Imbibition and Evaporation of Droplets of Colloidal Suspensions on Permeable Substrates

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Abstract

Recent experiments have shown that substrate permeability can suppress the coffee-ring pattern that is often left by evaporating droplets and promote more uniform solute deposition. Motivated by these observations, we have developed a lubrication-theory-based model to describe imbibition and evaporation of droplets of colloidal suspensions on permeable substrates. The model consists of a system of one-dimensional partial differential equations accounting for the changing droplet shape and depth-averaged concentration of colloidal particles. We also incorporate a precursor film, disjoining pressure, and substrate topography to control contact-line motion of the droplet. Solvent evaporation is described using the well-known one-sided model, and imbibition of solvent by the substrate is assumed to only depend on the excess pressure on the liquid side. The governing equations are solved with finite-difference methods. Our results reveal that solvent evaporation and solvent imbibition have the same qualitative effect on the final particle deposition pattern. For the case where the substrate is smooth, we find that increasing imbibition or evaporation leads to a transition from a cone-shaped deposition pattern to a ring-shaped deposition pattern. For the case where the substrate is rough, the droplet contact line is pinned at a defect on the substrate, and the pinning-depinning transition leads to the ``bullseye'' deposition pattern often observed in experiments. Finally, we also find that particle adsorption onto the substrate can promote more uniform particle deposition patterns for both smooth and rough substrates, and solvent imbibition can indirectly suppress the coffee-ring pattern by inducing more particle adsorption.