EXPERIMENTAL INVESTIGATION OF THE ESCAPE OF HELIUM, NEON, AND ARGON IN A VACUUM THROUGH A LONG SINGLE CAPILLARY AT TEMPERATURES OF 295-490°K

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The theoretical and experimental data available at the present time confirm that a diffuse-specular scheme of reflection of molecules incident on its walls (proposed in [1]) is completely applicable for describing the flow of rarefied gases in different capillary systems. Therefore, it will be of definite interest to investigate the flow of rarefied gases over a wide temperature range. These investigations will permit additional information to be obtained about the nature of interaction between the gas and a solid. A study of the dependence of the conductivity of capillary systems on the temperature and nature of the gas, carried out over the temperature range 77.2-293°K [2], indicates a systematic reduction in the conductivity of capillary systems with increase in temperature. The results of experiments at temperatures of 0-50°C [3] do not permit a definite tendency in the behavior of the conductivity of capillaries and porous samples at different temperatures to be observed, this being due to both the small range of temperatures used and the considerable experimental error. In this paper, the results are given of an investigation of the escape of the gases He, Ne, and Ar in a vacuum through a long glass capillary by a steady-state flow method at temperatures of 295, 395, 440, and 490°K over the range of Knudsen numbers 4-200.

The investigation of the escape of gases in a vacuum was conducted on the experimental facility shown schematically in Fig. 1. A glass capillary 11 with fused walls, a diameter of $(3.40 \pm 0.01)\cdot 10^{-2}$ cm, and a length of ~16.6 cm was used as the working channel. The capillary with the glass flask 9 forms the working cell, installed in the thermostat 12, which is a copper cylinder with a heater and which is enclosed in the thermostabilization system 13.

The flow rate of the gas under steady-state conditions was determined by measuring the magnitude of the movement of a calibrated rod 4 during a certain interval of time with a constant gas pressure in the flow-rate measurement system. In order to monitor the value of the gas pressure in the flow-rate measurement system and to measure the absolute pressure in the flask, capacity differential micromanometers with digital readout 7 and 8 and pressure sensors 6 and 10 were used (sensitivity $2\cdot 10^{-7}$ mm Hg/Hz). The operating principle and the construction of the micromanometers are described in [4].

The gas being investigated was admitted from the bottle 3 into the flow-rate measurement system, the units of which were installed in a thermostatically controlled oil bath, and into the working cell through the capillary-leak 5. The gas pressure in the admission and flow-rate measurement system was determined with the mercury 1 and oil 2 manometers. The purity of the gases investigated was not less than 99.8%.

The principal parameters being measured in the experiment were the volume flow rate of the gas M at unit difference of pressure (or the conductivity of the capillary), the pressure difference at the ends of the capillary Δp_0, and the temperature of the capillary wall and of the gas T.

A comparison of the experimental data for the different gases was carried out in terms of the relative flow rate of the gas ω as a function of the parameter δ, which is connected with the Knudsen number Kn by the relation

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

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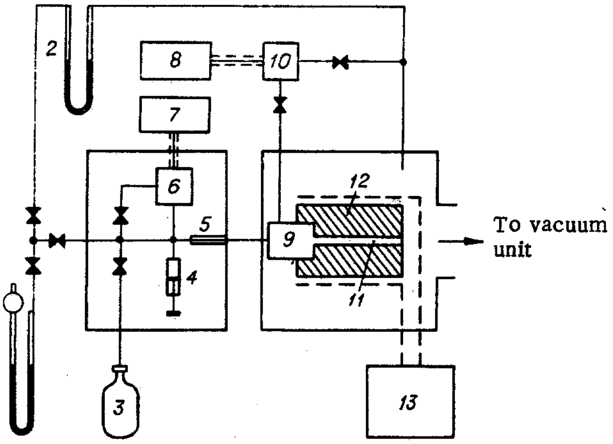

Fig. 1

where R is the mean radius of the capillary and λ is the average mean free path of the molecules, which is calculated for a model of solid spheres using the expression for the coefficient of viscosity in the second Chapman—Enskog approximation. The relative flow rate of the gas is determined by the ratio $\omega = M/M_0$ of the experimental gas flow rate to the theoretical flow rate for a free-molecular mode M_0 in a circular long capillary.

Since in the experiment the pressure sensor and the working cell were at different temperatures (room temperature and above, respectively), a pressure difference resulting from the effect of the thermomolecular difference of pressure (TDP) originated in the pipeline joining the cell with the sensor. The pressure difference at the ends of the capillary Δp_0 in this case is determined in the form

$$\Delta p_0 = \Delta p + \Delta p_1,$$

where Δp is the pressure difference recorded by the micromanometer sensor and Δp_1 is the pressure difference due to the TDP effect. The quantity Δp_1 was calculated by the procedure proposed in [5]. This correction increases with increase of the gas temperature in the working cell and the Knudsen number; in the region of large Knudsen numbers it did not exceed 15% in the case of the largest temperature difference and was almost nonexistent for $\delta > 0.4$. The error in determining the correction Δp_1 did not exceed 2-3%.

The experimental curves of $\omega(\delta)$ for He shown in Fig. 2 confirm the effect of temperature on the conductivity of the capillary systems. In Fig. 2, points 1-3 correspond to the temperatures 77.2, 194.7, and 293°K [2], while points 5-8 correspond to our data for the temperatures 295, 395, 440, and 490°K, respectively. Points 4 were obtained in experiments [6] on a single capillary by the method of non-steady-state flow.

The difference between the results of our work and those of [2] at a temperature of 293°K can be explained by the fact that the experiments in [2] were conducted on a capillary sieve, in which the capillaries were nonidentical in diameter. Therefore, the average radius of the capillary was determined in [2] by an indirect method — by means of experiments on Xe, the reflection of the molecules of which from the wall was assumed to be completely diffuse. Curves I and II in Fig. 2 correspond to the theoretical data of [7, 8] for accommodation coefficients of the tangential momentum $\varepsilon = 0.93$ and 0.97, respectively.

Figures 3 and 4 show the curves of $\omega(\delta)$ for Ne and Ar, respectively. All symbols are the same as in Fig. 2. Curves I and II in Fig. 3 correspond to the theoretical data of [7, 8] for $\varepsilon = 0.92$ and 0.95 (in Fig. 4) for $\varepsilon = 0.96$ and 0.98, respectively.

A comparison of the experimental results shows that if for He (see Fig. 2), a systematic decrease of the relative flow rate $\omega(\delta)$ (or the conductivity of the capillary M) is observed with increase of temperature for any Knudsen numbers (or the parameter δ), then for Ne (Fig. 3) this decrease is less expressed: The data of 395, 440, and 490°K almost coincide. However, the overall nature of the function $\omega(T)$ is the same as for He. In the experiments on Ar (see Fig. 4), the reverse effect is observed — an increase of the conductivity of the capillary with increase of temperature above room temperature.

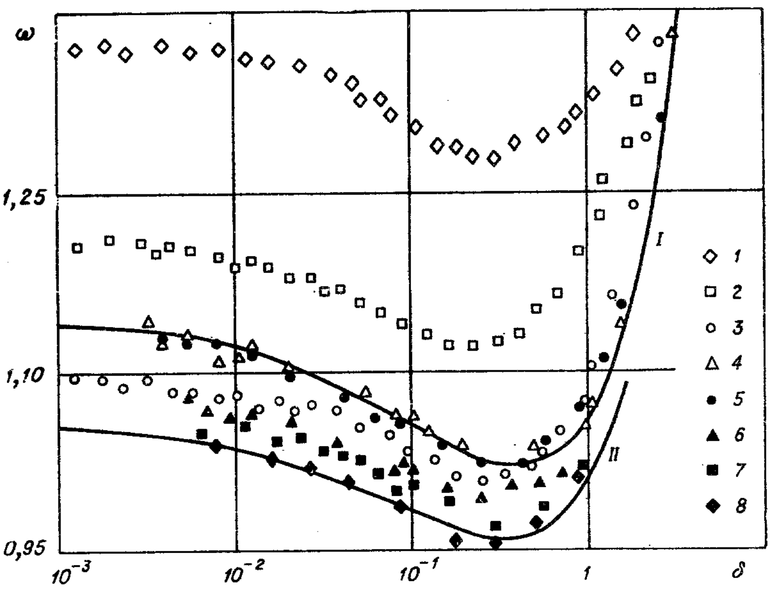

Fig. 2

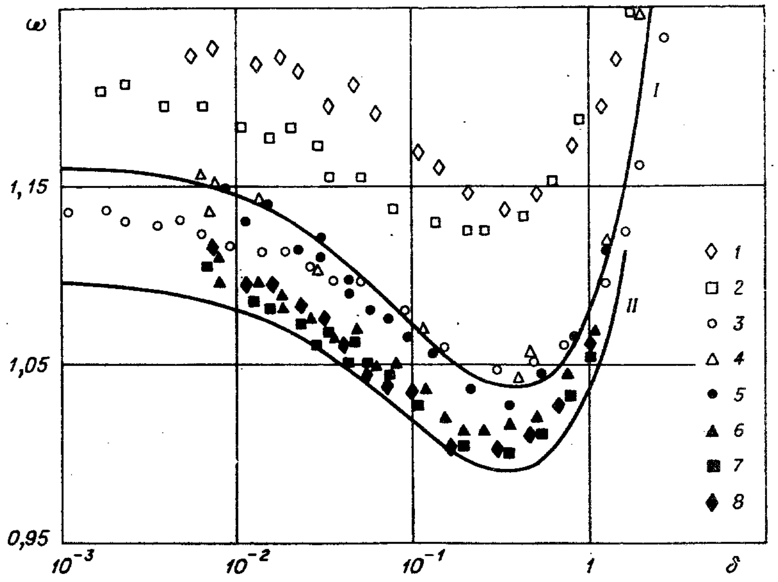

Fig. 3

Figure 5 shows the data of the experiments for Ne, He, and Ar (points 1-3, respectively) for temperatures of 295 and 490°K (open and filled points, respectively). A tendency toward convergence of the values of the flow rates of the different gases with increase of temperature is observed. An anomaly is observed in the function $\omega(T)$ with increase of T for Ar in comparison with He and Ne.

The excellent agreement between the experimental function $\omega(\delta)$ and the theoretical curves (see Figs. 2-4) in the region of $\delta < 0.4$ permitted further processing of the experimental data to be carried out. The processing consisted in calculating for every experimental value of $\omega(\delta)$ the values of the accommodation coefficient of tangential momentum ε of the molecules at the wall by means of the theoretical data of [7, 8], tabulated for a broad sequence of values of ε. Some of the values of ε found in this way are plotted in Fig. 6. Here points 1-3 correspond to Ne, He, and Ar at temperatures of 295 and 490°K (open and filled points, respectively), and the dashed lines correspond to the average values of ε. The average values of ε for all the gases and temperatures investigated, together with the mean-square errors $\Delta\varepsilon \cdot 10^3$, are given in Table 1.

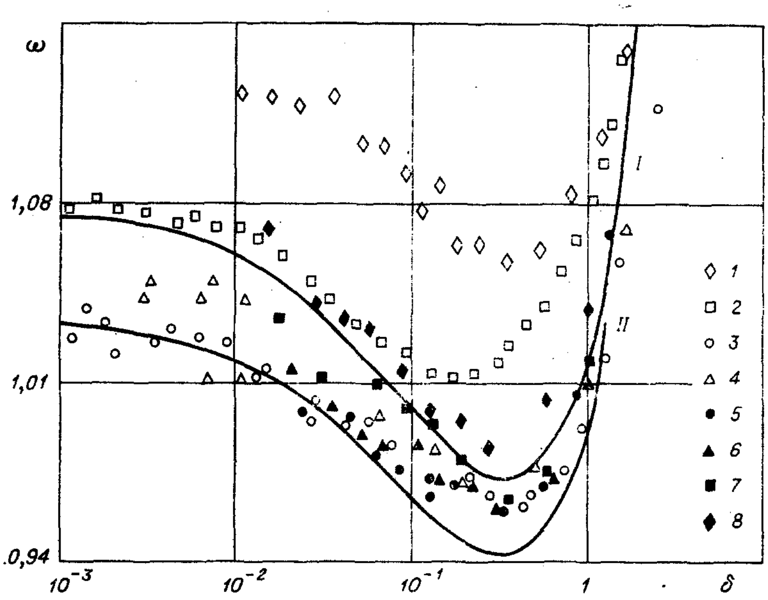

Fig. 4

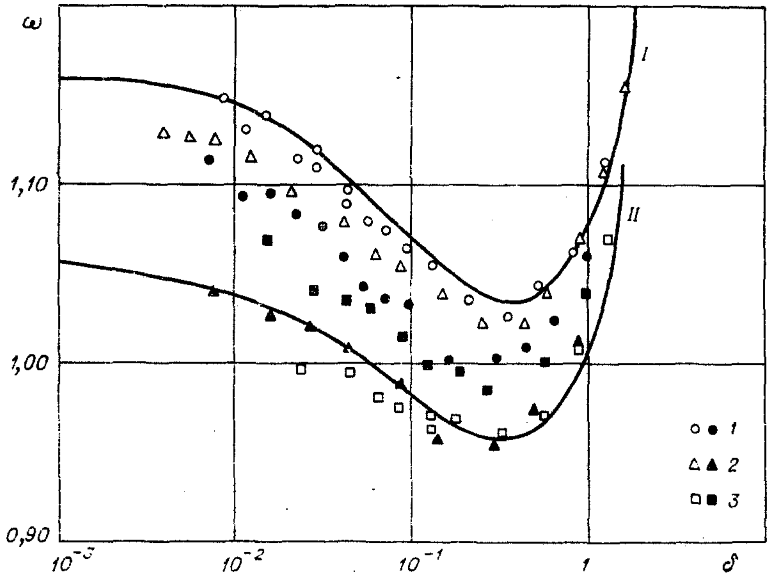

Fig. 5

The function $\varepsilon(T)$ in the temperature range 77-293°K [2] (open points) and 295-490°K (filled points) is plotted in Fig. 7 for Ne, He, and Ar (points 1 and 4, 2 and 5, and 3 and 6, respectively). It can be seen that with increase of temperature the accommodation coefficients increase, and the rate of increase of ε is the greatest for He in the region of $T < 295$°K. For $T > 295$°K, the values of ε for He are increased, for Ne they remain almost constant, but for Ar they decrease. An anomaly is also observed for the flow rate in the dependence of the accommodation coefficient ε on the temperature for argon in comparison with the other gases: For $T = 295$°K the value of ε is maximum.

Unfortunately, any quantitative explanation of the observed behavior of the accommodation coefficients of tangential momentum on the temperature for the gases investigated is made difficult at the present time in view of the absence of a theoretical description of the effects of interaction of the gases with the surface and of their effect on the flow macrocharacteristics near the surface.

From the point of view of a qualitative explanation, the experimental results obtained on the whole confirm the assumption expressed in [2] that the cause of the increase of the accommodation coefficient of tangential momentum with increase of temperature is obviously

TABLE 1

Gas \ T, °K	295		395		440		490	
	ε	$\Delta\varepsilon\cdot 10^3$	ε	$\Delta\varepsilon\cdot 10^3$	ε	$\Delta\varepsilon\cdot 10^3$	ε	$\Delta\varepsilon\cdot 10^3$
He	0,932	±2	0,954	±2	0,961	±2	0,969	±2
Ne	0,925	±2	0,941	±2	0,943	±2	0,942	±2
Ar	0,977	±3	0,973	±3	0,964	±3	0,954	±3

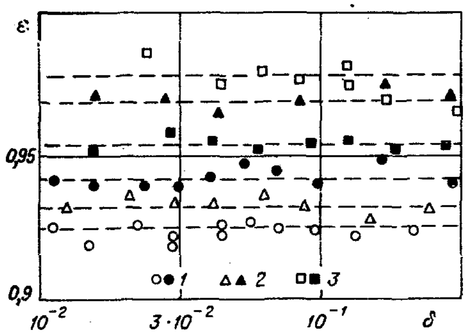

Fig. 6

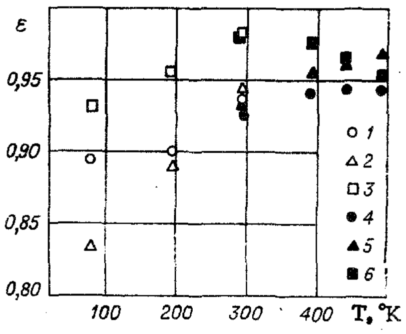

Fig. 7

the layer of easily condensed gaseous impurities and water vapor on the surface of the capillary walls. At low temperatures, this layer covers all the macro- and microroughnesses of the walls and screens the potential force field of the surface atoms or molecules, stimulating specular reflection of the molecules incident on the wall. With increase of temperature, the thickness of this layer decreases, as a result of which the macro- and microroughnesses of the walls is uncovered. This leads to an increase of the fraction of the molecules diffusely reflected from the walls and, consequently, to a reduction of the conductivity of the capillary (or of the gas flow rate), as shown in [9].

At T > 400°K, water vapor in the combined state is found mainly on the surface of the capillary walls, which covers the microroughness; obviously, the macroroughness is completely uncovered. In this case, the fraction of diffusely reflected molecules is almost identical for all the gases. However, even in this temperature range $\varepsilon(T)$ relations for the gases investigated are different, which obviously is due to the difference in the individual properties of interaction of the gas molecules with the surface atoms or molecules.

Thus, the range of suppositions and quite valid conclusions is restricted in that there are no theoretical papers related to this region of investigations, and the experimental results obtained are almost unique at the present time. Similar experiments carried out at higher temperatures and with capillaries of other materials would appear to be necessary in order to obtain further data about the interaction between gases and solids.

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INFLUENCE OF HEAT SPREAD IN THE MEASUREMENT LAYER ON THE ACCURACY IN MEASURING LOCAL HEAT FLUXES BY THE GRADIENT METHOD

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INTRODUCTION

One of the most widely known methods of measuring heat flux is the steady gradient method, or the method of an auxiliary wall [1]. But this method, despite its high sensitivity and relative simplicity, is used relatively rarely in model gas-dynamic experiments. Data are practically absent on the use of the method of an auxiliary wall in heat-transfer research carried out on models in low-density aerodynamic installations. The main reasons preventing its extensive use in measurements of such a kind are the inadequate spatial resolution of individual calorimeters at the relatively small dimensions of the models themselves and of the regions of action of the gas stream, as well as the appearance of temperature "steps" at the surface of the test model at the calorimeter mounting points in a number of cases. These drawbacks are eliminated to a considerable extent, however, when the method of an auxiliary wall is carried out in the installation proposed in [2] for bodies having a plane or slightly curved surface. The idea of the proposed realization consists in the following. The body of the model, thermostatically controlled in some way, is covered by a layer of material of low thermal conductivity (the measurement layer) so thin that the heat spread in it becomes insignificant at the places most important from the aspect of heat transfer. Then the local temperature drop between opposite sides of the layer, when the thermal conductivity $\lambda =$ const of the material is known, is proportional to the local value of the incident heat flux, and the problem is reduced to recording this temperature drop with the required accuracy. The distribution of the temperature difference between the surfaces of the measurement layer is measured with differential microthermocouples, the hot junctions of which are placed on the outer surface of the layer in a certain way which allows for the heat outflow along the thermocouple leads [2].

Consequently, in the realization of the method of an auxiliary wall in the given variant an important point, along with the question of the correct placement of the differential thermocouple junctions discussed earlier in [2], is the allowance for the influence of tangential heat fluxes in the measurement layer and the determination of the error introduced by these fluxes into the measurement result. A correct estimate of the latter would make it possible to select the required thickness of the measurement layer corresponding to the conditions of a specific experiment. The effects of heat spread have been analyzed earlier mainly for nonsteady methods of measuring heat fluxes [3, 4]. The problem of heat spread has evidently not been raised in general form in application to the method of an auxiliary wall. Only individual particular examples are known [1, 2].

In the present work an attempt is made to derive, from sufficiently general premises, approximate functions connecting the error in the measurement of the heat-flux distribution due to heat spread in the measurement layer with the parameters of the layer and the characteristics of the quantity being measured. The suitability of the equations obtained for prac-

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