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Statics and dynamics of capillary bridges

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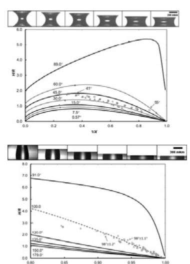
HIGHLIGHTS

- The study pertains both static and dynamic CB.
- The analysis of static CB emphasis on the 'definition domain'.
- Capillary attraction velocity of CB flattening (thinning) is measured.
- The thinning is governed by capillary and viscous forces.

GRAPHICAL ABSTRACT



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ABSTRACT

The present theoretical and experimental investigations concern static and dynamic properties of capillary bridges (CB) without gravity deformations. Central to their theoretical treatment is the capillary bridge definition domain, i.e. the determination of the permitted limits of the bridge parameters. Concave and convex bridges exhibit significant differences in these limits. The numerical calculations, presented as isogones (lines connecting points, characterizing constant contact angle) reveal some unexpected features in the behavior of the bridges. The experimental observations on static bridges confirm certain numerical results, while raising new problems of interest related to the stability of the equilibrium forms.

The dynamic aspects of the investigation comprise the capillary attraction (thinning) of concave bridge. The thinning velocities at the onset of the process were determined. The capillary attraction, weight of the plates and viscous forces were shown to be the governing factors, while the inertia forces turned to be negligible.

1. Introduction

The modern basis of capillary bridges investigation was set with the studies of Plateau, who 140 years ago defined a mathematical problem, known nowadays as Plateau's problem [1]. Defined originally as a purely mathematical issue (finding the surface with minimal area at given boundaries), it has turned in the years into an analytical tool for the description of capillary systems. Ever since the second half of the last century, capillary bridges (CB) have been among the intensively studied capillary systems. It corresponds to their increasing application in laboratory techniques and industrial praxis. For example: liquid material transferring from AFM tips to silicone substrates for lithographic purposes [2]. With the development of patterning and lithography studies of capillary bridges in slit pore geometry became important [3]. Further implementation of CB can be found in the so-called weakly adhesive solid surfaces studies [4]. CB between two bodies of spherical shape appears to be important for soil–water interaction. Interesting are the investigations of surface roughness influence on the CB behavior [5].

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There have been attempts to develop methods for contact angles measurement between the liquid and two particles [6].

The recent CB theoretical investigations primarily feed the experiment (see above), but attention is also paid to classical problems like equilibrium, stability, etc. [7–9].

Our study pertains to both the experiment and the theory of CB. In theoretical aspects the relations between CB geometrical parameters are investigated mainly (contact radius, height, contact angle, etc., Section 3). The emphasis is on the so-called 'definition domain', e.g. the upper CB height limit at given contact angle and volume. Some dynamic characteristics are also considered, such as the capillary pressure and CB-maintaining external force. The experimental part (Section 2) describes the setup and methods for measuring equilibrium (static) and nonequilibrium (dynamic) CB states. The new moment here is the measured velocity of mutual approach of the CB plates upon acting of capillary attraction. The analysis of the dependence 'attraction (thinning) velocity vs. CB height' clearly shows that the inertia forces are negligible, as compared to the drag forces. In Section 4, the main experimental results are presented, as well as their interpretation. The work is completed with concluding remarks (Section 5). Some mathematical details are incorporated as an appendix.

2. Experimental setup

Our experimental setup consists of a micrometer, onto the measuring arms of which two square (20 mm × 20 mm × 2 mm) stainless steel supporting plates were fixed parallel to each other.

Two 22 mm × 22 mm microscope cover glasses (ISOLAB) of soda lime silica composition were selected as working surfaces. They were glued to the supporting plates for static measurements. In the case of attraction kinetics experiments, only the upper glass was glued, while the lower one was placed on the corresponding stainless steel plate. Images were recorded by using a high-speed camera, MotionXtra N3, which was mounted onto a horizontal optical tube with appropriate magnification (Fig. 1). All experiments were carried out with deionized (Milipore) water.

2.1. Static capillary bridge experiments

Two types of static experiments were performed:

(1) Hydrophilic glass surfaces were pre-cleaned with 99.9% C_2H_5OH and washed with deionized (Millipore) water before being glued to the supporting plates. A small droplet of ≈1 mm^3 volume, was placed in the middle of the lower glass slide. The upper glass slide was moved toward the droplet until a capillary bridge was formed. Further, several equilibrium states were recorded; pressing the shape until thin film was formed. Afterwards stretching took place until breakage occurred (Fig. 5 presents several consecutive pictures of stretching). The experiment was repeated several times with varying initial droplet volume. Concerning the effects due to evaporation, the direct volume decrease played no role, since the theoretical relations are CB volume invariant (Section 3.3). Other effects related to the evaporation (e.g. thermo-effects) were not observed.

(2) Experiments with hydrophobized glass cover slides were performed. The preliminary hydrophobization was done with PDMS (Rhodia Silicones, 47V1000), following the procedure developed by Marinova et al. [10]. Before gluing the slides, they were washed with 99.9% C_2H_5OH. The capillary bridge was formed after placing a droplet on the lower surface and attaching it later to the upper glass slide. Stretching was applied onto the droplet until a breakage of the capillary bridge occurred. Selected sequential pictures of the experimental part are presented in Fig. 6.

2.2. Dynamic capillary bridge experiments

A single drop of volume $V \approx 1$ mm^3 was placed on a hydrophilic glass slide of weight, $m \approx 0.3 \times 10^{-3}$ kg. Another flat, hydrophilic planar cover glass was moved toward the droplet from above until a CB was formed in an equilibrium state. When the distance between the plates was slightly reduced, by Δh, the lower plate was taken off from the support by the capillary force F_γ and the CB began fast thinning. The recorded data of the dependence h vs. t, are presented in Fig. 7.

3. Mechanical balance and calculations

Our theoretical investigations concern only the mechanical properties of CB. We do not consider the processes of evaporation, condensation and the related potential temperature effects [11–13]. The gravitational deformation of the liquid/gas surfaces is neglected in the theoretical analysis, due to the small linear dimensions of the drop. Yet, in sufficiently stretched CB, especially if hydrophobic, signs of gravitational deformation were observed experimentally, which fact is discussed in Section 4. Here, in Section 3, we shall present separately the mechanical balance of static and dynamic CB.

3.1. Static balance

In general, the CB mechanical equilibrium comprises the pressure balance on liquid/gas interfaces and the external force on the CB plates balancing the capillary attraction/repulsion. Upon neglecting gravity effects and other external fields, the pressure balance is reduced to $\Delta P = P_\gamma = \text{const}$, where $\Delta P = P_i - P_e$ is the jump across the liquid/gas interfaces, P_i, P_e are the internal, external pressures. For CB with axial symmetry; the capillary pressure takes the form $P_\gamma = \gamma r^{-1}\partial(r \sin\varphi)/\partial r$, with γ as the interfacial tension

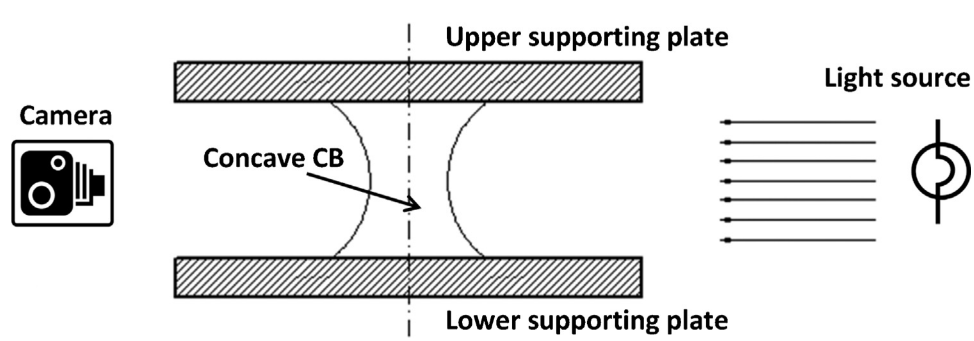

Fig. 1. Schematic representation of the experimental setup.

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