ABSTRACT

Wang, Lihui PhD, Purdue University, August 2019. Effects of Marangoni Flows on Particle Transport and Deposition during Drop Evaporation. Major Professor: Michael T. Harris.

The evaporation of a liquid drop containing particles resting on a substrate have diverse industrial applications including inkjet printing, spray coating, fabrication of functional nanomaterials, disease diagnosis, among others. In addition to these wide ranging practical applications, the sessile drop evaporation can be observed in everyday life with dew drops, coffee spills, and the dry patterns of other beverages.

The self-assembly of particles during drop evaporation is a process that is affected by various factors, such as contact line (CL) behaviors, microfluidic flows, short-range interactions of particle-interface and particle-particle. Each of these factors are complicated enough to study, let alone the total effects on the process. The primary goal of this work is to investigate the influence of microfluidic flows and the particle-interface interaction, viz. the evaporation process was subject to a pinned CL, the particle-particle interactions were neglected, and a dilute particle concentration was assumed. To accomplish this goal, the Galerkin/Finite Element Method (G/FEM) is used to solve the flow, the temperature and the particle concentration profiles.

The complexity of the problems comes from various surface phenomena, one of which is the surface tension. The surface tension brings capillary force in the normal direction and capillary flow toward CL, which are the explanation of the well-known coffee-ring effect. Moreover, the surface tension changes with temperature, surfactant amounts, etc. and results in Marangoni stresses in the tangential direction. The Marangoni stress on the surface leads to circulations of flow inside the drop and the circulation can be either clockwise or counterclockwise depending on the direction of the stress.

When the Marangoni stress is merely caused by temperature change, the circulation direction changes not only in time but also in space. At late stage of evaporation, i.e. with a small contact angle (CA), multi-circulation flow profiles emerge. This flow profiles are featured with stagnation points and transition points. The stagnation points can be further categorized into capillary-induced stagnation points and Marangoni-induced stagnation points. By introducing the concept of capillary-induced stagnation points, simulations reached agreement with experiments in terms of the radial location of the observed stagnation points.

A multi-circulation flow profiles implied regional segregation inside the drop. When a large circulation takes up the most part of the drop and a small circulation exists near CL, particle concentrations are relatively uniform in each individual region but different by several times across the two regions. Transition points are used to characterize the location of the segregation, which can be adjusted by Marangoni stresses.

Marangoni circulations in different directions revealed distinct influences on particle distribution and deposition. First, while both directions facilitate even distribution of particles, a clockwise circulation strengthens CL accumulation for a small Marangoni stress. Second, a counterclockwise circulation with a small Marangoni stress impedes the deposition rate of particles, while a clockwise circulation facilities the deposition no matter how small the Marangoni stress is. This results is under a condition of a strong adsorption of particles to substrates.

The analysis and understanding of the above results are crucial to elucidating and controlling the final deposition patterns of particles.