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Competing forces on a liquid bridge between parallel and orthogonal dissimilar fibers†

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This paper presents a detailed investigation on the mechanical forces acting on a liquid bridge between dissimilar fibers in parallel and orthogonal configurations. These forces were measured experimentally, using a sensitive scale, and were also predicted computationally, *via* numerical simulation. Special attention was paid to the fiber–fiber spacing at which the liquid bridge detached from the fibers, and to how a transition from an equilibrium liquid bridge to a spontaneously (time-dependent) detaching bridge took place. It was found that, while varying the spacing between the fibers affects a liquid bridge differently for fibers with different relative angles with respect to one another, the spacing at which the bridge detaches from the fibers is independent of the fibers' relative angle. This paper also formulates the contribution of the geometrical and wetting properties of the fibers competing for the droplet that results from a liquid bridge detachment, and presents a mathematical expression to predict the fate of that droplet.

1 Introduction

A liquid bridge between two solid surfaces has been the focus of many previous studies due to its ubiquitous presence in a variety of applications. The capillary force generated by a capillary bridge contributes to the adhesion force that frogs, insects, or geckoes create to climb a vertical surface.[1,2] For instance, a particular type of beetle can generate an adhesion force of more than 60 times its body weight thanks to an array of liquid bridges that forms between its feet and the surface on which it walks.[3] In industry, the liquid bridge plays a crucial role in underground oil recovery[4,5] and granular systems,[6–8] wetting and liquid transport in coalescence filters and textiles,[9–17] the design of magnetic hard-disks,[18] papermaking,[19] fiber-based microfluidics[20,21] and fuel cells[22,23] among many others.

Scientific research on liquid bridges started in 1805 by Young who investigated a liquid bridge formed between two flat plates to study the liquid surface tension.[24] Later, Gauss derived the Young-Laplace equation, which predicts the equilibrium shape of an interface separating two immiscible fluids.[25] Since then, many others have studied liquid bridges between smooth flat plates for their industrial relevance, and also for the simplicity of their axisymmetric profile. These include many pioneering investigations where the effects of surface roughness or contact angle hysteresis on the shape and stability of a capillary bridge were studied.[26–30] Significant attention has also been paid to the fluid mechanics of a liquid bridge between two spherical objects, or between a sphere and a flat plate. The main objective of these studies was to measure the forces between the involved surfaces in terms of the distance between them or as a function of their surface properties in the absence[31–33] or presence of gravity.[34,35]

Given the decades of research on different liquid bridges, very little attention has been paid to the case of a liquid bridge between two fibers. In contrast to most previous studies, a liquid bridge between two fibers does not have an axisymmetric profile. This makes it harder to develop a mathematical description for the 3-D shape of the bridge. The shape of a liquid bridge between two parallel cylinders with a small spacing and in the absence of gravity was first studied by Princen.[36] Later, Protiere *et al.*[37] modified Princen's equations to study how a liquid body transitions from a droplet shape to a long liquid bridge between two parallel fibers when varying the fiber–fiber spacing, fiber diameter, fiber's Young–Laplace contact angle (YLCA), or the liquid volume. Princen's equation was also used by Schellbach *et al.*[38] to propose a method to measure the contact angle of natural fibers. Virozub *et al.*,[39] Wu *et al.*,[40] and Bedarkar *et al.*[41] simulated the 3-D shape of a liquid bridge between two fibers and reported the capillary forces acting on the fibers as a function of fiber–fiber spacing or the relative angle between the fibers.[39] Duprat and Protiere,[42] Duprat *et al.*,[43] and Soleimani *et al.*[44] also studied the problem of a capillary bridge between two fibers but with the main focus on fiber deformation in response to capillary forces.

The study presented in this paper contributes to the above body of literature by presenting a one-on-one experiment–simulation comparison for a capillary bridge formed between

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