ABSTRACT

We investigate several facets of the dynamics of thin liquid-films with a free-surface (interface open to atmosphere or any other gaseous medium), under the action of various forces. Here, we specifically consider two classes of problems: (i) spreading of thin liquid-droplets, and (ii) dynamics of steadily moving long bubbles through liquid-filled cylindrical capillaries. We conduct simulation studies towards unveiling the detail phenomenological and hydrodynamic features, for both the mentioned classes of problems. First, we establish connection between the thin-film dynamics with the above mentioned categories of problems. This is substantiated by the agreements between the thin-film based predictions, and the present simulation results along with other reported studies. The agreements help us identifying the physical limits of the thin-film models towards capturing the underlying physics of the paradigms under concern.

Within the purview of category (i) problems, we envisage the spreading behavior of a thin liquid-droplet atop a nonisothermal substrate. Spatial variation of the temperature induces thermocapillary force (due to surface tension gradient triggered by the temperature gradient), in addition to the naturally occurring forces. Here we identify the existence of mutually contrasting multiple scaling regimes. This is attributable to the time-stage-wise sequential upsurge of the involved forces. Following pertinent thin-film and subsequent similarity analysis, we present a quantitative depiction of the regimes. Whereas simulation studies can depict the phenomenological features extensively, quantitative depiction of the time-stage wise upsurge of involved forces and the detailed characteristics of physical regimes can be satisfactorily obtained through the thin-film based analysis. Reported literature data are found to correspond well to the present interpretations and estimations.

Within category (ii) problems, we first study the influence of disjoining pressure for moving long bubbles inside cylindrical capillaries. Through disjoining pressure formalism, we emphasize on three different aspects of molecular scale interactions: (a) the van der Waals interaction, formalized by the classical Lifshitz form of disjoining pressure; (b) the nonuniformity in film thickness, accommodated by the necessary corrections in the disjoining pressure; and (c) the electrostatic component of disjoining pressure, reminiscent of the electrostatic interactions in the presence of surface charges. From the solution of the full scale liquid-film model, we observe the existence of thin- and ultra-thin-film regimes. While the former is characterized by the prevalence of certain popularly acknowledged macroscopic scaling laws, a severe breakdown of those laws is found to occur in the latter regime, attributable to the strong influence of molecular interactions at limitingly small magnitude of Capillary number. Combining the asymptotic and the scaling analysis, we further unveil the underlying physics, for the behavioral demarcation between the two regimes. Our theoretical depiction seems to offer consistent rationalization of reported experimental observations.

Finally, under class (ii) problems, we investigate the thermocapillary transport of confined long bubbles, in contrast to the transport by mechanical pumping as discussed above. We unveil the existence of a contrary-to-the conventional disjoining-pressure-dominant scaling regime. Such a regime is realized for limiting small magnitude of the Marangoni stress (surface tension gradient) when the separating liquid region reaches an ultra-thin dimension. Over this regime, we witness a severe breakdown of the seemingly intuitive scaling arguments based on the balance of viscous and capillary forces. Starting from relevant balance criteria, we uncover the characteristic length scales involved, leading towards obtaining the new consistent scaling laws of the disjoining-pressure-dominant regime, in a simple closed form analytical fashion. Our scaling estimations are substantiated by full-scale numerical simulations of the pertinent thin-film equations.

Keywords: Free-surface, Thin-film, Liquid-film, Interfacial region, Surface tension, Molecular scale interaction, Microfluidic systems, Film-profile, Scaling analysis, Similarity analysis, Asymptotic analysis, Viscous, Capillary, Thermocapillary, Marangoni stress, Disjoining pressure, van der Waals interaction, Lifshitz, Electrostatic, Capillary number, Length scale