Title

Investigations of Surface-Tension Effects Due to Small-Scale Complex Boundaries

Author

Jiansheng Feng, *University of Massachusetts Amherst* Follow

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First Advisor

Jonathan P. Rothstein

Second Advisor

Mark T. Tuominen

Third Advisor

Narayanan Menon

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Abstract

The earliest man-made irrigation systems in recorded history date back to the ancient Egypt and Mesopotamia era. After thousands of years of experience, exploration, and experimenting, mankind have learned how to construct canals and dams and use pipes and pumps to direct and control water flow, but till this day, there are still some behaviors of water and other simple fluids that surprise us. One such example is the lotus effect: a surface-tension effect which allows raindrops to roll freely on a lotus leaf as if they were drops of mercury. One of the key factors that determine how a fluid system behave is the size-scale. Fluids flow at small scales very differently than they do at large scales. The standard comparing to which small and large are defined is the capillary length. A number of surface-tension related phenomena are unfamiliar because they are only noticeable at length-scales of a few millimeters or below, and they look nothing like what we would expect fluids to behave when dominated by gravity. As fascinating as many of them may seem at first glance, surface-tension phenomena are actually not that far away from our daily lives.

Surface tension is everywhere because it costs energy to create areas of surfaces and interfaces, just like it costs energy to deform a solid (resulting in elasticity) or to elevate a weight (resulting in gravity). To minimize energy, a surface or an interface has the tendency to contract, and this tendency generates surface tension. The size of a system significantly affects the relative strengths of surface-tension effects comparing to effects of body forces, most commonly gravity. By equating the estimated magnitudes of surface tension and gravitational forces of a system, a length scale, know as the capillary length, can be defined. The capillary length of water on earth is about 2.7 mm. At the length scale of everyday objects, which is usually above the capillary length, surface-tension effects are not always prominent, because at those scales the competing force, gravity, is often much stronger. That is why the surface of a glass of water is more or less flat. However, as the size-scale decreases, surface tension decreases a lot slower than gravity, so when the size of a fluid system gets down to below the capillary length, surface tension takes over.

One of the defining characteristics of this moment in human history, is the tremendous efforts we are putting into the research and engineering of micro- and nano-scale materials and structures − systems where surface tension is often the predominant force. It is important to study surface-tension effects so that we can use them to our advantage. In this Ph.D. dissertation, we have investigated some important surface-tension phenomena including capillarity, wetting, and wicking. We mainly focus on the geometric aspects of these problems, and to learn about how structures affect properties. Understanding these phenomena can help develop fabrication methods (Chapter 2), study surface properties (Chapter 3), and design useful devices (Chapter 4) at scales below the capillary length.

In the first project (Chapter 2), we used numerical simulations and experiments to study the meniscus of a fluid confined in capillaries with complicated cross-sectional geometries. In the

simulations, we computed the three-dimensional shapes of the menisci formed in polygonal and star-shaped capillaries with sharp or rounded corners. Height variations across the menisci were used to quantify the effect of surface tension. Analytical solutions were derived for all the cases where the cross-sectional geometry was a regular polygon or a regular star-shape. Power indices that characterize the effects of corner rounding were extracted from simulation results. These findings can serve as guide for fabrications of unconventional three-dimensional structures in Capillary Force Lithography experiments [J. Feng (2011) (a)]. Experimental demonstrations of the working principle was also performed. Although quantitative matching between simulation and experimental results was not achieved due to the limitation of material properties, clear qualitative trends were observed and interesting three-dimensional nano-structures were produced.

A second project (Chapter 3) focused on developing techniques to produce three-dimensional hierarchically structured superhydrophobic surfaces with high aspect ratios. We experimented with two different high-throughput electron-beam-lithography processes featuring single and dual electron-beam exposures. After a surface modification procedure with a hydrophobic silane, the structured surfaces exhibited two distinct superhydrophobic behaviors − high and low adhesion. While both types of superhydrophobic surfaces exhibited very high (approximately 160_) water advancing contact angles, the water receding contact angles on these two different types of surfaces differed by about 50_ _ 60_, with the low-adhesion surfaces at about 120_ _ 130_ and the high-adhesion surfaces at about 70_ _ 80_. Characterizations of both the microscopic structures and macroscopic wetting properties of these product surfaces allowed us to pinpoint the structural features responsible for specific wetting properties. It is found that the advancing contact angle was mainly determined by the primary structures while the receding contact angle is largely affected by the side-wall slope of the secondary features. This study established a platform for further exploration of the structure aspects of surface wettability [J. Feng (2011) (b)].

In the third and final project (Chapter 4), we demonstrated a new type of microfluidic channel that enable asymmetric wicking of wetting fluids based on structure-induced direction-dependent surface-tension effect. By decorating the side-walls of open microfluidic channels with tilted fins, we were able to experimentally demonstrate preferential wicking behaviors of various IPA-water mixtures with a range of contact angles in these channels. A simplified 2D model was established to explain the wicking asymmetry, and a complete 3D model was developed to provide more accurate quantitative predictions. The design principles developed in this study provide an additional scheme for controlling the spreading of fluids [J. Feng (2012)].

The research presented in this dissertation spreads out across a wide range of physical phenomena (wicking, wetting, and capillarity), and involves a number of computational and experimental techniques, yet all of these projects are intrinsically united under a common theme: we want to better understand how simple fluids respond to small-scale complex surface structures as manifestations of surface-tension effects. We hope our findings can serve as building blocks for a larger scale endeavor of scientific research and engineering development. After all, the pursue of knowledge is most meaningful if the results improve the well-being of the society and the advancement of humanity.

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