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THE COMPLETE FILLING OF DEAD-END CONICAL CAPILLARIES WITH LIQUID

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We have observed the complete bilateral filling of dead-end conical capillaries with liquid, which is accompanied by the rapid dissolving of the air enclosed within the cavities.

We know that the nature of filling a dead-end capillary depends to a significant degree on the extent to which the gas enclosed within its cavity is dissolved and diffused into the liquid [1]. If the gas is poorly dissolved in the liquid, then in capillaries of a length $\ell_0 < 10^{-3}$ m and radius $R > 0.5$ μm during the time $t < 1$ sec a limit filling depth ℓ_∞ is established, which is defined by the equality of the capillary pressure and the pressure of the compressed air. As was demonstrated in [2], for conical capillaries the theoretical and experimental values of ℓ_∞ are in good agreement. In the case of good solubility and diffusion of the air in the liquid filling the capillaries, the depth of this filling may be considerably greater than ℓ_∞. A study was undertaken in [3] for the case in which dead-end conical capillaries are filled with defectoscopic liquids, when the meniscus continues rather rapidly to shift into the depth of the channel after establishment of the limit depth ℓ_∞.

Below we describe the results from the study into the filling of dead-end small-dimension capillaries (with a length of 30 μm $< \ell_0 < 10^3$ μm and a radius 0.4 μm $< R <$ 15 μm) with various liquids, thus making it possible to establish that in a number of cases the capillary is filled not only from the inlet side of the channel, but from the top as well. In this case, at the instant that the capillary is completely filled, the volume of liquid formed at the top and moving toward the inlet may be greater than half the total volume of liquid within the capillary.

We used dead-end conical and cylindrical capillaries which had been drawn, by means of a burner, out of cylindrical glass tubing, immediately prior to the experiment. The capillary was glued horizontally to the bottom of the vessel which was being filled with the liquid. A "Biolam-R-16" microscope was used to observe the displacement of the menisci of the liquid in the capillary. The measurement error amounted to ±0.5 μm.

The capillaries were filled with distilled water, ethyl alcohol, acetone, and kerosene. For the first of the three liquids, in each of the conical capillaries we observed the formation and subsequent growth in a cone of liquid at the apex of the channel (Fig. 1). Figure 2 illustrates the kinetics of the growth in each of the liquid volumes in the capillary. Within a specified period of time (4.4 h in Fig. 2) both fluid columns combine and the capillary is completely filled. As the dimensions of the capillary are reduced, the time required for the complete filling of the capillary is also shortened. For example, 415 sec are needed to fill completely a conical capillary with dimensions $\ell_9 = 210$ μm and $R = 4$ μm with distilled water. The conical capillaries were filled considerably more quickly with kerosene than with water, and this was not accompanied by any noticeable growth in the small column at the apex of the capillary, formed as a consequence of capillary condensation (the volume of this column amounted to $V_C < 10^{-3} V_0$, where V_0 is the total volume of the capillary channel).

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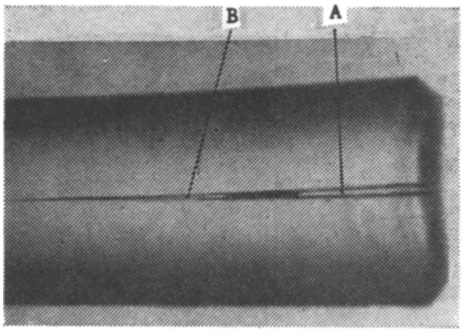

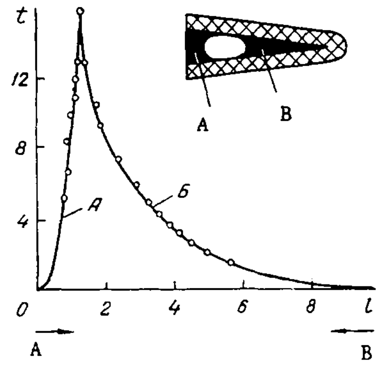

Fig. 1

Fig. 2

Fig. 1. Filling of a conical dead-end capillary ($R_0 = 6 \cdot 10^{-6}$ m, $\ell_0 = 4.64 \cdot 10^{-4}$ m) with acetone: A) principal liquid column; B) condensation column.

Fig. 2. Kinetics of filling a conical dead-end capillary ($R_0 = 1.1 \cdot 10^{-5}$ m, $\ell_0 = 9.9 \cdot 10^{-4}$ m) with distilled water: A) principal column; B) condensation column. t, 10^{-3} sec; ℓ, 10^{-4} m.

Similar investigations performed with cylindrical capillaries of radius R, equal to the inlet radius of the conical capillary, demonstrated that the capillaries are filled only from the side of the orifice. In this case, the calculation for the limit depth ℓ_∞ is based on the formula $\ell_\infty = 2\sigma\ell_0 \cos\theta/(2\sigma\cos\theta + p_a R)$, where σ is the coefficient of surface tension for the liquid; θ is the edge wetting angle; p_a is the atmospheric pressure, and this gives us values which differ from the experimental by no more than 5%. We should note that in a time t = 15 min the depth to which water penetrates into the dead-end cylindrical capillaries remains constant and equal to ℓ_∞, while it increases for the ethylene alcohol, acetone, and kerosene. This demonstrates the differing solubilities and diffusion of the air within the liquids being studied.

We thus observe a qualitative difference in the extent to which cylindrical and conical capillaries are filled with water, ethyl alcohol, and acetone, and this qualitative difference involves the fact that a conical capillary is filled by all three of the liquids from both sides, whereas a cylindrical capillary is filled only from the inlet side. Apparently this is associated with the presence of two menisci of different curvatures within the conical capillary. One of the menisci, as in the case of the cylindrical capillary, is formed on the side of the inlet to the channel, while the other (as a consequence of capillary condensation) is formed at the apex of the capillary. The pressure of the saturated vapor near the second meniscus is lower than in the vicinity of the first; therefore, the liquid vaporizes from the surface of the meniscus with the smaller curvature and it experiences condensation at the surface of the other meniscus, which forms the boundary of the liquid cone at the apex of the capillary.

Since the rate of vaporization at a given temperature in the case of kerosene is considerably lower than for the remaining three liquids under consideration, the vaporization processed from one of the menisci and the condensation at the other has virtually no effect on the manner in which the conical capillary is filled. An increase in capillary length ℓ_0 leads to a reduction in the diffusion flow of the vapor from one meniscus to the other and, correspondingly, to a reduction in the rate of liquid-column growth at the apex of the capillary.

Air is trapped in the channels of both the cylindrical and conical dead-end capillaries as they are filled with liquid. In the second case, as the capillary is completely filled, the air is obviously dissolved into the liquid, whereas in the case of the cylindrical capillary, particularly in the case of water, the rate at which it dissolves is considerably lower. In our opinion, the sharp increase in the rate at which the air is dissolved in the conical capillary is associated with the process of condensation, when droplets of the condensing liquid "bind" microvolumes of air and enhance the intensification of the solution process.

Summarizing the above, let us highlight the basic conclusions of this paper. First of all, dead-end conical capillaries of small dimensions are filled with water, ethyl alcohol, and acetone from both sides, and here, in a number of cases, the volume of liquid moving from the apex of the channel to the outlet exceeds the volume of the liquid penetrating into the depth of the channel from the orifice. Secondly, here we encounter intense dissolution of the air trapped in the channel, and the rate at which this occurs substantially exceeds (in the case of water, by several orders of magnitude) the speed with which the solution is accomplished in a cylindrical capillary.

These results are important in the practice of capillary defectoscopy, pointing the way to finding optimum conditions for more complete and rapid filling of defects by means of tracer fluids.

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NUMERICAL MODELING OF NONSTEADY NATURAL CONVECTION IN PRISMATIC CAVITIES

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UDC 536.25

A finite-difference method is described for the calculation of the two-dimensional nonsteady natural convection in arbitrary areas. This method is used to investigate convection in a cavity of trapezoidal cross section.

One of the fundamental questions that arises in the numerical modeling of the processes of natural convection in cavities of arbitrary configuration is the choice of the coordinate system. The utilization of a rectangular Cartesian system involves certain difficulties in the formulation of the boundary conditions at irregular grid nodes and leads to a loss of accuracy in the solution. In a number of cases, it is possible to introduce mixed systems (rectangular Cartesian systems in rectilinear segments, and polar systems in those segments formed by circles, etc.). It is obvious that not every configuration of this region lends itself to this approach; moreover, difficulties arise in joining the solutions at the boundaries of the subregions.

The most effective coordinate system is the one in which the boundaries of the region being studied coincide with the coordinate lines. In the general case, this system will be curvilinear and nonorthogonal. It is precisely systems such as these that are examined in this paper.

Convection in prismatic cavities of nonrectangular lateral cross section has been investigated in [1-5]. The two-dimensional natural convection in a cavity whose lateral cross section is in the form of a parallelogram is examined in [1]. The vertical walls are assumed to be isothermal (hot and cold), and either a linear distribution of temperature or a condition of thermal insulation is specified for the remaining two parallel walls. The calculation results are compared with experimental data. The same authors, in [2], solved the problem in a conjugate formulation.

Convection in a trapezoidal region formed by the arcs of concentric circles and radial straight lines is examined in [3]. In [4], the authors investigate the problem experimentally. Finally, convection is modeled in [5] in a trapezoidal cavity with thermally insulated bases and walls that are isothermally inclined at an angle of 45° to the base. The numerical solution of the problem is found by utilizing variable stream functions, i.e., vorticity in a range of $10^2 \leq Ra \leq 10^5$ for various orientations of the cavity relative to the vector of the force of gravity.

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