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Tension grips the flow

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Bounding wire curved due to surface tension

Surface tension plays a dominant role in the formation and stability of soap films. It renders them both a quasi-two-dimensional fluid and an elastic membrane at the same time. The techniques for measuring the surface tension of the soap solution may very well apply to the static soap film, but how can the surface tension of a soap film be unintrusively measured, and what value would it assume? The answer, being at the intersection of physical chemistry, non-equilibrium physics and interfacial fluid dynamics, is not amenable to deduction *via* established methods. In a joint theoretical and experimental study, Sane *et al.* (*J. Fluid Mech.*, vol. 841, 2018, R2) exploit elasticity theory to glean the answer through a simple, yet elegant framework.

Key words: interfacial flows (free surface)

1. Introduction

The earliest observations of capillary action, at least within occidental records, are traced to Leonardo da Vinci (1452–1519), Maxwell & Strutt (1911) and Galileo's student Niccoló Aggiunti Nelli (1759). The first measurements by Francis Hauksbee (1709) were expanded upon by James Jurin, resulting in Jurin's law (Jurin 1718, 1719). The formal introduction of surface tension by Johann Andreas von Segner (1751) paved the way for establishing the theoretical foundations of interfacial science with the Young–Laplace equation (Young 1805; Laplace 1806). The three century delay from the first observations by Leonardo (1452–1519) to the Young–Laplace equation was neither for lack of effort nor ingenuity, but for the fact that in spite of the simplicity of its basis, interfacial science is notorious for its misunderstandings and interpretational difficulties. Even Young and Laplace succumbed to such obscurities (Maxwell 1878) until Carl Friedrich Gauss unified their approaches (Gauss 1830); such difficulties were not limited to theory alone but plagued experiments alike. For instance, easy contamination of the water surface rendered reliable experimental determination of surface tension nearly impossible until the development of the Pöckels scale (1891). All these advances concerned static interfaces where the equilibrium shape or geometry of the surface took centre stage.

An understanding of the Marangoni stress arising from gradients of surface tension arose along a similarly convoluted path. Althoughinterfacial dynamics of

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doi:10.1017/jfm.2018.301

https://doi.org/10.1017/jfm.2018.301 Published online by Cambridge University Press

self-propelled camphor particles was reported by the late 17th century (Heyde 1686) and investigated by some brilliant minds (Tomlinson (1869) provides a historical review), the phenomenon was explained as arising from surface tension gradients only two centuries hence (Van der Mensbrugghe 1869). Mistaken hypotheses percolating along the way had to be painstakingly disproven before the correct explanation could emerge; yet another example of the difficulties that beset this field. The Marangoni effect – mass transfer along a fluid interface due to a surface tension gradient – was only identified in 1855 by James Thomson, brother of Lord Kelvin (Thomson 1855), explained 14 years later by Carlo Marangoni (Marangoni 1869) and eventually received complete theoretical treatment with the Gibbs adsorption isotherm (Gibbs 1878).

Soap films hold special significance in interfacial science owing to them being the prototypical instance of surface tension dominated effects. Much like the development of interfacial science, static soap film behaviour, e.g. minimal surfaces and related geometric properties (Plateau 1873; Dewar, Ross & Dickson 1927) formed the focus of early studies and soap film dynamics was rarely studied (Mysels 1959). Soap film hydrodynamics (Couder, Chomaz & Rabaud 1989; Chomaz 2001) as a study in and of itself is relatively recent and has rapidly gained a footing as a standard experimental tool in the investigation of two-dimensional hydrodynamics, including turbulence (Kellay & Goldburg 2002), vortex dynamics (Roushan & Wu 2005) and fluid–structure interactions (Zhang *et al.* 2000). Unlike early works, both the three-dimensional character of soap films and the effect of surface tension have become prominent in recent studies (Gilet & Bush 2009; Tran *et al.* 2009), thus prompting the question, 'What is the surface tension of a flowing soap film?'

2. Overview

The article by Sane, Mandre & Kim (2018) addresses precisely this question, both theoretically and experimentally. The question assumes significance in the first place because it is the surfactant that imparts stability to the soap film. The surfactant molecules populate the interface and the bulk fluid. In equilibrium, the molecules are distributed in the two phases according to the adsorption isotherm, and the surface tension of the soap film is reduced below that of pure water by the adsorbed surfactant. Upon stretching the film, bulk molecules are transferred to the freshly created surface, a process whose duration is dictated by surfactant transport and sorption kinetics. For a soap film constantly flowing under external pumping of a solution, it is not clear how the time scale of the hydrodynamics that deforms the interface compares with the surfactant equilibration time scales. The film's surface tension could vary with the flow regime, thereby necessitating its experimental determination. Such a measurement probes the extent to which the surfactant dynamics is out of equilibrium.

Unfortunately, standard surface tension measurement techniques fail here. For instance, the pendant drop method requires bulk fluid and is therefore disqualified by default whereas other techniques such as the du Noüy and Wilhelmy plate methods are invasive and become especially problematic if the film flow speed exceeds the Marangoni wave speed (Kim & Mandre 2017). Sane *et al.* (2018) circumvent all these difficulties by imaginatively exploiting the Euler–Bernoulli equation to relate the bending curvature of wires that bound the flowing film to its surface tension. Standard gravity-driven soap films employ two nylon wires held in tension by a hanging mass of known weight, and the soap solution is drained down the wires under gravity. When the nylon wires are pulled apart, a soap film is created between the wires and the solution now flows down the film. But the film's surface tension, which tries to minimize its surface area, exerts a force that tries to pull the nylon

https://doi.org/10.1017/jfm.2018.301 Published online by Cambridge University Press

wires back together and imparts curvature to them while in tension (see title image). Measuring the bending curvature of the nylon wire against the applied tension yields the surface tension of the film in flow.

Sane *et al.* (2018) have measured the surface tension of flowing soap films under different film thicknesses and soap concentrations and found an apparent equivalence between surfactant dilution and thinning of the soap film. Since the film's surface tension depends upon surfactant concentration at the interface, this translates to the fact that thinner films possess higher surface tension. Relating the film thickness and surfactant concentration through surfactant conservation, they develop a quantitative model based on Langmuir's adsorption isotherm. This model finds confirmation when surface tension, measured at different values of the solution flux and at different concentrations, collapses onto a master curve. This observation also explains that the soap film's Marangoni elasticity measured using the angle of oblique Marangoni shocks (see title figure) does not vary with the film width, flow rate or soap concentration because the interface is saturated with soap (see Kim & Mandre 2017).

3. Outlook

In the process of determining the surface tension of flowing soap films, Sane *et al.* (2018) have also discovered a heretofore unknown dependence of the soap film's terminal velocity on the film thickness and its flux. Standard two-dimensional hydrodynamics assumes the terminal velocity arises from air drag, which is expected to be substantial on account of the large exposed area of the film to surrounding air, and is usually modelled as a linear drag term in the two-dimensional Navier–Stokes equation. The additional dependence on film thickness and flux points to a gaping hole in our understanding and one hazards to proffer the informed opinion that there is most probably new physics in the two-dimensional hydrodynamics.

Furthermore, commercial detergents employed in soap film experiments are complex formulations comprised of different surfactants. The proof of principle presented by Sane *et al.* (2018) begs careful characterization against pure surfactants not just for surface tension measurement, but more importantly to gain a better understanding of stationary state sorption kinetics. This point applies beyond soap films to the general problem of surfactant transport. Surfactants dissolve to varying degrees in bulk fluid and can be transported either in the adsorbed layer (at the interface) or in bulk phase. Simultaneous measurement of surface and bulk surfactant concentrations, Marangoni stresses and surface rheology, sorption kinetics and how these quantities are correlated is an experimentally formidable task (Langevin & Monroy 2014; Elfring, Leal & Squires 2016; Bandi *et al.* 2017; Mandre 2017) and contains all of the hallmarks of the obscurities faced by interfacial science since its inception. It is in this context the work of Sane *et al.* (2018) bears hope that perhaps a renaissance is afoot in interfacial science, prompting one to close with the famous quote by Leonardo da Vinci, the discoverer of capillary action, 'che non terminano in nota experientia'.

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https://doi.org/10.1017/jfm.2018.301 Published online by Cambridge University Press