# Thin layers in acoustics and optics. Changes in the transmission and reflection of sound and light on creation of a thin gas layer on the surface of a body in a liquid

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It is shown that a thin vapor-gas layer near the surface of a medium in a liquid may appreciably alter the transmission and reflection of sound. Thermal methods of creating a vapor-gas layer on pulsed heating of a metallic foil during the discharge of a capacitor (the authors previously investigated for this purpose the heating of a surface by a laser beam for production of a vapor layer[3]) and also electrolytic evolution of gas near the electrode are investigated. Very rapid blocking of sound transmission and changes in scattering, over periods not exceeding a few microseconds, are obtained, as well as a very large blocking time, which may be as long as a fraction of a second. Rapid blocking of light reflection on pulsed formation of vapor near the surface is obtained. It is mentioned that the process may be employed for rapid blocking or modulation of transmission and reflection. Very thin vapor or gas layers at the surface of bodies in a liquid may be the cause of strong nonlinear effects when the acoustic oscillation amplitude is commensurable with the thickness of the layer.

## INTRODUCTION

It is known in optics that a thin dielectric layer of thickness exceeding several tenths of a wavelength can, when deposited on the surface of a medium, greatly alter the transmission of light through the surface and the reflection from it. We show in the present paper that in acoustics this change can turn out to be much larger even at layer thicknesses smaller by several orders of magnitude than the acoustic wavelength, inasmuch as it is possible in acoustics to produce a much larger drop of the acoustic properties across a liquid-gas interface by producing thin gas layers on the surface of a body in a liquid. Thus, the ratio of the acoustic resistances $\rho c_s$ of a gas and of a liquid is $\rho_g c_{sg}/\rho_l c_{sl} \approx 3 \times 10^{-4}$ at normal pressure.

In this article we investigate methods of producing thin gas layers in acoustics and optics, and the properties of these layers.

## 1. INFLUENCE OF A THIN GAS LAYER ON THE SURFACE OF A BODY IN A LIQUID ON THE TRANSMISSION AND REFLECTION OF SOUND

Assume that the surface of medium 1 is separated by a layer 2 from medium 3. The known formulas[1] for the transparency coefficient D and for the reflection coefficient U in the case of normal incidence assume in our case a simple form. For example, for the transparency coefficient we have

$$|D|^2 = |D(0)|^2 \left\{\cos^2 k_2 d + \left[\frac{Z_1 Z_3 + Z_2^2}{Z_2(Z_1 + Z_3)}\right]^2 \sin^2 k_2 d\right\}^{-1},$$

where $|D(0)|^2$ is the transmission coefficient in the case when the layer 2 is absent (i.e., as the layer thickness $d \to 0$), and $k_2$ is the wave number for the sound in medium 2 ($k_2 = 1/\lambda\!\!\!^{-}_{s2}$). It is seen from this formula that the condition for a noticeable decrease of the value of D following the appearance of layer 2 is that the expression in the curly brackets differ from unity, for example, $\{\ \} \approx 3$. Putting $Z_2 \ll Z_{1,3}$ and assuming the layer to be thin, $k_2 d \ll 1$, we obtain the condition under which the transparency coefficient experiences a large decrease:

$$k_2 d \geqslant Z_2(Z_1^{-1} + Z_3^{-1}).$$

A similar relation determines the condition under which the reflection coefficient is strongly altered. In our case $Z_2/Z_3 \approx 3 \times 10^{-4}\, p_{atm} \approx 3 \times 10^{-4}$ at a steady-state pressure $p \approx 1$ atm in the gas layer, so that a strong decrease of the transmission should be observed already at $k_2 d = d\lambda\!\!\!^{-}_{s2} \approx 10^{-3}$. At a frequency $\nu_s \sim 1$ MHz ($\lambda_s \approx 0.1$ cm) we obtain a sufficient layer thickness $d \approx 0.1-0.3\ \mu$, i.e., a rather small quantity. During the earlier stages of formation of this layer, the pressure can be increased by the counterpressure of the liquid layer ($p \sim \rho_l c_{sl} d$); in this time, the formation conditions are worse, owing to the smaller thickness of the layer and the larger gas pressure. At the instant of layer formation, the quasistatic formulas employed above no longer hold, and during the time of layer formation (which can be $t_{exp} \gtrsim d/0.1c_{sl} \approx 10^{-9}$ sec in the case of explosive formation and $t \gg t_{exp}$ in the case of quiescent formation), strong changes can occur in the sound frequency, and an intrinsic acoustic pulse can be generated. However, after several pulsations, a quasistatic vapor-gas layer is produced, with an interior pressure $p \approx 1$ atm, with a sufficiently long lifetime determined either by the thermal conductivity and the cooling of the heated surface, or else by the diffusion of the gas. The small layer thickness that suffices to produce the covering, and the low gas density, enable us to produce the layer without consuming much energy, and permit rapid realization of the modulation.

## 2. EXPERIMENTAL INVESTIGATION OF THE CHANGE OF THE TRANSMISSION OF SOUND AND LIGHT WHEN A THIN VAPOR-GAS LAYER IS PRODUCED ON THE SURFACE OF A MEDIUM IN A LIQUID

A thin vapor-gas layer can be produced on the surface of a body by many methods. In[2,3] they used the emission of Q-switched and non-Q-switched lasers for pulsed heating of a surface immersed in a liquid. The advantages of this method are the possibility of using both conducting and dielectric surfaces, and the short time of energy release, which makes it possible to heat thin surface layers of the medium. The poor power efficiency of the laser, however, and the difficulty of acting on sufficiently large areas, have induced us to investigate possible methods of gas-layer formation other than by optical heating. Since a three-dimensional energy supply is required to produce the energy release, our main choice was resistive heating of conducting surfaces, whereby a thin foil was heated by a current pulse discharged from a capacitor.

Figure 1 shows the experimental setup. Stainless steel foil 4, of thickness 100 or 30 $\mu$, was placed in a water-filled cell 3. The foil was soldered to electrodes 5, which were connected through discharge gap 7 to a capacitor 6 rated 2 $\mu$F, charged from a rectifier 8. An ultrasound beam from radiator 2, fed from a generator 1, passed through foil 4 to receiver 9, from which the signal was fed to oscilloscope 10. The ultrasound oscillation frequency was 2.3 MHz.

For the foil of thickness 100 $\mu$ and dimensions $2 \times 1$ cm (the foil resistance was 0.02 $\Omega$ at a total discharge-circuit resistance 0.04 $\Omega$ and inductance 0.12 $\mu$H), the energy release time was $\approx 10$ $\mu$sec. When the foil is heated by the pulse, its surface is covered by a vapor layer that blocks the transmission of the sound.

Figure 2 shows oscillograms of the front (a) and of the duration (b) of the blocking of the sound when a capacitor is discharged through the foil. We see that the signal decreased to zero within a time $\tau_{fr}$, and that the blocking duration $\tau_d$ exceeded $\tau_{fr}$ by many times. The dependence of $\tau_{fr}$ and $\tau_d$ on the volume concentration of the energy input $E_f$ to the foil are shown in Fig. 3. Experiments were performed with a thin foil (thickness $d_f \approx 30$, resistance $R_f \simeq 0.07$ $\Omega$). The results are also shown in Fig. 3. In the case of a thin foil, the volume concentration of the energy release increases not only as a result of the decrease in the foil volume but also as

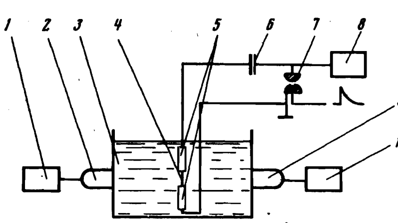


FIG. 1. Setup for the investigation of the variation of the transmission of ultrasound through a foil in a liquid following pulsed heating of the foil with electric current (the callouts are given in the text).

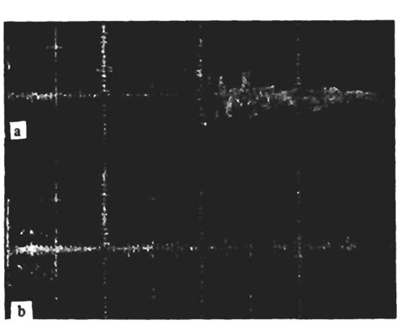


FIG. 2. Oscillograms of the front (a) and of the duration of the blocking of the passage of sound (b) following pulsed heating of a foil 300 $\mu$ thick by discharging a 2 $\mu$F capacitor charged to 3 kV (a) or to 2 kV (b) (this voltage was close to the threshold value). The sweeps in cases a and b are 2 and 100 $\mu$sec/division, respectively.

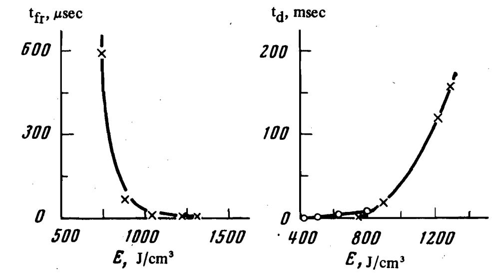


FIG. 3. Dependence of the rise time and of the sound blocking duration on the volume energy-release density following heating of a foil of thickness 100 (X) and 30 (O) microns.

a result of the larger energy released by the foil (the ratio of the energy released by the foil to the total energy is $E_f V_f / \mathscr{E}_{tot} \approx R_f/(R_f + R_{lead})$, where $R_{lead} \approx 0.02$ $\Omega$).

It follows from the reported experiments that an energy release $\mathscr{E} \approx 1-5$ J per square centimeter of surface is sufficient to produce strong blocking of the sound. The time required to produce a layer may not exceed 3 $\mu$sec (shorter times could not be resolved, owing to the damping time of the tuned receiver itself), and the lifetime of the layer can exceed hundreds of milliseconds.

It should be noted that when the entire energy is released the foil is heated to 150—200°, and that the formation of a vapor-gas layer begins only when the foil surface reaches the boiling temperature of the liquid. A thin vapor-gas layer is rapidly produced and receives the heat from the foil, and it is this which enables the layer to exist for so long a time. The long lifetime of the vapor-gas layer leads to large losses of heat to heating of the liquid layer adjacent to the vapor. Indeed, specifying the temperature of the liquid on the boundary with the vapor to be $T \approx T_{boil} \approx 100°$, we find that at a heated liquid-layer thickness $\delta \approx \sqrt{\kappa t}$ the heat consumed per cm² is $Q_1 \sim c\rho T\delta$, where $C\rho \sim 1$ cal/cm³ is the volume specific heat of the liquid and $\kappa$ is its thermal diffusivity ($\kappa \approx 10^{-3}$ cm²/sec for water). For $t \sim 100$ msec we obtain $Q_1 \approx 1$ cal/cm², which is quite close to the total energy released by the foil. Thus, a small fraction of the energy was consumed in the evaporation and there are possibilities of further decreasing the necessary heat release. The fact that a small fraction of the energy is consumed in the formation of the layer is confirmed by comparison of the energy $Q \approx \rho_{vap} d\Lambda$ needed to produce the layer ($\Lambda$ is the heat of evaporation of one gram of liquid). At a vapor density $\rho_{vap} \approx 10^{-3}-10^{-2}$ g/cm³ and at a sufficient layer thickness $d \approx 3$ $\mu$, we obtain $Q_1 \approx 2 \times (10^{-4}$ to $10^{-3})$ cal, which is many times less than the released energy. A decrease in the thickness of the heated layer, a decrease in the time necessary to maintain the layer, preheating of the liquid, and the use of liquids with low boiling points and low evaporation heats will all reduce the necessary energy release and accelerate the process of layer formation.

The same setup was used to investigate the change of the reflection of light from a polished foil immersed in a liquid and heated by a pulse. A light beam from a helium-neon gas laser was incident at an angle 45° on a polished stainless-steel foil 100 $\mu$ thick. The light beam reflected from the foil entered a photomultiplier and was registered with an oscilloscope. When the incidence angles were not very large, a decrease of the reflec-

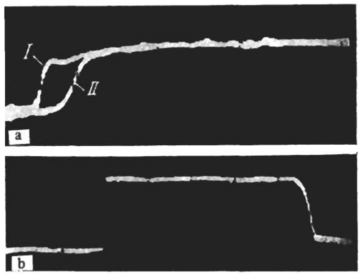


FIG. 4. Oscillogram of the front (a) and of the duration (b) of the decrease in the reflection of light from a polished foil heated by current. In case (a) (sweep duration 20 μsec.), the front is shown for two different capacitor voltages, 8.2 kV (I) and 7.2 kV (II). We see that with increasing voltage the time elapsed before the start of blocking and the time of the blocking itself both decrease. In case (b), the sweep duration is 1 sec.

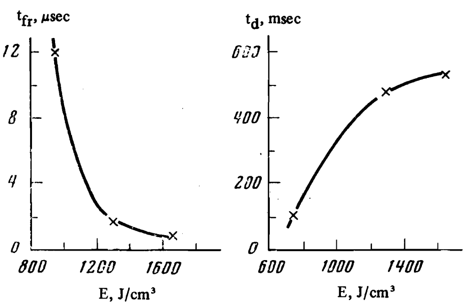


FIG. 5. Dependence of the front time and of the blocking duration of light reflection from a foil at different energies released per unit volume.

tion, due to the appearance of vapor bubbles or to the unevenness of the vapor-gas layer, was registered. Figure 4 shows an oscillogram illustrating the decrease of the reflection at a heat release $E_f$ [J/cm³] in the foil. At small glancing incidence angles one could apparently observe total internal reflection from the boundary of the vapor-liquid layer, provided this boundary is not too rough. Figure 5 shows plots of the rise front $\tau_{fr}$ and of the blocking duration $\tau_d$ of the light scattering against the heat-release energy $E_f$ in a foil 100 μ thick.

We note that the use of gasified liquids can decrease the necessary energy required to produce the layer, since the surface will have to be heated to a lower temperature, owing to the sharp decrease in the solubility of the gas in the liquid when the latter is heated. The use of liquids with low boiling points or of heated liquids can also decrease the required energy consumption and shorten the time of layer formation.

We tried systems of heated thin wires to produce a bubble screen for ultrasound. A strong blocking of the ultrasound was obtained when the same capacitor was discharged through a system of nichrome wires of 0.2 mm diameter, spaced 1 mm apart.

In addition to the thermal method of producing a vapor-gas layer on the surface of the medium, one can use gas release by electrolysis at an electrode in an electrolyte. We investigated experimentally the change in the reflection and transmission of radiation through a plate of stainless steel with an area 10 cm², immersed in a solution of table salt, when a 200 μF capacitor charged to 1–2 kV was discharged through the electrolyte. This corresponded to a charge $q_1 \sim CU/S \approx 3 \times 10^{-2}$ C/cm² per unit surface of the electrode, i.e., $N_1 \approx 10^{17}$ gas molecules, which is equivalent to a gas layer thickness $d \sim N_1/N_2 \approx 30$ μ at a pressure of 1 atmosphere.

## 3. APPLICATIONS. BLOCKING THE PASSAGE OF RADIATION AND CHANGING ITS REFLECTION. NONLINEAR PROPERTIES OF THIN LAYERS

Our study has shown that the production of a very thin gas layer on the surface in a liquid can greatly alter the acoustic conditions on the surface. The results can be used to vary the transmission and reflection of ultrasound, and this method makes possible ultrafast variation of the conditions on the boundary. The usual methods of modulating sound are limited by the intrinsic damping time of the radiators, which customarily operate in a resonant mode. This time can amount to several dozen oscillations, whereas the gas layer is produced in much shorter times.

The rapidly produced layer can also be used to alter the reflection and transmission of light.

We note one more valuable quality of thin gas layers in acoustics, namely their nonlinear properties. All the expressions derived for the transmission and reflection are valid at oscillation amplitudes that are small in comparison with the gas-layer thickness. If the oscillation amplitude $x_0$ becomes commensurate with the layer thickness, and this takes place at flux densities $I_s \approx \rho c\, x_0^2\omega^2 \approx \rho c_s d^2\omega^2$, then at $x_0 \sim d$ one surface of the medium can almost "strike" against the other, and the sound will start to pass with large nonlinear changes, such as harmonic generation, etc. In the case when the gas pressure in the layer cannot be neglected, layer oscillations that are commensurate with its thickness also lead to a sharp improvement of the transfer of pressure oscillations. It is interesting to note that since a small layer thickness d is sufficient, these nonlinear phenomena begin at not very high values of the power. For example, at $d/\lambda \sim 10^{-3}$, the necessary flux density is

$$I \approx \rho c_s^3 (d/\lambda)^2 \approx 300\ \mathrm{W/cm^2}.$$

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[2] G. A. Askar'yan and T. G. Rakhmanina, Zh. Eksp. Teor. Fiz. 61, 1199 (1971) [Sov. Phys.-JETP 34, 639 (1972)].
[3] G. A. Askar'yan, É. Ya. Gol'ts, and T. G. Rakhmanina, ibid. 62, 1072 (1972) [35, 566 (1972)].

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