Fig. 9. Atomization of mercury after passage of detonation wave in a $2H_2 + O_2$ mixture. Time between frames 360 μsec. 1) Gas, 2) liquid.

In the experiments with mercury the atomization effect is clearly observed (Fig. 9). The particles ejected from the surface are smaller and the settling of the mist more rapid than in the case of water or glycerin, but the atomization process itself is very intense.

Experiments with kerosene and cetane $(D > c_1$ and $D < c_1)$. These experiments were made in order to ascertain the nature of the interaction of detonation and shock waves with the surface of a liquid fuel. For a detonation wave in a $2H_2 + O_2$ mixture the interaction pattern is identical with that in water or glycerin. For kerosene and cetane we also used a mixture enriched in oxygen $2H_2 + 6O_2$ to create a secondary mixture consisting of oxygen remaining after the reaction in the detonation wave and the fuel mist. If one takes a large amount of fuel (liquid layer 2 mm thick or more), then the mist contains such a large amount of kerosene or cetane that the secondary mixture cannot burn. If, however, one takes a small amount of fuel (layer 0.03 mm thick or less), the resulting secondary mixture is partially burned up.
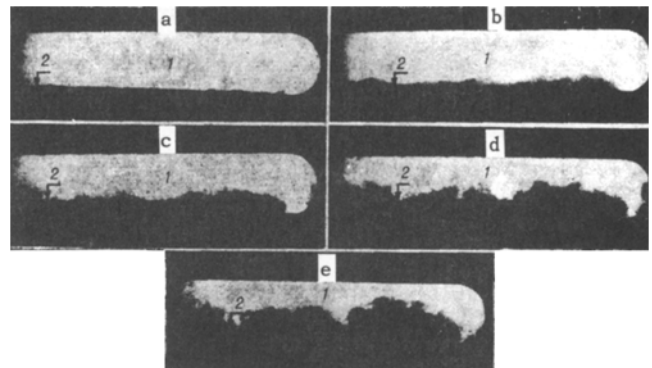

Fig. 10. Atomization of commercial petrolatum after passage of a detonation wave in a $CH_4 + 2O_2$ mixture at $p_0 = 1$ abs. atm. Time between frames 190 μsec. 1) Gas, 2) liquid.

For a more detailed investigation of this effect, the mist was created not by a detonation, but by a shock wave in pure oxygen or air at an initial pressure of 1 abs. atm and less. The shock wave was excited: 1) Using a detonation shock tube whose compression chamber held a mixture of $2H_2 + O_2$ or $CH_4 + 2O_2$ at a pressure of 1 abs. atm.; 2) using a simple shock tube with nitrogen or helium in the compression chamber. The first method was used to register the half-shade interference figure and autoignition, the second to register the velocity of the incident shock wave and the luminescence upon ignition. The resulting heterogeneous mixture of fuel and oxygen obtained by the first method for shock waves with $M \leq 2$ (M is the Mach number) burns up very slowly. The mixture is ignited by the hot detonation products from the compression chamber. In the second method for shock waves with $M > 2$, the heterogeneous mixture of fuel and oxygen is observed to ignite in the reflected and incident shocks. Thus, for cetane, introduced into the shock tube in the amount of 4 ml at a point close to the end face of the tube, and oxygen at an initial pressure of 100 mm Hg, the mixture is observed to ignite in the reflected wave with ignition lags $\tau = 500$ μsec for an incident wave with a Mach number of 2.3 ($T_{ref} = 900°$ K is the temperature in the reflected shock). For a mixture of

cetane and air under the same initial conditions embryonic ignition was observed at M = 2.6 (T_{ref} = 1060° K). The heterogeneous mixture formed upon atomization burns in the gas phase, a conclusion indicated by estimates of the time required to heat and vaporize the micron-sized fuel droplets formed; the evaporation time for kerosene is of the order of 10 μsec, the heating time of the order of 1 μsec. Thus the ignition process is basically determined by the time required to atomize the fuel to droplets of micron size.

Experiments with commercial petrolatum and solid paraffin. Commercial petrolatum is a very viscous material, while solid paraffin is comparatively soft. Figure 10 shows the atomization of a layer of petrolatum 3 mm thick behind a detonation wave in a CH_4 + $2O_2$ mixture. After the experiment a dense mist of petrolatum droplets is observed. If the layer is very thin ($h_0 \simeq 0.01$ mm), almost all the petrolatum is atomized. It is interesting to note that paraffin behaves like a liquid. Particles are ejected from the surface and a mist of fine paraffin droplets is formed.

Thus, the experiments confirm the instability of the surface of liquids and viscous materials over which a detonation or shock wave slides. This instability has been observed in different liquids and viscous materials up to formation of a dense mist of very fine liquid particles in the gas.

Our preliminary studies of the ignition of heterogeneous mixtures of fuel and oxygen (air) thus formed may prove valuable from the standpoint of safety engineering in connection with the transport of gases through pipelines.

The possibility of obtaining very fine mists of liquids and viscous materials in gases might be utilized in further studies of the ignition of heterogeneous mixtures.

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