The Konstantinov effect and sound absorption in inhomogeneous media

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Theoretical and experimental aspects of sound absorption at the boundary between two media with different acoustic properties (the Konstantinov effect) are reviewed. Possible applications of the Konstantinov effect in architectural and technical acoustics are discussed.

CONTENTS

1. INTRODUCTION

Sound propagation in a confined medium was first treated by Kirchhoff,[1] studying the propagation problem of plane acoustic waves in air-filled cylindrical tubes with rigid walls. Kirchhoff was also the first to turn attention to the fact that the thermal conductivity of the medium is as important as its viscosity in sound absorption.

The Kirchhoff method was further developed in the 1939 publication of B. P. Konstantinov,[2] in which he considered the problem of the interaction of a plane harmonic wave with the separation boundary between a gas and a heat-conducting rigid body. The solution of the problem for a plane wave substantially enhanced the possibilities of the Kirchhoff method, if only for the reason that the results of Ref. 2 can be used to analyze the interaction of waves with an arbitrary wave front with a gas-rigid body separation boundary.

Konstantinov first defined in Ref. 2 a range of problems, for which the solution of the problem of sound absorption during wave propagation near rigid boundaries is of substantial interest. Among the important problems of this type he pointed out: ultrasound absorption by walls and reflecting gases of acoustic interferometers, absorption by the surface of a rigid body while it emits ultrasound into the gas, sound absorption during wave propagation in tubes, sound absorption in a gas containing suspended rigid particles, sound absorption by simple and filamentary materials, and sound absorption in small rooms. Clearly, similar effects will occur whenever there is contact between media with different physical properties.

Following Ref. 2, another paper appeared,[3] devoted to sound absorption in reverberating rooms. In that paper, based on applying the concept of a diffuse acoustic field to architectural acoustics, Konstantinov obtained for closed volumes an expression for the averaged over the angles of incidence (diffuse) sound absorption coefficient. The results obtained for this case are in quite good agreement with results of measurements at high acoustic frequencies (10–20 kHz) in air-filled rooms.

The development of the applied aspects of sound propagation in confined media was also reflected in the doctoral dissertation of B. P. Konstantinov, defended by him in 1943 and published as a monograph[4] in 1974. In this study, along with the problems considered earlier,[2,3] the sound absorption problem was solved for wave propagation with an arbitrary characteristic amplitude distribution over the cross section in cylindrical tubes with rigid walls. The basic result of Ref. 4 consists of equations for the attenuation and phase shift of any normal wave, which under certain conditions reduce to the Kirchhoff equation for a plane wave (zero-order mode).

Konstantinov showed that constructing the theory of sound propagation and absorption in confined media is still far from complete. In the conclusion to Ref. 2 he mentioned his desire to solve and publish the problem of sound absorption in boundary layers at the separation boundary of media, characterized by an arbitrary set of physical parameters. The solution of this problem would allow an extension of the Konstantinov theory to any shape of real separation boundary encountered in acoustics.

However, as rarely happens in the history of physics, this work, promising fruitful theoretical and practical possibilities, was not further developed following this careful preparation. B. P. Konstantinov never returned to problems of sound propagation in confined media. Soon after defending his doctoral dissertation Konstantinov moved on to solving one of the most important problems of the day, the problem of creating industrial methods of isotope separation.[5]

After Refs. 2–4 were published, the theory of sound

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propagation in confined media underwent further development.

A review and references on sound propagation in confined media, without taking absorption at the boundary surfaces into account can be found in the monographs of L. M. Brekhovskikh[6] and E. Shudrzyk.[7]

Sound absorption at the boundary of two media (the Konstantinov effect) was investigated in Refs. 8–17.

At the present time it has become clear that in many experimental situations sound absorption in inhomogeneous media is predominantly due to the Konstantinov effect. The occurrence of media manifesting a thermo-optic effect (i.e., capable of changing their optical characteristics when acted upon by heat) made it possible to initiate quantitative measurements of the contribution of the Konstantinov effect to the total sound absorption, and, besides, to construct a number of devices based on the effect of sound absorption in the boundary layer.

The main purpose of the present paper is to review experiments on the Konstantinov effect, to discuss the possibility of using this effect for intensification of sound absorption in technical acoustics, and to demonstrate the principles of constructing various devices on the example of visualization of ultrasound fields in gases.

The Konstantinov effect can be explained qualitatively as follows.[18]

Consider inclined incidence of a sound wave on a liquid-rigid body boundary, and assume that the thermal conductivity of the rigid body is large.

In a sound wave propagating in the liquid, the temperature, as well as density and pressure, undergoes periodic oscillations around its mean value. Therefore, near the boundary between the liquid and the rigid body there occurs a periodically varying difference in the temperatures between the liquid and the boundary, even if the mean temperature of the liquid equals the rigid body temperature. At the very surface the temperatures of the contiguous liquid and the wall must be identical. As a result there appears a large temperature gradient in the thin boundary layer of the liquid; the temperature varies rapidly from its value in the sound wave to the wall temperature. The presence of large temperature gradients leads to substantial energy dissipation by means of thermal conductivity. For a similar reason the liquid viscosity leads also to strong sound absorption for inclined wave incidence. For such incidence the liquid velocity in the wave (directed along the wave propagation direction) has a nonvanishing component tangent to the surface. At the surface itself the liquid must totally "adhere" to the wall. Therefore a large gradient of the tangential velocity component is generated in the boundary layer of the liquid, which also leads to a large viscous energy dissipation.

The situation described above of sound absorption at the boundary of two media is valid at quite high temperatures, when, on the one hand, the Kapitza temperature discontinuity at the boundary of two media can be neglected, while on the other—the relaxation lengths in the liquid and in the solid body are small, so that quasiequilibrium states are quickly established, and to describe sound propagation one can use the equations of hydrodynamics.

At low temperatures, first of all, most of the thermal resistance of the separation boundary of two media is related to the so-called Kapitza resistance. In this case the boundary conditions of the equations of hydrodynamics must be different from those used above. The derivation of these boundary conditions and the study of their effect on Konstantinov absorption is still an unsolved theoretical problem.

Secondly, the increase in excitation relaxation times at low temperatures can lead to the consequence that in an actual spatial region equilibrium can generally not be established, and for this reason the equations of hydrodynamics cannot be used in the near-surface region.

In this case sound absorption begins to depend strongly on the specific nature of the nonequilibrium relaxation processes occurring near the boundary. This effect has been investigated[19] on the example of second sound reflection from a superconductor-HeII boundary. In the present paper, however, we restrict ourselves to the case of high temperatures. Using the Kirchhoff-Konstantinov method,[2,4] Savel'ev[14] investigated the influence of the Konstantinov effect on reflection of sound waves from a planar separation boundary of liquid media, characterized by an arbitrary set of physical parameters.

It was shown in Ref. 14, in particular, that the Konstantinov effect in the case of scattering of a plane wave by a sloping sinusoidal boundary can suppress the Wood effect. The Wood effect consists of the fact that if a plane wave is incident on a rigid surface, whose roughness varies according to a sine law (sinusoidal solid surface), inclined at a small angle to the mean surface contour, then under certain conditions the amplitudes of grazing spectra of the scattered field generated in this case are large, and can even substantially exceed the initial wave amplitude.[20] Besides, Savel'ev also showed that the Konstantinov effect can be the reason of formation of gaps in the directivity characteristic of the reflected field in the case of spherical wave reflection from a rigid wall.

However, the results obtained in Ref. 14 are valid only for small grazing angles, and are not valid when the grazing angles which are important in the problem are sufficiently large (for example, in calculating the diffuse absorption coefficient in architectual acoustics, in estimating attenuation coefficients of high-order normal waves propagating in tubes, in calculating sound absorption in filamentary materials, etc.).

Expressions for the reflection and transmission coefficients of a planar sound wave, incident at an arbitrary angle θ on the separation boundary between liquid semiconductors, were obtained by Legusha[16,17] by means of the Kirchhoff-Konstantinov method.

2. CALCULATION OF KONSTANTINOV ABSORPTION

We start from the linearized equations of hydrodynamics for a harmonic sound wave[2,18]

$$\Delta Q_1 - \varepsilon^2 Q_1 = 0, \quad (1)$$

$$\Delta Q_2 - \varepsilon_T^2 Q_2 = 0, \quad (2)$$

$$\Delta\bar{v} - \varepsilon_B^2 \bar{v} = 0, \tag{3}$$

$$\operatorname{div} \bar{v} = 0, \tag{4}$$

where

$$Q_1 = \exp(-\varepsilon x), \quad \varepsilon^2 = h^2 c^{-2} \left\{1 - h\left[\frac{4}{3}\nu + (\gamma - 1)\, a\right] c^{-2}\right\},$$

$$Q_2 = \exp(-\varepsilon_T x), \quad \varepsilon_T^2 = \frac{h}{a}, \quad \varepsilon_B^2 = \frac{h}{\nu}, \quad h = i\omega;$$

ω is the frequency of the sound wave, $a = \varkappa / C_P \rho$ is the thermal diffusivity coefficient of the liquid, $\varkappa$ is the thermal conductivity coefficient, ρ is the liquid density, $\bar{v}$ is the component of the oscillating velocity vector due to viscous waves, c is the speed of sound, $\nu = \eta/\rho$ is the kinematic viscosity, η is the dynamic viscosity, γ is the adiabatic constant, and C_P and C_V are the heat capacities at constant pressure and volume. We use boundary conditions on a planar boundary with a normal directed along the x-axis:

$$u_x = u_{x2}, \quad u_y = u_{y2}, \quad T = T_2, \tag{5}$$

$$\varkappa \frac{\partial T}{\partial x} = \varkappa_2 \frac{\partial T_2}{\partial x}, \tag{6}$$

$$\eta \left(\frac{\partial u_y}{\partial x} + \frac{\partial u_x}{\partial y}\right) = \eta_2 \left(\frac{\partial u_{y2}}{\partial x} + \frac{\partial u_{x2}}{\partial y}\right), \tag{7}$$

$$p - 2\eta \frac{\partial u_x}{\partial y} = p_2 - 2\eta_2 \frac{\partial u_{x2}}{\partial y}, \tag{8}$$

where p and T are, respectively, the acoustic corrections to the medium pressure and temperature, and u_x and u_y are the normal and tangential components of the oscillation velocity.

The wave is incident from the first medium, whose parameters have no subscripts, into the second, whose parameters have the subscript 2. The Konstantinov absorption is most substantial when $\rho c / \rho_2 c_2 \ll 1$. This situation is easily realized, for example, on the separation boundaries of gases with liquids or rigid bodies. Solving Eqs. (1)–(8), we obtain for this case an expression for the Konstantinov absorption coefficient, which is numerically equal to the ratio of the energy absorbed in the boundary layer to the total energy of the incident wave, in the following form

$$D = \begin{cases} \dfrac{4m}{1 + 2m + 2m^2}, & \theta \leqslant \theta_K = \arcsin \dfrac{c}{c_2}, \\[2ex] \dfrac{4m}{(1+m)^2 + (X_B - m)^2}, & \theta \geqslant \theta_K, \end{cases}$$

where

$$m = \cos^{-1}\theta\,(b_{21}\sin^2\theta + b_{11}),$$

$$b_{21} = \sqrt{\frac{\omega\nu}{2c^2}}, \quad b_{11} = (\gamma - 1)\sqrt{\frac{\omega a}{2c^2}},$$

$$X_B = \frac{\rho c}{\rho_2 c_2} \frac{\sqrt{\left(\frac{c_2}{c}\right)^2 \sin^2\theta - 1}}{\cos\theta},$$

and θ is the incidence angle of the wave.

For contact between media characterized by an arbitrary set of physical parameters the Konstantinov absorption coefficient was calculated in Ref. 16. It is also easily obtained from the results of Ref. 17. We note that the medium viscosity does not contribute to the absorption of acoustic energy at the separation boundary if the media densities are identical ($\rho = \rho_2$). The thermal conductivity of the media does not affect sound absorption at the boundary if $C_{P_2}\rho\beta_2 = C_{P_2}\rho_2\beta$, where β is the bulk coefficient of thermal expansion. The second viscosity does not appear in the expression for the Konstantinov absorption coefficient, since according to Eq. (4) div $\bar{v} = 0$.

The absorption coefficient (9) has a maximum at an incidence angle $\theta_m > \theta_k$, where the quantity θ_m can be found from the expression

$$\theta_m = \frac{\pi}{2} - B_m \sqrt{1 - 2Q + 2Q^2}, \tag{10}$$

where

$$Q = m_0 / B_m, \quad m_0 = b_{21} + b_{11}, \quad B_m = \rho c (\sqrt{c_2^2/c^2 - 1}/\rho_2 c_2.$$

At low frequencies ($Q \ll 1$) Eq. (10) acquires the form $\theta_m = (\pi/2) - B_m$, i.e., the magnitude of the incidence angle θ_m depends only on acoustic parameter ratios of the adjacent media. At high frequencies ($Q \gg 1$) we obtain the expression $\theta_m = (\pi/2) - \sqrt{2} m_0$, which coincides with a similar equation obtained by Konstantinov.[2,4]

Substituting the value of the incidence angle (10) into Eq. (9), one easily finds an expression for the maximum Konstantinov absorption coefficient:

$$D_m = \frac{2Q}{\sqrt{1 - 2Q + 2Q^2} + Q}. \tag{11}$$

At low frequencies Eq. (11) transforms to the expression $D_m \simeq 2Q$. At $Q = 1$ the incident wave is totally absorbed ($D_m = 1$). From the condition $Q = 1$ one easily finds the value of the critical frequency f_{cr}, at which $D_m = 1$.

At high frequencies ($f \gg f_{cr}$, $X_B \ll m$) expression (9) coincides with the equation for the absorption coefficient, obtained by Konstantinov for a separation boundary gas—totally thermally conducting rigid body[2,4] and having a maximum $D_{mK} = 0.8284$ at $m = \sqrt{2}$. It is also seen from Eq. (11) that for $f \to \infty$ the value of the absorption coefficient is $D_{mK} = 0.8284$, i.e., at high frequencies all separation boundaries behave similarly to the gas—totally thermally conducting rigid body boundary.

A basic feature of the expressions derived above is that they do not contain thermal and viscous characteristics of the second media. The values of all calculated parameters depend only on ratios of the acoustic constants of the media forming the boundary, and on the viscosity and thermal conductivity of the first medium.[1)]

Consider several examples of calculations by means of expressions (9)–(11). Figure 1 shows the dependence of the total absorption coefficient on the incidence angle at an air-water separation boundary. It is easily seen that for low frequencies the total sound absorption (the solid curve) is determined for $\theta \leqslant \theta_k$ only by the ratio $\rho c / \rho_2 c_2$ of the adjacent

[1)]All the results discussed above were obtained without taking into account Rayleigh surface waves at the interface of two media with different acoustic impedances. In a narrow angular interval near the critical angle, at which transformation of a bulk into a surface wave is possible, surface absorption of a bulk wave is primarily determined by this transformation. The total sound absorption effect related to this mechanism is, however, small in comparison with Konstantinov absorption. The effect mentioned above of transformation by the thermal Kapitza discontinuity at the boundary between two media was investigated by Andreev.[21]

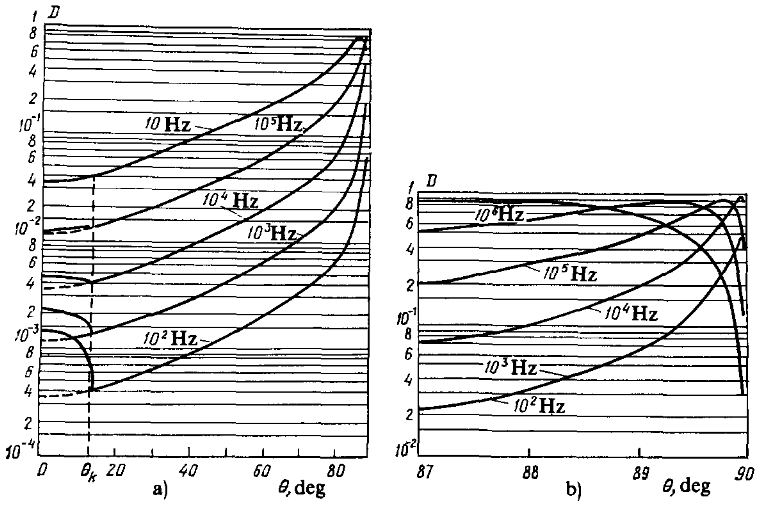

FIG. 1. The absorption coefficient D as a function of incidence angle for air-water separation boundary at a temperature of 20°C and static pressure in both media of 1 atm. The solid lines are the total absorption, and the dashed lines show absorption due to the Konstantinov effect for $\theta \leqslant \theta_K$.

media, and the Konstantinov absorption contribution (9) is small. With increasing frequency ($\theta \leqslant \theta_k$) the magnitude of the second absorption in the boundary layer increases, and at frequencies above 1 kHz total absorption is due entirely to the Konstantinov effect.

For $\theta > \theta_k$ the value of the Konstantinov absorption coefficient (9) is significantly larger than zero. This result differs substantially from the condition usually adopted in acoustics[6,7,32] $D = 0$ for $\theta \geqslant \theta_k$.

Figure 2 shows the dependences $D(\theta)$ for the separation boundaries between air, argon, and neon and hard rubber. It is seen that under otherwise equal conditions sound absorption in the boundary layer is stronger in inert gases.

It is easily observed from Figs. 1 and 2 that the incidence angles (10), at which a maximum of the Konstantinov absorption (11) is observed, are very close to 90°, while the quantities θ_m and D_m are frequency dependent. The functional forms of $D_m(\omega)$ and $\theta_m(\omega)$ are shown in Figs. 3 and 4.

If the effect of total internal wave reflection ($c > c_2$) is

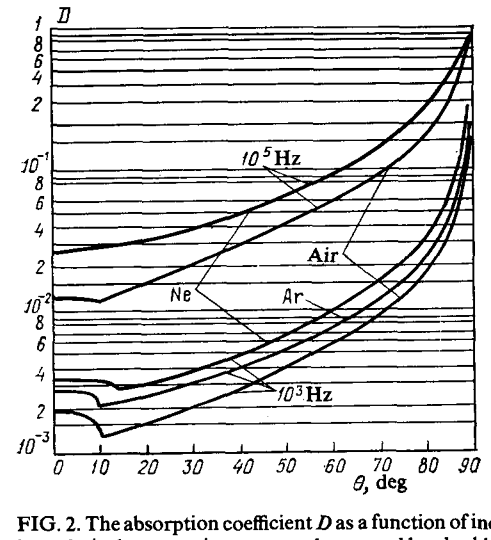

FIG. 2. The absorption coefficient D as a function of incidence angle at the boundaries between air, argon, and neon and hard rubber at a temperature of 20°C and static pressure in the media of 1 atm.

not observed at the separation boundary of media, then taking into account the real physical properties of the contiguous media leads to the consequence that for any values of frequency and incidence angle the quantity D_m cannot exceed the value $D_{mK} = 0.8284$. In the case of total internal reflection ($c < c_2$) three frequency ranges can be distinguished: for $f \ll f_{cr}$ we have $D_m < D_{mK}$; near the critical frequency f_{cr} we have $D_m > D_{mK}$; at high frequencies $f \gg f_{cr}$ we have the value $D_m \to D_{mK} = 0.8284$ for $f \to \infty$.

The behavior of the curve $\theta_m(\omega)$ also depends on the ratio of speeds of sound in the contiguous media, but independently of their physical properties at high frequencies it varies according to the law $\theta_m = (\pi/2) - \sqrt{2}m_0$, the characteristic of the separation boundary between a gas and a totally thermally conducting rigid body[2,4] (see Fig. 4).

The value of the sound energy absorption in the boundary layer of a gas-liquid boundary, the incidence angle θ_m, and the maximum of the Konstantinov absorption coefficient D_m (see Eqs. (9)–(11)) depend primarily on the parameters b_{11} and b_{21}, which on taking into account the relation $c^2 = \gamma p_0/\rho$, where p_0 is the static pressure in the medium, can be represented in the following form:

$$b_{11} = K_1 \sqrt{\frac{f}{p_0}}, \quad b_{21} = K_2 \sqrt{\frac{f}{p_0}}; \qquad (12)$$

where

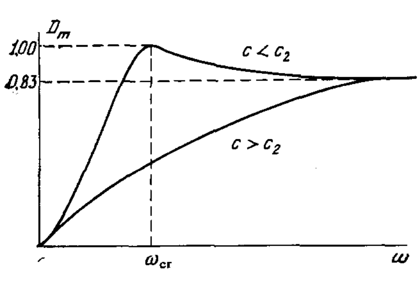

FIG. 3. Qualitative shape of the function $D_m(\omega)$.

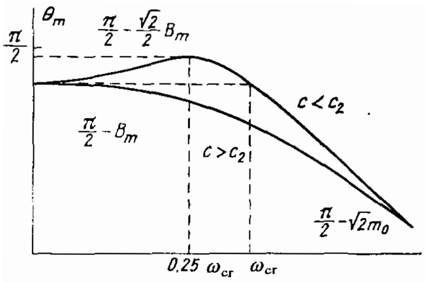

FIG. 4. Qualitative shape of the function $\theta_m(\omega)$.

$$K_1=(\gamma-1)\sqrt{\frac{\pi\varkappa}{\gamma C_P}},\quad K_2=\sqrt{\frac{\pi\eta}{\gamma}}.$$

From expressions (12) one can easily infer the dependence of the parameters b_{11} and b_{21} on the frequency and on the static pressure of the gas. The coefficients K_1 and K_2, appearing in Eq. (12), can be estimated from the data of Table I.

3. MANIFESTATIONS OF THE KONSTANTINOV EFFECT IN ACOUSTICS

a) The relative importance of taking into account the Konstantinov effect in studying sound absorption depends, among other things, on the experimental conditions. For example, in problems of architectural acoustics one is primarily interested in the total power of sound absorption in a given volume. If bulk absorption can be neglected, the total power of sound absorption is determined entirely by the Konstantinov effect.

b) Another example is sound propagation in a tube. According to Kirchhoff[1] and Konstantinov[2,4] the attenuation coefficient for a wave with a planar front (zero order mode), propagating along a tube, is determined by an expression, which in our notation is

$$\alpha=(b_{11}+b_{21})R^{-1},\tag{13}$$

where R is the radius of the tube in meters.

As shown by acoustic measurements,[22] at low frequencies and in smooth metallic tubes expression (13) provides an attenuation coefficient lower by approximately 15% than the measured values, while at high frequencies the results of calculations and measurements are in quite good agreement.

It is well known that expression (13) for the attenuation coefficient was found for a tube with rigid, totally thermally conducting walls. At the same time it was shown above that at high frequencies the separation boundaries between any media behave similarly to a rigid, totally thermally conducting wall. Based on this, it can be assumed that Eq. (13) is a high-frequency approximation for the attenuation coefficient of a tube with walls made of actual materials. The frequency dependence of the maximum of the sound absorption coefficient (11) (see Fig. 3, $c<c_2$) can be used to normalize the sound absorption in an actual tube at low frequencies and, consequently, to obtain the real frequency-dependence of the attentuation coefficient of a plane wave, propagating along a smooth tube. Naturally, in this case the dependence $D_m(\omega)$ must be constructed for a pair of media, one of which has the physical properties of the gas filling the tube, and the other—the material of its wall.

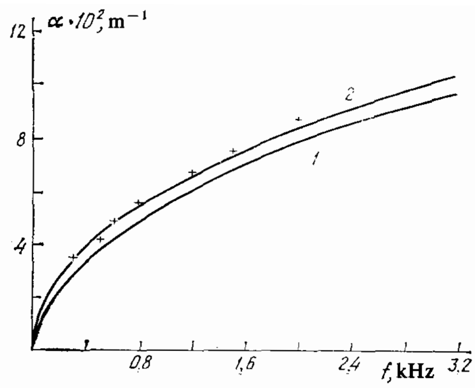

FIG. 5. Results of calculating the attenuation coefficient of a plane wave, propagating along a cylindrical tube of diameter 31.8 mm at a temperature of 17°C and a pressure of 1 atm. 1) calculated by the Kirchhoff equation (13); 2) calculated by using Eq. (11).

Figure 5, for example, shows the frequency dependence of the wave attentuation coefficient in a smooth cylindrical steel tube filled by air. In calculating curve 1 we used the Kirchhoff equation (13). To normalize the sound absorption at the tube walls we used the frequency dependence of the maximum of sound absorption (11), calculated for the air-steel separation boundary ($f_{cr}=32$ Hz), and curve 2 was thus obtained. Comparing both curves, it is seen that curve 2 is in better agreement with measurement results.[23]

c) We turn now to manifestations of the Konstantinov effect in the case of sound absorption in emulsions and in suspensions of rigid particles in liquids. In this case one is usually interested in the attenuation of a plane sound wave, for which several mechanisms contribute at the boundary: sound attenuation in liquids, Rayleigh scattering of sound waves by particles in the liquid and by drops of emulsions, and the thermal and viscous Konstantinov effect near liquid particles and drops of emulsions. If the suspension or emulsion concentration is sufficiently high, sound absorption in the liquid itself can be neglected.

Figures 6, 7 show results of experiments and theoretical

TABLE I. Values of the coefficients K_1 and K_2 and of their temperature gradients for several gases at a temperature of 20°C.

Gas	$10^3\ K_1$	$10^3\ K_2$	$10^6\ \Delta K_1/\Delta T$, K^{-1}	$10^6\ \Delta K_2/\Delta T$, K^{-1}
Air	2.99	6.37	2.5	3.0
Carbon dioxide	1.92	5.96	1.5	9.5
Argon	5.24	6.48	4.5	4.5
Neon	6.67	7.65	6.0	8.0

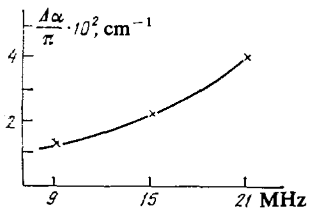

FIG. 6. Frequency dependence of the excess attenuation per unit concentration at a temperature of 20°C for an emulsion of transformer oil in water.

calculations on excess attenuation of sound waves in emulsions.[10] The theoretical calculation was performed taking into account Rayleigh sound scattering by drops in emulsions, as well as thermal and viscous Konstantinov effects. It is seen that the agreement between experiment and theory is quite good. It is interesting to note that according to the authors of Ref. 10 the excess sound absorption under the conditions of their experiment was predominantly determined by the Konstantinov effect at frequencies less than 15 MHz.

d) We note, finally, that taking the Konstantinov absorption into account in making calculations for layered systems does not lead to any changes in the calculation method,[6] since this type of absorption can be automatically accounted for by an appropriate expression for the acoustic impedance of half-space.[15]

4. APPLICATIONS OF THE KONSTANTINOV EFFECT IN TECHNOLOGY

a) Intensification of sound absorption

Sound-absorbing structures, containing perforated panels, are widely used in technical acoustics.[24,25] To enhance sound absorption in these structures one introduces between the perforated panel and the wall a layer (or layers) of filamentary absorbers, whose high sound absorption capability is predominantly determined by absorption in the boundary layers at the air-mineral fiber separation boundary. To prevent the filamentary absorber from falling out of the sound-absorbing structure one uses thin polymer films.[25] Sound passes through these films without noticeable attenuation (acoustically transparent films), but they remain impermeable to gases.

All this makes it possible to suggest a method of sound absorption intensification in sound-absorbing structures. The proposed method consists in that air in the absorbing structure must be replaced by a gas providing high Konstantinov absorption. As such gases one can use, for example, inert gases: argon, neon (see Fig. 2). For near-atmospheric pressure there is no substantial difficulty in containing the gas within the sound-absorbing structure by means of thin films. If further measures are adopted, some enhancement of sound absorption can be achieved by decreasing the static pressure inside the sound-absorbing structures, since according to expressions (9) and (12) a reduced pressure leads to enhanced Konstantinov absorption.

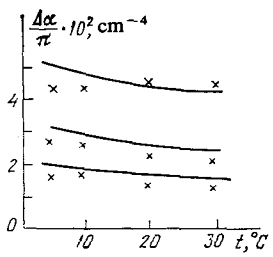

FIG. 7. Temperature dependence of the ultrasound attenuation coefficient in emulsions at frequencies of 9, 15, and 21 MHz.

b) Visualization of ultrasound in gases

The possibility of using media with a thermo-optic effect for visualization of high-frequency (above 900 kHz) acoustic fields in gases was first demonstrated in Ref. 26. Somewhat later it was shown that such media could also be used for visualization of low-frequency (around 50 kHz) ultrasound fields in air.[27] Films of cholesteric liquid crystals were used in both cases as media displaying a thermo-optic effect. One would suppose that this is not the only medium suitable for this purpose.

Visualization of ultrasound fields in gases (air) is performed by the scheme shown in Fig. 8. The main element of the scheme of Fig. 8 is an ultrasound detector, consisting of a light transparent rigid plate 1 (glass) and a layer 2, displaying the thermo-optic effect, deposited on it by some neutral liquid. The ultrasound source 3 creates an acoustic field in the gas interval between the screen 4 and the lower surface of layer 2. Several structural properties and characteristics of ultrasound visualization devices of this type can be found in Refs. 27–31.

According to Fig. 8 the given case is typical in the theory of sound propagation in confined media. An acoustic field is excited in a thin gas layer between two rigid walls. A calculation of the long-range acoustic field without taking into account losses in the gas and at the infinite rigid walls, in one of which is embedded an emitting piston ($l = b$), was performed, for example, by Shenderov.[32] The results of Ref. 32 were generalized to the case of ultrasound visualization in gases of Legusha.[33] A calculation of the acoustic field parameters directly over the emitting surface of the ultrasound source was carried out in Ref. 34, where it was also shown that the temperature discontinuities generated in a medium

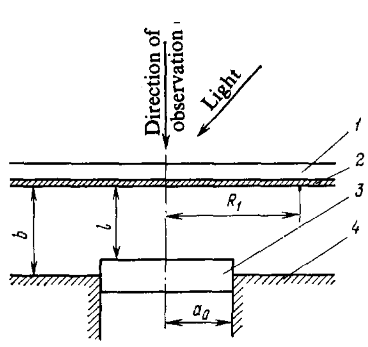

FIG. 8. Scheme of ultrasound field visualization in gases. 1) light-transparent plate; 2) medium with a thermo-optic effect; 3) ultrasound emitter; 4) screen.

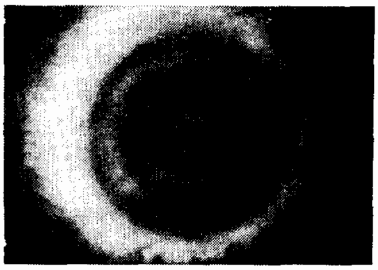

FIG. 9. Result of acoustic field visualization of a piezoceramic element in air at a frequency of 49.4 kHz ($l = \lambda/4 = 1.74$ mm).

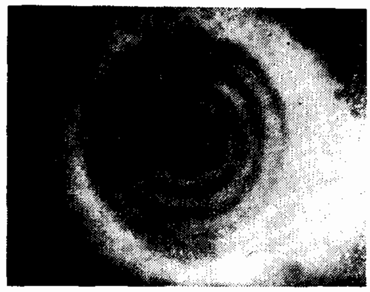

FIG. 10. Field of a piezoceramic element in carbon dioxide at a frequency of 49.4 kHz ($l = \lambda/4 = 1.34$ mm).

with thermo-optic properties due to Konstantinov absorption are proportional to $|\Phi|^2$, where $|\Phi|$ is the absolute value of the velocity potential at the gas-thermally sensitive layer separation boundary.

We dwell in some more detail on the thermo-optic effect of cholesteric liquid crystals. Within a narrow spectral band, corresponding to the visible part of the spectrum, one observes selective reflection of light incident on a layer of liquid crystals, with the wave length of the reflected light being dependent only on temperature and on the observation angle. In observations at a constant viewing angle, but with varying temperature, the color of the cholesteric crystal varies from red to violet, traversing the entire light spectrum. The temperature T_l, at which the crystal becomes red, is called the lower threshold of existence of the cholesteric mesophase, and the temperature T_u is called the upper threshold of the mesophase. The temperature difference $\Delta T = T_u - T_l$ is called th dynamic range of the cholesteric mesophase, within whose limits small temperature changes in the cholesteric liquid crystal lead to quite substantial changes in the wave length of the scattered light (up to 1000 Å per degree), which are easily observed visually.[35,36]

The films presently produced based on cholesteric liquid crystals have sufficient mechanical strength and elasticity, a large area (more than 10^4 cm^2) and a small thickness (50-150μ), can be reused many times and have long shelf life (in excess of half a year). These and other properties make it possible to manufacture without particular difficulties ultrasound detectors of arbitrary cofiguration, and not only planar detectors can be prepared easily, but also detectors reproducing the shape of practically any curvilinear surface.

We provide several technical characteristics of ultrasound detectors, using the thermo-optic effect of cholesteric liquid crystals. The operating frequency region extends from 30 kHz to 2.5 MHz. The resolving power is better than 10 lines/mm. The range of variation of the lower mesophase threshold T_l varies from 5 to 80°C. The limits of variation of the existence region of the mesophase are from 0.1°C to 20°C. The detector sensitivity at the frequency of 50 kHz is of the order of 10^{-4} K·m^2/W, and the formation time of the image is 1–2 sec. According to expression (9) the Konstantinov absorption at the gas-liquid crystal film boundary increases with frequency and this leads to a corresponding sensitivity enhancement and to a decrease in the response time of the detector. The time of image stability is determined by the operating time of the thermally stabilizing device, which is usually also used to provide preliminary heating of the film up to a temperature somewhat exceeding or equal to the lower threshold temperature of the mesophase. The light-transparent plate 1 (see Fig. 8) is, as a rule, an element of the thermally stabilizing device.[28,30,31]

Consider examples of ultrasound field visualization. Figure 9 shows the field created by a piezoceramic element of diameter 25 mm and thickness 4 mm. The upper surface of the piezoelement was placed level with a plastic screen surface, while the gap between the lateral surface of the piezoceramic element and the screen did not exceed 0.05 λ, where λ is the wave length of ultrasound in air. The excitation frequency is 49.4 kHz. The dark regions correspond to higher temperature regions. In a color image the field pattern (Fig. 9) has the following appearance. Against the red background are clearly seen images of maxima of a different color. The central maximum is blue, and in moving away from the center to the periphery the rings are respectively, green, yellow, and orange.

If in the preceding case the air in the spacing between

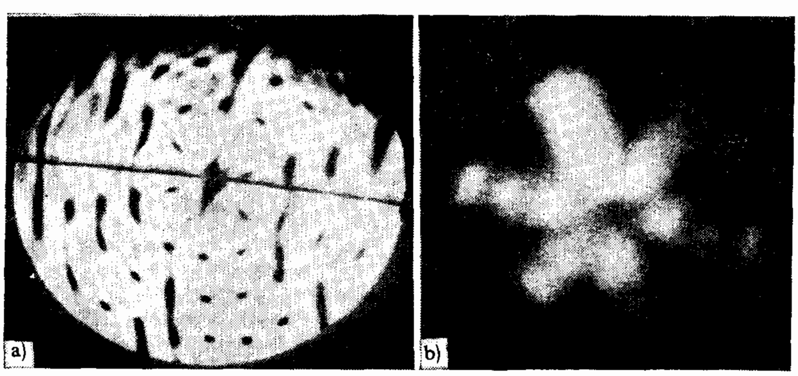

FIG. 11. Visualization of the shape of oscillating of a quartz plate in air at a frequency of 778686 Hz. a) the method of two-beam interferometry; b) a detector with a film of cholesteric liquid crystals.

FIG. 12. The acoustic field excited in a closed cylindrical volume confined by rigid walls. The frequency is 50 kHz, $a_0 = 12.5$ mm, $l = 8$ mm, $b = 12$ mm, $R_1 = 20$ mm.

the screen and the film is replaced by carbon dioxide, the field pattern changes (Fig. 10). Four ring-shaped temperature minima are observed in carbon dioxide (Fig. 10), instead of three in air. The latter circumstance is related to the fact that the ultrasound wave length in carbon dioxide is 1.3 times smaller than in air. This experiment shows that a detector, whose active element is a liquid crystal film, can be used in a system measuring the speed of sound in gases.

A quartz plate in the form of a Z-cut of thickness 2 mm and diameter 18 mm was used in high-frequency experiments. The resonance frequency of the plate was 778686 Hz. The surface oscillation distribution of the plate was obtained by a method of two-beam interferometry (Fig. 11a). In this distribution zones with a maximum oscillation amplitude (of the order of 0.25 μ) were located near the center. The results of visualization of the field of the quartz plate by means of a detector with a liquid crystal film of $l = 3$ mm are shown in Fig. 11b. Comparing both patterns (Fig. 11), it is easily noted that both distributions have a similar structure. For this reason, at high frequencies one may speak not of near field visualization, but of visualization of the shape of oscillations of the plate surface.

Ultrasound field visualization in gases can also be applied to visualization of oscillation eigenmodes of closed gas volumes of arbitrary shape.[37] Thus, for example, Fig. 12 shows the result of acoustic field excitation in a cylindrical volume, filled by air, at a frequency of 50 kHz. According to the notation of Fig. 8, the principal dimensions of the closed volume are: $R_1 = 20$ mm, $l = 8$ mm, $b = 12$ mm, $a_0 = 12.5$ mm.

The list of practical problems, for which one can use ultrasound detectors, utilizing the Konstantinov effect to obtain two-dimensional images of acoustic fields, can be expanded substantially. First, it is necessary to note the development of the method of nondestructive control of piezoceramic elements.[31,38] The basis of this method is the correlated mapping of the acoustic fields, produced by piezoelements in air. Ultrasound visualization in air can also be used for nondestructive control of layered materials, for which the ultrasound field, generated by induced oscillations of the layer region,[39] is recorded by the detector. Ultrasound detectors, whose active part consists of a medium with a thermo-optic effect, have also been used in gas analyzers.[40]

In conclusion we note that further refinement of devices based on the Konstantinov effect, and the possible creation of new instruments involves development of media displaying the thermo-optic effect. As promising media one can mention phase-transformation interference reversible light reflectors based on vanadium oxides[41] and spatial light modulators based on deformation of the liquid layer under the action of surface tension forces, generated by heating of a liquid subject of radiation.[42]

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