density; R_0, tube radius; T, temperature; q, specific heat flow on tube surface; u_c, flow velocity on tube axis; ξ, hydraulic resistance coefficient; Δ, boundary-layer thickness; ε, turbulent-diffusion coefficient; $\bar{u}$, mean flow velocity; α, heat-transfer coefficient; Re, Reynolds number; Pr, Prandtl number; L, tube length; T_m, mean flow temperature; T_w, wall temperature.

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EFFECT OF ABSORPTION-TIME DIFFERENCES ON GAS FLOW IN CAPILLARIES

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The effect of differences in absorption time at a capillary surface on the free-molecular gas flow is analyzed, taking into account surface diffusion.

In the analysis of gas flow in capillaries, it is often necessary to take into account the specific properties of the interaction of gas molecules with the capillary wall. On contact of the gas with the solid surface, physical adsorption and surface diffusion of the adsorbed molecules usually occur [1]. The surface-diffusion process may lead to a selective inleakage of a gas-mixture component through the porous body [2]. In this context, it is of interest to carry out a kinetic investigation of the gas flow in a single capillary.

We consider free-molecular gas flow in a microcapillary of finite length. We assume that the diffusional-transfer potential $\varphi = P/\sqrt{T}$ is the same at both ends of the capillary (i.e., in the absence of surface diffusion there is no resultant molecular flux in the system). It is known that molecules incident on the surface of the solid usually remain on it for an adsorption time τ, the magnitude of which, generally speaking, may vary over the length of the capillary. Apart from nonisothermal conditions, the change in τ may be caused by the incidence of various kinds of radiation on the surface [3].

To elucidate the effect of differences in adsorption time, we consider the following model problem. It is assumed that the adsorption times on the inner capillary surface (τ_2) and its ends (τ_1 and τ_3) may differ and that $\tau_1 \geq \tau_2 \geq \tau_3$. In addition, it is assumed that the degree of filling of the surface by adsorbed molecules is sufficiently low for Henry's law to be applied. Then the difference in τ may create conditions for the appearance of

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TABLE 1. Dependence of γ and ψ on System Parameters ($D_S = 10^{-4}$ cm^2/sec, $L = 10^{-4}$ cm)

R, cm	γ	ψ	
	$\tau_1=\tau_2=10^{-5}$ sec, $\tau_3=10^{-8}$ sec	$\tau_1=10^{-6}$ sec, $\tau_2==10^{-7}$ sec, $\tau_3==10^{-8}$ sec	$\tau_1=10^{-6}$ sec, $\tau_2=10^{-7}$ sec, $\tau_3=10^{-9}$ sec
10^{-4}	1,255	1,093	1,330
$8{,}5\cdot10^{-5}$	1,291	1,111	1,392
$7{,}0\cdot10^{-5}$	1,340	1,136	1,483
$5{,}5\cdot10^{-5}$	1,409	1,176	1,628
$4{,}0\cdot10^{-5}$	1,521	1,249	1,897
$2{,}5\cdot10^{-5}$	1,745	1,423	2,557
$7{,}0\cdot10^{-6}$	3,245	3,204	10,478

surface diffusion due to the different densities of adsorbed molecules on sections of the surface with different adsorption times (this occurs if the difference in densities which arises is not compensated by a change in the mobility of the adsorbed molecules). To eliminate the possibility of reverse overflow of the molecules from the external surface to the capillary, we assume that the size of the end surfaces (with adsorption times τ_1 and τ_3) greatly exceeds the mean distance that a molecule can traverse in the adsorption time. No accurate correlation between the adsorption time and the surface-diffusion coefficient is available in the literature, and, therefore, taking a two-dimensional gas as the model of the adsorbed molecules [1], we assume for simplicity that the surface-diffusion coefficient on all surfaces is equal.

We calculate the ratio of molecules leaving and entering the capillary:

$$\gamma = \frac{N}{N_0 \pi R^2}, \text{ where } N_0 = \frac{P}{\sqrt{2\pi mkT}}.$$

To determine the number of molecules leaving the capillary, it is necessary to know the distribution of the density of adsorbed molecules over the inner surface of the capillary, which is found from the solution of the integrodifferential equation (x is dimensionless)

$$\frac{D_S}{L^2}\cdot\frac{d^2n}{dx^2} = \frac{n}{\tau_2} - \int\limits_0^1 \frac{n}{\tau_2} K_1(|x-\xi|)\, d\xi - N_0 K(x) - N_0 K(1-x), \tag{1}$$

where D_S is the surface-diffusion coefficient, L is the capillary length,

$$K(x) = \frac{l^2x^2+2}{2(l^2x^2+4)^{1/2}} - \frac{l}{2}x, \quad K_1(x) = -\frac{dK(x)}{dx}, \quad l = \frac{L}{R}.$$

At junctions, the end and inner surfaces of the capillary should satisfy the following boundary conditions:

$$\begin{aligned} \left.\frac{dn}{dx}\right|_{x=0} &= \frac{L}{\sqrt{D_S\tau_1}}[n(0) - n_0], \\ \left.\frac{dn}{dx}\right|_{x=1} &= \frac{L}{\sqrt{D_S\tau_3}}[n_1 - n(1)], \end{aligned} \tag{2}$$

where

$$n_0 = N_0\tau_1, \quad n_1 = N_0\tau_3.$$

An approximate method of solving Eq. (1) is given in [4].

The resultant flux of particles leaving the capillary is equal to the sum of the flux of particles desorbed from the wall and released over the capillary section and the surface-diffusion flux.

If two closed gas-filled volumes are joined by a capillary with an asymmetry of the adsorption times similar to that described above, the values of φ_i in the volumes will differ in the steady state. To find the value $\psi = \varphi_1/\varphi_2$ a boundary-value problem as in Eqs. (1) and (2) must be solved for the case when there is no resultant molecular flux through the capillary. For an exponential approximation of the function K(x), finding ψ reduces to the solution of the following system of algebraic equations:

$$a_1 \frac{l}{l-c_1} + a_2 \frac{l}{l+c_1} \exp\{-c_1\} - \frac{a_3}{l} + a_4 = \tau_2,$$

$$a_1 \frac{l}{l+c_1} \exp\{-c_1\} + a_2 \frac{l}{l-c_1} + a_3 \frac{l+1}{l} + a_4 - \tau_2 a_5 = 0,$$

$$a_1 (c_1 \sqrt{G_1} + 1) + a_2 \exp\{-c_1\} (1 - c_1 \sqrt{G_1}) - a_3 \sqrt{G_1} + a_4 = \tau_1,$$

$$a_1 \exp\{-c_1\} (1 - c_1 \sqrt{G_3}) + a_2 (1 + c_1 \sqrt{G_3}) + a_3 (\sqrt{G_3} + 1) + a_4 - a_5 \tau_3 = 0,$$

$$a_1 \left[\frac{l}{\tau_2} \cdot \frac{\exp\{-c_1\} - \exp\{-l\}}{l - c_1} + \frac{2D_S}{lR^2} c_1 \exp\{-c_1\} \right] + a_2 \left[\frac{l}{\tau_2} \cdot \frac{1 - \exp\{-(c_1 + l)\}}{c_1 + l} - \frac{2D_S}{lR^2} c_1 \right]$$

$$+ a_3 \left[\frac{1}{\tau_2 l} (l - 1 + \exp\{-l\}) - \frac{2D_S}{lR^2} \right] + a_4 \left(\frac{1}{\tau_2} - \frac{1}{\tau_2} \exp\{-l\} \right) - a_5 = -\exp\{-l\};$$

$$c_1 = \sqrt{l^2 + G_2^{-1}}, \quad G_i = \frac{\tau_i D_S}{L^2}, \; \psi = a_5.$$

Calculated values of γ and ψ are shown in Table 1.

As is evident from Table 1, the considered phenomenon depends strongly on the capillary radius; with decrease in the radius, the effect increases. This too should be expected, since the magnitude of the effect is influenced by the ratio of the volume and surface fluxes, which may be evaluated using the dimensionless parameter $G_R = D_S \tau / R^2$. Apart from gas-mixture separation processes, the given effect should be taken into account in calculations on various kinds of vacuum system and also, probably, in the radiation drying of microporous bodies, since the effect of radiation on the surface close to the capillary outlet may alter its adsorptive properties, leading to a change in the surface-diffusion outflow of material from the porous body.

NOTATION

R, capillary radius; L, capillary length; τ, adsorption time; P, pressure; m, molecular mass; k, Boltzmann constant; T, temperature.

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