EFFECT OF SOUND ON HEAT- AND MASS-TRANSFER PROCESSES IN GASEOUS MEDIA

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Expressions are derived for the dimensionless heat- and mass-transfer coefficients for bodies of simple shape and the calculated relations are compared with the existing experimental data. The limits of applicability of the results are considered.

A number of theoretical and experimental papers have appeared in recent years on the effect of elastic waves propagated in a medium on heat- and mass-transfer processes. Most authors [1–3] relate the acceleration of these processes in high-intensity acoustic fields to the appearance near the sound-irradiated body of acoustic flows, formed as a result of interaction of the sound wave with the interface between the medium and the solid body. However, the (at first glance) contradictory experimental results of various authors do not allow the effectiveness of the acoustic method of acceleration of these processes to be evaluated. It is sufficient to point out that, according to the experimental data in [2,4], the processes are intensified with an increase in the sound frequency, while, from the results in [3,5], it is evident that the reverse dependence of heat and mass transfer upon frequency is observed under other conditions.

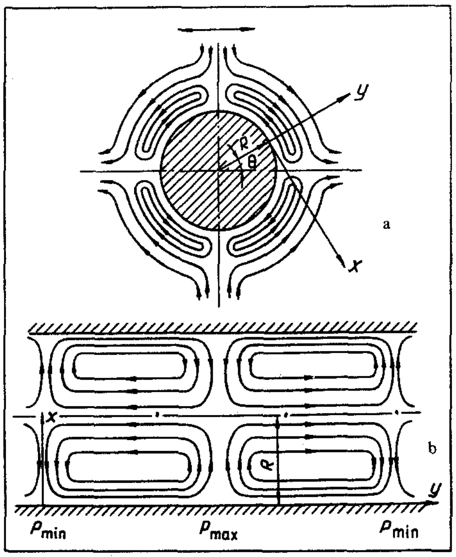

Fig. 1. Acoustic flows near cylinder (a) and in plane layer (b).

In this paper, we have attempted to give a general method for calculating the dimensionless heat- and mass-transfer coefficients, and expressions are derived for the Nusselt number for bodies of simple shape: a sphere and a plane. First, let us consider the case of heat transfer from a sphere ($R \ll \lambda$), whose surface temperature is held constant and which is subjected to a plane sound wave. In the coordinate system associated with the sphere (see Fig. 1a), the incident wave is given as $V_{1\infty}(-V_0 \sin\theta \cos\omega t, V_0 \cos\theta \cos\omega t)$. To determine the heat-transfer coefficient

$$\mathrm{Nu} = \frac{l}{T_0 - T_\infty}\left(\frac{\partial \langle T \rangle}{\partial y}\right)_{y=0}, \tag{1}$$

we must solve the heat-transfer equation

$$(\mathbf{u}\nabla)\langle T \rangle = D\,\Delta T \tag{2}$$

with the boundary conditions

$$T = T_0 \text{ when } y = 0 \text{ and } T = T_\infty \text{ when } y \to \infty. \tag{3}$$

To determine u in Eq. (2), we use the equation of motion with allowance for convective heat transfer from the heated body [6]:

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u}\nabla)\,\mathbf{u} =$$

$$= -\frac{\nabla P}{\rho} + \gamma \nabla^2 \mathbf{u} - g\beta(T - T_0). \tag{4}$$

The boundary conditions for (4) have the form

$$\mathbf{u} = 0 \quad \text{when} \quad y = 0.$$

Since the plane sound wave creates in the vicinity of the sphere a flow that is constant with respect to time (the configuration of the streamlines can be seen in Fig. 1a), the motion velocity of the medium and the pressure can be represented as a sum of constant and pulsating terms:

$$\mathbf{u} = \mathbf{u}_0 + \mathbf{V}_1,\ P = P_0 + P_1. \tag{5}$$

The velocity and pressure pulsations cause the density of the medium and the temperature to vary with respect to time; therefore,

$$\rho = \rho_0 + \rho_1,\ T = \langle T \rangle + T_1, \tag{6}$$

and the relationship between the variable velocity component and the temperature pulsation beyond the limits of the boundary layer ($y \gg \delta = (2\gamma/\omega)^{1/2}$) can be written [7] as

$$T_1 =$$

$$= \mathrm{Real}\left[\frac{i}{\omega}\left(\frac{\partial \langle T \rangle}{\partial x} V_{1x} + \frac{\partial \langle T \rangle}{\partial y} V_{1y}\right)\right]. \tag{7}$$

We use the method described in [8] to solve the flow equation (4). Then, omitting the intermediate transformations, which are described in detail in [8], we can show that (4) becomes

$$(\mathbf{u}_0\nabla)\mathbf{u}_0 - \gamma\nabla^2\mathbf{u}_0 = = -\frac{\nabla P_0}{\rho_0} - g\beta(\langle T\rangle - T_0) - \langle(\mathbf{V}_1\nabla)\mathbf{V}_1\rangle, \quad (8)$$

where $\mathbf{V}_1$ (for $u_0 \ll c$) can be found by solving the system of equations of motion, continuity, and state in the first (acoustic) approximation,

$$\frac{\partial \mathbf{V}_1}{\partial t} = -\frac{\nabla P_1}{\rho_0} + \gamma\Delta\mathbf{V}_1,$$
$$\frac{\partial \rho_1}{\partial t} + \rho_0\nabla\mathbf{V}_1 = 0,$$
$$P_1 = \rho_1 c^2, \quad (9)$$

under the boundary conditions $y = 0$ and $V_{1x} = V_{1y} = 0$. The solution of system (9) has the form [9]

$$V_{1x} = = V_0\sin\theta\left[\cos\omega t - \exp\left(-\frac{\delta}{y}\right)\cos\left(\omega t - \frac{\delta}{y}\right)\right],$$
$$V_{1y} = -V_0\cos\theta\left\{\frac{y}{d_0}\cos\omega t + \frac{\delta}{\sqrt{2}d_0}\times\right.$$
$$\times\left[\cos\left(\omega t - \frac{\pi}{4}\right) - \exp\left(-\frac{\delta}{y}\right)\times\right.$$
$$\left.\left.\times\cos\omega t - \frac{\pi}{4} - \frac{\delta}{y}\right]\right\}. \quad (10)$$

This solution is valid when

$$\frac{d_0}{\delta} \gg 1 \text{ and } \frac{V_0 d_0}{\gamma} \gg 1. \quad (11)$$

Equation (8) is the equation of motion of the medium under the influence of two forces: a force of acoustic origin $\langle\rho_0(\mathbf{V}_1\nabla)\mathbf{V}_1\rangle$ and a lifting force $\rho_0\beta g(\langle T\rangle - T_0)$ due to the presence of a temperature difference. Such flows are called thermoacoustic [1]. Since finding the velocity and configuration of such flows involves great theoretical difficulties, we shall consider the action of high-intensity sound when

$$g\beta(\langle T\rangle - T_0) \ll \langle(\mathbf{V}_1\nabla)\mathbf{V}_1\rangle. \quad (12)$$

Then, (8) takes the form

$$(\mathbf{u}_0\nabla)\mathbf{u}_0 - \gamma\Delta\mathbf{u}_0 = -\frac{\nabla P_0}{\rho_0} - \langle(\mathbf{V}_1\nabla)\mathbf{V}_1\rangle. \quad (13)$$

This equation describes the behavior of the acoustic flows in the absence of natural convection (Fig. 1a) and its solution when $(\mathbf{u}_0\nabla)\mathbf{u}_0 \ll \gamma\Delta\mathbf{u}_0$, which is equivalent to

$$\frac{u_0\delta}{\gamma} \ll 1. \quad (14)$$

It is known [9] that

$$u_{0x} = \frac{3}{2}\frac{V_0^2}{\omega R}\sin 2\theta\times$$
$$\times\left\{\exp\left(-\frac{y}{\delta}\right)\left[\frac{2\delta}{11}\sin\frac{y}{\delta} - \exp\left(-\frac{y}{\delta}\right)\right] + 1\right\}. \quad (15)$$

Then, the tangential component of the flow velocity outside of the boundary layer can be written as

$$u_{0x} \simeq \frac{3}{2}\frac{V_0^2}{\omega R}\sin 2\theta. \quad (16)$$

Here it must be noted that limitation (12) on the amplitude of the fluctuating velocity is stronger than (11). Therefore, assuming that for a sphere [9]

$$(\mathbf{V}_1\nabla)\mathbf{V}_1 \simeq \frac{V_0^2}{R}, \quad (17)$$

on the basis of (12) and (14), using (16) and (17), we can write

$$[\beta gR(T_0 - T_\infty)]^{1/2} \ll V_0 \ll [\gamma R^2\omega^3]^{1/4}. \quad (18)$$

If we substitute (16) and (15) into (12) and average with respect to time, we obtain the heat-transfer equation as

$$(\mathbf{u}_0\nabla)\langle T\rangle + \langle(\mathbf{V}_1\nabla)T_1\rangle = D\nabla^2\langle T\rangle. \quad (19)$$

We specify the boundary conditions for this equation on the surface $d_0 + \delta$. If $\delta \ll d_0$, the temperature at the surface $d_0 + \delta$ will equal the temperature of the sphere, since the time in which the temperature of the surface $d_0 + \delta$ becomes equal to T_0 ($\tau = \delta^2/D$) is considerably less than the characteristic time of the process. Therefore, when

$$\frac{R}{u_0} \gg \frac{\delta^2}{D}, \quad (20)$$

it does not matter where the boundary conditions are assigned: at $y = 0$ or $y = \delta$. Thus, the problem of finding the temperature distribution of the medium reduces to solving Eq. (19) under the boundary conditions

$$T = T_0 \text{ when } y = \delta \text{ and } T = T_\infty \text{ when } y \to \infty. \quad (21)$$

We solve (19) in two steps. First, let us consider the case in which the temperature of the medium is determined only by the velocity of the constant (acoustic) flow, i.e., $(u_0\nabla)\langle T\rangle \gg \langle(\mathbf{V}_1\nabla)T_1\rangle$. Then, (19) becomes

$$(\mathbf{u}_0\nabla)\langle T\rangle = D\Delta\langle T\rangle. \quad (22)$$

With the standard Mises substitution [10]

$$V_\theta = -\frac{\partial\psi}{\partial r}[(R+y)\sin\theta]^{-1},$$
$$V_r = \frac{\partial\psi}{\partial\theta}[(R+y)^2\sin\theta]^{-1} \quad (23)$$

it reduces to

$$\left(\frac{\partial\langle T\rangle}{\partial\theta}\right)_\psi = DR^3u_{0x}\sin^2\theta\,\frac{\partial^2\langle T\rangle}{\partial\psi^2}. \quad (24)$$

If we substitute (16) into (24) and introduce the new variable

$$\alpha = \frac{3}{4}DR^2\frac{V_0^2}{\omega}\int\sin 2\theta\sin^2\theta\,d\theta = = -\frac{3DR^2V_0^2}{4\omega}\sin^4\theta + B_1, \quad (25)$$

where B_1 is the constant of integration, we arrive at

$$\frac{\partial \langle T \rangle}{\partial \alpha} = \frac{\partial^2 \langle T \rangle}{\partial \psi^2}, \tag{26}$$

with the boundary conditions

$$T = T_\infty \text{ when } \psi \to \infty,\ T = T_0 \text{ when } \psi = 0,$$

$$\alpha - \alpha_0 = B_1 \text{ when } \theta \to 0. \tag{27}$$

The solution of Eq. (26) has the form

$$\langle T \rangle = \frac{2}{\sqrt{\pi}} (T_\infty - T_0) \int\limits_0^{\psi/2\sqrt{\alpha-\alpha_0}} \exp(-z^2)\, dz + B_2. \tag{28}$$

Then

$$\frac{\partial \langle T \rangle}{\partial y} = \frac{1}{\sqrt{\pi}} \frac{(T_\infty - T_0)}{\sqrt{\alpha - \alpha_0}} \exp\left[-\frac{\psi^2}{4(\alpha - \alpha_0)}\right] \frac{\partial \psi}{\partial y}. \tag{29}$$

From (23), $\psi = \int\limits_0^y V_\theta r \sin\theta\, dy$; therefore, finally ($r = y + R$)

$$\left(\frac{\partial \langle T \rangle}{\partial y}\right)_{y=0} = \frac{4\sqrt{3}\, V_0 (T_0 - T_\infty)}{\pi \sqrt{\pi} R \sqrt{D\omega}}. \tag{30}$$

Since 2R is the characteristic dimension of the sphere, if we substitute (30) into (1) we obtain

$$\mathrm{Nu}'_a = \frac{2.4 V_0}{\sqrt{\omega D}}. \tag{31}$$

Now let us consider the second case, in which the first term on the left-hand side of Eq. (19) is small in comparison with the second, i.e., the temperature is determined chiefly by the pulsating component of the flow velocity. In this case, (19) is transformed to

$$\langle (\mathbf{V}_1 \nabla) T_1 \rangle = D \nabla^2 \langle T \rangle. \tag{32}$$

If the sphere is heated uniformly and $\mathrm{Pe} = u_0 l / D \gg 1$, then $\partial\langle T\rangle/\partial x \ll \partial\langle T\rangle/\partial y$, since the temperature varies greatest radially. Therefore, (32) can be written as

$$\langle (\mathbf{V}_1 \nabla) T_1 \rangle = D \frac{\partial^2 \langle T \rangle}{\partial y^2}. \tag{33}$$

Substituting (10) into (7), we obtain

$$T_1 \simeq -\left[\frac{\sin\omega t}{\omega} + \frac{\delta \sin\left(\omega t - \frac{\pi}{4}\right)}{\sqrt{2} R \omega}\right] \times V_0 \cos\theta \frac{\partial \langle T \rangle}{\partial y} \tag{34}$$

and

$$\left\langle V_{1y} \frac{\partial T_1}{\partial y} + V_{1x} \frac{\partial T_1}{\partial x} \right\rangle = -\frac{\delta V_0^2 \sin^2\theta}{4R^2} \frac{\partial \langle T \rangle}{\partial y}. \tag{35}$$

Hence, (33) becomes

$$D \frac{\partial^2 \langle T \rangle}{\partial y^2} + \frac{V_0^2 \delta \sin^2\theta}{4\omega R^2} \frac{\partial \langle T \rangle}{\partial y} = 0. \tag{36}$$

If we integrate (36), we obtain

$$\langle T \rangle = (T_0 - T_\infty) \exp(-\varkappa y)/\varkappa + T_\infty, \tag{37}$$

where $\varkappa = V_0^2 \delta \sin^2\theta / 4\omega D R^2$. Then

$$\left(\frac{\partial \langle T \rangle}{\partial y}\right)_{y=0} = \frac{V_0^2 \delta \sin^2\theta (T_0 - T_\infty)}{4\omega D R^2}, \tag{38}$$

and, substituting (38) into (1), we obtain

$$\mathrm{Nu}''_a = \frac{\delta V_0^2}{4R\omega D}. \tag{39}$$

The over-all heat-transfer coefficient, which is determined by the effect of the acoustic flows Nu'_a and pulsations Nu''_a, is equal to the sum of these components,

$$\mathrm{Nu}_a = \mathrm{Nu}'_a + \mathrm{Nu}''_a, \tag{40}$$

since the heat-transfer equation is linear in $\langle T \rangle$.

Let us estimate the contribution to the heat-transfer process made by each of these terms:

$$\varphi = \frac{\mathrm{Nu}'_a}{\mathrm{Nu}''_a} = \frac{9.6 R \sqrt{\omega D}}{\delta V_0} = \frac{6.8 \omega R}{V_0} \sqrt{\frac{D}{\gamma}}. \tag{41}$$

In the derivation of the expressions for the heat-transfer coefficent it was assumed that V_0 could be chosen within the limits defined by condition (18), while the radius of the sphere was bounded by the reflections

$$\delta \ll R < \frac{\lambda}{8}, \tag{42}$$

and, in addition, the requirement $A/R < 1$ had to be met, which can be written as

$$\omega > \frac{V_0}{R} \tag{43}$$

and which imposes a limitation on the possible lowering of the working frequency. Considering (43), therefore, it is obvious that under the chosen conditions $\varphi \gg 1$, i.e., the heat-transfer process in an acoustic field is determined chiefly by the acoustic flows and is independent of the pulsation term, although it is natural that, since the acoustic-flow velocity (16) is proportional to the kinetic energy of the sound wave, heat transfer is increased when the amplitude of the fluctuating velocity (31) is increased.

It should be noted that formula (31) is valid not only for a sphere but also for a cylinder, since the expressions for flow velocity near a sphere and near a cylinder (outside the boundary layer) are identical [11] and are written in the form of (16). This allows us to use expression (31) to compare the calculated values of the dimensionless heat-transfer coefficient with the experimental data in [1].

Heat transfer from a horizontal cylinder (d_0 = 18.8 mm) when it was placed at the standing-wave velocity antinode was studied in [1]. The sound frequency varied from 1.1 to 6 kHz, and the sound pressure P_1 = 140–150 dB. In Fig. 2, curve 1 corresponds to $Nu_0 + Nu'_a$, where Nu_0 was calculated according to [1] and Nu'_a by (31), while curve 2 is the experimental relation obtained at 1.5 kHz [1]. Since formula (31) was derived under assumption (12), then, bearing in mind (17), we can show that for the temperature potential $T_0 - T_\infty$ = = 110° C, for which the experimental data are given, (31) is valid when $P_1 \geq 2 \cdot 10^3$ bars (140 dB). Comparison of curves 1 and 2 shows that for sound pressures close to the critical value P_{cr}, the difference between the calculated and experimental values can reach 25%, whereas this difference is substantially reduced when the sound intensity is increased.

Figure 2 also shows the frequency dependence of the dimensionless heat-transfer coefficient (curve 3) ($P = 6.3 \cdot 10^3$ bars), which was plotted from (31). The experimental value (for $P_1 = 6 \cdot 10^3$ bars) from [1] are shown by points. The graphs show that formula (31)

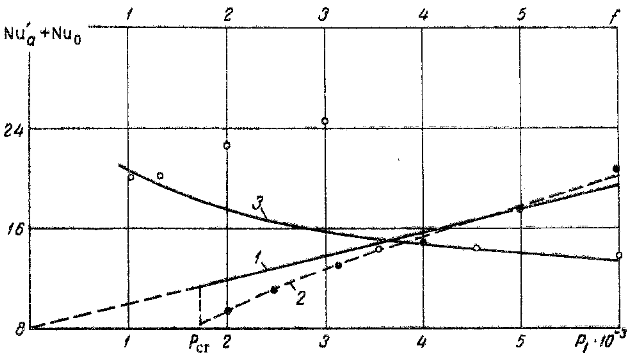

Fig. 2. Heat-transfer coefficient versus frequency and intensity for a cylinder.

explains satisfactorily the variation of Nu_a as a function of the parameters of the sound field. It must be noted that (31) differs from the formula for mass transfer from a sphere in a sound field [2] only by a coefficient,

$$Nu_a = 1.07 \frac{V}{\sqrt{\omega D}} . \qquad (44)$$

Since the mass-transfer equation is similar to the heat-transfer equation, and, in particular, when the pulsation term is negligible it has the form

$$(\mathbf{u}_0 \nabla) C = D \Delta C, \qquad (45)$$

which is similar to Eq. (22), then solution of the mass-transfer problem reduces formally to solution of a system of equations consisting of (45) and general equations of motion. In particular, the flow equation can be taken in the form of (13). Therefore, the coefficient of mass transfer from a sphere in a sound field will be determined by the same expression as for heat transfer, i.e,, formula (31). Expression (44), however, which was given in [2], was derived under the assumption that the sphere was placed in the field of an airstream whose velocity is determined by (16), i.e., the authors actually ignored the characteristics of the boundary layer of the acoustic flows, as a result of which a different value of the coefficient was obtained. These acoustic-flow boundary-layer characteristics are taken into account in formula (31).

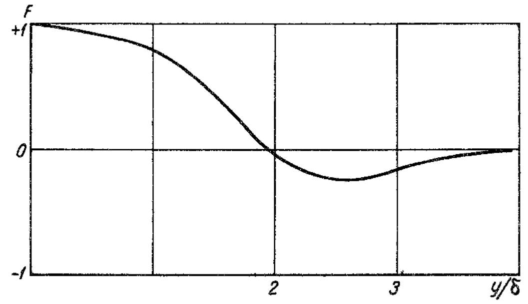

Fig. 3. Distribution of a force causing a flow near a surface.

Now let us consider the case of mass transfer from the walls of a channel within which a standing sound wave has been set up. As in the case of heat transfer, we shall assume that the mass transfer is chiefly affected by the acoustic flows, which in this case are of the Rayleigh type and whose configuration is shown in Fig. 1b. The complexity of the solution of this problem lies in the fact that for Rayleigh flows the characteristic dimension of motion is R, and, therefore, when $Re = u_0 R/\gamma \gg 1$, Eq. (13) is not linearized. In the area of the viscous sublayer, however, the equation can be linearized, since $u_0 \delta_0/\gamma \ll 1$. Then the equation of motion takes the form

$$\gamma \Delta \mathbf{u}_0 = -\frac{\nabla P_0}{\rho_0} + (\mathbf{V}_1 \nabla) \mathbf{V}_1 \qquad (46)$$

and corresponds to the equation of the acoustic flows caused by the force $F = \rho_0 (V_1 \nabla) V_1$. The thickness δ_0 of the viscous sublayer can be defined as the distance at which F = 0. As is apparent from Fig. 3, this condition is met when $y = 4\delta$.

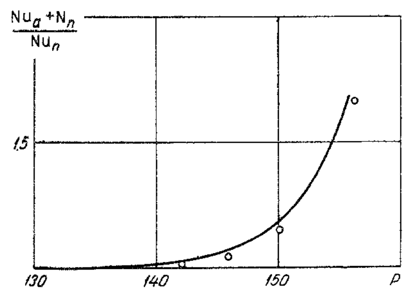

Fig. 4. Comparison of theoretical and experimental values of mass-transfer coefficient as a function of sound pressure (P, dB) for a plane at f = 286 Hz.

The solution of (46) with the boundary conditions $u_0 = 0$ at $y = 0$ has the form

$$u_{0x} = \frac{V_0^2}{4c} \sin 2kx \left\{\left[3 \sin \frac{y}{\delta} + \cos \frac{y}{\delta} + \frac{1}{2} \exp\left(-\frac{y}{\delta}\right)\right] \exp\left(-\frac{y}{\delta}\right) - \frac{3}{2}\right\} + B_1 y^2 + B_2 y,$$

$$u_{0y} = \frac{V_0^2 k \delta}{2c} \cos 2kx \times \left\{\left[2 \sin \frac{y}{\delta} - 4\cos \frac{y}{\delta} - \frac{1}{4} \exp\left(-\frac{y}{\delta}\right)\right] \times \exp\left(-\frac{y}{\delta}\right) - \frac{3}{2} \frac{y}{\delta} + \frac{17}{4}\right\} + \frac{dB_1}{dx} \frac{y^3}{3} + \frac{dB_2}{dx} \frac{y^2}{2}. \quad (47)$$

The constants of integration B_1 and B_2 are determined from the condition that when $y = 4\delta$, u_{0x} and u_{0y} must equal the velocity components at infinity. The latter can be found experimentally. Among other things, it is shown in [12] that for $\delta < y < R$

$$u_\infty = 2.7 \cdot 10^{-4} V_0^2 \sin 2kx. \quad (48)$$

Then $B_1 = 1.5 \cdot 10^{-4} (V_0^2/\delta_2) \sin 2kx$ and $B_2 = -5.4 \cdot 10^{-4} \times (V_0^2/\delta) \sin 2kx$.

If we know u_0 in the range $0 \le y \le R$, we can solve (45) with the boundary conditions

$$C = C_0 \text{ when } y = 0,\ C = C_\infty \text{ when } y = R. \quad (49)$$

For this, we use the integral relation [13]

$$\frac{d}{dx} \int_0^\infty (C - C_0) u dy = -D \left(\frac{\partial C}{\partial y}\right)_{y=0}. \quad (50)$$

The left-hand side of this equation can be determined from the following identity, which is valid for $Pr = 1$:

$$\frac{C - C_0}{C_\infty - C_0} = \frac{u - u_\infty}{u_\infty}. \quad (51)$$

Since for gases $Pr \simeq 1$, (51) is valid with an accuracy of $1 - (Pr)^{1/3}$, if we substitute (51) into (50) and use (47) and (48), we obtain

$$\left(\frac{\partial C}{\partial y}\right)_{y=0} = \frac{4u_\infty k \delta \cos 2kx}{D} (C_0 - C_\infty). \quad (52)$$

Hence, from a formula similar to (1) we find that

$$Nu_a = \frac{u_\infty k \delta R \cos 2kx}{D}. \quad (53)$$

The value of Nu_a averaged over the length of the channel is

$$\overline{Nu}_a = \frac{8.8 \delta \omega L u_\infty}{\pi c D} \left[1 + \frac{1}{2kL}\right]. \quad (54)$$

Since $\delta = (2\gamma/\omega)^{1/2}$, when $L \gg \lambda/2$ the dimensionless mass-transfer coefficient increases with an increase in frequency as $\sqrt{\omega}$, which has been observed for large bodies [4]. On the other hand, when $L \ll \lambda/2$, $\lambda/2kL \gg 1$ and $\overline{Nu}_a$ is proportional to $1/\sqrt{\omega}$, which has been observed in practice [5]. In the intermediate region, the frequency dependence is more complicated.

The periodic variation of the local values of Nu_a obtained in (53) is in good agreement with the experimental results of [14], where heat transfer in a pipe under the influence of acoustic vibrations for $kL > 1$ was studied.

Figure 4 shows the ratio of the dimensionless mass-transfer coefficients in an acoustic field for forced convection ($Re = 1430$) as a function of P, as calculated by (54) assuming $2kL \ll 1$; Nu_n was calculated according to [13] and u_∞ by (48); the experimental points were taken from [5], in which the sublimation of naphthalene ($D = 0.6\ cm^2/sec$) at 285 Hz when the samples ($L = 2$ cm) were flush with the walls of the column was studied. As can be seen from Fig. 4, the theory is in good agreement with the experiment.

NOTATION

u is the velocity of the medium; ρ is the density of the medium; P is the pressure in the medium; γ is the kinematic viscosity; g is the acceleration of gravity; β is the isothermal compressibility; c is the speed of sound; T is the temperature of the medium; $\langle T \rangle$ is the time-averaged temperature of the medium; T_1 is the time-varying temperature of the medium; $V_1(V_{1x}, V_{1y})$ is the rate of oscillation of the medium; V_0 is the amplitude of the oscillation rate; ρ_0 is the mean density of the medium; ρ_1 is the time-varying density of the medium; P_0 is the mean pressure in the medium; P_1 is the variable pressure in the medium; ω is the cyclic frequency of the sound oscillations; $u_0(u_{0x}, u_{0y})$ is the acoustic flow velocity; D is the thermal diffusivity (in diffusion equations, it is the diffusion coefficient); C is the concentration of the substance in the medium; T_0 and C_0 are, respectively, the temperature and concentration of the substance at the surface of the body; T_∞ and C_∞ are, respectively, the temperature and concentration of the substance at a point remote from the surface of the body; $V_{1\infty}$ is the oscillation rate of the medium remote from the surface of the body; u_∞ is the acoustic flow velocity remote from the surface of the body; λ is the acoustic wavelength; k is the wave number; A is the displacement amplitude; d_0 is the diameter of the body; R is its radius; l is the characteristic dimension of the motion; δ is the thickness of the dynamic boundary layer; L is the sample length; Nu'_a is the Nusselt number, a function of the acoustic flow; Nu''_a is the Nusselt number, a function of the oscillation rate; Nu_0 is the Nusselt number in free convection; Nu_n is the Nusselt number in forced convection; $\langle\,\rangle$ signifies averaging with respect to time.

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