increase in buoyancy. Thus, e.g., the maximum increase in the buoyancy coefficient at $\alpha = 0.5$, $\Lambda = 1$, and $Re^* = 5$ is about 30% of its value at $Re^* = 0$.

NOTATION

u, v, components of lubricant velocity; x, y, Cartesian coordinates; p, pressure; ρ, density; μ, dynamic viscosity coefficient; h, enthalpy; δ, thickness of lubricant layer.

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JET FLOW OF SUPERCRITICAL AQUEOUS SOLUTIONS OF ELECTROLYTES WITH JOULE HEATING IN THIN CAPILLARY TUBES

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It was established that the heating of an aqueous solution of electrolyte in a thin capillary tube by a current passed through the solution is accompanied by movement of the liquid in the heated volume. Jet flow of the liquid was observed at certain values of the capillary-tube parameters and geometry.

The heating of an electrolyte solution in a capillary tube by a current passed through the solution leads to the onset of steady-state flow of the liquid.

The electrolytic cell used to study the properties of electrolyte solutions in the supercritical region takes the form of two glass vessels filled with the test liquid. The vessels are joined only by a thin ruby capillary tube. The electrodes are located a considerable distance from the tube. Watch-grade jewels of the STs type, made of synthetic ruby-10 (GOST 7137-73), were used for the capillary tubes. Ruby-10 can be soldered with molybdenum glass [1].

The capillary tube plays the role of concentrator of the electric field when a current is passed through the cell, so that the electrolyte is heated within the small ($\sim 10^{-5}$ cm^3) volume of the tube.

The pressure in the test liquid was greater than the critical value, amounting to $\sim$250 bar for aqueous solutions of LiCl, NaCl, and KCl at concentrations from 0.0125 to 0.05 M (molality) [2].

With the heating of the solution inside the capillary tube by an alternating current, one can observe transient ejections of heated liquid from the channel. At a certain value of supply voltage (with a certain amount of heating), these transients develop into steady-state flow in the form of a jet of heated liquid issuing from the capillary tube (Fig. 1).

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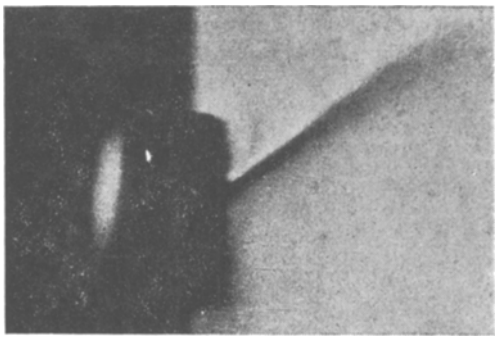

Fig. 1. Photograph of jet efflux of liquid from capillary tube.

If the pressure in the cell is below the critical value, jet flow of the liquid does not occur. Instead, the liquid boils inside the tube channel. The movement of the liquid in the heated volume changes the ohmic resistance of the electrolytic cell. This change is easily detected with the recording of a volt–ampere characteristic.

We observed the layer of liquid adjacent to the capillary tube, since the roughness of the lateral surface of the ruby and the optical properties of the solder with the glass did not allow us to examine the liquid in the channel. In order to permit observation of the liquid immediately upon its exit from the channel, the tube was installed in the glass so that it projected somewhat from the latter.

Figure 1 presents a photograph of jet flow of a heated aqueous solution of NaCl of concentration 0.0125 M from a horizontal capillary tube. The inside diameter of the tube was about 0.180 mm, outside diameter about 1 mm, length about 0.39 mm. Since the solution is flowing out of a tightly closed volume, there is a counter flow of liquid into the capillary tube. To obtain steady-state efflux of the liquid, it is necessary to select the proper tube geometry, type of electrolyte, solution concentration, and frequency of the heating current. The current frequency selected should exceed a certain threshold value dependent on the other factors just mentioned.

Figure 2 shows the dependence of the ohmic resistance on the applied voltage of an electrolytic cell with STs-1209 × 0.36 rubies. The inside diameter of the capillary tube was 90 μm, length 360 μm (curves 1, 2, and 3 correspond to aqueous solutions of LiCl, NaCl, and KCl of 0.05 M concentration); STs-1215 × 0.36 rubies, tube internal diameter 150 μm, length 360 μm (curve 4 — aqueous solution of NaCl, 0.0125 M concentration); STs-1018 × 0.39, tube internal diameter 180 μm, length 390 μm (curve 5 — aqueous NaCl solution, 0.0125 M).

The above-noted characteristics were recorded at a supply voltage frequency of 5 kHz. The voltage generator fed a bridge circuit, one leg of which was the electrolytic cell.

One feature of these curves (except for curve 3, corresponding to the case where steady-state flow was not realized at 5 kHz) is the sudden increase in cell resistance at a certain threshold voltage (voltage U_A, curve 5). This increase is due to the appearance of the outflowing jet of hot liquid. Curves 1, 2, and 4 are similar to curve 5 and, in order to avoid crowding Fig. 2, are shown in simplified form. A subsequent increase in the supply voltage changes the angle of inclination of the jet to the horizontal from about 70° to 0°. The intensity of the jet also leads ultimately to disruption of steady flow (U_B) and a sharp decrease in cell resistance (curves 4, 5).

The electrolytic cell with the STs-1209 × 0.36 ruby (curves 1 and 2) is characterized by a smooth change in resistance in the transition from steady to unsteady flow. The cell resistance oscillates (sections LA and BM) due to the unsteady nature of the liquid flow in the capillary tube. The jet flow which develops (voltage U_A) is unstable, which leads to fluctuations in cell resistance with a frequency of ∿1 Hz within the limits of the jump seen on the curve. Stable flow is subsequently achieved through an increase in the supply voltage (section AB). The transition from jet flow to transient flow (voltage U_B) is also associated with abrupt changes in cell resistance with a frequency of about 1 Hz within the limits of the jump on the curve. When the process reverses itself, jet flow commences at a voltage $U_C < U_B$ and ceases at $U_D < U_A$, i.e., hysteresis takes place.

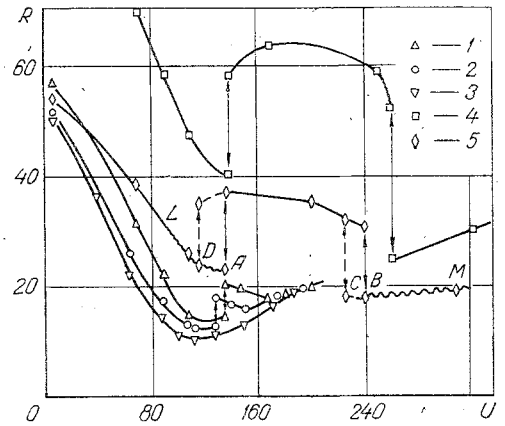

Fig. 2

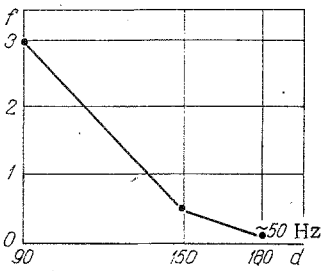

Fig. 3

Fig. 2. Dependence of resistance R, K, of electrolytic cell on applied voltage U, V.

Fig. 3. Dependence of threshold value of frequency f, kHz, on diameter d, μm, of capillary tube for 0.0125 M NaCl solution.

As noted earlier, steady flow arises only when the frequency of the heating current exceeds a certain threshold value. This value is dependent on the geometry of the tube, the type of electrolyte, and the concentration of the solution. Figure 3 shows the dependence of the threshold frequency f on the diameter of the capillary tube d for a 0.0125 M solution of NaCl in water. For an electrolytic cell with a ruby of the STs-1209 × 0.36 type, an increase in the concentration of the NaCl solution to 0.05 M leads to an increase in the threshold frequency to 5 kHz.

A model of the phenomenon might look as follows.

With the heating of an electrolyte by an alternating current in a capillary tube, the distribution of the solution concentration across the electrolyte becomes uneven. This uneven distribution depends on the frequency and the amount of heating, and it results in pressure and temperature gradients directed from the surface of the tube to its axis and having a component along the tube axis (due to the finite dimensions of the tube). When this gradient reaches a certain critical value corresponding to the voltage U_A, ejection of the liquid from the tube begins. This ejection is initially of a fluctuating nature, due to the finite angle of inclination of the jet to the tube axis. The ejections then become stably dynamic in nature, and the angle of inclination approaches zero. As the voltage is increased (with a fixed frequency), the degree of heating of the electrolyte in the tube volume increases. The latter, in turn, leads to more uniform distribution of the solution concentration and a decrease in the pressure gradient.

Thus, there is a second critical value (U_B) of supply voltage, at which jet efflux of the liquid is disrupted. The threshold value of frequency depends on the dimensions of the tube: with large tube radii, the necessary concentration gradient (and, thus, the necessary pressure gradient) is developed more readily at lower frequencies, since the wavelength associated with the standing oscillations is commensurate with the size of the tube.

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