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A Rigorous Theoretical Framework for the Spreading of Liquid Droplets on Soft Solid Substrates

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Background

The spreading of liquids on soft solid substrates is a problem of fundamental interest that is also relevant to numerous applications including oil recovery. Experimental data published nearly two decades ago reveal that substrate deformability can significantly slow the spreading of liquid droplets. However, there is currently no rigorous theoretical framework that (i) is capable of explaining these data and (ii) can be generalized to other situations of interest. The objective of this proposal is to develop such a framework using lubrication theory and finite-element methods. The lubrication-theory-based approach will yield a simplified set of equations that permits rapid parametric studies. The finite-element approach will be used to test the limits of applicability of the former approach and to overcome its limitations. The results of the proposed work will bridge the gap between theory and experiment, and will lay the foundation for a powerful computational tool that can be used to explore more general situations involving droplet spreading on soft solid substrates. The resulting knowledge will advance the rational design of soft solid substrates for a broad range of applications.

The lubrication-theory-based approach will exploit the fact the droplets are often thin, enabling us to simplify the full governing equations to yield a set of evolution equations that are much easier to solve. Such an approach also has great potential to yield deep physical insight since analytical relationships are more easily extracted from the simplified equations. Our hypothesis is that such an approach will be able to describe the experimental data qualitatively, and perhaps even quantitatively.

Recognizing that the assumption of thin droplets used in the lubrication-theory-based approach may not always be valid, we also propose solving the full governing equations via the finite-element method. Such an effort will not only yield a theoretical tool that can be applied to more general situations of interest (e.g., droplets that are not thin), but will also provide insight into the conditions under which the simplified lubrication-theory-based approach is valid. Our hypothesis is that the finite-element approach will be able to overcome the limitations of the lubrication theory-based approach.

The proposed work is fundamental in nature because it involves detailed consideration of assumptions underlying a theoretical framework and examining why the framework might work best under a certain range of experimental conditions. The development of computational tools as part of the proposed research is an outgrowth of developing such a fundamentals-based framework, i.e., the tools need to be developed to bridge the gap between theory and experiment.

The proposed work is of relevance to the petroleum industry in two broad ways. First, soft solid substrates are often made of polymers, many of which are petroleum-based. If we understood better the fundamentals of droplet spreading on soft solid substrates, this would make it easier to design the substrates for specific applications (e.g., water recovery, heat transfer, coating and printing, microfluidics, mechanical property measurement of soft solids, studies of spreading of cellular aggregates to understand tumor biophysics). Second, soft solids in the form of gels are used in various stages of oil-recovery operations. Because liquids are also present and wetting plays a key role in understanding oil recovery, it is of fundamental interest to better understand the spreading of liquid droplets on soft solid substrates.

Progress and Impact

During the past reporting period, a senior graduate student laid more of the groundwork for this project by gathering and organizing background material on the topic of contact angle hysteresis, a phenomenon that we expect will play an important role in the proposed research. We had weekly group meetings in which all of my group members gave presentations on different aspects of this topic. This experience represented a wonderful opportunity for my group members to hone their communication skills, and for all of us to broaden and deepen our knowledge of wetting phenomena. This experience also provided the senior graduate student with a valuable learning, communication, and leadership experience before he defended his PhD thesis earlier this year. Recently, we were able to recruit another graduate student to work full-time on this project starting this fall, and we expect to obtain our first results during the next reporting period.