

NOTATION

u_∞ , undisturbed flow velocity; v_w , u_w , surface suction rate; $Re = u_\infty R/\nu$, Reynolds number; τ_w , surface friction stress; $\bar{u} = u/u_\infty$, dimensionless velocity; $\bar{X} = x/R$, dimensionless coordinate; R , characteristic dimension (radius) of body flowed over; f , dimensionless flow function; η , self-similar coordinate; $B \sim \sqrt{Re}/(d\bar{u}/d\bar{X})_0$, velocity gradient parameter; T , temperature, λ , thermal conductivity coefficient; ρ , flow density; $Pe = u_\infty R C_p \rho / \lambda$, Peclet number; κ , thermal diffusivity coefficient; q_w , thermal flux surface density.

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KNUDSEN MOLECULAR FLOW IN A CHANNEL WITH A SMALL TEMPERATURE DIFFERENCE AT ITS ENDS

V. D. Seleznev, B. T. Porodnov, A. N. Kulev,
A. G. Flyagin, A. N. Kudertsev, and S. P. Obraz

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The thermomolecular pressure difference (TPD) of helium, argon, and krypton is measured in a packet of glass capillaries for temperatures 273 and 293 K at their ends in a 10-100 range of Knudsen numbers.

The temperature difference at the ends of a gas-filled channel results in the occurrence of a mass flow. In a closed system this flow causes the so-called thermomolecular pressure difference.

Elementary kinetic theory, based on the assumption that the density of molecule collisions with the channel wall in the Knudsen mode should not depend on the coordinates, yields the following result [1] for the pressure ratio at the ends of the channel:

$$\frac{P_h}{P_c} = \left(\frac{T_h}{T_c} \right)^\gamma; \quad \gamma = 1/2. \quad (1)$$

A strict kinetic solution of the corresponding boundary-value problem with specularly diffuse molecule scattering at the walls allows one to find an expression for the exponent γ of the effect for arbitrary Knudsen numbers [2] in terms of the reduced flux of numbers of particles subjected to the temperature gradient (thermal creep) Q_T and the pressure gradient (Poiseuille flow) Q_p in the form

S. M. Kirov Ural Polytechnic Institute, Sverdlovsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 54, No. 5, pp. 719-724, May, 1988. Original article submitted January 16, 1987.

$$\gamma = \frac{Q_T}{Q_P} \quad (2)$$

In the limit when the Knudsen number $Kn \rightarrow \infty$, under the boundary conditions mentioned Q_T and Q_P depend in an identical manner on the fraction ε of molecules reflected diffusely by the walls [3] and the exponent γ also equals 1/2.

However, Hobson [4] showed experimentally that the exponent γ of the TPD effect in (1) differs from 1/2 and for different gas-surface combinations is in the range $\gamma = 0.4-0.5$. This effect permitted Hobson [5] to propose and realize a new kind of vacuum pumping by using accommodation pumps. But the mechanism of accommodation pump action remains unclear. Tests were performed in the papers mentioned under conditions of a large temperature difference ($T_c = 77$ K; $T_h = 293$ K) when nonlinear effects can occur without the realization of a separate measurement of the fluxes Q_P and Q_T . This makes a theoretical interpretation of the phenomenon difficult.

On the basis of a separate measurement of the exponent γ and the Poiseuille flow Q_P in channels from one batch, values are established in this paper for the Knudsen nonisothermal flux Q_T for helium, argon, and krypton in fused glass capillaries. The small temperature difference utilized ($\Delta T = 20$ K) reduces the possibility of the appearance of nonlinear effects during execution of the experiment and removes the problem of determining the mean temperature to which the obtained experimental data should be referred.

1. Experimental Set-Up

The diagram, in principle, of the experimental installation to measure the thermomolecular pressure difference is presented in Fig. 1. The main component of the installation is the system of "hot" 3 (V_h) and "cold" 1 (V_c) volumes connected by the capillary packet 2. In order to avoid taking account of temperature corrections when measuring the pressure differences in volumes 1 and 3, the pressure change in the volume 3 due to the passage from the isothermal state of the closed system of flasks 3 and 1 to a steady nonisothermal state. The gas particle redistribution associated with this passage can be described by an equation of state of the following kind:

$$\frac{P_0(V_h + V_c)}{T_h} = \frac{P_h V_h}{T_h} + \frac{P_c V_c}{T_c} \quad (3)$$

Here P_0 is the gas pressure in the system in the isothermal state. It was assumed in the derivation of (3) that the temperature T_h of the "hot" volume equals the initial temperature of the system isothermal state, and it was also taken into account that the capillary volume is $V_{cap} \ll V_h + V_c$.

It is easy to obtain for the exponent of the TPD effect

$$\gamma = \frac{\ln(P_h/P_c)}{\ln(T_h/T_c)} = 1 - \frac{\ln \left[\frac{P_0}{P_h} \left(1 + \frac{V_h}{V_c} \right) - \frac{V_h}{V_c} \right]}{\ln \left(\frac{T_h}{T_c} \right)} \quad (4)$$

from the solution of the system (3) and (1). In conformity with (4), the quantities P_0 , P_h , V_h/V_c and T_h/T_c must be measured to determine the exponent γ .

In order not to cool the volume 1 again during each admission of gas in the system, an auxiliary volume 17 is used, which has been selected so that the gas pressure therein would correspond to P_0 . In the experiment the micromanometer 21 determines the pressure difference in volumes 3 and 17, i.e.,

$$\Delta P = P_0 - P_h \quad (5)$$

Substituting (5) into (4), we obtain the final expression to determine γ :

$$\gamma = 1 - \frac{\ln \left[\frac{P_0}{P_0 - \Delta P} \left(1 + \frac{V_h}{V_c} \right) - \frac{V_h}{V_c} \right]}{\ln \left(\frac{T_h}{T_c} \right)} \quad (6)$$

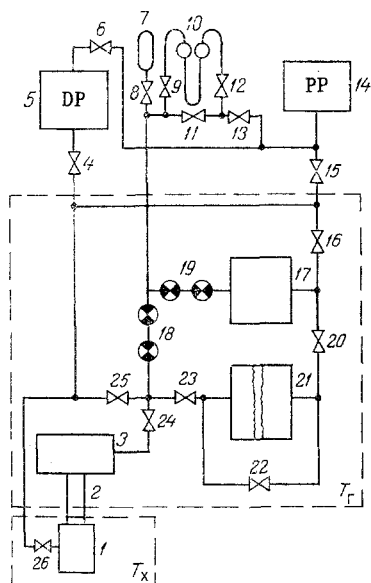


Fig. 1

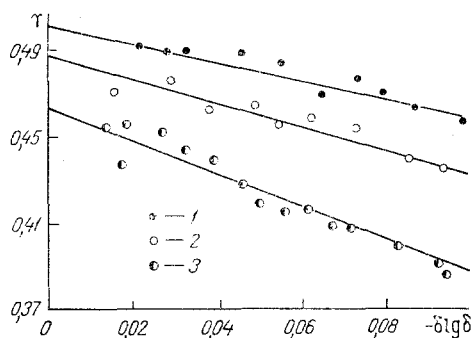


Fig. 2

Fig. 1. Diagram, in principle, of the experimental set-up: 1) "cold" volume; 2) capillary packet; 3) upper ("hot") chamber; 4) valve of the diffusion pump evacuation track; 5) diffusion pump (DP); 6) valve of diffusion pump prevacuum exhaustion; 7) tank with gas being investigated; 8) needle valve; 9, 12) valves of oil manometer legs; 10) oil manometer; 11) oil manometer bypass valve; 13) valve of prevacuum evacuation of oil manometer track; 14) prevacuum pump (PP); 15) evacuation valve of prevacuum pump; 16) valve of installation evacuation; 17) auxiliary volume; 18, 19) calibrated volumes; 20, 23) pressure sensor valves; 21) capacitive pressure sensor; 22) pressure sensor bypass valve; 24) working chamber valve; 25) installation evacuation valve; 26) evacuation valve of "cold" volume.

Fig. 2. Experimental dependence $\gamma = f(-\delta \log \delta)$: 1) Kr; 2) Ar; 3) He. γ , δ dimensionless.

2. Experimental Methodology

The following method is used to measure the thermomolecular pressure difference. Part of the system in which the upper "hot" chamber 3, the calibrated volumes 18 and 19, the auxiliary volume 17, and capacitive pressure sensor 21 [6], the valves and piping connecting the chamber with the admission, evacuation tracks and the pressure sensor enter (see Fig. 1) is thermostatted at room temperature. The "cold" volume 1 is at the temperature of thawing ice. The installation is evacuated prior to the admission of gas. The diffusion oil-vapor pump 5 in the system with the prevacuum pump 14 assures vacuum evacuation to the pressure 10^{-2} - 10^{-3} Pa. Then the system is scavenged of the gas under investigation after which it is again evacuated to the above-mentioned pressure. The gas under investigation is admitted from the tank 7 into the calibrated volumes 18 and 19 by means of the needle valve 8 up to a given pressure P_M determined by means of the oil manometer 10. The calibrated volumes are cut off from the bypass lines bounded by the valves in the system prior to gas admission; the valves 16, 22, 25, and 26 are closed while the valves 20, 23, and 24 are open. The gas spreads isothermally into the auxiliary volume 17 and the working volumes 1 and 3 of the installation. The working, auxiliary, and calibrated volumes are chosen in such a way as to satisfy the relationship

$$\frac{V_{cal1}}{V_{aux}} = \frac{V_{cal2}}{V_{wor}} \quad (7)$$

Using the equation of state, we determine the pressure P_0 for a known ratio (7) and the pressure P_H in the calibrated volumes.

TABLE 1. Isothermal and Nonisothermal Gas Flow Parameters

Gas	He	Ar	Kr
$\gamma \pm \Delta\gamma \cdot 10^3$	0,464 \pm 4	0,488 \pm 5	0,502 \pm 4
$\omega_p \pm \Delta\omega_p \cdot 10^3$	1,140 \pm 4	1,042 \pm 3	1,003 \pm 4
$\omega_T \pm \Delta\omega_T \cdot 10^3$	1,06 \pm 1	1,02 \pm 1	1,01 \pm 1
$1 - \varepsilon \pm \Delta(1 - \varepsilon) \cdot 10^3$	0,029 \pm 5	0,009 \pm 5	0,004 \pm 5
$\alpha_t \pm \Delta\alpha_t \cdot 10^3$	0,929 \pm 6	0,978 \pm 7	1,003 \pm 6

When a definite thermomolecular pressure difference is set in the working chamber and there is a pressure P_h in its upper ("hot") part, the capacitive sensor records the pressure difference ΔP between the working and auxiliary parts of the installation. The measurement of T_h and T_c is by thermocouples to accuracy no worse than 0.1 K. To measure the ratio of the volumes V_h/V_c a special series of tests was performed whereupon $V_h/V_c = 0.103 \pm 0.001$ was found.

The packet 2 consists of 98 capillaries from $L = (316 \pm 2)$ mm long fused glass and $D = (0.496 \pm 0.001)$ mm channel diameter.

3. Experiment Results

Experiments were performed to measure the effect of the thermomolecular pressure difference for the gases Ar, Kr, and He for $T_c = 273$ K, $\Delta T = 20$ K on the basis of the methodology described. The gas rarefaction parameter δ was determined from the following formula:

$$\delta = \frac{V\pi}{2} \frac{1}{Kn} = \frac{D\bar{P}}{2\eta \left(\frac{2kT}{m}\right)^{1/2}} \quad (8)$$

The range of variation of the parameter δ in the experiment was 0.1-0.01.

Results of the experiments are represented in Fig. 2. It is shown theoretically in [7] that γ depends linearly on the complex $\delta \log \delta$ near the free-module mode. By linear extrapolation of the dependence $\gamma = \gamma(-\delta \log \delta)$ to zero values of the argument, the limit ($Kn \rightarrow \infty$) quantities of γ were found. As is seen from Table 1, the values of the exponent γ of the TPD effect in the Knudsen mode differ noticeably from 1/2 for helium and argon.

The values determined experimentally for the exponent γ are conveniently used to seek the Knudsen nonisothermal flux Q_T in conformity with (2). The magnitudes of the Poiseuille flux Q_p were determined experimentally in analogous channels in [8, 9]. Values of the dimensionless fluxes $\omega_{p,T} = Q_{p,T}/Q_{p,T}^0$, where $Q_{p,T}^0$ is the Poiseuille flux or thermocreep flux for diffuse molecule scattering by a wall. The results show that the thermal creep, although to a lesser degree than the Poiseuille flux, depends on the nature of the gas-solid interaction.

Theoretical expressions for γ and ω_T , based on using the Maxwell specularly diffuse scattering kernel (γ^M and ω_T^M) and the one-parameter Cercignani-Lampis kernel (γ^C and ω_T^C) obtained in [10], yield the following dependence of these quantities on the fraction ε of diffuse molecule scattering by a wall and the accommodation coefficient of the tangential moment α_t :

$$\gamma^M = 1/2, \quad \gamma^C = \frac{1}{2 + \frac{3\pi(1-\alpha_t)}{4\alpha_t}} \quad (9)$$

$$\omega_T^M = \frac{2-\varepsilon}{\varepsilon} \frac{4}{3\sqrt{\pi}}, \quad \omega_T^C = \frac{4}{3\sqrt{\pi}}$$

Comparing (9) with test data (see Table 1), we see that neither the specularly diffuse nor the Cercignani-Lampis models permit simultaneous description of the experimental results on isothermal and nonisothermal gas motion in channels. This is apparently associated with

the fact that the models mentioned do not reflect any essential features of the inert gas scattering phenomenon by solid surfaces.

In conformity with the more adequate model of gas atom scattering [11], the reflected particles can be separated into two parts: molecules of a single passage of the near-surface layer (I), and molecules that have been reflected at least once from the potential barrier of far-reaching attraction (II). Reflection by the first mechanism is almost specular [11]. Molecules that have resided in a state associated with the surface (mechanism II) have a high probability of arriving in thermal equilibrium with the surface; consequently, they should have a velocity distribution similar to the Maxwellian. However, it is impossible to expect total equilibrium since a nonzero probability exists for the escape of particles that have not reached thermal equilibrium with the surface (the so-called "hot" atoms).

The specularly diffuse mode of the scattering kernel does not take account of the "hot" particles, while the Cercignani-Lampis model has no partition into two kinds of interaction. It is useful to introduce a fraction of gas atoms that pass through the surface layer $(1 - \varepsilon)$ once and to describe this fraction by a specular scattering kernel R and to use a one-parameter Cercignani-Lampis scattering kernel $C(\alpha_t)$ to describe the remaining particles. The scattering kernel taking account of both the specularity of the reflection and the "hot" particles of incomplete thermalization has the form

$$W = \varepsilon C(\alpha_t) + (1 - \varepsilon)R. \quad (10)$$

Experiments on the isothermal [8, 9] and nonisothermal gas flow show that Q_T and Q_p differ from Q_T, p^0 by not more than 10-12%. It is consequently reasonable to assume that $(1 - \varepsilon) \ll 1$ and $(1 - \alpha_t) \ll 1$ in the model (10). The expressions for fluxes using the kernel (10) have the form

$$Q_T = Q_T^0(1 + 2(1 - \varepsilon)), \quad Q_p = Q_p^0 \left(1 + 2(1 - \varepsilon) + \frac{3\pi}{8}(1 - \alpha_t) \right). \quad (11)$$

Expressions (11) permit conception of the reason for the experimental dependence of the TPD exponent γ and the thermal creep Q_T on the incompleteness of the accommodation. The parameters $(1 - \varepsilon)$ and α_t of the model (10), which are represented in Table 1, were determined from the condition of best agreement between the theoretical results and the experimental data.

Therefore, the exponents γ of the TPD effect and the magnitudes of the thermal creep Q_T fluxes of the gases He, Ar, and Kr are determined from experimental data for the limit free-molecule flow mode. Their essential dependence on the nature of the gas-solid interaction is shown. The parameters of the modified scattering kernel (10), the fraction $(1 - \varepsilon)$ of the gas atoms being scattered specularly by the wall, and the coefficient α_t of accommodation of the tangential momentum of molecules scattered inelastically are determined from the condition of agreement between the theoretical description and the test data.

NOTATION

γ , exponent of the thermomolecular pressure difference effect; Kn , Knudsen number; δ , rarefaction parameter; Q_T , reduced thermal creep flux; Q_p , reduced Poiseuille flux; $C(\alpha_t)$, Cercignani-Lampis scattering kernel; R , specular scattering kernel; $(1 - \varepsilon)$, fraction of specular reflection; α_t , accommodation coefficient of the tangential momentum; P_c, P_h , gas pressure in the "cold" and "hot" volumes, respectively; $\bar{P} = (P_h + P_c)/2$; $\bar{T} = (T_h + T_c)/2$; η , coefficient of dynamic viscosity; m , mass of gas molecules; k , Boltzmann constant; and D, L , the capillary diameter and length, respectively.

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MOTION OF A BINARY GAS MIXTURE IN A POROUS MEMBRANE WITH A STRAIGHT CHANNEL

B. A. Ivakin, V. M. Malakhin, B. T. Porodnov,
and V. D. Seleznev

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The diffusional baric effect at a porous barrier with a straight channel is investigated theoretically and experimentally with an arbitrary ratio of the channel and pore diameter to the free path length of molecules of the gas mixture.

Porous membranes with straight channels of diameter considerably differing from the characteristic dimensions of the pores are widely used in various technological processes. The straight channels are used for sharp reduction in the diffusional and hydraulic resistance in drying friable and porous materials, and with heterogeneous catalysis in the cores of the thermal tubes. A finely porous membrane with broad penetrating channels combines high specific surface with large conduction. Expansion of the region of application of such membranes is delayed by the limited study of their properties, especially at intermediate Knudsen numbers.

In the present work, a method of determining the effective kinetic coefficients of motion of binary gas mixtures in such membranes over a wide range of Knudsen membranes is described and experimentally tested.

1. Effective Kinetic Coefficients for a Gas of Any Degree of Rarefaction

Consider the isothermal motion of a binary gas mixture under the action of pressure and concentration differences in a porous cylindrical membrane of length l and radius R , along the axis of which there is a straight cylindrical channel of radius r_0 (Fig. 1). Suppose that the lateral surface of the membrane is impermeable, while the mean pore radius is equal to r . With variation in gas-mixture pressure in the membrane with $r \ll r_0$, the following combinations of flow conditions may be realized: $r \ll r_0 \ll \lambda$, free-molecular conditions in the whole membrane; $r \ll r_0 \sim \lambda$, intermediate conditions in the straight channel and free-molecular conditions in the pores; $r \ll \lambda \ll r_0$, viscous flow conditions in the straight channel and free-molecular conditions in the pores; $r \sim \lambda \ll r_0$, viscous conditions in the straight channel and intermediate conditions in the pores; $\lambda \ll r \ll r_0$, viscous flow conditions in the whole membrane.

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