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Experimental study of liquid level rise in a plane capillary formed by elastic periodically stretched walls

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A water rise in a plane capillary with elastic periodically stretched walls is experimentally demonstrated. Dependence of the water meniscus rise height on the value of time-periodic elastic extension of capillary walls was measured. A deviation of the measured dependence from the linear dependence was recorded. The latter one could be realized in the mode of an ideal pinning of a meniscus edge.

Keywords: plane elastic capillary, stretching, meniscus, rise height.

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Capillary effect (CE) is a fundamental hydrodynamic phenomenon. It consists in the fact that liquid in a vertical capillary, which has one of its ends immersed into a vessel filled with liquid, rises to a height that exceeds its level in the vessel. The wetting of capillary walls is the physical mechanism of CE [1,2]. This effect is found and used everywhere: in nature, everyday life, medicine, and various technological processes.

The issue of liquid level rise in capillaries has long been recognized and addressed. For example, an ultrasonic CE, the observation of which was catalogued as discovery No. 109 [4] in 1961 in the State Register of Discoveries in the USSR, was characterized in [3]. A magnetic CE (occurring in magnetic liquids) is also known [5], and the existence of a plasma CE was reported in [6–8].

Elastocapillarity is a new research trend that has emerged recently in wetting and capillary science and is concerned with the behavior of liquids in contact with elastic deformable surfaces [9–11]. The studies of, e.g., liquid drops sitting on plane horizontal stretched rubber substrates follow this trend [12,13].

The specifics of CE in a capillary with transversally deformed flexible walls were examined in [14]. A question then arises as to the magnitude of CE in a capillary with longitudinally deformed elastic walls.

In the present study, the water level rise in a capillary with elastic walls subjected to periodic longitudinal extension was examined via digital microscopy. A specialized test stand (see the diagram in Fig. 1, *a*) was constructed for the purpose.

This stand operates by converting rotational motion into periodic translational motion in the fashion of a crank-and-rod mechanism [15]. It features a crank with an adjustable radius of rotation $R = 18-47$ mm, a flywheel to stabilize the rotation rate, and a drive. A plane-parallel capillary with elastic walls serves as a rod. Capillary walls were fabricated from 100% rubber ribbons 15 mm in width and 0.5 mm in thickness. The lower end of the capillary was secured to a clear beaker, and the upper end was attached

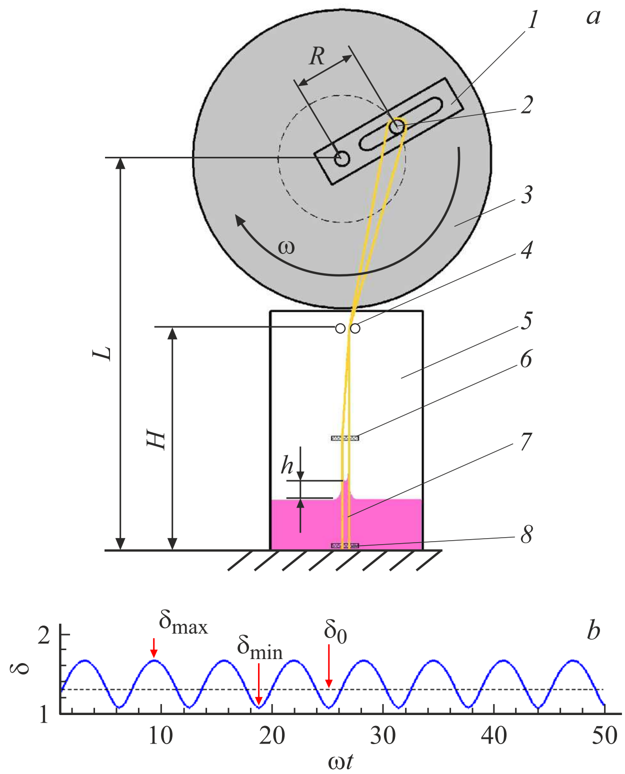

Figure 1. Diagram of the experiment. *a* — Test stand: *1* — crank, *2* — axis of attachment of the capillary walls to the crank, *3* — flywheel, *4* — guide rollers, *5* — beaker, *6* — guide spacers, *7* — capillary, and *8* — guide clasp. *b* — Example temporal variation of relative extension $\delta(t)$ of capillary walls.

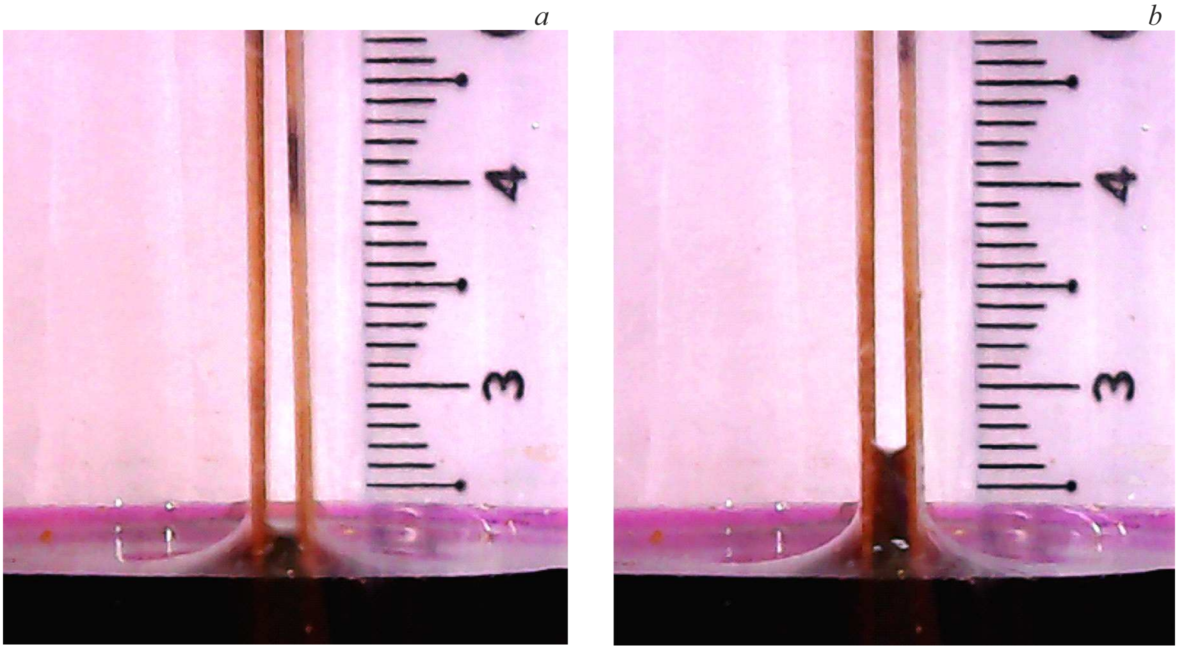

Figure 2. Images of liquid in the capillary at time points corresponding to $h_{\min}$ (a) and $h_{\max}$ (b).

to the crank. The gap between capillary walls (maintained by special guide spacers) was 1.5 mm. The beaker was filled with water. Water was dyed with several $KMnO_4$ crystals for better visual clarity.

All experimental data were obtained under elastic (reversible) one-dimensional extensions of the ribbon in the linear mode governed by the Hooke's law.

Relative ribbon elongation δ was determined by measuring the elongation of a special color marker at the end of ribbons. Relative elongation $\delta = 1$ corresponds to the undeformed marker length.

A Celestron (MODEL#44302-A) [16] digital optical microscope operated in the video recording mode was used to track the rise of the water meniscus in the capillary above the water level in the beaker.

With the drive rotating at constant rate ω, relative extension $\delta(t)$ of the capillary walls varies periodically as

$$\delta(t) = \frac{\delta_0}{L-R}\left[H + \sqrt{R^2 + (L-H)^2 - 2R(L-H)\cos\omega t}\right], \quad (1)$$

where δ_0 is the initial extension of the capillary walls corresponding to the horizontal crank position, L is the distance from the point of attachment of the capillary at the bottom of the beaker to the crank rotation axis, and H is the distance from the point of attachment of the capillary at the bottom of the beaker to the guide rollers (Fig. 1, a). Note that the value of δ_0 was chosen so that minimum relative elongation $\delta_{\min}$, which corresponds to the lowermost position of the crank, slightly exceed unity. This was done to exclude slacking of ribbons. The phase dependence of the relative extension of capillary walls, which follows Eq. (1), is presented in Fig. 1, b, where $\delta(t)$ varies from $\delta_{\min}$ to $\delta_{\max}$.

Certain sections of walls, which were initially immersed in water, periodically rise above the initial water level in the beaker. When these sections rise, a certain amount of water is entrained upward due to wettability. This effect is somewhat similar to the known effect (examined by Landau and Levich [19]) of liquid entrainment by an inextensible ribbon pulled out of this liquid at a constant rate [17,18].

It was found that the meniscus rise height in the capillary varies periodically from the minimum value to maximum $h_{\max}$ at the drive rotation rate. The images of liquid in the capillary at time points corresponding to $h_{\min}$ and $h_{\max}$ are presented in Figs. 2, a, b, respectively.

The crank was rotated in our experiments at various frequencies $\nu = \omega/2\pi = 0.2-3$ Hz. It was established that the maximum liquid rise height ($h_{\max}$) is independent of rotation rate ω, but depends on $\delta_{\max}$.

Figure 3 shows the $h_{\max}(\delta_{\max})$ dependence obtained at a frequency of 1 Hz within the $1.49 \le \delta_{\max} \le 1.66$ argument range. This range corresponds to the following interval of crank radius values: $R = 18-47$ mm. The indicated measurement errors emerged as a result of statistical processing as mean-square deviations of $h_{\max}$ from their mean values in different test runs. They do not exceed $\pm 5\%$.

The straight line in Fig. 3 corresponds to ideal (with no sliding down) pinning of the meniscus edge to the capillary wall surface. As extension amplitude $\delta_{\max}$ grows, the measured values of $h_{\max}$ deviate more and more strongly from the pinning line, since water slides down under the influence of gravity.

Thus, the effect of water rise in plane capillaries with elastic walls subjected to periodic extension, which is similar to the known Landau–Levich effect, was demonstrated

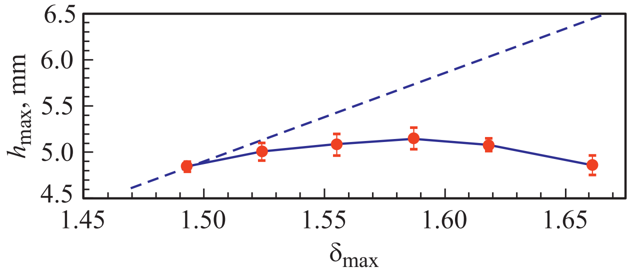

Figure 3. Dependence $h_{max}(\delta_{max})$. The dashed line represents ideal pinning of the meniscus edge.

experimentally. The dependence of the water meniscus rise height on the magnitude of time-periodic elastic extension of capillary walls was determined. A deviation of the measured dependence from a linear one, which could potentially be observed in the regime of ideal pinning of the meniscus edge, was noted.

Conflict of interest

The authors declare that they have no conflict of interest.

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