FLOW OF RAREFIED GASES IN A CAPILLARY SCREEN AT DIFFERENT TEMPERATURES

V. D. Akin'shin, S. F. Borisov,
B. T. Porodnov, and P. E. Suetin

UDC 533.6.011.8

An experimental study was made of the flow of the gases He, Ne, Ar, Kr, Xe, H_2, D_2, N_2, CO_2, and CH_4 in the range of Knudsen numbers of 10^4-10^{-1} at room temperature in a capillary screen. A study was also made of the flow of a number of inert and diatomic gases at temperatures of 77.2 and 194.7°K in an orifice and in a capillary screen. The relative flow rates were determined in the free-molecular mode of flow. The coefficients of accomodation of tangential momentum are calculated for the gases studied at different temperatures.

Almost no experimental research has been done on the study of the flow of rarefied gases in a wide temperature range. The flow of rarefied gases in glass capillaries at ~195°K was studied in [1]. Analogous studies were made [2] in the temperature range of (0-50) °C. Because of the low accuracy of the results obtained and the small range of temperatures studied it is hard to draw any conclusions concerning the temperature dependence of the conductance of the channels. Therefore the conducting of systematic studies of modes of flow which are free-molecular or close to it for a broad array of gases at different temperatures is of undoubted interest. Such a study makes it possible to obtain additional information on the nature and characteristics of the gas–solid interaction.

In the present report the results are presented for an experimental study of the flow of inert gases and several polyatomic gases through an orifice and a capillary screen at temperatures of 293, 194.7, and 77.2°K in the range of Knudsen numbers of 10^4-10^{-1}.

The study of the flow of gases through an orifice and a capillary screen was conducted on an experimental apparatus for which a schematic diagram and the measurement method were described in detail in [3]. The measurement method used was the method of nonstationary flow proposed by Knudsen [4]. The method is based on the determination of the relaxation time of a small pressure drop between volumes joined by the experimental channel with a constant average pressure in the system.

An almost ideal orifice, for which the process of fabrication and the parameters are presented in [5], was used in the experiments.

The capillary screen was made from a set of thin-walled capillaries of identical diameter placed in a glass tube and then sintered and drawn out. The screen had the following parameters: average diameter of capillaries $(1.35 \pm 0.01) \cdot 10^{-2}$ cm, length 5.0 cm, transmittance ~90%, number of capillaries ~640.

The purity of the inert gases studied was 99.96-99.98% and of the polyatomic gases 99.7%. Before admission to the experimental apparatus all the gases were passed through a trap cooled with liquid nitrogen. Measurements were made at 77.2°K on the orifice and capillary screen with the gases He, Ne, Ar, H_2, D_2, and N_2 and on the capillary screen at a temperature of 194.7°K. At the temperature of 293°K in addition to these gases Kr, Xe, CO_2 and CH_4 were also used. The reproducibility of the experimental results of two independent series of measurements was in the range of 0.2-1%.

The experimental method and the method of analyzing the experimental data obtained on the orifice at 293°K are described in [5]. Therefore here we will only briefly describe the necessity of conducting the experiment on the orifice at 77.2°K and the principal experimental results.

Sverdlovsk. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 2, pp. 45-49, March-April, 1974. Original article submitted July 18, 1973.

TABLE 1. Calculated Values of $\gamma_0 \pm \Delta\gamma_0 \cdot 10^3$

Gases		He	Ne	Ar	Kr	Xe	H_2	D_2	N_2	CO_2	CH_4
γ_0	293 °K	1.119	1.141	1.037	1.018	1.000	1.050	1.064	1.048	1.005	1.016
		5	5	10	8	12	11	4	12	9	9
	194.7 °K	1.247	1.223	1.092	—	—	1.137	1.152	1.096	—	—
$\pm\Delta\gamma_0 \cdot 10^3$		4	14	6			5	7	7		
	77.2 °K	1.389	1.233	1.144	—	—	1.211	1.209	1.142	—	—
		8	12	10			12	9	15		

It can be shown that the standard working formula for calculating the observed flow rate of gas in the nonstationary method of measurement includes a correction resulting from the adsorption of gas on the surfaces of the working volumes. This correction must increase with a decrease in temperature. Its magnitude is difficult to calculate because of the impossibility of determining with sufficient accuracy the surfaces of the working volumes and because of the indeterminacy in the average lifetime of the molecules in the adsorbed state.

In order to estimate the effect of adsorption of the gas on the measured flow rate measurements were made on an orifice in modes of flow which are free-molecular or close to it at a temperature of 77.2°K. An analysis of the results obtained shows that for all the gases studied the observed flow rates coincide with the theoretical values within the limits of the experimental error of 1-1.5%. We note that in calculating the theoretical flow rate (free-molecular limit) allowance was made for the correction caused by the nonideal nature of the orifice in accordance with the equations of [6]. The agreement of the results indicates the absence of a marked systematic error arising because of the adsorption of gas on the surfaces of the working volumes of the system.

The experimental dependence of the relative flow rate γ on the parameter δ for He, D_2, and Ar (points 1, 2, and 3) at a temperature of 194.7°K for the capillary screen is presented in Fig. 1. The relative flow rate γ was calculated from the equation

$$\gamma = M_+/M_- \tag{1}$$

Here M_+ is the volumetric flow rate of the gas per unit pressure difference at the ends of the channel and M_- is the volumetric flow rate of zenon at 293°K in the free-molecular mode of flow. The parameter δ is determined by the expression

$$\delta = \frac{\sqrt{\pi}}{2}\frac{R}{\lambda} = \frac{\sqrt{\pi}}{2}\frac{1}{\mathrm{Kn}} \tag{2}$$

where R is the radius of the capillary and λ is the mean free path length of the gas molecules corresponding to the average pressure in the system. The calculation of λ was made from an equation for the coefficient of viscosity of a gas of solid spherical molecules in the higher approximations of the Chapman–Enskog theory.

As seen from Fig. 1, a considerable difference is observed in the relative flow rates γ for different gases in modes of flow which are free-molecular or close to it.

In calculating the free-molecular value of the relative flow rate γ_0 the following empirical equation was used:

$$\gamma = \gamma_0 (1 + 0.7\delta \lg \delta) \tag{3}$$

where γ_0 is the relative flow rate of the gas in the free-molecular mode of flow. The functional dependence $\gamma(\delta)$ of the flow rate according to (3) is analogous to the theoretical dependence for a mode of flow close to free-molecular ($\delta \leq 10^{-2}$). The calculations showed that the values of γ calculated from (3) coincide with the theoretical values [7] within the limits of 0.2% in the region of $\delta < 5 \cdot 10^{-2}$.

The analysis of all the experimental data in this region of δ numbers was conducted by the method of least squares using (3). The calculated values of γ_0 for the gases studied at the different temperatures with the corresponding standard deviations are presented in Table 1.

It is seen from Table 1 that the relative flow rate γ_0 depends essentially not only on the type of gas but on the temperature at which the measurements were made. The greatest difference in γ_0, reaching

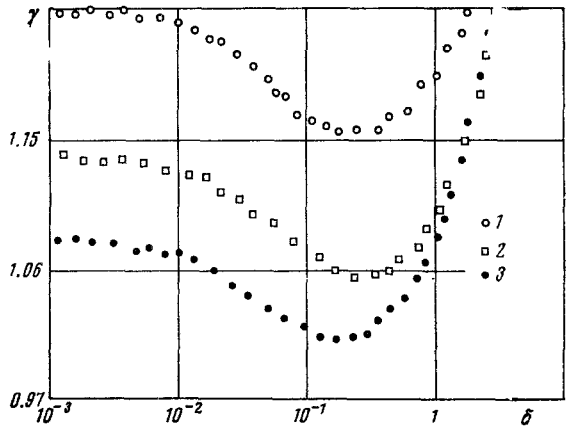

Fig. 1

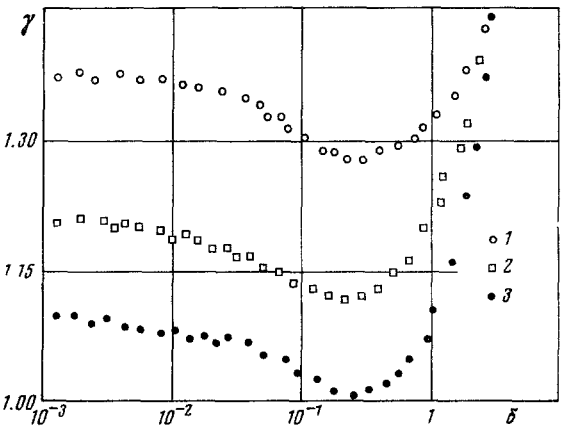

Fig. 2

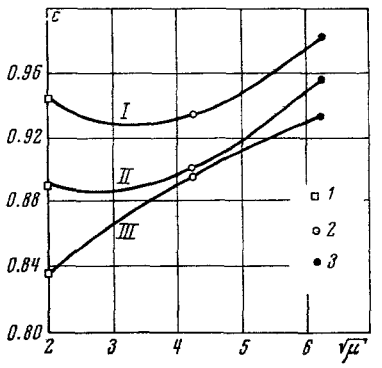

Fig. 3

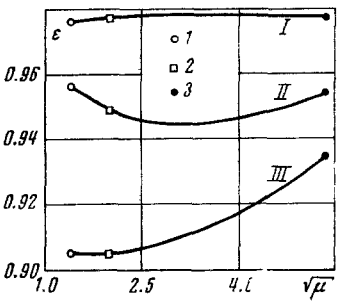

Fig. 4

~24%, is observed for helium at the temperatures of 293 and 77.2°K. The dependence of the relative flow rate γ on the parameter δ for helium at 77.2, 194.7, and 293°K (points 1, 2, and 3) is shown in Fig. 2.

Results obtained on single capillaries with smooth walls at 293°K [3] show that for xenon both in a viscous mode of flow with slippage and in an almost free-molecular mode of flow the experimental data coincide with the theoretical data within the limits of the experimental error if it is assumed in the theoretical consideration that all the molecules are scattered diffusely by the wall. Since a capillary screen with smooth glass walls was used in the experiment it can be assumed that in the present case the xenon molecules are scattered diffusely by the capillary wall.

The difference in γ_0 at different temperatures for the gases studied can be explained by the incomplete accommodation of the tangential momentum of the molecules striking the wall. The coefficient of accommodation of tangential momentum ε can be calculated from the experimental values of γ_0 using the equation [7]

$$\gamma_0(\varepsilon) = \gamma_0(\varepsilon = 1)\ (2 - \varepsilon)/\varepsilon$$

According to the assumptions made, γ_0 ($\varepsilon = 1$) in (4) is the relative flow rate of xenon at 293°K. The dependence of ε on the molecular weight μ for several inert and diatomic gases at different temperatures is shown in Figs. 3 and 4. Points 1, 2, and 3 in Fig. 3 pertain to He, Ne, and Ar and lines I, II, and III to T=293, 194.7, and 77.2°K. Points 1, 2, and 3 in Fig. 4 pertain to H_2, D_2, and N_2 and lines I, II, and III to T=293, 194.7, and 77.2°K. It is seen from these figures that with an increase in temperature the coefficient of accommodation of the tangential momentum systematically increases for all the gases.

An analysis of the experimental data obtained shows that a significant increase in the relative flow rates with a decrease in the temperature is observed for all the gases studied both in the free-molecular mode of flow and in modes close to it. The use of the Maxwellian system of boundary conditions which takes into account the diffuse-mirror scattering of molecules by the wall made it possible to determine the temperature dependence of the coefficients of accomodation of the tangential momentum of the molecules.

The coefficients of accomodation decrease with a decrease in temperature for all the gases. We note that the coefficients of accomodation calculated at room temperature for helium, neon, and argon coincide with those obtained on single capillaries [7] within limits of $< 0.5\%$.

This behavior of the flow rates and coefficients of accomodation with variation in the temperature is the result of the influence of different effects occurring at the gas-solid surface of separation. Surface diffusion of the molecules and adsorption may be such effects. A qualitative examination of the effect of surface diffusion of gas molecules at different temperatures on the flow of the gas in channels does not permit an explanation of the increase in the observed relative flow rates and the decrease in the coefficients of accomodation of tangential momentum with a decrease in the temperature.

Another reason may be the presence of a layer of adsorbed molecules of easily condensed impurities. It is known that the average lifetime of molecules in an adsorbed state on the wall and the density of covering of the walls with adsorbed molecules increase with a decrease in temperature. In this case the molecules incident on the wall interact not with the wall but with a surface film of adsorbed molecules. In such an interaction the probability of mirror reflection of the molecules increases.

A quantitative interpretation of the results obtained is difficult because of the absence of a theoretical description of the influence of these surface effects on the flow of rarefied gases in channels.

We should note that the results presented report are almost unique. Therefore the conducting of similar experiments by some other independent method (such as the method of stationary flow) under conditions of a cleaner surface and higher vacuum may provide additional information on the temperature dependence of the coefficient of accomodation.

LITERATURE CITED

1. R. M. Barrer and D. Nicholson, "Flow in capillary systems. II. Low pressure transition flow of gases in short capillaries, rectangular slits, beds of spheres and parallel capillary bundles," Brit. J. Appl. Phys., 17, No. 8, (1966).
2. L. M. Lund and A. S. Berman, "Flow of noble gases at low pressures through porous media and capillaries," J. Chem. Phys., 28, No. 2 (1958).
3. S. F. Borisov, B. T. Porodnov, and P. E. Suetin, "Experimental study of gas flow in capillaries," Zh. Tekh. Fiz., 42, No. 6 (1972).
4. M. Knudsen, "Die Gesetze der Molekularströmung und der inneren Reibungsströmung der Gase durch Röhren," Ann. Phys., 28, No. 4, 75-130 (1909).
5. S. F. Borisov, I. G. Neudachin, B. T. Porodnov, and P. E. Suetin, "Flow of rarefied gases through an orifice with small pressure drops," Zh. Tekh. Fiz., 43, No. 8 (1973).
6. A. S. Berman, "Free molecule transmission probabilities," J. Appl. Phys., 36, No. 10 (1965).
7. P. E. Suetin, B. T.Porodnov, V. G. Cherniak, and S. F. Borisov, "Poiseuille flow at arbitrary Knudsen numbers and tangential momentum accomodation," J. Fluid Mech., 60, Part 3 (1973).