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OPTICOACOUSTIC DETERMINATION OF THERMOPHYSICAL CHARACTERISTICS

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UDC [535/534:53.082] + 536.21

The possibilities of utilizing two-layered systems of standard and studied specimens to determine thermophysical characteristics under opticoacoustic experimental conditions are theoretically analyzed.

The opticoacoustic method of investigating solid and liquid media is based on the effect of pressure vibrations originating under the illumination of a specimen in an insulated gas-filled chamber by modulated radiation.

The magnitude and phase shift of the acoustic signal under specific conditions are related uniquely to the magnitude and phase shift of the temperature fluctuations on the specimen surface [1]. This permits utilization of the opticoacoustic method to determine thermophysical characteristics [2-6].

The thermal diffusivity coefficient is determined by exposing one surface of a plane opaque specimen and recording the magnitude or phase of the acoustic signal from the side of its second surface [2-5]. A fine strongly absorbing layer is deposited on the surface being exposed on transparent specimens. The specimen thickness should be within the limits $1.5\mu \leqslant l \leqslant (3\text{-}3.5)\mu$, where $\mu = (2\alpha/\omega)^{1/2}$ is the thermal diffusion length.

If $l > 1.5$ μm, a thermal activity coefficient $(\lambda c\rho)^{1/2}$ can be found for opaque specimens from a comparison of acoustic signals during alternate exposure of the specimen being studied and the standard [6]. But the absorption by the exposed surfaces of the specimen and standard in this case should be or is known to be the same or determined in advance by some method. In addition, the methods mentioned do not permit execution of measurements on thin specimens whose thickness is < 1.5 μm in the whole frequency band utilized.

The opticoacoustic determination of thermophysical characteristics is substantially a modification of the method of plane temperature waves. For the complex determination of thermophysical characteristics in such a method, it is convenient to perform the measurements on two-layered systems consisting of test and standard specimens [7].

It is expedient to use the two-layered system also in the opticoacoustic modification of the method. For opticoacoustic measurements the two-layered system moreover permits studying materials with other optical properties since the radiation can always be directed from the side of the opaque standard. In this connection, the utilization of two-layered systems consisting of test and standard specimens to determine thermophysical characteristics under the conditions of an opticoacoustic experiment is examined in this paper for measurements from both the exposed, as well as the opposite surface.

The one-dimensional model is shown in Fig. 1. Two plane specimens of thickness l_1 and l_2 are in ideal thermal contact and communicate with external surfaces with two volumes of depths l_g and l_b. Sinusoidally modulated radiation is directed at specimen surface 2 for $x = -(l_1 + l_2)$. The radiation absorbed by the surface is converted into heat. This is equivalent to the action of a heat source of the form $I_0[1 + \exp(j\omega t)]$ on the surface.

For measurements from the specimen 2 side the volume before it should be filled with a nonabsorbing gas. When measurements are carried out from specimen 1 the volume behind it can be filled with any gas while the medium in front of specimen 2 should be transparent.

As in [1], we consider the thermal flux and temperature are continuous on the boundaries between the specimens and between each specimen and the corresponding medium, i.e., heat transfer occurs exclusively by heat conduction. Since the temperature rise in such experi-

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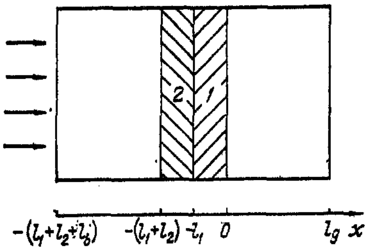

Fig. 1. One-dimensional theoretical model.

ments is insignificant, while the chamber dimensions are small for the origination of convection, the convective and radiative heat transfer components are negligible and the assumption made is sufficiently rigorous.* We also assume that the volume thicknesses l_g and l_b are greater than the thermal wavelength in the media filling them. This means there are no heat losses through them for the periodic component of the temperature distribution.

The heat-conduction equations for each of the domains have the form

$$\frac{\partial^2 T_i}{\partial x^2} = \frac{1}{\alpha_i}\frac{\partial T_i}{\partial t},$$

where i = b, g, 2, 1 for the two media and specimens 1 and 2, respectively.

Solving the system of four equations with the boundary conditions taken analogously to [5], we obtain expression for the temperature fluctuations on the specimen outer surfaces:

$$\Delta T|_{x=0} = \Theta\exp(j\omega t) = s\frac{I_0}{\lambda_2\sigma_2}\{[\mathrm{ch}(\sigma_2 l_2) + b\,\mathrm{sh}(\sigma_2 l_2)] \times$$

$$\times [\mathrm{sh}(\sigma_1 l_1) + g\,\mathrm{ch}(\sigma_1 l_1)] + s[\mathrm{sh}(\sigma_2 l_2) + b\,\mathrm{ch}(\sigma_2 l_2)] \quad [\mathrm{ch}(\sigma_1 l_1) + g\,\mathrm{sh}(\sigma_1 l_1)]\}^{-1}\exp(j\omega t), \tag{1}$$

$$\Delta T|_{x=-(l_1+l_2)} = W\exp(j\omega t) = \frac{I_0}{\lambda_2\sigma_2}\left\{\frac{\mathrm{sh}[\sigma_2(l_1+l_2)] - A\,\mathrm{ch}[\sigma_2(l_1+l_2)]}{\mathrm{ch}[\sigma_2(l_1+l_2)] - A\,\mathrm{sh}[\sigma_2(l_1+l_2)]} + b\right\}^{-1}\exp(j\omega t),$$

where

$$A = \frac{\mathrm{ch}(\sigma_2 l_1)[\mathrm{sh}(\sigma_1 l_1) + g\,\mathrm{ch}(\sigma_1 l_1)] - s\,\mathrm{sh}(\sigma_2 l_1)[\mathrm{ch}(\sigma_1 l_1) + g\,\mathrm{sh}(\sigma_1 l_1)]}{\mathrm{sh}(\sigma_2 l_1)[\mathrm{sh}(\sigma_1 l_1) + g\,\mathrm{ch}(\sigma_1 l_1)] - s\,\mathrm{ch}(\sigma_2 l_1)[\mathrm{ch}(\sigma_1 l_1) + g\,\mathrm{sh}(\sigma_1 l_1)]};$$

$$\sigma_i = (1+j)a_i;\ a_i = \frac{1}{\mu_i} = \left(\frac{\omega}{2\alpha_i}\right)^{1/2};\ j = \sqrt{-1};$$

$$s = \frac{\lambda_2 a_2}{\lambda_1 a_1} = \frac{(\lambda_2 c_2 \rho_2)^{1/2}}{(\lambda_1 c_1 \rho_1)^{1/2}};\quad g = \frac{\lambda_g a_g}{\lambda_1 a_1};\quad b = \frac{\lambda_b a_b}{\lambda_2 a_2}.$$

If the gas is taken ideal and it is considered that the pressure varies the same amount simultaneously over the whole volume, then for gas thicknesses greater than the thermal wavelength the pressure fluctuations are related to the temperature fluctuations on the specimen surface by the dependence [1]

$$\Delta P = \frac{\Delta T\,\gamma P_0}{\sqrt{2}\,a_g l_g T_0}\exp\left(-j\frac{\pi}{4}\right).$$

Here $\Delta T = \Theta\exp(j\omega t)$ or $\Delta T = W\exp(j\omega t)$.

The amplitude of the pressure fluctuations is proportional to the amplitude of the temperature fluctuations, while the phase shift differs by a constant $\pi/4$. Consequently, we henceforth limit ourselves to the analysis of the temperature fluctuations.

In general form (1) and (2) are complicated to analyze and do not permit analytic separation of the influence of the thermophysical and geometric parameters of each specimen into the magnitude and phase of the temperature fluctuations. But if at least one of the specimens satisfies the condition $a_i l_i > 1.5$, such a separation is possible.

Let us examine two cases.

1. Specimen 1 is relatively thick, i.e., $a_1 l_1 > 1.5$. Then $\mathrm{ch}(\sigma_1 l_1) \approx \mathrm{sh}(\sigma_1 l_1)$.

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*Radiant heat exchange at ordinary temperatures becomes perceptible for modulation frequencies less than 10 Hz if the specimen is very thin ($<10^{-3}$-10^{-4} of the thermal wavelength) and surrounded by gas on two sides.

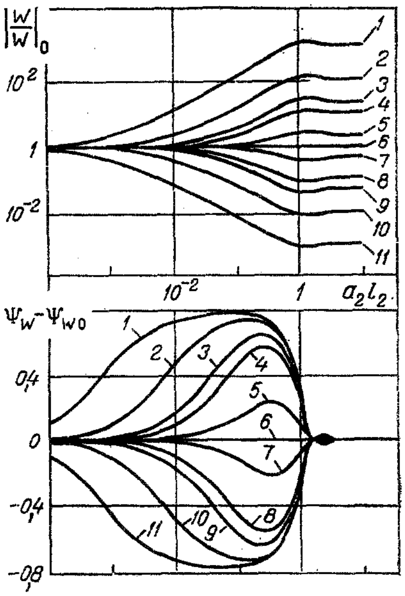

Fig. 2. Relative change in the amplitude and phase shift for the temperature fluctuations on the surface $x = -(l_1 + l_2)$ induced by specimen 2: 1) $s = 10^{-3}$; 2) 10^{-2}; 3) $5 \cdot 10^{-2}$; 4) 10^{-1}; 5) $5 \cdot 10^{-1}$; 6) 1; 7) 2; 8) 10^1; 9) $2 \cdot 10^1$; 10) 10^2; 11) 10^3; $b \ll s$, $bs \ll 1$. $[W]/[W]_0$ and $a_2 l_2$ dimensionless, Ψ_W in rad.

Simplifying (1) and (2) and extracting real and imaginary parts, we determine the amplitude of the temperature fluctuations on the specimen outer surfaces, and their phase shift relative to the radiation intensity fluctuations (heat source intensity fluctuations):

$$|W| = \frac{I_0}{\sqrt{2}\lambda_1 a_1 s} \left\{ \frac{[s\,\mathrm{sh}(a_2 l_2) + \mathrm{ch}(a_2 l_2)]^2 + \cos^2(a_2 l_2)(s^2 - 1)}{[(1+bs)\mathrm{ch}(a_2 l_2) + (s+b)\mathrm{sh}(a_2 l_2)]^2 + \sin^2(a_2 l_2)[(s+b)^2 - (1+sb)^2]} \right\}^{1/2}, \tag{3}$$

$$\Psi_W = \Psi|_{x=-(l_1+l_2)} = -\frac{\pi}{4} + \mathrm{arctg}\left[\mathrm{tg}\,(a_2 l_2)\frac{\mathrm{ch}(a_2 l_2) + s\,\mathrm{sh}(a_2 l_2)}{\mathrm{sh}(a_2 l_2) + s\,\mathrm{ch}(a_2 l_2)}\right] \tag{4}$$

$$- \mathrm{arctg}\left[\mathrm{tg}\,(a_2 l_2)\frac{(1+bs)\,\mathrm{sh}(a_2 l_2) + (s+b)\,\mathrm{ch}(a_2 l_2)}{(1+bs)\,\mathrm{ch}(a_2 l_2) + (s+b)\,\mathrm{sh}(a_2 l_2)}\right],$$

$$|\Theta| = \frac{I_0}{\sqrt{2}\lambda_1 a_1 (1+g)\dfrac{\exp(a_1 l_1)}{2}} \{[(1+bs)\,\mathrm{ch}(a_2 l_2) + (s+b)\,\mathrm{sh}(a_2 l_2)]^2 + \sin^2(a_2 l_2)[(s+b)^2 - (1+sb)^2]\}^{-1/2}, \tag{5}$$

$$\Psi_\theta = \Psi|_{x=0} = -\frac{\pi}{4} - a_1 b_1 - \mathrm{arctg}\left[\mathrm{tg}\,(a_2 l_2)\frac{(1+bs)\,\mathrm{sh}(a_2 l_2) + (s+b)\,\mathrm{ch}(a_2 l_2)}{(1+bs)\,\mathrm{ch}(a_2 l_2) + (s+b)\,\mathrm{sh}(a_2 l_2)}\right]. \tag{6}$$

The contribution induced by each of the specimens in these expressions is represented in the form of a separate factor or component.

If $l_2 \to 0$, expressions (3)-(6) become

$$|W|_0 = \frac{I_0}{\sqrt{2}\lambda_1 a_1 (1+bs)}, \tag{7}$$

$$\Psi_{W0} = -\frac{\pi}{4}. \tag{8}$$

$$|\Theta|_0 = \frac{I_0}{\sqrt{2}\,\lambda_1 a_1 (1+g)\,\dfrac{\exp(a_1 l_1)}{2}\,(1+bs)}\,, \tag{9}$$

$$\Psi_{\theta 0} = -\frac{\pi}{4} - a_1 b_1, \tag{10}$$

where

$$bs = \frac{\lambda_b a_b}{\lambda_2 a_2}\,\frac{\lambda_2 a_2}{\lambda_1 a_1} = \frac{\lambda_b a_b}{\lambda_1 a_1}\,.$$

The quantities a_i and s are in the expressions for the temperature fluctuations on each of the surfaces. The latter contains information about the thermal diffusivity coefficient α_i, while s is the ratio between the thermal activity coefficients $(\lambda_i c_i \rho_i)^{1/2}$ of the two specimens. Let us examine how these quantities influence the temperature fluctuations on the specimen outer surfaces.

The relative change in amplitude and phase of the temperature fluctuations on the surface $x = -(l_1 + l_2)$ induced by specimen 2 is shown in Fig. 2 as a function of $a_2 l_2$.

The phase in the domain $a_2 l_2 < 1.5$ and the amplitude in domain $a_2 l_2 < 0.6$ for the temperature fluctuations are sensitive to the change in $a_2 l_2$ and s. The stronger the distinction between the thermal properties of the specimens, i.e., the greater s differs from 1 on any side, the smaller the values of $a_2 l_2$ at which the influence of specimen 2 is felt.

For $a_2 l_2 > 1.5$ the temperature fluctuations on the outer surface of specimen 2 are independent of the properties of specimen 1 and (3) and (4) become

$$|W| = \frac{I_0}{\sqrt{2}\,\lambda_2 a_2 (1+b)}\,, \tag{11}$$

$$\Psi_W = -\frac{\pi}{4}\,. \tag{12}$$

To determine the domain W of sensitivity to a change in s we consider the amplitude and phase of the temperature fluctuations as a function of s (Fig. 3). For greater graphicalness, the amplitude of the temperature fluctuations is represented in the form of a dimensionless quantity $|W|/I_0 \cdot \lambda_2/l_2$.

We can see from the figure that if $a_2 l_2 \geqslant 0.1$, then both the amplitude and the phase of the temperature fluctuations are sensitive to s when s differs from one by not more than one order.

As $a_2 l_2$ diminishes, the domain of phase sensitivity to the change in s is shifted to the value of s, more and more different from one, and there is no phase shift near s = 1. This means that as $a_2 l_2$ diminishes, the domain of values s in which the specimen 2 does not induce changes in the temperature distribution is broadened more and more. This corresponds to straight lines of identical slope on the graphs for $\dfrac{|W|}{I_0}\dfrac{\lambda_2}{l_2}$.

For an appropriate selection of the standard, the coefficient of thermal activity of specimen 1 can be determined by the magnitude or phase of W if specimen 2 is the standard, one of the thermophysical characteristics α_2 or $(\lambda_2 c_2 \rho_2)^{1/2}$ of specimen 2 if the second is known and specimen 1 is the standard, or even both at once by the magnitude and position of the phase extremum.

In the case of transparent materials, a strongly absorbing layer must be deposited on the specimen surface, whose thickness should be smaller the stronger the difference between its thermal properties and those of the specimen itself.

As follows from Fig. 2, if the coefficients of thermal activity of the coating and the specimen differ by not more than 10 times, the relative thickness of the coating should not exceed $a_i l_i \approx (3\text{-}5)\cdot 10^{-3}$. This corresponds to a thickness of $(0.5\text{-}1)\cdot 10^{-5}$ m for dielectrics at a modulation frequency of 100 Hz. Consequently, in studying such materials it is often simpler not to use a thin coating but a thicker opaque standard specimen.

Shown in Fig. 4 is the relative change in amplitude and phase of temperature fluctuations on the surface x = 0 induced by specimen 2. The strong dependence of the temperature fluctua-

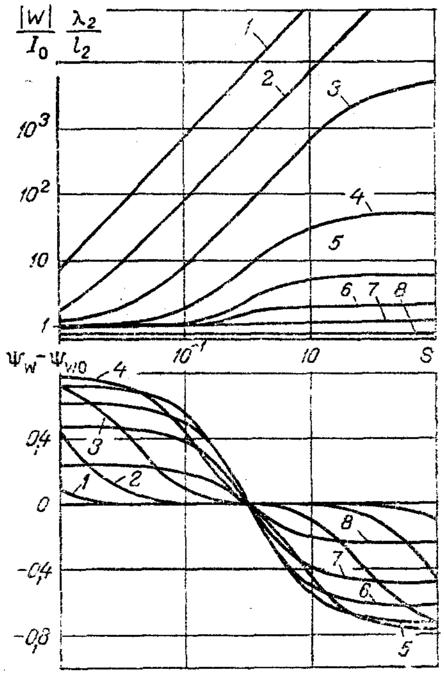

Fig. 3

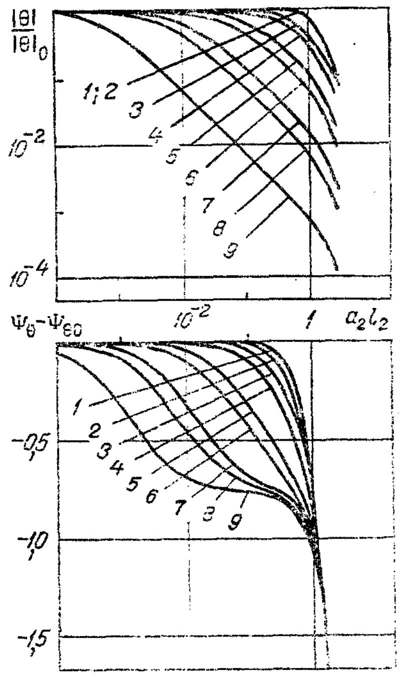

Fig. 4

Fig. 3. Sensitivity of the amplitude and phase shift of the temperature vibrations on the surface $x = -(l_1 + l_2)$ to a change in the quantity s: 1) $a_2l_2 = 10^{-4}$; 2) 10^{-3}; 3) 10^{-2}; 4) 10^{-1}; 5) 0.3; 6) 0.5; 7) 0.7; 8) 1.0, $\frac{|W|}{I_0}\frac{\lambda_2}{l_2}$ and s are nondimensional, while Ψ_W is in rad.

Fig. 4. Relative change in the amplitude and phase shift of temperature fluctuations on the surface $x = 0$ induced by specimen 2: 1) $s = 10^{-3}$, 10^{-2}; 2) 10^{-1}; 3) $5\cdot10^{-1}$; 4) 1; 5) 5; 6) 10^1; 7) $5\cdot10^1$; 8) 10^2; 9) $s = 10^3$. $b \ll s$, $bs \ll 1$ and $|\Theta|/|\Theta|_0$ and a_2l_2 dimensionless, Ψ_Θ in rad.

tion parameters on s for small a_2l_2 now holds only for $s > 1$, i.e., when specimen 2 conducts heat better than specimen 1. This imposes additional constraints on the selection of the standard, while at the same time its thermal activity coefficient need not be known for the determination of the thermal diffisuvity coefficient of specimen 2 for $s < 10^{-1}$.

The insensitivity of thermal fluctuations to the presence of the thin heat insulating layer can be used also in measuring the thermal diffusivity coefficients of weakly absorbing materials.

Another distinction of the measurement conducted from the side of specimen 1 is a different dependence of the amplitude and phase of the temperature fluctuations on a_2l_2. This permits determination of the coefficients of both the thermal diffusivity and the thermal activity of either of the specimens by means of $|\Theta|$ and $|W|$ or Ψ_Θ and Ψ_W if the other is the standard.

2. The specimen 2 is relatively thick, i.e., $a_2l_2 > 1.5$ and $\mathrm{ch}(\sigma_2l_2) \approx \mathrm{sh}(\sigma_2l_2)$. On the surface $x = 0$ we obtain from (1)

$$|\Theta| = \frac{I_0 s}{\sqrt{2}\,\lambda_2 a_2 (1+b)\,\dfrac{\exp(a_2 l_2)}{2}} \times$$

$$\times\{[(s+g)\mathrm{ch}\,(a_1 l_1) + (1+gs)\,\mathrm{sh}\,(a_1 l_1)]^2 + \sin^2(a_1 l_1)\,[(1+gs)^2 - (s+g)^2]\}^{-1/2}, \tag{13}$$

$$\Psi_\Theta = -\frac{\pi}{4} - a_2 l_2 - \mathrm{arctg}\left[\mathrm{tg}\,(a_1 l_1)\frac{(1+gs)\,\mathrm{ch}\,(a_1l_1)+(s+g)\mathrm{sh}\,(a_1l_1)}{(1+gs)\,\mathrm{sh}\,(a_1l_1)+(s+g)\mathrm{ch}(a_1l_1)}\right]. \tag{14}$$

The dependences (13) and (14) are analogous to (5) and (6) if s is replaced by 1/s and $a_2 l_2$ by $a_1 l_1$. But this case is more convenient when studying thin specimens transmitting radiation.

The change in the amplitude and phase of the temperature fluctuations on the surface $x = -(l_1 + l_2)$ has already been examined above for $a_2 l_2 > 1.5$ and is described by (11) and (12).

Utilization of a two-layered system consisting of standard and test specimens permits determination of the thermal diffusivity and thermal activity coefficients by which the heat-conduction coefficient can also be computed under the conditions of an opticoacoustic experiment. Different modifications of the measurements afford the possibility of determining the thermophysical characteristics of specimens with different optical and geometric parameters with least difficulties.

Thermal wave propagation is a modification of the wave process with the distinction that the thermal wave damps out practically completely at a distance of one wavelength. A thermal wave is partially reflected and partially transmitted from one medium to another on the boundary between two media. The thermal wave reflection and transmission coefficients depend on the relationships between the thermal properties of the two media. If conditions of temperature and heat flux continuity are conserved on the boundary, then for the passage of a wave from medium 1 to medium 2 they have the form [8]

$$R = \frac{1 - \lambda_2 a_2/\lambda_1 a_1}{1 + \lambda_2 a_2/\lambda_1 a_1};\ T = \frac{2}{1 + \lambda_2 a_2/\lambda_1 a_1}.$$

Examination of the thermal wave propagation process is carried out from this viewpoint in [9]. The results of this paper are similar to our case displayed in Fig. 2, but the reflection coefficient R is used as parameter rather than s.

The thinner the specimen, the greater the number of times does the thermal wave succeed in being reflected from its surface, i.e., the temperature on the surface of a thin specimen depends on its thickness. Utilization of the constant magnitude of the temperature fluctuations on the surface as the boundary condition, as is done in [7], results in a loss of part of the solution.

NOTATION

ω, angular modulation frequency; l, length; t, time; I_0, half the heat source intensity; ΔT, periodic component of the temperature distribution; Ψ, phase shift; α, thermal diffusivity coefficient; λ, heat-conduction coefficient; c, specific heat; γ, ratio of the gas specific heats at constant pressure and constant volume; P_0, gas pressure level in the chamber; T_0, gas temperature level in the chamber; R, coefficient of thermal wave reflection; and T, coefficient of thermal wave transmission.

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CHOICE OF THE INTERMOLECULAR COLLISION FREQUENCY FOR MODEL KINETIC EQUATIONS IN THE THEORY OF MOTION OF A RAREFIED GAS

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B. T. Porodnov, and V. D. Seleznev

UDC 533.722 + 533.6.011.8

The effect of the intermolecular collision frequency on the nonisothermal motion of a rarefied gas is considered.

1. The motion of a one-component rarefied gas in a channel has been theoretically treated using various methods based on the Boltzmann equation or models derivable from it. A fairly complete review of this approach can be found in [1-4]. The problem has been solved using the BGK equations [1-3], the ellipsoidal statistical model (EL model) of [5, 6], and the S model of [7, 8]. The advantage of third-order models, such as the EL and S models, compared to the BGK model is that in the approach to a continuous medium, the former give correct expressions for the stress tensor and heat-flux density [9].

The general form of the linearized kinetic equation for the third-order models is given in [10]. In the solution of the equation, one must choose the intermolecular collision frequency γ. The choice for γ is fairly arbitrary [9, 10], but at the same time it should be done such that the solution obtained from the model equation correspond to that of the Boltzmann equation.

In [11, 12] the effect of the choice for the intermolecular collision frequency on the solutions for Couette flow and the structure of shock waves was studied using a method based on the model equations proposed by Gross and Jackson [13].

In the present paper, we study the heat and mass transport of a rarefied gas moving in a plane channel under temperature and pressure gradients using the third-order model kinetic equation [10] for different values of the frequency γ. We then study the effect of the value γ on the solution over the whole range of Knudsen numbers.

2. We consider motion of a monoatomic one-component rarefied gas in a channel formed by two infinite parallel plates ($x = \pm d/2$) and induced by pressure and temperature gradients along the channel, where the z axis is taken along the channel. We consider the state of the gas to be weakly perturbed and therefore the distribution function can be written in the form

$$f(\vec{r}, \vec{v}) = f_0(z, \vec{v})[1 + h(x, \vec{v})], \quad \|h(x, \vec{v})\| \ll 1, \tag{1}$$

$$f_0(z, \vec{v}) = n(z) \left(\frac{m}{2\pi k T(z)}\right)^{3/2} \exp\left(-\frac{mv^2}{2kT(z)}\right),$$

where $n(z)$, $T(z)$, and m are, respectively, the number density, temperature of the gas, and mass of the molecule. The function $h(x, \vec{v})$ is the perturbation.

We write the third-order linearized model kinetic equation in the form [7, 10]

$$v_x \frac{\partial h}{\partial x} + v_z \left[\nu + \tau\left(c^2 - \frac{5}{2}\right)\right] = -\gamma h + 2\gamma u_z c_z + 4P_{xz}(\gamma - \nu^{(3)} + \nu^{(4)}) c_x c_z + \frac{8}{5} q_z (\gamma - \nu^{(5)} + \nu^{(6)}) \left(c^2 - \frac{5}{2}\right) c_z, \tag{2}$$

where the macroscopic quantities, in correspondence with their kinetic definitions, can be written in the form

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