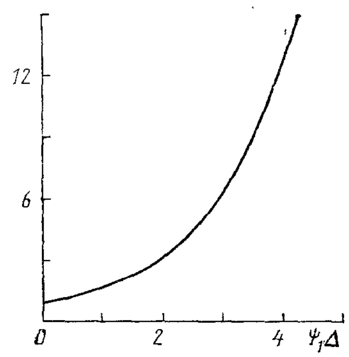

Fig. 4. The efficiency of active thermal shielding versus the parameter $\psi_1\Delta$

ial; λ_{fw} and λ_g, component of the effective thermal conductivity of the porous material determined by its framework and the gas phase, respectively; and, ξ and ψ, roots of the characteristic equations.

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ENERGY DISSIPATION IN A SOUND WAVE IN THE PRESENCE OF EVAPORATION AND CONDENSATION AT A SURFACE

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We consider the transmission and absorption of plane and spherical acoustic waves in the presence of evaporation and condensation at a flat surface. A sound absorbing device is considered as an example.

The reduction of noise is a crucial problem in many fields of technology: ship-building and aircraft construction, architecture, radio, television, and concert studios, and in manufacturing plants. Noise from internal sources is reduced using devices based on absorption of sound waves caused by friction in porous bodies, resonators, surface vibrations, and so forth. Noise from external sources can be reduced by means of sound insulation (soundproofing), where, together with energy absorption, reflection and refraction of waves on the boundary between media with different impedances are also important. The search for new ways of dissipating sound wave energy is important in both sound absorption and in sound insulation.

Hence it is of interest to consider the interaction of sound waves propagating through a saturated vapor with the surface between two phases. Indeed, pressure oscillations in the gas caused by the incident wave excite velocity oscillations at the interface because of the Hertz–Knudsen condition [1-3] and therefore the intensities of the reflected and refracted waves change. As shown in [4-6], the intensity of the reflected wave can be significantly reduced as a result of evaporation and condensation at the surface. This result is obtained

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for a normally incident plane wave on a perfectly rigid surface with attenuation in the gas phase [4], for the case when the elasticity of the condensed phase is taken into account (normally incident plane wave) [5], and finally in the case of oblique incidence of a plane wave on a perfectly rigid surface accompanied by the precipitation of a boundary layer [6].

However, the cause of the attenuation of the reflected wave remains to be determined: is it due to energy dissipation, or, as claimed in [5], to an increase in the transparency of the surface? In addition, for sound insulation problems it is necessary to consider the refracted wave, which was not studied in [4-6]. The case of oblique incidence on a surface has also be studied insufficiently, especially for a gas-solid interface, since in this case both longitudinal and transverse waves can be generated in the condensed phase.

We consider the reflection, transmission, and absorption of plane and spherical sound waves propagating through a saturated vapor and incident upon a plane interface. We discuss the possibility of using energy dissipation resulting from evaporation and condensation processes in sound absorbing and sound insulating devices.

1. The z axis is directed along the outward normal to the surface and the x and y axes are tangent to the surface. We consider the case when the acoustic Mach number is small and the mean free path of a gas molecule is short in comparison with the wave length. Then, neglecting condensation in the bulk, the problem is described in the first approximation by the linear equations of acoustics subject to boundary conditions which take into account the kinetics of evaporation and the elastic properties of the condensed phase: the mass balance conditions and the equality of the normal and tangential stresses. In the first approximation the stress in the gas p_{ij} is zero and the rate of evaporation is determined by the generalized Hertz—Knudsen condition [2], hence, letting ζ be the velocity of the boundary between the phases, we can write:

$$p_{zz}=p'_{zz},\ p'_{xz}=0,\ p'_{yz}=0, \tag{1}$$

$$\rho_0(v_z-\zeta)=\rho'_0(v'_z-\zeta)=j=\beta\,[p_e(T')-p]/\sqrt{\varkappa RT_0},$$
$$\beta=\sqrt{\frac{\varkappa}{2\pi}}\,\frac{\sigma}{1-0{,}411\sigma}. \tag{2}$$

Since the boundary condition involves the saturated vapor pressure $p_e = p^* e^{-Q/RT}$, which depends upon the surface temperature in the condensed phase, we must also solve the heat-conduction equation in the condensed phase with the boundary conditions

$$T'=0\ (z=-\infty),\ -\lambda'\frac{\partial T'}{\partial z}=Qj\ (z=0). \tag{3}$$

In the above equations we have omitted corrections which are quadratic in the small parameters, gradient terms in the Hertz—Knudsen condition, and the heat flux into the gas phase. These assumptions are valid because the omitted terms lead only to small corrections. The treatment of the layers near the surface requires a condition on the temperature jump and the slip condition for the tangential velocities, and is important from the point of view of constructing an accurate physical picture of the processes involved. Such a treatment leads to new effects (new types of acoustic flow [6] and higher wave attenuation than in the bulk), but it contributes only small corrections to the reflection and transmission coefficients. We note that in the first approximation the expressions for the reflection coefficients in [4-6] are the same, in spite of differences in the formulation of the problem.

We limit ourselves to waves which are harmonic in time. Because of the linearity of the problem, one can introduce complex potentials: the scalar $\varphi(\mathbf{x}),\ \varphi'(\mathbf{x})$ and vector $\boldsymbol{\psi}'(\mathbf{x})$ potentials (here and below the common factor $\exp(-i\omega t)$ is omitted) are related to the velocity and acoustic corrections to the pressure by the equations [7] $\mathbf{v}=\Delta\varphi,\ \mathbf{v}'=\nabla\varphi'+\nabla\times\boldsymbol{\psi}'$. The need for the vector potential arises because of the existence of transverse waves in a solid. In the case of a liquid one can put $\boldsymbol{\psi}'=0$.

The equations of acoustics and the heat conduction equation for the condensed phase then take the form

$$\Delta\varphi+k^2\varphi=0,\ \Delta\varphi'+k'^2\varphi'=0,\ \Delta\boldsymbol{\psi}'+k_\perp^2\boldsymbol{\psi}'=0,\ \nabla\boldsymbol{\psi}'=0,$$

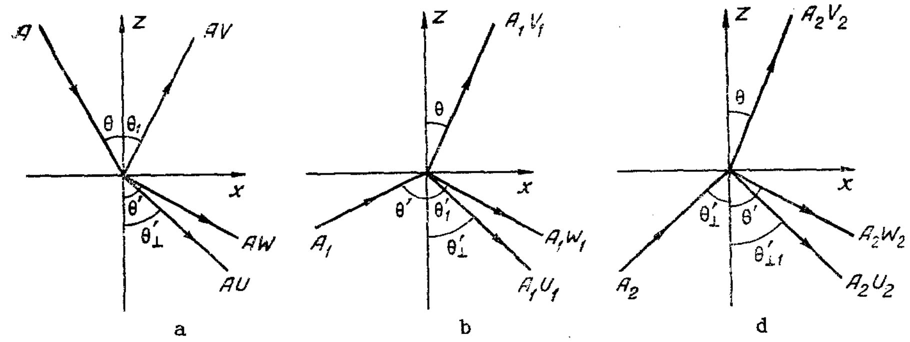

Fig. 1. Interaction between an interface and a plane wave incident from the gas phase (a), and a longitudinal (b) and a transverse (c) wave incident from the condensed phase.

$$\delta^2 \frac{\partial^2 T'}{\partial z^2} + iT' = 0,\ k = \omega/c,\ k' = \omega/c',\ k'_\perp = \omega/c'_\perp,\ \delta^2 = \lambda'/\rho'_0 c'_p \omega. \tag{4}$$

Here we have used the fact that the thickness of the heated layer in the condensed phase is normally small in comparison with the wave length, and hence the heat conduction problem is one-dimensional.

In the plane case, when $v_y = 0$, $\psi'_y = \psi'$, the boundary conditions (1)-(3) become

$$\varphi/m = \varphi' - 2/k'^2_\perp \left[\frac{\partial^2 \psi'}{\partial x \partial z} - \frac{\partial^2 \varphi'}{\partial x^2} \right],\ m = \rho'_0/\rho_0, \tag{5}$$

$$2\frac{\partial^2 \varphi'}{\partial x \partial z} + \frac{\partial^2 \psi'}{\partial x^2} - \frac{\partial^2 \psi'}{\partial z^2} = 0, \tag{6}$$

$$\frac{\partial \varphi}{\partial z} - \frac{\partial \varphi'}{\partial z} - \frac{\partial \psi'}{\partial x} = \frac{m-1}{m} \frac{\beta}{c} \left[\frac{Q}{T_0} T' - i\omega\varphi \right], \tag{7}$$

$$-\frac{\partial T'}{\partial z} = \frac{Q\rho_0}{\lambda'} \frac{m}{m-1} \left[\frac{\partial \varphi}{\partial z} - \frac{\partial \varphi'}{\partial z} - \frac{\partial \psi'}{\partial x} \right]. \tag{8}$$

The problem is mathematically closed by requiring that the temperature perturbation damp out with depth into the condensed phase and by specifying the potential of the incident wave.

2. To clarify the effect of evaporation and condensation on energy dissipation in the sound wave we consider some classical problems of acoustics. The simplest of these is the interaction of a plane wave, incident from either the gas or condensed phase, with plane interface. From the solution of this problem it is possible to obtain the solution for an arbitrary wave by expanding the wave in a set of plane waves [7].

Let a wave of amplitude A be incident from the gas phase. We assume a solution in the form of a sum of a reflected wave and two refracted waves (longitudinal and transverse; Fig. 1a). The potentials in the gas phase φ and in the condensed phase φ' and ψ', and also the temperature T', are written in the form

$$\varphi = A\{\exp[ik(x\sin\theta - z\cos\theta)] + V\exp[ik(x\sin\theta_1 + z\cos\theta_1)]\},$$

$$\varphi' = AW\exp[ik'(x\sin\theta' - z\cos\theta')],\ \ \psi' = AU\exp[ik'_\perp(x\sin\theta'_\perp - z\cos\theta'_\perp)],$$

$$T' = AD\exp[\sqrt{1/2\delta^2}(1-i)z + ikx\sin\theta].$$

These expressions satisfy (4), the amplitude A is given, and the angles θ_1, θ', $\theta'_\perp$ and the complex amplitudes V, W, U, and D are found from the boundary conditions (5)-(8).

The boundary conditions must be satisfied for arbitrary x, which is possible only if the arguments of the exponentials are identical at z = 0. Hence

$$\theta_1 = \theta,\ k\sin\theta = k'\sin\theta' = k'_\perp \sin\theta'_\perp. \tag{9}$$

The laws of reflection and refraction of plane waves are therefore the same as in "classical" acoustics (without evaporation).

The reflection and transmission coefficients are found from the boundary conditions (5)-(8). Because of the complexity of the expressions, and because we normally have $\rho_0' \gg \rho_0$ and $c' > c$, we consider only this case. Then

$$V = \left\{\frac{S-\Delta\xi}{S+\Delta\xi}\right\},\ W = \frac{2}{m\cos 2\theta_\perp'\,(1+a)}\left\{\frac{S}{S+\Delta\xi}\right\},$$

$$U = \frac{-2a}{m\sin 2\theta_\perp'\,(1+a)}\left\{\frac{S}{S+\Delta\xi}\right\},\ D = \frac{2(i-1)T_0\omega}{Q(S+\Delta\xi)},\ S = 1+\Delta+i,$$

$$a = n_\perp\frac{\sqrt{-\sin^2\theta/n^2+1}}{\cos\theta_\perp'}\,\mathrm{tg}^2 2\theta_\perp',\ \Delta = \frac{cT_0\sqrt{2\rho_0' c_p'\lambda'\omega}}{\beta Q^2\rho_0},$$

$$\xi = \frac{\beta}{\cos\theta},\ m = \frac{\rho_0'}{\rho_0},\ n = \frac{c}{c'},\ n_\perp = \frac{c_\perp'}{c'}.$$

Here and below the terms resulting from evaporation and condensation are grouped together inside the braces. Evaporation is absent for $\Delta = 0$, and in this case the terms inside the braces are equal to unity. The presence of evaporation and condensation leads to changes in the amplitudes and phases of the reflected and refracted waves. The velocity of the reflected wave is of the same order of magnitude as the velocity v^* of the incident wave, while the velocities of the refracted waves are of order v^*/m, as in "classical" acoustics. Instead of a velocity node and pressure antinode at the boundary there will be velocity and pressure oscillations, however the intensity of the refracted wave does not increase, but decreases. Indeed, defining the energy transmission coefficients of longitudinal r and transverse $r_\perp$ waves and the energy reflection coefficient R as the ratios of the corresponding energy fluxes to the energy flux of the incident wave, and defining the total energy absorption by $P \equiv 1 - R - r - r_\perp$, we obtain

$$r = \frac{4n\,|1+a|^{-2}}{m\cos^2 2\theta_\perp'}\{1-\tau\},\quad r_\perp = \frac{|a|^2\,\mathrm{ctg}\,2\theta_\perp'}{n_\perp}r,\ R = \{1-\alpha\}, \tag{10}$$

$$P = \alpha + O\left(\frac{1}{m}\right),\ \tau = 1 - \frac{1+(1+\Delta)^2}{1+(1+\Delta+\Delta\xi)^2},\ \alpha = \frac{4(1+\Delta)\Delta\xi}{1+(1+\Delta+\Delta\xi)^2}.$$

The expressions inside the braces are less than one when $\Delta \neq 0$, which implies energy dissipation in the reflected and transmitted waves.

Suppose now that a longitudinal wave of amplitude A_1 is incident from the condensed phase at angle θ' (Fig. 1b). We assume a solution in the form

$$\varphi = A_1V_1\exp[ik(x\sin\theta + z\cos\theta)],\ \varphi' = A_1\{\exp[ik'(x\sin\theta' + z\cos\theta')] +$$

$$+ W_1\exp[ik'(x\sin\theta_1' - z\cos\theta_1')]\},\quad \psi' = A_1V_1\exp[ik_\perp'(x\sin\theta_\perp' - z\cos\theta_\perp')],$$

$$T' = A_1D_1\exp[\sqrt{1/2\delta^2}(1-i)z + ikx\sin\theta].$$

As in the case considered above, these expressions satisfy (4) and the unknown constants are determined from the boundary conditions (5)-(8). As before, we find that the laws of reflection and refraction are the same as in the "classical" case (and are given by (9)). The reflection and transmission coefficients and the parameter D_1 are, for $m \gg 1$, $n < 1$

$$W_1 = \frac{a-1}{a+1},\ V_1 = \frac{2n\cos\theta'}{(1+a)\cos 2\theta_\perp'\cos\theta}\left\{\frac{S}{S+\Delta\xi}\right\},\ U_1 = \frac{2n_\perp^2\sin 2\theta'}{(1+a)\cos 2\theta_\perp'},$$

$$D_1 = \frac{2\omega(i-1)}{Q}\,\frac{\mathrm{tg}\,\theta\,\mathrm{ctg}\,\theta'}{(1+a)\cos 2\theta_\perp'(S+\Delta\xi)}.$$

The reflection coefficients W_1 and U_1 are the same as in "classical" acoustics, but the transmission coefficient V_1 differs by the factor inside the braces. Hence the reflected waves do not change, even though in the presence of evaporation and condensation at the surface the velocities in the gas and condensed phases differ. Note that the expression inside the braces is formally identical to the function describing the effect of evaporation on the refracted waves in the preceding problem, although the angle θ is now the angle of refraction and not the angle of reflection. This asymmetry follows from the asymmetry of the problem: evaporation and condensation proceed in the less dense medium and in the first approximation affect only the energy flux in the less dense medium; the energy flux in the denser phase is affected only in the next approximation. Indeed, we obtain for the energy coefficients

$$r_1 = \left|\frac{1-a}{1+a}\right|^2, \quad R_1 = \frac{4n}{m} \frac{\cos^2\theta'}{|1+a|^2 \cos^2 2\theta'_\perp \cos^2\theta} \{1-\tau\},$$

$$r_{1\perp} = \frac{4n_\perp^3 \sin^2 2\theta}{|1+a|^2 \cos^2 2\theta'_\perp}, \quad P = O\left(\frac{1}{m}\right),$$

where the only difference from "classical" acoustics is in the refracted wave.

It is well known that transverse waves in which the velocity oscillations are parallel to the interface do not affect either the normal displacement of the surface or the normal component of the stress and hence the reflected transverse wave has the same polarization and intensity [7]. Hence we consider the reflection of a transverse wave in which the velocity oscillations lie in the plane passing through the normal to the interface (Fig. 1c). We assume a solution of the form

$$\varphi = A_2 V_2 \exp[ik(x\sin\theta + z\cos\theta)], \quad \varphi' = A_2 W_2 \exp[ik'(x\sin\theta' - z\cos\theta')],$$

$$\psi' = A_2\{\exp[ik'_\perp(x\sin\theta'_\perp + z\cos\theta'_\perp)] + U_2\exp[ik'_\perp(x\sin\theta'_{\perp 1} - z\cos\theta'_{\perp 1})]\},$$

$$T_2 = A_2 D_2 \exp[\sqrt{1/2\delta^2}(1-i)z + ikx\sin\theta].$$

As before, it can be shown that these expressions satisfy (4) and that the laws of reflection and refraction are the same as before and given by (9). The other coefficients are, in the case $m \gg 1$ and $n < 1$

$$U_2 = \frac{a-1}{a+1}, \quad V_2 = \frac{a}{(1+a)\,\mathrm{ctg}\,\theta\sin^2 2\theta'_\perp}\left\{\frac{S}{S+\Delta\xi}\right\},$$

$$W_2 = -\frac{2a\cos 2\theta'_\perp}{n_\perp^2(1+a)\sin 2\theta'}.$$

As in the preceding problem evaporation does not affect the reflected waves, but changes the amplitude and phase of the refracted wave. The energy coefficients are similar to the preceding case:

$$r_{2\perp} = \left|\frac{1-a}{1+a}\right|^2, \quad R_2 = \frac{n_\perp}{mn} \frac{a^2}{\mathrm{ctg}^2\theta\sin^4 2\theta'_\perp|1+a|^2}\{1-\tau\},$$

$$r_2 = \frac{4a^2\cos^2 2\theta'_\perp}{n_\perp^4|1+a|^2\sin^2 2\theta'}, \quad P = O\left(\frac{1}{m}\right).$$

Therefore for sufficiently high frequencies ($\Delta \gtrsim 1$) evaporation and condensation at the surface leads to a decrease in the energy of the refracted wave and also the reflected wave for the case of incidence from the gas phase. The total energy dissipation is small when the wave is incident from the condensed phase.

Having expressions for the reflection and transmission coefficients of plane waves, we can consider the interaction of an arbitrary harmonic wave by expanding the wave in plane waves [7]. As an example, we consider the reflection and refraction of a spherical wave from a flat vapor—liquid interphase, such that there is no transverse wave in the condensed phase.

The spherical wave $\exp(ik\rho)/\rho$ ($\rho = \{x, y, z\}$ is the distance to the source) is represented in the form of a superposition of plane waves with all possible (including complex) values of the wave vector $\mathbf{k}$:

$$\varphi_0 = \exp(ik\rho)/\rho = \frac{i}{2\pi}\int_{-\infty}^{+\infty}\int \exp[i(k_x x + k_y y \pm k_z z)]\frac{dk_x dk_y}{k_z}, \quad z \gtrless 0.$$

Using the reflection coefficient for plane waves $V(\theta)$ obtained above, we find an expression for the potential ϕ of the reflected wave

$$\varphi = \frac{ik}{2\pi}\int_0^{\frac{\pi}{2}-i\infty}\int_0^{2\pi} \exp[ik(x\sin\theta\cos\varphi + y\sin\theta\sin\varphi + (z+z_0)\cos\theta)] \times V(\theta)\sin\theta\, d\theta d\varphi.$$

Here $k = |\mathbf{k}|$, and z_0 is the distance between the source and the interface. The potential ϕ' of the transmitted wave is given by a similar expression with $V(\theta)$ replaced by the transmission coefficient $W(\theta)$.

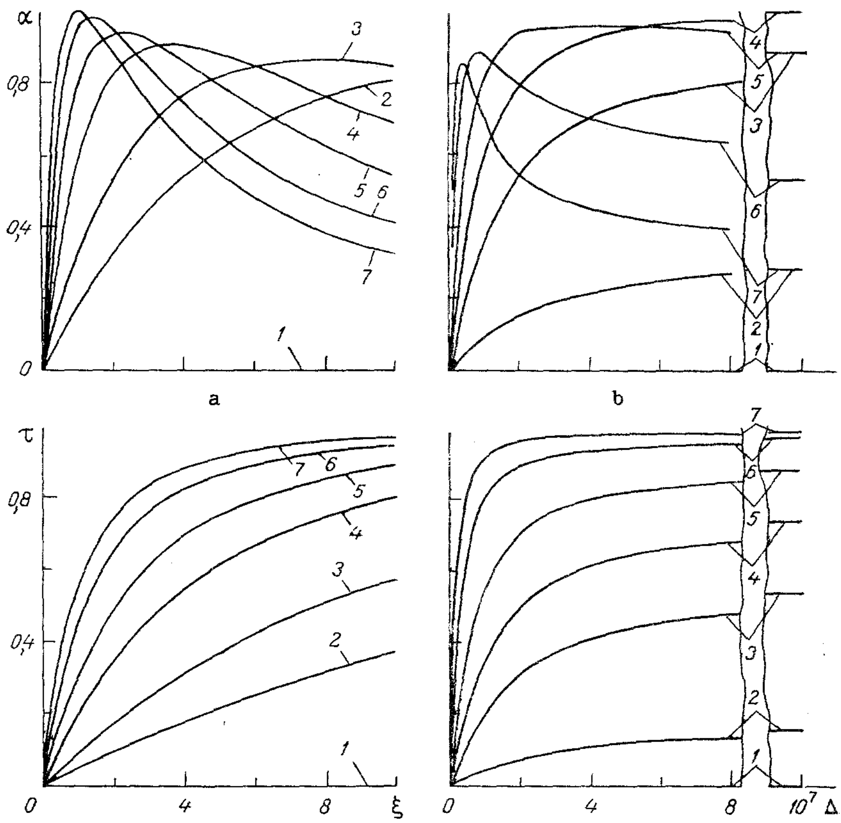

Fig. 2. Dependence of the attenuation coefficient of the reflected wave α and the refracted wave τ on the parameters ξ (a) and Δ (b): In Fig. 2a: 1) Δ = 0, 2) 0.1, 3) 0.2, 4) 0.5, 5) 1, 6) 3, 7) ∞; in Fig. 2b: 1) ξ = 0, 2) 0.1, 3) 0.5, 4) 1, 5) 2, 6) 5, 7) 10.

Explicit expressions can be obtained in the case $m \gg 1$, $n < 1$, $k\rho \gg 1$, $n\rho' \ll \rho \cos\theta$ ($n\rho'$ is the optical path length from the interface to the receiver). Applying the usual procedure of the method of steepest descent [7], we have

$$\varphi = \exp(ik\rho_1)/\rho_1 [V(\theta) - iN(\theta)/k\rho_1], \quad N = 1/2\,[V''(\theta) + V'(\theta)\operatorname{ctg}\theta],$$

$$\varphi' = \exp(ik\rho)/\rho\,[W(\theta) - iN_1(\theta)/k\rho], \quad N_1 = 1/2\,[W''(\theta) + W'(\theta)\operatorname{ctg}\theta],$$

where ρ_1 is the distance from the image source.

In the approximation of geometrical acoustics the energy fluxes of the reflected I and transmitted I' waves are

$$I = \frac{\omega^2\rho_0}{2c\rho_1^2}\{1-\alpha\}, \quad I' = \frac{2\omega^2\rho_0'}{mc'\rho^2}\{1-\tau\}.$$

3. We have seen that evaporation and condensation processes at the surface do not change the angles of reflection and refraction of plane waves. The relative decrease in the energy of the refracted wave is described by the function τ, and the decrease in the energy of the reflected wave (incidence from the gas phase) is described by the function α (see (10)). The decrease in the energy of the reflected wave is insignificant for incidence from the condensed phase.

Energy dissipation due to evaporation and condensation processes does not depend on the viscosity and the thermal properties of the gas and is determined by two parameters: Δ and ξ. The parameter Δ expresses the dependence on frequency, temperature, and the properties of the condensed phase, while ξ is determined by the condensation coefficient and by the angle of incidence.

The dependence of α on ξ (Fig. 2) is nonmonotonic and the position of the maximum and its value depend on frequency. The maximum is displaced toward smaller ξ as Δ increases and

TABLE 1. Attenuation Coefficient of the Reflected α and Transmitted τ Wave for Standard Frequencies

Material	σ	Coefficient	63	125	250	500	1000	2000	4000	8000	Note
			Frequency f, Hz								
Water	1	α	0,0736	0,101	0,141	0,192	0,259	0,341	0,438	0,523	Normal incidence
		τ	0,0375	0,0523	0,0728	0,101	0,138	0,185	0,243	0,309	
Water	1	α	0,128	0,173	0,232	0,305	0,392	0,490	0,593	0,692	Diffuse incidence
		τ	0,0383	0,0534	0,0743	0,103	0,140	0,189	0,247	0,336	
Naphthalene	1	α	0,944	0,953	0,959	0,963	0,966	0,967	0,968	0,969	Normal incidence
		τ	0,621	0,632	0,640	0,645	0,649	0,652	0,653	0,655	
Naphthalene	0,5	α	0,641	0,647	0,651	0,653	0,655	0,657	0,658	0,658	Diffuse incidence
		τ	0,361	0,365	0,367	0,369	0,370	0,371	0,372	0,372	

α reaches a value of unity at the point $\xi = 1$ ($\theta = \arccos \beta$). In contrast t the well-known cases in electrodynamics and acoustics, the decrease in the intensity of the reflected wave is not caused by an abnormally large value of the transmission coefficient (see Fig. 2), but by an increase in energy dissipation. Note that the position of the maximum and the value of α_{max} do not depend on the acoustic properties of the condensed phase. Absorption of energy becomes significant for moderate values of ξ and $\alpha \to 0$ in the limit $\xi \to \infty$ (glancing incidence).

The dependence α (Δ) (Fig. 2) is qualitatively different in the regions $\xi < 1$ and $\xi > 1$. In the first case (small condensation coefficient, sufficiently small angle of incidence) α increases monotonically with increasing frequency from zero up to a limiting value which increases with increasing ξ. Energy absorption is significant for $\Delta > 1$. In the second case (large angle of incidence) the dependence is nonmonotonic and α_{max} becomes comparable to unity for $\Delta \lesssim 1$. The quantity α decreases with further increase of Δ and approaches a limiting value such that $\alpha(\xi)$ and $\alpha(1/\xi)$ become equal in the limit $\Delta \to \infty$.

The dependences of the attenuation coefficient τ of the transmitted wave on Δ and ξ are monotonic (see Fig. 2). The growth of τ with increasing ξ is stronger, the larger the value of Δ. In the limit $\xi \to \infty$ (glancing incidence) the quantity τ approaches unity for any value of Δ. The quantity τ increases sharply with increasing Δ and approaches the limiting value $(1 + \xi)^{-2}$ when $\Delta \to \infty$. Therefore the attenuation increases with increasing angle of incidence and increasing Hertz–Knudsen coefficient. The effect of attenuation is significant when $\Delta \gtrsim 1$.

Hence we find that evaporation and condensation processes lead to attenuation of both the reflected and refracted waves, except when the frequency or condensation coefficient vanish ($\Delta = 0$ or $\xi = 0$, respectively).

The dependences discussed above are universal; the particular frequencies at which the effects become significant and the angles corresponding to the extrema are determined by the properties of the material. We note that the interval of the parameter ξ is also determined by the properties of the material. The interval of ξ for the analysis of the total energy absorption is (β, ∞); for the attenuation of the transmitted wave it is $(\beta, \beta/\cos \theta_x)$, where θ_x is the angle of total internal reflection.

It follows from our results that one must have $\Delta \gtrsim 1$ in order to get significant energy absorption. From the definition of Δ, this implies a large value of the thermal conductivity in the condensed phase and a small heat of vaporization. The effect of energy dissipation is stronger in the case of low pressure and high frequency.

We consider the attenuation coefficients of sound α and τ for water and naphthalene (see Table 1) at a temperature of 300 K, when the saturated vapor pressure is 3564 Pa for water and 14.8 Pa for naphthalene. We then find $\Delta = 0.995 \sqrt{f}$ for naphthalene and $\Delta = 6.19 \cdot 10^{-3}\sqrt{f}$ for water.

The coefficients α and τ are higher for naphthalene than for water because of the larger value of Δ in naphthalene. This also explains the weak frequency dependence of α and τ in naphthalene (see Fig. 2). Note that energy dissipation is stronger for diffuse incidence. Energy dissipation decreases with decreasing condensation coefficient.

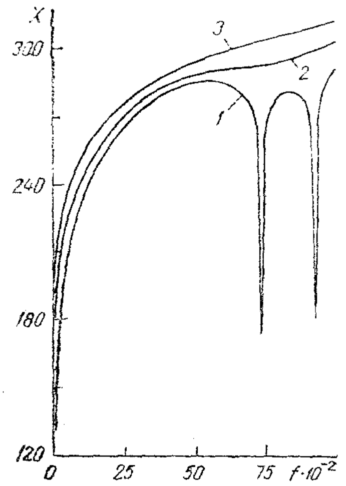

Fig. 3. Attenuation X (dB) as a function of frequency f (Hz): 1) $\sigma = 0$; 2) 0.6; 3) 1.

A layered structure can be used to produce greater attenuation of sound. For example, in the case of three aluminum plates of thicknesses 1.5, 1, and 1.5 mm, respectively, with gaps of 8 and 10 mm between the plates filled with naphthalene vapor (a 0.5 mm layer of naphthalene is applied to the plates), the decrease in the energy of a normally incident sound wave at T_0 = 300 K due to evaporation and condensation reaches 20-40 dB (Fig. 3). The complicated frequency dependence is due to resonance phenomena [7].

We note that the above results apply to the case of evaporation into an atmosphere of the same kind of gas. The presence of a noncondensing diluent can significantly affect the quantitative and qualitative features of the energy dissipation process.

In the absence of neutral gas (low vapor pressure), evaporation and condensation on the boundary between phases leads to a significant decrease in the energy of the reflected and refracted waves (except for reflection into the condensed phase) for volatile heat-conducting materials in the high-frequency region. The dependence of the energy of the reflected wave (incidence from the gas phase) on the angle of incidence is nonmonotonic. Energy dissipation due to evaporation and condensation processes can be used to measure the condensation coefficients, and can also be used in sound-absorbing and sound-insulating devices.

NOTATION

ρ_0, p_0, T_0, density, pressure, and temperature of the gas phase; ρ_0', p_0', T_0', density, pressure, and temperature of the condensed phase; ρ, ρ', p, p', T, T', acoustic corrections to the density, pressure, and temperature in the gas and condensed phases, respectively; v, v', velocities of the gas and condensed phases; R gas constant; κ, adiabatic exponent of the gas; Q heat of vaporization; ϕ, ϕ', scalar potentials of the gas and condensed phases; ψ' vector potential; ω, circular frequency; k, k', $k_\perp'$, wave numbers of the wave in the gas phase, the longitudinal wave in the condensed phase, and the transverse wave in the condensed phase, respectively; c, c', c', speed of sound in the gas phase and the longitudinal and transverse speeds of sound in the condensed phase; c_p', heat capacity of the condensed phase; β, generalized Hertz–Knudsen coefficient; σ condensation coefficient; $\Delta = cT_0\sqrt{2p_0'c_p'\lambda'\omega}/\beta\rho_0Q^2$, parameter describing the effect of evaporation; $\xi = \beta/\cos\theta$, parameter describing the effect of the angle of incidence; α, τ, relative attenuation coefficients of the reflected and refracted waves.

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CAPILLARY RISE WITH MENISCUS EVAPORATION FOR $Kn \geq 0.01$

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A meniscus step in a capillary has been observed at reduced gas pressures; a physical explanation is given.

Capillary impregnation is widely used in temperature-control systems (porous evaporative cooling) for use at various pressures and temperatures. Research has shown [1] that when an open-pore material is wetted at a certain external pressure, there is a sharp change in the liquid position, with the boundary descending, which affects the thermostatic control. The thicker the specimen and the smaller the capillary radius, the lower the pressure at which the step occurs.

We have examined impregnation accompanied by evaporation subject to changes in the thermodynamic parameters for the medium and the liquid. The apparatus and methods have been described in [2].

We used cylindrical glass capillaries under a glass vacuum chamber cover in the strictly vertical position. The menisci were observed and photographed via an optical system. The time was recorded by a timer and a cine camera with built-in clock. A capillary was fixed in a holder fitted with a measurement scale (division 4×10^{-4} m) and filled by bringing up a cell containing the liquid to the lower end. The liquids were outgassed distilled water, ethyl alcohol, benzene, acetone, dibutyl phthalate, and glycerol.

The equilibrium rise was measured in two ways for various gas pressures: 1) the capillary was filled at atmospheric pressure, after which the pressure was reduced; and 2) the liquid was introduced at reduced pressure, the pressure then being raised to atmospheric. The experiments were done with a single radius and various lengths or with various radii but a single length. The minimum length was equal to the maximum height of rise at atmospheric pressure for the given radius, while the maximum was 0.25 m. The radii varied from 0.17×10^{-3} to 0.50×10^{-3} m.

When the pressure was reduced from atmospheric to 1.33×10^3 Pa, the rise was unaltered and the menisci remained fixed in all the capillaries. At 1.20×10^3 Pa, with capillaries 0.25 m long (or on further pressure reduction for shorter capillaries), the menisci for water descended somewhat below the maximum rise in the atmosphere. At 0.67×10^3 Pa, the menisci for water in all the capillaries remained at certain heights characteristic of the radius and length, with no alteration as the gas pressure was reduced further. Figure 1 shows that the sinking was the larger the greater the length for a given radius. In capillaries with the minimum length, there was no change in menuscus position as the pressure was reduced. As the step $\Delta\ell$, we took the difference between the heights of the menisci at atmospheric pressure and at 0.67×10^3 Pa. Figure 2 shows that $\Delta\ell = 0$ for capillaries whose lengths were equal to the maximum rise in air. The value of $\Delta\ell$ increases with the length for r = const, while it decreases as the radius increases for L = const (curves 1-6). For $r = 0.17 \cdot 10^{-3}$ m or less, steps occurred even when the length was about 5 mm greater than the maximum rise for water at atmospheric pressure. For $r > 0.4 \cdot 10^{-3}$ m, and for all the lengths ($L \leq 0.25$ m), there was virtually no shift for water.

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