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

B. T. Porodnov and A. G. Flyagin

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 ± 0.01)·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 2·10⁻⁷ 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 ∆p₀, 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

δ = \frac{V_π R}{2 \lambda} = \frac{V_π 1}{2 Kn^*}
where $R$ is the mean radius of the capillary and $\lambda$ 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 $\Delta p_0$ in this case is determined in the form

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

where $\Delta p$ is the pressure difference recorded by the micromanometer sensor and $\Delta p_1$ is the pressure difference due to the TDP effect. The quantity $\Delta p_1$ 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 $\Delta p_1$ 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 $\delta$), 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.