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TRANSITIONAL REGIME IN THE RAPID EVAPORATION OF LIQUIDS FROM CAPILLARY TUBES

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The region in which excess pressure exists in capillary tubes is determined. A table of values of excess pressure in the case of water evaporation is presented. The results of calculations are compared with experimental data. A new method is proposed for determining the radii of capillary tubes.

The use of Stefan's equation is generally accepted as an approach to theoretically describing the evaporation of liquids from a cylindrical capillary tube. This equation is valid when the atmospheric pressure is greater than the saturation pressure at the given temperature. The discrepancy between experimental results and the Stefan theory at room temperature is attributable to the contribution of liquid boundary films to the mass flow, a contribution which the theory ignores. However, this contribution can be ignored above 70°C [1] and, as numerous experiments have shown, Stefan's equation is satisfied with a high degree of accuracy. As the evaporation temperature of the liquid increases above the boiling point, the saturation pressure becomes greater than the atmospheric pressure and the Stefan regime of vapor flow in the capillary tube is replaced by viscous flow. However, viscous flow of the gas cannot explain the empirical fact of the generation of excess pressure inside a porous body at drying temperatures above the boiling point [2]. The excess-pressure generation has to do with a radius-independent counterdirected diffusional flow of air. As the dimensions of the capillary tube are reduced, this air flow is compensated for by an increase in the total pressure above the meniscus. Obviously, there should be a region which is intermediate between the Stefan and viscous regimes of vapor flow in capillary tubes. Let us turn our attention to this region, characterized by the presence of a pressure of the vapor–gas mixture above the meniscus which is higher than the saturation pressure at the given temperature.

The authors of [3] developed a theory of isothermal evaporation of liquids from capillary tubes at temperatures above the boiling point. They obtained an equation making it possible, with known boundary conditions, to calculate the excess pressure. After refining of the numerical multiplier and assuming that the slip diffusion coefficient is negligibly small, this equation is written in the form

$$\ln \frac{P_X}{P_X - P_s} = \frac{r^2 (P_X^2 - P_\infty^2)}{16 \eta P_\infty D}. \tag{1}$$

To solve Eq. (1), a computing program was devised which makes it possible to determine P_X as a function of temperature and the tube radius with an accuracy limited only by the accuracy of the parameters introduced. The temperature dependences of the viscosities of the vapor and surrounding gas, the diffusion coefficient of the vapor–gas mixture, the pressure of the saturated vapor, and the heat of vaporization — all needed for the calculations — were taken from handbooks [4, 5].

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TABLE 1. Values of Excess Pressure in the High-Temperature Evaporation of Water from Capillary Tubes

T, K	$P_s\cdot10^{-5}$, Pa	$P_X\cdot10^{-5}$, Pa, at r, μm			
		0,2	0,5	1,0	2,0
343	0,31	1,29	1,06	1,02	1,00
348	0,39	1,35	1,08	1,02	1,01
353	0,47	1,42	1,10	1,03	1,01
358	0,58	1,50	1,14	1,04	1,01
363	0,70	1,58	1,17	1,05	1,01
368	0,85	1,68	1,22	1,08	1,02
373	1,01	1,79	1,29	1,12	1,04
378	1,21	1,92	1,38	1,21	1,21
383	1,43	2,06	1,51	1,43	1,43
388	1,69	2,23	1,69	1,69	1,69
393	1,99	2,43	1,99	1,99	1,99
398	2,32	2,65	2,32	2,32	2,32
403	2,70	2,92	2,70	2,70	2,70
408	3,13	3,26	3,13	3,13	3,13
413	3,61	3,67	3,61	3,61	3,61

The quantity P_X was evaluated for the evaporation of water from quartz capillary tubes in the ambient air at normal atmospheric pressure. The results of calculations for certain capillary-tube radii are shown in Table 1.

Analysis of data shows that excess pressure can be seen in the tubes not only at temperatures above the boiling point, but also below same. Here, the excess pressure may exceed the atmospheric pressure by more than threefold and may exceed the saturation pressure by more than fourfold.

Figure 1 shows the calculated region of existence of the transitional regime for water. The isothermal theory of a transitional regime was checked quantitatively by observing the rate of evaporation of water from quartz microcapillary tubes using the well-known method in [6]. The test results were compared with the expression for the mass flow of vapor

$$M=\frac{r^2(P_X^2-P_\infty^2)}{16\eta RTl}. \tag{2}$$

Since the evaporation rate depends on the position of the meniscus relative to the mouth, to eliminate this variable from consideration it is expedient to introduce the evaporation constant

$$C=Ml/\rho. \tag{3}$$

The test results are shown in Figs. 2 and 3 in the form of the relation $l(\sqrt{t})$. There is a simple relationship between the evaporation constant and the slopes of the empirical straight lines. Let us explain. Since the slope $k = l/\sqrt{t}$, then the evaporation rate $V = dl/dt = k/(2\sqrt{t})$. The mass flow of the vapor depends on the rate of change in the mass of the liquid being evaporated. We will write this dependence in the form $M = V\rho$. Substituting V from this equation into (3), we obtain $C = Vl$. Thus, $C = k^2/2$.

Analysis of the test results for all temperatures and radii in the region of existence of P_X showed their quantitative agreement with Eq. (2).

An important consequence of the above conclusion is the possibility of determining the radii of microcapillary tubes from the rate of evaporation of liquid in them. For this purpose, (2) should be substituted into (3) and the radius should be expressed as

$$r=\sqrt{\frac{16\eta RT\rho C}{(P_X^2-P_\infty^2)}}, \tag{4}$$

where C is determined by experiment.

To find the unknown value of P_X, we insert r from (4) into (1) and obtain

$$\ln\frac{P_X}{P_X-P_s}=\frac{RT\rho C}{P_\infty D}. \tag{5}$$

Since P_X is absent from the right side of Eq. (5), the equation reduces to the explicit form:

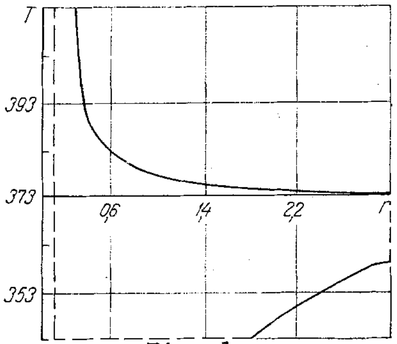

Fig. 1

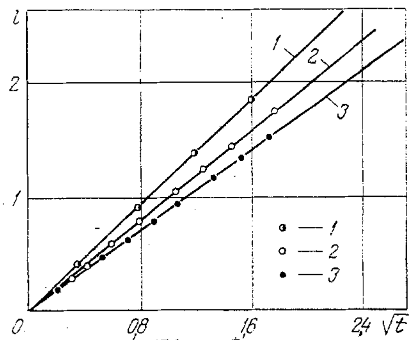

Fig. 2

Fig. 1. Region of existence of excess pressure, characteristic of the transitional regime: the dashed lines show the limits of applicability of Eq. (1). r, μm; T, °K.

Fig. 2. Rate of evaporation of water from quartz capillary tubes at T = 365°K, below the boiling point: 1) r = 0.9 μm; 2) 0.3; 3) 0.2. Lines 1-3 were constructed from Eq. (2). *l*, cm; t, h.

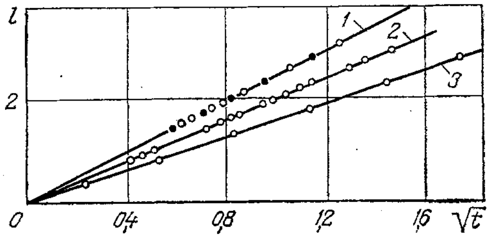

Fig. 3. Rate of evaporation of water from quartz capillary tubes at temperatures above the boiling point: 1) r = 0.9 μm, T = 378°K (clear points); r = 1.5 μm, T = 375°K (black points); 2) r = 1.2 μm, T = 375°K; 3) r = 2.3 μm, T = 373°K. Lines 1-3 were plotted from Eq. (2).

$$P_X = \frac{P_s}{1 - \exp(-\alpha)}, \tag{6}$$

where the right side of Eq. (5) has been designated through $\alpha = RT\rho C/P_\infty D$. Equation (6) contains only tabulated data and the empirically determined quantity C.

If water is used as the liquid being evaporated, the proposed method is applicable in the temperature range $343 \leqslant T \leqslant 413$°K. Film mass transfer cannot be ignored at lower temperatures, while at higher temperatures P_X becomes equal to P_S, which is not independent of the radius.

In accordance with the above results, for example, with an evaporation temperature of 373°K, the proposed method can be used to determine any radii in the interval $0.1 \leqslant r \leqslant 3$ μm. The lower limit is due to the transition of evaporation in capillaries thinner than 0.1 μm to the free-molecular regime. The upper limit is connected with the transition in broader capillary tubes to the Stefan regime of vapor flow. In this regime, the evaporation rate is no longer dependent on the radius.

The limits of applicability of the proposed method can be changed by selecting an appropriate liquid.

The calculations show that the error of the measurement of the radii of microcapillary tubes by the method of excess pressure is determined mainly by the error of the measurement of the coordinate of the moving meniscus *l*.

NOTATION

P_X, excess pressure of vapor—gas mixture, Pa; P_S, pressure of saturated vapor, Pa; P_∞, atmospheric pressure, Pa; r, radius of capillary tube, μm; D, coefficient of diffusion of vapor through the gas at the test temperature and the pressure P_∞, m^2/sec; η, viscosity of vapor–gas mixture averaged over the partial pressures [3], $N \cdot sec/m^2$; M, mass density of the vapor flow, $kg/m^2 \cdot sec$; $R = R_0/\mu$, specific gas constant, $J/kg \cdot K$; μ, molecular weight of liquid being evaporated, kg/kmole; T, temperature, °K; l, coordinate of meniscus of liquid during evaporation, m; ρ, density of liquid, kg/m^3; t, time, sec; R_0, universal gas constant.

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EXPERIMENTAL INVESTIGATION OF THE WORKING PROCESS IN A VORTEX TUBE

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The authors present the results of an experimental investigation of the temperature separation process in the chamber of an energy separation vortex tube.

The use of the vortex effect in industry requires improvement both in vortex tubes themselves and in the method of their design. This can be achieved primarily by the accumulation of information on the nature of the processes occurring in a vortex tube. Unfortunately, the experimental study of the high-speed three-dimensional flow in small diameter vortex tubes is very complex, and the published data are few and have not been classified. In this paper, besides the experimental investigation, the authors have tried to analyze flow within the energy separation chamber of a vortex tube.

The tests were performed in a counterflow adiabatic vortex tube with a cylindrical energy separation chamber of diameter 0.1 m. A four-channel nozzle insert was made up in the form of an Archimedes spiral with a total geometrical area of channels of 0.1 F at the throat section. The relative diameter of the diaphragm aperture was $\bar{d} = 0.5$. The relative roughness of the inner surface of the energy separation chamber was $\bar{\Delta} = 1 \cdot 10^{-3}$. The chamber length was 12.5D.

The flow parameters inside the energy chamber were investigated at four sections. Section I was at a distance of 0.01 m ($\bar{L} = 0.1$) from the diaphragm plane, and sections II, III, and IV were at distances of $\bar{L} = 1.5$, 5.0 and 8.5, respectively.

To investigate the distribution of the parameters at sections II–IV we used a variable-attitude combination Γ-shaped head, made of a tube of outer diameter 0.001 m according to the recommendations of [1]. Before the investigations were conducted the head was calibrated in a wind tunnel in the test range of reduced flow velocities.

The radial distribution of stagnation temperature and pressure at the nozzle section ($\bar{L} = 0.1$) was investigated by means of two heads which were inserted into the vortex tube

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