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Laplace pressure evolution and four instabilities in evaporating two-grain liquid bridges

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ABSTRACT

Dynamic variables characterizing evolution during evaporation of capillary bridge between two spheres are analyzed. The variables include: average Laplace pressure, pressure resulting force, surface tension force and total capillary force calculated based on the previously reported geometrical variables using Young-Laplace law [1,2]. This is the first time to our knowledge that Laplace pressure is calculated from the measured bridge curvatures along the process of evaporation and compared to experimental measurement data. A comparison with the experimental data from analogous capillary bridge extension tests is also shown and discussed.
The behavior of evaporating liquid bridges is seen as strongly dependent on the grain separation. Initial negative Laplace pressure at small separations is seen to significantly augment during an advanced stage of evaporation, but to turn into positive pressure, after an instability toward the end of the process, and prior to rupture. At larger separations the pressure is positive all the time, changing a little, but rupturing early. Rupture in all cases occurs at positive pressure. However, because of the evolution of the surface area of contact, the resultant total capillary forces are always tensile, and decreasing toward zero in all cases. Comparison between measured total resultant capillary forces and those calculated from the Young-Laplace law is very good, except for some discrepancies at very small separations (below 50 μm). Up to four consecutive instabilities of capillary bridge are seen developing at some sphere separations. They are: re-pinning-induced suction (pressure) instability; Rayleigh nodoid/catenoid/unduloid unstable transition, associated with zero-pressure; Rayleigh unduloid/cylinder unstable transition, associated with the formation of a liquid-wire; and lastly, a pinching instability of the liquid-wire, associated with the bridge rupture. Rupture of the bridges is seen at large separations to occur quite early, at only 1/4–1/3 of the initial water volume evaporated. At smallest separations, rupture occurs in a seemingly unstable way when water evaporates from the bridge thinnest section of the neck.

1. Introduction

Evaporating capillary bridges between two glass spheres at fixed separations revealed in recent isothermal experiments characteristic patterns of their evolution during liquid evaporation [1]. That includes total mass-evaporation rate, average evaporation flux, evolution of geometric characteristics, such as the radius of bridge gorge, central external radius, angles and radii of contact, and evolution of capillary force. These patterns bear similarities to, as well as differences from, the analogous quantities measured during more familiar short-term axial extension tests of such bridges, with negligible evaporation. An important part of such evolution is rupture of liquid bridges at some separations and other forms of bridge instability [2]. An importance of a better understanding of rupture conditions comes from the role of liquid bridges in mechanical strengthening of granular media, and in the change of liquid repartition pattern.

The objective of this paper is to process, analyze, and discuss the numerical data from the aforementioned experiments on the evaporation-induced evolution of the following bridge characteristics: gorge radius, r_g and of a mean value of two measured external radii, r_{ext} (Fig. 1) for a series of separations between grains D, to calculate the Laplace pressure, Δp and Laplace pressure resulting force, $F_{\Delta p}$ as well as the surface tension component of the evolving capillary force F_{ST} with the use of "gorge method" [3]. The use of the gorge and a single external radius is equivalent to treating the bridge as a structured water body of a uniform external radius of curvature, and implying a uniform liquid pressure throughout.

The evolution of contact angle (hysteresis), pinning, de-pinning and re-pinning of the contact line are reported by Mielniczuk et al. [1], but are

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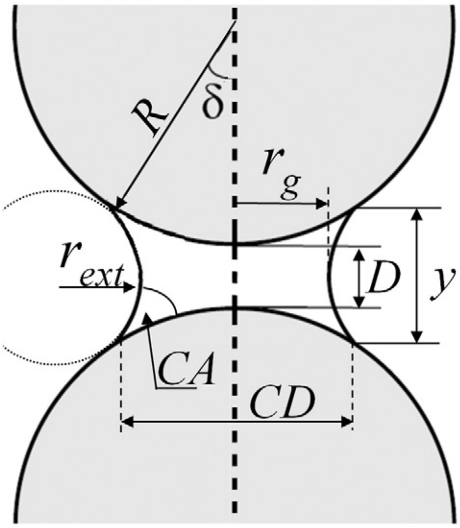

Fig. 1. Liquid bridge between two spheres.

not considered in Laplace-Young law and in the expression for the Laplace pressure. However, as seen, they heavily affect the evolution of Laplace pressure. The calculated total capillary force F_{CAP} being a resultant of the pressure force $F_{\Delta p}$, and the surface tension components F_{ST}, is compared to the values obtained experimentally. A similar comparison is also made with, and discussed in the context of the analogous conditions during capillary bridge extension (separation increase) tests. Rigid spheres of equal radius and constant separation systems are considered only.

2. Experimental input

The main dynamic data from our recent experiments (see [1] for details) are synthetized in Fig. 2a and b, visualizing the total measured capillary force, F_{CAP-m} against the current volume of the liquid bridge and separation between the spheres. A description of the experimental conditions is provided by [1].

The curves at constant separations D from 0.01 to 2.0 mm were obtained in evaporation driven tests, all starting from the same initial liquid volume of 4.0 µl. The curves at constant volume V were obtained from extension tests, all started at a zero separation.

All the data of total capillary force denoted in what follows as "*measured*", both during evaporation and extension, in reality were *calculated* from the *truly measured* total intergranular force by subtracting from the latter the hydrostatic pressure resultant force (weight effect), acting on the surface area of cross-section at gorge level, as proposed by Princen [4] and Adams et al. [5]. This was performed to be able to directly compare the force F_{CAP-m} to the one calculated from the curvature radii, F_{CAP}. The gravity (hydrostatic) force contribution has nevertheless been very small, never higher than 5% of the total measured intergranular force.

In general, the capillary force, F_{CAP-m} (Fig. 2) decreases, both during evaporation and during extension. There is a difference in this trend for the two processes: the capillary force is a convex function (of liquid volume loss) for evaporation (slow evolution at the beginning, fast at the end), while for extension the capillary force is largely a concave function of varying separation at constant volume (fast evolution at the beginning and slow at the end).

Both graphs indicate that the surface F_{CAP-m} (V, D) hypothetically spanning the constant separation (evaporation) curves does not exist in a relatively vast range of liquid volumes (less than 2 µl, at $D = 1.3$ mm, and less than 1 µl, at $D = 0.7$ mm) as marked on the "floor" of the graph, while it does certainly exist in that range for the extension processes. The principal cause of that is rupture of the bridges occurring within the domain and hence cutting off portions of the range. Apart from the rupture range, there are differences between the capillary force value for evaporation and extension that may reach up to 80 % of the maximum value (e.g. for separation of 0.1 mm). The overall conclusion from these observations is that the capillary force, F_{CAP-m} is not a state function of volume and separation [1], but does depend on the history of evaporation or extension and on the solid-liquid contact evolution, in particular the history of contact diameter CD and contact angle CA.

2.1. Radii of curvature of liquid bridge and their evolution

To quantify the evolution of the profile of the liquid body, the two principal geometric characteristics of the liquid bridges were determined by image-processing: the radii of their gorge r_g and of the external meridian curvature r_{ext} (and hence, the mean surface curvature). These two variables enter the Laplace-Young law for capillary pressure, which is a macroscopic equilibrium theory based on the assumption of constant pressure throughout the bridge.

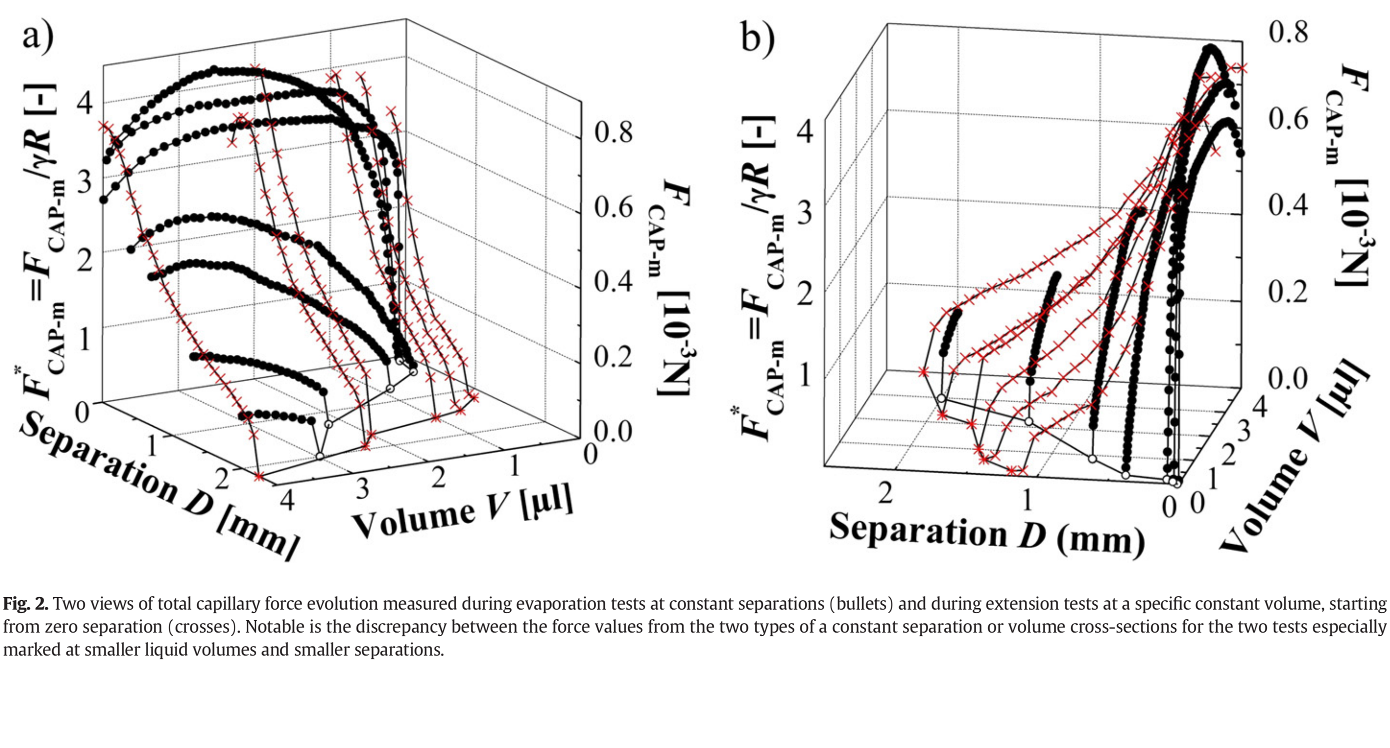

Fig. 2. Two views of total capillary force evolution measured during evaporation tests at constant separations (bullets) and during extension tests at a specific constant volume, starting from zero separation (crosses). Notable is the discrepancy between the force values from the two types of a constant separation or volume cross-sections for the two tests especially marked at smaller liquid volumes and smaller separations.