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Acoustic boundary layer of a solid absolutely thermally conductive surface

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Abstract: **The paper presents the analysis results of formation theoretical descriptions of an acoustic boundary layer near solid absolutely thermally conductive surface, obtained by G. Kirchhoff and L.D. Landau. In both cases, the acoustic boundary layer is formed by inhomogeneous viscous and thermal waves in the wall layer of a liquid medium in contact with the surface of a solid body, from which a plane traveling sound wave is reflected. Based on the analysis, conclusions can be drawn: the analyzed problem solutions are physically sound, independent and complementary to each other. During the formation of an acoustic boundary layer, viscous and thermal waves are excited synchronously in pairs. Inside the acoustic boundary layer, each pair of inhomogeneous waves propagates towards each other. Inhomogeneous waves originate on parallel surfaces that limit the volume of the acoustic boundary layer. The analysis of the process of transformation of heat waves into additional one-dimensional inhomogeneous waves, the appearance of which in the boundary layer was predicted by G. Kirchhoff. It is shown that when interacting with the surface of the body of a traveling sound wave in the sound frequency range, these waves do not affect the formation of the boundary layer. The expressions allowing for a numerical estimation of the heat dissipation power density in the boundary layer are refined. A formula has been obtained that allows us to determine the proportion of the energy of the sound wave that is absorbed in the acoustic boundary layer. In practice, the results obtained in the article can be used, for example, in aeroacoustics to assess the dissipative properties of solid surfaces.**

Keywords: **sound wave, surface of a solid absolutely thermally conductive body, viscous wave, heat wave, acoustic boundary layer, energy dissipation**

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Contents

1. INTRODUCTION

Theory fundamentals of acoustic boundary layer (ABL) were developed by G. Kirchhoff. In 1868, he published an article [1], in which he was the first to consider the problem on a sound wave interaction propagating in a gas with a flat infinite surface of a solid absolutely heat-conducting body. It was shown that ABL is formed in a liquid medium layer located near the solid body surface. The ABL basis consists of inhomogeneous viscous and thermal waves, which are excited by the sound wave interaction with the solid body surface.

The ABL theory was further developed in the B.P. Konstantinov work, which presents a method for calculating the acoustic field that is formed in a liquid medium as a reflection result of a traveling sound wave from an infinite flat surface of a solid absolutely heat-conducting body. Article [2] shows that as a result of ABL excitation, the pressure reflection coefficient of a sound wave becomes a complex quantity depending on the sound wave frequency, and a phase difference also appears between the incident and reflected sound waves. At any incidence angle of the sound wave, the wave energy dissipates due to the processes of viscous and thermal waves attenuation in the ABL. B.P. Konstantinov also showed that outside the ABL, the physical processes occurring in it do not affect the interaction between the incident and reflected sound waves from the surface. In addition, the forming ABL does not affect the reflection law of a sound wave from the solid bodysurface.

In the course of the research presented in [1], G. Kirchhoff points out possible application areas of the theory he developed in acoustics. For example, he solved the problem of the propagation and attenuation of a traveling sound wave with a flat front in a cylindrical pipe with solid, absolutely heat-conducting walls. The formula for calculating the frequency dependence of the spatial attenuation coefficient (SAC) of a traveling sound wave, obtained in the course of solving this problem, is still used in aerodynamics. It was also shown that energy dissipation in the ABL near the walls of narrow pipes is quite large and should affect the propagation speed of the front of the sound wave traveling in the pipe.

In December 1867, A. Kundt published work [3,4], in which he first experimentally established the fact of slowing down the propagation speed of the front of a zero-order sound wave. A. Kundt conducted research on narrow glass pipes of different diameters. As a research result, it was shown that the sound speed in the air in the pipe is less than the sound speed in free air space and becomes dependent on frequency. It was found that the sound speed is lower, the smaller the pipe radius and the lower the sound wave frequency.

The experimental data obtained by A. Kundt were used by G. Kirchhoff to test the theory he developed. To do this, he considered the problem of speed slowing down of the front of a plane sound wave traveling in a cylindrical pipe with solid, absolutely heat-conducting walls. As a this research result, G. Kirchhoff obtained an expression for calculating the frequency dependence of the sound speed in cylindrical pipes with solid, absolutely heat-conducting walls.

A results comparison of calculations of the sound speed in the air filling the pipes, performed using the formula of G. Kirchhoff, with the experimental data obtained by A. Kundt, allowed us to establish the following. G. Kirchhoff's formula correctly predicts the trend of changes in the sound speed in a gas with changes in the sound wave frequency and the pipe radius. However, over the entire frequency range, the theoretical values of the sound speed exceeded the measurement results. The reasons for the discrepancy between the results of calculations and measurements in article [1] have not been established.

Finding out the reasons for such a discrepancy between the calculation results and experimental data requires additional research into the formation features of ABL. To do this, it was decided to repeat A. Kundt's experiment using modern acoustic equipment. When preparing for the experiment, the following circumstance was taken into account. In [5-7], it was shown that, according to the conditions for the formation of an ABL and the dissipative properties of the gas-solid interface, the substance of which has finite values of thermophysical parameters, the acoustic characteristics are close to the gas-solid interface of an absolutely thermally conductive body. On this basis, for conducting experimental studies, you can use pipes whose walls are made of any substance existing in nature.

To repeat A. Kundt's experiment, a cylindrical quarter-wave resonator was made, the walls of which were made of polyvinyl chloride. A setup description, experimental conditions and its results are presented in [8]. Analysis of the measurement results allows us to draw the following conclusions. The frequency dependence presence of the propagation speed of the front of a normal zero-order sound wave propagating in the air, filling the cylindrical pipe volume, is experimentally confirmed. G. Kirchhoff's formula for calculating the dispersion curve correctly predicts the dependence of the sound speed on frequency. The difference between the theoretical and experimental values of the sound speed in the pipe is large and increases as the wave frequency decreases.

In the frequency range studied, the experimental values of the sound speed also turned out to be less than the theoretical values. If we assume that the real energy dissipation in the APS of pipe is approximately 2.5 times greater than the dissipative losses predicted by G. Kirchhoff's theory, then the theoretical dispersion curve shifts to the region of experimental values of the sound speed and practically coincides with the experimental dispersion curve.

The obtained result indicates that in the APS of a solid surface, in addition to the dissipative process, the theoretical description of which was made by G. Kirchhoff, there must be an additional dissipative process that compensates for the missing amount of heat released in the APS of a solid absolutely heat-conducting surface. Such a process actually exists. Its description can be found, for example, in volume 6 of the course by L.D. Landau [9], where the problem of the ABL formation in viscous and heat-conducting liquid media in contact with the surface of a solid absolutely heat-conducting body is solved from the hydrodynamics general perspective. It is shown that in the case under consideration, the ABL is also formed due to the excitation of inhomogeneous viscous and thermal waves in the near-wall layer of liquid.

The motion equations of viscous and thermal waves obtained in [9] differ from similar inhomogeneous waves equations used in the G. Kirchhoff theory [1]. First of all, inhomogeneous waves, described in [9], have a amplitudes distribution along the direction of their propagation, which differs from similar distributions of inhomogeneous waves amplitudes, described in the article [1]. In addition, according to L.D. Landau, inhomogeneous waves in his solution are excited in a plane located at a distance of the order of the boundary layer thickness from the solid body surface, and propagate along the normal to the body surface. Inhomogeneous waves, described by G. Kirchhoff, are excited on the solid body surface and propagate along the normal in a liquid medium from the solid body surface.

Oscillatory velocities fields interacting with the surfaces of solid absolutely heat-conducting bodies in the problems of G. Kirchhoff and L.D. Landau are potential physical fields. On this basis, it can be assumed that both tasks independently describe a single process of ABL formation. Consequently, two viscous and two thermal waves simultaneously participate in the process of ABL formation. Taking these circumstances into account, it is necessary to study the influence of this set of inhomogeneous waves on the physical processes occurring in the ABL.

2. INHOMOGENEOUS WAVES FORMING AN ACOUSTIC BOUNDARY LAYER

Let us consider a set of inhomogeneous waves participating in the ABL formation near the surface of a solid absolutely thermally conductive body. Articles [1,2] show that viscous and thermal waves are involved in the formation of ABL, excited on the surface of the physical contact of the media and propagating deep into the liquid medium. At the same time, in the book [9] we find solutions to problems in the form of viscous and thermal waves originating in a liquid medium and moving to the solid body surface. Both inhomogeneous waves pairs exist in a liquid medium independently of each other and contribute to the ABL formation.

To assess the ABL physical properties that arises in the near-wall layer of a liquid medium as a excitation result of the entire inhomogeneous waves set in it, we consider the motion equations of these waves. First, let us consider the interaction case of a plane traveling sound wave with an infinite flat surface of a solid absolutely heat-conducting body, studied by L.D. Landau. According to the problem solution presented in the book [9], as a result of such interaction, an inhomogeneous viscous wave is excited in the near-wall layer of the liquid medium:

$$u_{V11} = u_{0\eta11}\left\{1-\exp\left[\frac{-(1-i)x}{\delta}\right]\right\}, \tag{1}$$

where $\delta = \sqrt{2\nu/\omega}$ is the boundary layer thickness; ν is the coefficient of kinematic liquid viscosity; $u_{0\eta11} = 2u_m \sin\theta$ – viscous wave amplitude; u_m is the amplitude of the sound wave vibrational speed incident on a reflecting surface; θ is the angle of wave incidence.

In equation (1) and below, the harmonic factor exp(iωt) is omitted for brevity. The viscous wave (1) is excited in the plane $x = \Delta$, where Δ is the effective ABL thickness (see **Fig. 1**) and propagates in the negative direction of the 0x axis to the solid body surface. The viscous wave amplitude $u_{0\eta11}$ is equal to the vibrational velocity amplitude in the velocity field excited in the liquid outside the ABL.

In the book [9] we also find a problem solution for the case when a wave propagates in a heat-conducting medium. The result of the intsound wave eraction with the surface of a solid absolutely heat-conducting body is the inhomogeneous thermal wave excitation in the

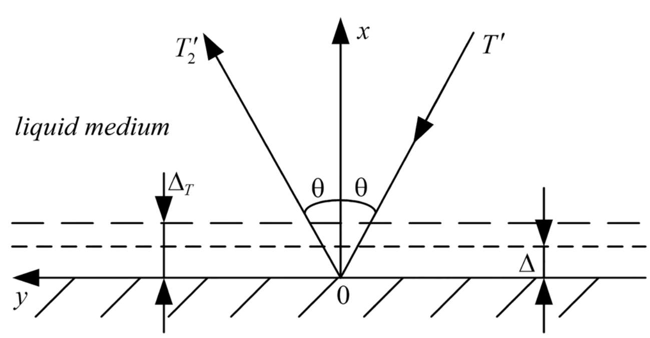

Fig. 1. *An acoustic field formation over a flat surface of a solid absolutely thermally conductive body.*

near-wall layer of the liquid medium, the motion equation of which has the form

$$T'_{h11} = T'_{m11}\left\{1-\exp\left[\frac{-(1-i)x}{\delta_T}\right]\right\}, \quad (2)$$

where $\delta_T = \sqrt{2a/\omega}$ is the thermal boundary layer thickness; α is the liquid medium thermal diffusivity coefficient; $T'_{m11} = 2T'_m$ – thermal wave amplitude; T'_m – acoustic additive amplitude to the medium temperature in a traveling sound wave interacting with a reflecting surface.

Thermal wave (2) is excited in the plane $x = \Delta_T$, where Δ_T is the thermal boundary layer effective thickness (see Fig. 1) and propagates along the 0x axis towards the reflecting surface ($x = 0$).

Note that in order to obtain the expression for the oscillatory velocity tangential component that necessary to derive formula (2), L.D. Landau used the distribution of viscous wave amplitudes (1) along the direction of its propagation.

As a result of problem solving the sound wave interaction propagating in a viscous and heat-conducting medium with the surface of a solid absolutely heat-conducting body, G. Kirchhoff established that inhomogeneous waves are excited on the body surface, the motion equations of which have a form different from the motion equation of waves (1) and (2). According to articles [1,2], the motion equation of a viscous wave in this case has the form

$$u_{V12} = u_{0\eta 12}\exp\left[\frac{-(1+i)x}{\delta}\right], \quad (3)$$

where $u_{0\eta 12} = 2u_m \sin\theta$ is the viscous wave amplitude.

In accordance with G. Kirchhoff's solution, a thermal wave is also excited on the surface of a solid absolutely heat-conducting body. The motion equation of this inhomogeneous wave has the form

$$T'_{h12} = T'_{m12}\exp\left[\frac{-(1+i)x}{\delta_T}\right], \quad (4)$$

where $T'_{m12} = T'_m$ is the thermal wave amplitude.

Viscous (3) and thermal (4) waves originate on the surface of a solid absolutely heat-conducting body in the $x = 0$ plane. The wave fronts move in the positive direction of the 0x axis. The waves completely attenuate, respectively, at distances $x = \Delta$ and $x = \Delta_T$ from the surface $x = 0$ (see Fig. 1).

3. PROPERTIES OF INHOMOGENEOUS VISCOUS AND HEAT WAVES

The ABl physical characteristics are determined by the parameters of inhomogeneous viscous and thermal waves that take part in its formation. To further establish cause-and-effect relationships between the physical processes occurring in the ABL, we will consider the viscous and thermal waves main characteristics. Expressions for calculating the parameters of viscous and thermal waves, which are given below, are mainly taken from the book [9]. Formulas have been added to them that make it possible to calculate the parameters characterizing the decay over time of oscillatory processes in viscous and thermal waves.

Let us dwell on the viscous waves parameters. If we isolate the real parts from expressions (1) and (3), we obtain the equation for the viscous waves propagation in the form:

$$u_{V12} = u_{0\eta} e^{-\frac{x}{\delta}}\cos\left(\omega t - \frac{x}{\delta}\right), \quad (5)$$

where $u_{0\eta}$ is the viscous wave amplitude;

$$u_{V11} = u_{0\eta}\left[1 - e^{-\frac{x}{\delta}}\cos\left(\omega t + \frac{x}{\delta}\right)\right]. \quad (6)$$

Viscous waves (5) and (6) belong to the one-dimensional inhomogeneous transverse waves class. The wave vectors of these waves coincide with the normal direction to the solid body surface, near which they are excited. In viscous waves, liquid medium particles oscillate in a plane perpendicular to the wave vector. The wave vectors of waves (5) and (6) are directed towards each other.

Viscous waves have the following physical parameters set:

– wave phase velocity

$$c_V = \omega\delta = \sqrt{2\omega\nu}, \qquad (7)$$

– wavelength

$$\lambda_V = 2\pi\delta; \qquad (8)$$

– complex wave number

$$\tilde{k}_V = (1+i)/\delta; \qquad (9)$$

– wave number

$$k_V = 1/\delta,\ \mathrm{m}^{-1}; \qquad (10)$$

– spatial attenuation coefficient

$$\alpha_V = 1/\delta,\ \mathrm{m}^{-1}; \qquad (11)$$

– time decay coefficient

$$\beta_V = \alpha_V c_V = \omega,\ c^{-1}; \qquad (12)$$

– wave time constant

$$\tau_V = 1/\beta_V = 0/159T, \qquad (13)$$

where T is the oscillation period of the sound wave.

Now let's consider the inhomogeneous thermal waves physical parameters. If we isolate the real parts from expressions (2) and (4), we can write one-dimensional equations for the thermal waves propagation:

$$T'_{h12} = T'_{m1} e^{-\frac{x}{\delta_T}} \cos\left(\omega t - \frac{x}{\delta_T}\right), \qquad (14)$$

where T'_{m1} is the thermal wave amplitude;

$$T'_{h11} = T'_{m1}\left[1 - e^{-\frac{x}{\delta_T}} \cos\left(\omega t + \frac{x}{\delta_T}\right)\right]. \qquad (15)$$

Thermal waves (14) and (15) belong to the one-dimensional scalar waves class. The wave vectors of these waves coincide with the normal direction to the solid body surface, in the ABL of which they are excited, and are directed towards each other.

The thermal wave properties can be characterized by the following parameters:

– phase speed

$$c_T = \omega\delta_T = \sqrt{2\omega\alpha}; \qquad (16)$$

– wavelength

$$\lambda_T = 2\pi\delta_T; \qquad (17)$$

– complex wave number

$$\tilde{k}_T = (1+i)/\delta_T; \qquad (18)$$

– wave number

$$k_T = 1/\delta_T,\ \mathrm{m}^{-1}; \qquad (19)$$

– spatial attenuation coefficient

$$\alpha_T = 1/\delta_T,\ \mathrm{m}^{-1}; \qquad (20)$$

– time decay coefficient

$$\beta_T = \alpha_T c_T = \omega,\ c^{-1}; \qquad (21)$$

– wave time constant

$$\tau_T = 1/\beta_T = 0.159T, \qquad (22)$$

where T is the oscillation period of the sound wave.

If we compare the writing options for the motion equations of viscous waves (5) and (6) with the writing of similar equations for thermal waves (14) and (15), then it is easy to notice that the forms of writing these expressions completely coincide. This is due to the fact that these motion equations are solutions to one-dimensional differential equations such as the heat equation. This is also due to the fact that the calculating formulas the physical parameters of these waves have similar notation forms.

Here it is necessary to note the viscous and thermal waves amazing property. According to formulas (12) and (21), the viscous and thermal waves attenuation over time in any media does not depend on the physical parameters of the these media substance and is determined only by the sound wave frequency ω, as a her interaction result with reflective solid surface by wich these viscous and thermal waves appeared.

The time constants of all damped oscillatory processes in these inhomogeneous waves are determined by formulas (13) and (22). From these expressions it is clear that the time constants values also do not depend on the physical parameters of the medium substance in which viscous and thermal waves are excited. The time constants τV and τT are small. This allows us to assume that viscous and thermal waves are excited and disappear almost in real time, following changes in the external acoustic field amplitude. On this basis, we can assume that at the moment the field of the acoustic additive to the medium temperature is turned on viscous waves (5) and (6), as well as thermal waves (14) and (15), are excited almost instantly and synchronously.

Viscous and thermal waves exist in a liquid due to the energy taken from the acoustic field. These waves are greatly attenuated as they propagate through matter. For example, if the viscous wave front (5) travels a distance $x = 0.5\lambda_V$, and the thermal wave front (14) travels a distance $x = 0.5\lambda_T$, then the these waves amplitudes will decrease by a factor of $\exp(\pi) = 23.1$ and amount to 4.3% of the original value.

Thus, at distances $x > \pi\delta$ viscous waves (5) and at distances $x > \pi\delta_T$ thermal waves (14) completely attenuate and no longer affect the acoustic field parameters outside the ABL and on the solid body surface. On this basis, the parameter $\Delta = \pi\delta$ for viscous waves and the parameter $\Delta T = \pi\delta_T$ for thermal waves were chosen as the thickness characteristic dimensions of the viscous and thermal boundary layers, respectively.

To maintain continuous oscillatory processes in viscous and thermal waves, the external acoustic field oscillatory energy is continuously selected. This energy is irreversibly converted into heat by inhomogeneous waves, ensuring the process of energy dissipation in the ABL. When an ABL is formed near a solid and absolutely heat-conducting surface, the viscous waves amplitudes (5) and (6), as well as the thermal waves amplitudes (14) and (15), are pairwise equal to each other. On this basis, it can be assumed that the heat release in the ABL of a solid absolutely heat-conducting boundary should be approximately 2 times greater compared to the amount of heat, the value of which is obtained using separately the G. Kirchhoff theory and the L.D. Landau solution.

Note that there are differences in the consequences of viscous and thermal waves excitation in the ABL. If viscous waves simply attenuate inside the ABL, then when thermal waves are excited, in addition to the process of their attenuation, additional physical effects are observed. First of all, we note that due to the thermal waves transformation in the ABL, inhomogeneous longitudinal waves additionally arise. The appearance possibility of such waves in the ABL was predicted by G. Kirchhoff in article [1]. The transformation waves physical properties have not yet been studied. For this reason, below is a study of the conditions for their excitation and the main characteristics of these waves.

In addition, the thermal waves propagation in a substance is always accompanied by the emission of secondary sound waves. In physics, this phenomenon is called the thermoacoustic effect. The thermoacoustic effect has been well studied. A modern theoretical description of the thermoacoustic effect can be found in the book [9]. This effect, for example, is used by electrothermal sound sources - thermophones. Acoustic parameters experimental studies of thermophones, which are presented, for example, in articles [10-13], confirm the thermoacoustic effect existence and show the building possibility broadband piston sound sources on this effect. Research in recent years has made it possible to establish that, under certain conditions, these sources can serve as acoustic signals receivers [14, 15].

4. ACOUSTIC FIELD OF A SOLID ABSOLUTE HEAT CONDUCTION SURFACE

The problem of the acoustic field formation when a plane traveling sound wave is reflected from the infinite surface of a solid absolutely heat-conducting body was solved by B.P. Konstantinov [2]. In the course of problem solving B.P. Konstantinov, in addition to sound pressure p and vibrational velocity $\mathbf{u}$, took into account the acoustic additive presence to the medium temperature T' in the traveling sound wave.

The problem geometry is shown in Fig. 1. The upper half-space is filled with a viscous and heat-conducting liquid medium. A sound wave falls at an arbitrary incidence angle θ onto an infinite smooth surface of a solid absolutely thermally conductive body. The acoustic parameters values of the wave are specified. The reflecting surface coincides with the plane x = 0. In the initial state, the upper and lower half-spaces are motionless relative to the one introduced in Fig. 1 coordinate system. The liquid medium and the solid are in thermodynamic equilibrium at a static temperature T_0. The solid surface is impermeable to liquid.

The propagation of a plane traveling harmonic sound wave in the form of an acoustic additive to the medium temperature is described by the equation

$$T' = T'_{\rm m} \exp\left[i\left(k_{\rm x}x - k_{\rm y}y\right)\right], \tag{23}$$

where $T'_{\rm m}$ is the acoustic additive amplitude to the medium temperature; $k_{\rm x} = k\cos\theta$; $k_{\rm y} = k\sin\theta$ – wave vector **k** projections onto the corresponding axes; $k = \omega / c$ – wave number; c is the sound speed in a liquid medium; $\omega = 2\pi f$ – wave frequency.

According to G. Kirchhoff [1], the amplitude of the acoustic addition to the medium temperature in a traveling sound wave is calculated using the expression

$$T'_{\rm m} = \frac{(\gamma - 1)}{\beta_{\rm V}} \cdot \frac{u_{\rm m}}{c}, \tag{24}$$

where $u_{\rm m}$ is the oscillatory velocity amplitude, γ is the medium nonlinear parameter, $\beta_{\rm V}$ is the coefficient of medium thermal volumetric expansion.

Boundary conditions used by B.P. Konstantinov to solve the problem have the form:

$$u_x = 0; \tag{25}$$

$$u_y = 0,\ by\ x = 0; \tag{26}$$

$$T'_{11} = 0. \tag{27}$$

In equations (25), (26) and (27), the following notations are introduced: $u_{\rm x}$ – oscillatory velocity normal component; $u_{\rm y}$ is the oscillatory velocity tangential component; T'_{11} – an acoustic additive to the temperature of the liquid medium in the acoustic field formed in it.

Based on the solution to the problem presented in the B.P. Konstantinov work [2], let us consider the formation features of the acoustic field that arises above the solid body reflecting surface (plane x = 0, Fig. 1) when a traveling sound wave interacts with it (23). As an example, let us consider the amplitude distribution of the acoustic additive to the medium temperature in this field. In the general case, the acoustic additive field to the liquid medium temperature has the form

$$T'_{11} = T'_{12} + T'_{\rm h12}. \tag{28}$$

The scalar equation components (28) are:

– acoustic field in the volume of liquid medium

$$T'_{12} = T' + T'_2 = \\ = T'_{\rm m}\left\{\exp\left[i\left(k_{\rm x}x - k_{\rm y}y\right)\right] + R_{\rm p}\exp\left[i\left(-k_{\rm x}x - k_{\rm y}y\right)\right]\right\} \tag{29}$$

where $R_{\rm p}$ is the complex reflection coefficient of a sound wave by pressure;

– thermal wave (4), the motion equation of which is written in the form

$$T'_{\rm h12} = T'_{\rm m12} e^{-k_{\rm T}x} \cos\left(-k_{\rm T}x - k_{\rm y}y\right). \tag{30}$$

If expressions (28) and (30) are substituted into the boundary condition (27), then for the surface of a solid absolutely heat-conducting body at x = 0 we obtain the equation

$$T'_{\rm m}\left(1 + \left|R_{\rm p}\right|\right) - T'_{\rm m12} = 0.$$

This equation takes into account the fact that the thermal wave excited on the body surface is included in antiphase with respect to the external acoustic field. Therefore, the thermal wave amplitude the (30) can be calculated using the formula

$$T'_{\rm m12} = T'_{\rm m}\left(1 + \left|R_{\rm p}\right|\right). \tag{31}$$

Using the calculations results available in [2,5], it can be established that for gases in the sound frequency range and incidence angles θ from 0° to 75°, the difference is $1 - |R_p| \leq 0.05$. Therefore, we can assume that $|R_p| = 1$. In this case $T'_{m12} = 2T'_m$, as was accepted in formulas (2) and (4).

In the ultrasonic frequency range, to calculate the thermal waves amplitude (2) and (4), it is necessary to use formula (31), in which to estimate the value of $|R_p|$ as a first approximation, we can use expressions for the complex sound wave reflection coefficients obtained in [2,5].

If in equation (29) we replace the variable temperature amplitude T'_m with the value $u_m \sin\theta$, where u_m is the vibrational velocity amplitude in a sound wave incident on the surface, then we obtain the distribution of the tangential component of the vibrational velocity vector u of the acoustic field

$$u_y = u_m \sin\theta \left\{ \exp\left[i\left(k_x x - k_y y\right)\right] + \right. \\ \left. + R_p \exp\left[i\left(-k_x x - k_y y\right)\right] \right\}. \quad (32)$$

Expression (32) B.P. Konstantinov [2] used to determine the viscous wave amplitude (3) excited on the surface of a solid absolutely thermally conductive body. As a calculation result, the formula was obtained

$$u_{0\eta} = u_m \left(1 + \left|R_p\right|\right). \quad (33)$$

As in the thermal wave case (4), expression (33) should be used to calculate the viscous waves amplitude (1) and (3) at high frequencies.

Note that equation (32) in its written form coincides with a similar distribution u_y, obtained in the case of the classical calculation of the sound wave reflection from a flat infinite solid body surface [16]. The difference between the cases under consideration is that in the classical case the value reflection coefficient R_p does not depend on frequency.

Scalar equation (28) was obtained by G. Kirchhoff to describe the thermal processes occurring inside the ABL during the sound wave interaction with a solid absolutely heat-conducting surface. The thermal wave (30), propagating in the ABL, quickly decays and outside the ABL (at $x \geq \Delta_T$) does not affect the acoustic field parameters (29).

At incidence angles of the sound wave θ > 0, a viscous wave (3) is excited on the reflecting surface, which also completely attenuates in the ABL. Outside the ABL (at $x \geq \Delta_T$), the viscous wave (3) also does not affect the acoustic field parameters (29).

5. ACOUSTIC BOUNDARY LAYER STRUCTURE

Let us consider the ABL structure that arises in the near-wall layer of a liquid medium during the interaction of a traveling sound wave with the solid absolutely thermally conductive body surface. The G. Kirchhoff work [1] shows that the vibrational velocities distribution of the sound field inside the ABL can be described by the following vector equation

$$\mathbf{u} = \mathbf{u}_1 + \mathbf{u}_{V12} + \mathbf{u}_{t12}, \quad (34)$$

where $\mathbf{u}$ is the vector of the total oscillatory velocity in the ABL; $\mathbf{u}_1$ is the acoustic field vector resulting from the interaction of direct and reflected sound waves; $\mathbf{u}_{V12}$ – vector of viscous wave; $\mathbf{u}_{t12}$ is the vector of an inhomogeneous wave appearing due to the transformation of a thermal wave (30).

Equations (28) and (34) form a complete equations system the ABL of a solid absolutely heat-conducting surface. This equations system, together with boundary conditions (25), (26) and (27), was used by B.P. Konstantinov for calculating the complex reflection coefficient from the absolutely thermally conductive surface surface. The calculation results are presented in [2,5]. It should be noted here that when problem solving B.P. Konstantinov excluded from equation (34) the vector of the inhomogeneous wave $\mathbf{u}_{t12}$, which appears in the ABL as a result of the thermal wave transformation (30). The basis for excluding the inhomogeneous wave $\mathbf{u}_{t12}$ was the assumption that its contribution to the dissipative processes occurring in the ABL is small.

Equations (28) and (34) were obtained by G. Kirchhoff [1] without taking into account the excitation in the ABL of additional viscous waves (1) and thermal waves (2), the appearance of which in the ABL follows from the L.D. Landau solution [9]. Consequently, the equations system for the ABL of a solid absolutely heat-conducting surface must be written taking into account these inhomogeneous waves. As a result of taking into account the presence of a thermal wave in the ABL (2), equation (28) takes the form

$$T' = T'_{12} + T'_{h11} + T'_{h12}, \quad (35)$$

where T'_{h11} is the thermal wave (2).

The viscous wave (1) must be introduced into the vector equation (34), which, taking into account the thermal wave transformation T'_{h11}, can finally be written as follows

$$\mathbf{u} = \mathbf{u}_1 + \mathbf{u}_{V11} + \mathbf{u}_{V12} + \mathbf{u}_{t11} + \mathbf{u}_{t12}, \quad (36)$$

where $\mathbf{u}_{V11}$ is the vector of viscous wave (1); $\mathbf{u}_{t11}$ is the vector of an inhomogeneous wave excited in the ABL as a result of the transformation of a thermal wave (2).

If we do not take into account the existence of inhomogeneous transformation waves $\mathbf{u}_{t11}$ and $\mathbf{u}_{t12}$ in the ABL, then schematically the set of main inhomogeneous waves excited in the ABL of a solid absolutely thermally conductive body flat surface can be represented in the form of a structural scheme (**Fig. 2**). The scheme shown in Fig. 2, reflects the fact that viscous and thermal waves in the ABL are generated in pairs and their wave vectors are directed towards each other.

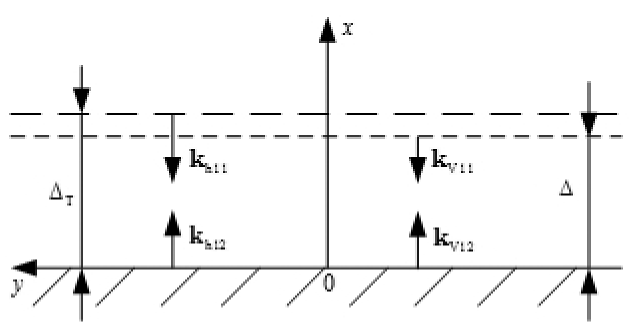

Fig. 2. *ABL structural scheme without taking into account the transformation of thermal waves:* $\mathbf{k}_{h11}$ *and* $\mathbf{k}_{h12}$ *– thermal waves wave vectors;* $\mathbf{k}_{V11}$ *and* $\mathbf{k}_{V12}$ *are viscous waves wave vectors.*

In cases where the influence of inhomogeneous transformation waves $\mathbf{u}_{t11}$ and $\mathbf{u}_{t12}$ cannot be neglected, the wave vectors of these waves should also be included in the ABL structural scheme. However, this type of inhomogeneous waves has not yet been adequately studied.

6. HEAT WAVE TRANSFORMATION INTO AN INHOMOGENEOUS WAVE OF VIBRATIONAL VELOCITY

As was shown by G. Kirchhoff [1], the thermal waves excitation in the ABL should be accompanied by the appearance of additional inhomogeneous waves. Inhomogeneous waves $\mathbf{u}_{t11}$ and $\mathbf{u}_{t12}$ arise in the ABL due to the transformation of thermal waves T'_{h11} and T'_{h12}. Let us consider the physical properties of these waves using the $\mathbf{u}_{t12}$ component as an example. According to G. Kirchhoff [1], the vector $\mathbf{u}_{t12}$ components can be found from the equation

$$\mathbf{u}_{t12} = a(\gamma - 1)\,\mathrm{grad}T'_r, \quad (37)$$

where T'_r is the reduced or dimensionless distribution of the any thermal waves amplitudes. To go to the dimensional temperature amplitude in a thermal wave, it is necessary to use the formula $T'_r = T'_{h12}\beta_V/(\gamma - 1)$. After substituting this expression into formula (37), we have

$$\mathbf{u}_{t12} = a\beta_V\,\mathrm{grad}T'_h, \quad (38)$$

where T'_h is the motion equation of any thermal wave excited in the ABL.

Let's calculate the components of the vector $\mathbf{u}_{t12}$. In order to satisfy the boundary condition (26), B.P. Konstantinov [2] proposed in the motion equations of viscous and thermal waves to take the dependence on the *y* coordinate in these waves in the form of a factor exp(– ik$_y$y), where ky = ksinθ. Then the motion equation of the thermal wave (4) takes the form

$$T'_{h12} = 2T'_m e^{-k_T x} \exp\left[-i\left(k_T x + k_y y\right)\right]. \quad (39)$$

When carrying out calculations we will use the equation real part (39)

$$T'_{h12} = 2T'_m e^{-k_T x} \cos\left(-k_T x - k_y y\right). \quad (40)$$

In accordance with the interaction scheme of a sound wave with a surface (see Fig. 1), the tangent component of vector (38) can be determined from the expression

$$\mathbf{u}_{t12y} = a\beta_V \frac{\partial T'_{h12}}{\partial y} = = a\beta_V k_y 2T'_m e^{-k_T x} \sin\left(-k_T x - k_y y\right). \quad (41)$$

After substituting the tangent component of the wave vector ky into formula (41) and simple transformations, we finally obtain

$$\mathbf{u}_{t12y} = K_t f \sin\theta T'_m e^{-k_T x} \sin\left(-k_T x - k_y y\right). \quad (42)$$

where $K_t = (4\pi\alpha\beta v)/c$.

Let us carry out a numerical assessment of the dimensional coefficient K_t values included in formula (42). Under normal thermodynamic conditions, calculations give the following results. For gases, the K_t coefficient value is of the following order $(10^{-10}\ldots10^{-9})$ m/K, and for liquids of the order of $(10^{-13}\ldots10^{-11})$ m/K. The coefficient K_t values do not depend on frequency; therefore, in the entire practically important frequency range, the tangential component of the oscillatory velocity vector (42) is very small and can be excluded from solving ABL problems. Physically, this means that vector (37) has only a normal component of the vibrational velocity $\mathbf{u}_{t12x}$.

Analysis of the thermal wave transformation process (2) gives results similar to the study results of thermal wave transformation (4), presented above. On this basis, we can immediately write that as a result of the transformation of the thermal wave (9), a one-dimensional inhomogeneous wave $\mathbf{u}_{t11}$ is excited in the ABL, the wave vector of which is directed along the normal direction to the surface of the body. Inhomogeneous waves $\mathbf{u}_{t11}$ and $\mathbf{u}_{t12}$ belong to the class of longitudinal waves. In the future, when compiling the system of ABL equations (35)-(36), we will take into account that their tangent components are $\mathbf{u}_{t11y} = 0$ and $\mathbf{u}_{t12y} = 0$.

To calculate the normal components parameters of the thermal waves transformation vectors $\mathbf{u}_{t11}$ and $\mathbf{u}_{t12}$, we use the motion equation of the thermal wave (15). Taking into account the fact that a one-dimensional thermal wave (15) is excited on the plane $x = \Delta_T$ and moves in the negative direction of the $0x$ axis, the motion equation of the thermal wave (15) takes the form

$$T'_{h11} = 2T'_m \left[1 - e^{(\alpha_T x - \pi)} \cos\left(k_T x - \pi\right)\right]. \quad (43)$$

Next, using equation (38), we obtain formulas that allow us to calculate the parameters of the transformation waves normal components:

$$u_{t12x} = a\beta_V \frac{\partial T'_{h12}}{\partial x} = = u_{t0} e^{-k_T x} \cdot \left[\sin\left(-k_T x\right) - \cos\left(-k_T x\right)\right], \quad (44)$$

$$u_{t11x} = a\beta_V \frac{\partial T'_{h11}}{\partial x} = = u_{t0} e^{(k_T x - \pi)} \cdot \left[\sin\left(k_T x - \pi\right) - \cos\left(k_T x - \pi\right)\right], \quad (45)$$

where $u_{t0} = \sqrt{2\omega a}\,\beta_V T'_m$. It is easy to show that the inhomogeneous waves (44) and (45) amplitudes have the velocity dimension. It is logical to move in these formulas from the amplitude of the acoustic additive to the temperature of the medium T'_m, to the amplitude of the vibrational speed of the traveling sound wave u_m. To do this, we use expression (24). After transforming the motion equations of inhomogeneous waves (44) and (45), we obtain:

$$u_{t12x} = -u_{tm} e^{-\alpha_T x} \cdot \sin\left(k_T x + \frac{\pi}{4}\right), \quad (46)$$

$$u_{t11x} = -u_{tm} e^{(\alpha_T x - \pi)} \cdot \sin\left(k_T x - \frac{5\pi}{4}\right), \quad (47)$$

where $u_{tm} = 2\sqrt{2} b_{11} u_m$ is the amplitude of the transformation wave; $b_{11} = (\gamma - 1)\sqrt{\omega a / 2c^2}$.

Due to the fact that all calculations in this work are carried out within the framework of G. Kirchhoff's theory [1], expressions (46) and (47) remain exact solutions in cases where the inequality $b_{11} << 1$ is satisfied. An frequencies estimate at which this inequality is satisfied is allows us to establish that in the saund frequency range the inhomogeneous waves amplitudes (46) and (47) are small. As a consequence of this, the transformation wave amplitude is $u_{tm} << u_m$. On this basis, when solving problems of ABL formation in aerodynamics and hydroacoustics at low frequencies, inhomogeneous waves (46) and (47) and the physical effects associated with their appearance can be ignored.

It is easy to notice that inhomogeneous waves (46) and (47) are included in antiphase with respect to each other. This circumstance leads to the following ABL features, formed in a liquid medium, in contact with the surface of a solid absolutely thermally conductive body. Inhomogeneous waves excitation (46) and (47) does not lead to changes in the normal component amplitude of the vibrational velocity vector u inside the ABL. The inhomogeneous waves presence (46) and (47) in the ABL also does not lead to a violation of the boundary condition (3).

Inhomogeneous waves (46) and (47) are one-dimensional waves, the wave vectors of which are directed along the normal to the solid body surface. The oscillations direction of liquid medium particles in these waves also coincides with the direction of the normal and, therefore, waves (46) and (47) can be classified as inhomogeneous longitudinal waves. The appearance reason of such waves is periodic thermal expansion of the liquid medium in which an inhomogeneous thermal wave is excited.

Inside the ABL, inhomogeneous waves (46) and (47) interact with each other, forming a standing wave, the oscillations of which occur in antiphase with respect to the sound wave (23) incident on the body surface.

In the ultrasonic frequency range, the inhomogeneous wave amplitude utm and the vibrational velocity amplitude of the sound wave um can be comparable in magnitude. In this case, it is necessary to conduct an additional study of the transformation waves influence (46) and (47) on the ABL physical properties. In this case, the influence of a solid surface impermeable to a liquid medium, limiting the ABL on one side, on the liquid oscillatory flows in the near-surface layer should be additionally studied.

7. ENERGY DISSIPATION IN THE ACOUSTIC BOUNDARY LAYER

Dissipative processes occurring in physical contact zone of a liquid medium with the solid absolutely heat-conducting body surface are ensured by the attenuation of viscous and thermal waves excited in the ABL. As shown above, as a result of the isound wave nteraction (23) with the solid body surface, viscous waves (1) and (3), as well as thermal waves (2) and (4), are excited in its ABL.

To calculate the specific power of heat release in the ABL provided by these inhomogeneous waves, we will use the technique described in the book [9]. According to this technique, the dissipative integral for any viscous waves takes the form

$$q_V = -\frac{\eta}{2}\int_0^{\Delta}\left(\frac{du_V(x)}{dx}\right)^2 dx, \tag{49}$$

where η is the dynamic viscosity coefficient of the liquid medium; $\Delta = \pi\delta$ – ABL effective thickness; $u_V(x)$ is a viscous wave excited in the ABL.

We obtain the specific power of heat release in the ABL, provided by any thermal waves, using the dissipative integral

$$q_T = -\frac{\chi}{T_0}\int_0^{\Delta_T}\left(\frac{dT_h'(x)}{dx}\right)^2 dx, \tag{50}$$

where χ is the thermal conductivity coefficient of the liquid medium; $\Delta_T = \pi\delta_T$ – effective thickness of thermal ABL; $T_h'(x)$ – heat wave existing in the ABL; T_0 is the static temperature of the physical system in which the sound wave is excited.

If we substitute equation (5) into integral (49), we obtain an expression for calculating the specific power of heat generation arising in the ABL due to the viscous wave damping (5). After simple calculations we have

$$q_{\mathrm{V1}} = -\frac{1.5\eta u_{\mathrm{m}}^2 \sin^2\theta}{\delta}. \qquad (51)$$

Similarly, for the viscous wave (6) we obtain

$$q_{\mathrm{V2}} = -\frac{1.5\eta u_{\mathrm{m}}^2 \sin^2\theta}{\delta}. \qquad (52)$$

A comparison of formulas (51) and (52) shows that viscous waves (5) and (6) make the same contribution to the heat fluxes arising in the ABL.

Let us determine the contribution to the thermal balance of the system from each of the thermal waves existing in the ABL. To do this, let's substitute equation (14) into integral (50). After simple calculations, we obtain an expression for calculating the specific power of heat generation appearing in the ABL due to the thermal wave attenuation

$$q_{\mathrm{T1}} = -3.0\frac{\chi}{T}\frac{T_{\mathrm{m}}'^2}{\delta_{\mathrm{T}}}. \qquad (53)$$

For thermal wave (15), similar calculations allow us to obtain

$$q_{\mathrm{T2}} = -3.0\frac{\chi}{T}\frac{T_{\mathrm{m}}'^2}{\delta_{\mathrm{T}}}. \qquad (54)$$

If we compare expressions (53) and (54), we can see that thermal waves also make the same contribution to the thermal balance of the ABL.

The minus sign (51)-(54) indicates that all heat flows are directed in the negative direction of the 0*x* axis (see Fig. 1) towards the surface of the solid. Taking into account the properties of a solid absolutely heat-conducting body, it can be argued that the static value of the liquid medium temperature T_0 always remains a constant value. Based on this, the influence of temperature changes on the liquid medium physical parameters entering the ABL, provided that this problem is solved, can be neglected.

Let us return once again to expressions (51) and (52). Let us substitute the expression for the amplitude ABL into them $\delta = \sqrt{2\nu/\omega}$. After transformation taking into account the averaging of the function over time, these expressions take the form

$$q_{\mathrm{V1}} = q_{\mathrm{V2}} = -D_{\mathrm{V}} J_0, \qquad (55)$$

where $J_0 = \rho c u_{\mathrm{m}}^2/2$ is the reserve of the sound wave interacting with the body surface; $D_{\mathrm{V}} = b_{21}\sin^2\theta.$

If we substitute the expression for the thermal boundary layer thickness $\delta_{\mathrm{T}} = \sqrt{2a/\omega}$ into formulas (53) and (54) and increase the acoustic addition to the medium temperature in the traveling sound wave (24), then after transformation these formulas will take the form

$$q_{\mathrm{T1}} = q_{\mathrm{T2}} = -D_{\mathrm{T}} J_0, \qquad (56)$$

where $D_T = 3.0 b_{11} k_T$; $k_T = (\gamma-1)C_p/\beta_V c^2$.

The total specific power of heat release in the ABL is an integral part of heat flows.

$$q = q_{\mathrm{V1}} + q_{\mathrm{V2}} + q_{\mathrm{T1}} + q_{\mathrm{T2}} \qquad (57)$$

or by specifying the images entered above, we get

$$q = \left(2D_{\mathrm{V}} + 2D_{\mathrm{T}}\right) J_0. \qquad (58)$$

The coefficient characterizing the component of the sound wave energy reflected from the surface of a solid absolutely thermally conductive body can be found as follows. It is known that the average energy flux incident over time per unit wall surface in a sound wave is equal to $J_0\cos\theta$. Consequently, the fraction of energy observed when a sound wave exits the wall surface will be equal to

$$M = \frac{q}{J_0\cos\theta} = \frac{2\left(D_{\mathrm{V}} + D_{\mathrm{T}}\right)}{\cos\theta}. \qquad (59)$$

As we see from expression (59), the sound absorption by the solid body surface depends on the incidence angle of the wave θ. With normal sound wave incidence on the solid body surface (θ = 0), viscous waves are not excited, and the coefficient M has a minimum value

$$M_{\min} = 2D_{\mathrm{T}}. \qquad (60)$$

As the incidence angle θ increases, the contribution of viscous waves to energy dissipation in the ABL increases (see, for example, formula (51)), this leads to a corresponding increase in the coefficient value (59).

An assessment of the energy amount absorbed in the ABL of a solid absolutely heat-conducting surface was previously carried out by B.P. Konstantinov and L.D. Landau (see works [2,9]). A comparison of these calculations shows that in both cases the energy amount absorbed in the ABL is the same. If we use the physical quantities notation adopted in article [2], then to calculate the fraction of wave energy dissipated in the ABL, we can use the formula

$$m = \left(b_{11} + b_{21}\sin^2\theta\right)/\cos\theta. \quad (61)$$

From a comparison of expressions (59) and (61) it follows that the participation of viscous wave (1) in the formation of an ABL leads to a 3-fold increase in energy dissipation in the ABL due to the liquid medium viscosity.

The absorption of sound wave energy in the ABL, due to the liquid medium thermal conductivity, in our calculations exceeds 6.0 k_T times (see formula (58)). This is due to the fact that the value Δ_T was chosen as the upper limit of the dissipative integral (50), as well as the use of the thermal waves amplitude (2) and (4) and formula (24) to estimate the magnitude.

Thus, the dissipative process efficiency in the ABL turns out to depend on the thermophysical parameters of the liquid medium included in the coefficient k_T. For definiteness, we will assume that the acoustic field is excited in the gas. Under normal conditions the values k_T are: air 0.94; argon 0.90; carbon dioxide 0.87. It is easy to notice that the gas coefficients values k_T are close in value to 1. If we substitute the obtained values k_T into formula (56), we obtain that in air the energy dissipation in the ABL for thermal waves (2) and (4) is 2.82 times greater compared to the calculations results carried out in [2,9].

The expressions obtained above can be used for a preliminary assessment of heat release in the ABL of gas-solid interfaces, the substance of which has finite values of thermophysical parameters. However, these formulas cannot be used to calculate heat flows arising in the ABL boundaries of a liquid-solid heat-conducting body. This is due to the fact that during the formation of an ABL boundary between a liquid and a solid heat-conducting body, an additional thermal wave appears in the system. Due to the boundary conditions (see articles [5-7]), this thermal wave is excited at the interface between the media and propagates deep into the solid matter. The physical properties of waves in a solid substance do not differ from the physical properties of thermal waves existing in a liquid. As a consequence of this, an additional heat flux q_{T2} appears on the right side of equation (57). In this case, the heat flows are already $q_{T1} \neq q_{T2}$; $q_{T1} > q_{T2}$. In addition, the thermal wave propagation in a solid is accompanied by the secondary sound waves generation and the excitation of inhomogeneous transformation waves such as waves (46) and (47).

8. CONCLUSION

Solutions to problems that describe the excitation physical processes of inhomogeneous viscous and thermal waves, obtained by G. Kirchhoff [1] and L.D. Landau [9], are independent, complementary solutions. These solutions provide a description of the excitation physical processes and propagation of viscous and thermal waves occurring synchronously in the ABL of a solid absolutely heat-conducting surface. Viscous and thermal waves are excited in the ABL simultaneously in pairs and decay synchronously as they propagate through the substance volume filling the ABL.

When a traveling sound wave interacts with an infinite flat surface of a solid absolutely heat-conducting body, an ABL arises in which both pairs of inhomogeneous waves are excited on parallel surfaces that limit the ABL volume on both sides. Inside the ABL in each pair, viscous and thermal waves propagate towards each other.

In the ABL volume, due to the thermal waves transformation, two additional inhomogeneous longitudinal waves (46) and (47) are excited. These waves are excited in the ABL due to periodic oscillations of the liquid volume located inside the ABL, and are a consequence of the thermal medium expansion in which a variable temperature field is excited. In the sound frequency range, the influence of inhomogeneous waves (46) and (47) on the physical processes occurring in the ABL can be neglected.

In the future, it is advisable to consider the excitation process of inhomogeneous waves of type (46) and (47) in the case of the ABL formation during the interaction of a standing sound wave with the solid body surface. Based on a preliminary analysis of this process, it can be assumed that the excitation result of inhomogeneous waves (46) and (47) is the acoustic flows emergence such as Schlichting vortices inside the ABL.

Inhomogeneous waves excited in the ABL exist due to the energy taken from the main sound wave interacting with the solid surface absolutely thermally conductive body. As a result of combining the decisions of G. Kirchhoff and L.D. Landau, the total number of inhomogeneous waves in the ABL increases, which leads to an increase in the heat release power in the ABL by approximately 2 times. The consequence of heat release in the ABL is a decrease in the amplitude of sound wave reflections. However, energy dissipation in the ABL does not affect the process of acoustic interaction of sound waves incident on the interface and reflected from it.

To calculate the parameters of a sound wave reflected from the surface of a solid absolutely heat-conducting body, you can use the calculation method developed by B.P. Konstantinov [2]. In the case under consideration, the received B.P. Konstantinov's expressions for calculating the reflection coefficient of a sound wave by pressure and its phase angle retain their form. To obtain the result in these formulas, it is enough to replace the calculation complex (61) with parameter (59).

The expressions obtained in this way can be used to estimate the dissipative properties of solid surfaces in aeroacoustics. However, these expressions can be used to estimate the acoustic field parameters that arises under the influence of sound waves propagating in liquids from the surface of a solid heat-conducting body. Approaching the ABL and studying its acoustic properties, it is necessary to separately consider the interface between a liquid and a solid - a substance that has finite values of thermophysical parameters.

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