Evaporation of Binary Mixture Nanofluid Drops: Pattern Formation

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ABSTRACT

The deposition patterns and internal flows inside drying binary nanofluid drops on heated substrates have been investigated. The evaporation of a binary mixture causes local concentration gradients at the air-liquid interface, resulting in a Marangoni flow. A temperature-dependant Marangoni flow has also been found, which has a crucial role in the final form of the dried deposits. The influence of substrate temperatures on the pattern formation has also been studied.

Keywords: pattern formation, nanofluids, sessile drops, Marangoni flow, evaporation

1 INTRODUCTION

Patterning of nanoparticles on a substrate has attracted much attention in many applications such as medical tests [1], coating technologies [2], and inkjet printing [3]. Evaporation of sessile droplets is a simple way to create dried patterns of particles. The final pattern is strongly dependant on the internal flows of evaporating droplets [4]. The environmental conditions [5], the substrate properties including surface temperature [6], roughness, and many other factors affect the internal flow field as well as the nanoparticles deposition. The base fluid of a sessile droplet can also modulate the internal flow field by employing liquids with different properties, or adding surfactants [7].

It has been shown that the evaporation of a sessile nanofluid drop on a substrate leaves a ring-shaped stain, known as the "coffee-ring" effect. The formation of this pattern is mainly due to the deposition of solutes in the vicinity of the contact line, which are brought by the outward capillary flow there. In some cases, surface tension gradients along the air-liquid interface of a drop can reverse the coffee-ring effect, leading to a nearly uniform coverage formation. The inhomogeneous temperature distributions at the free surface of a sessile drop can induce the surface tension gradients, which drives a convective Marangoni flow. Apart from this, the concentration gradients at the free surface can induce surface tension gradients, and thus lead to the Marangoni effect. The concentration gradients can be created by either adding surfactants, or different liquids (i.e., ethanol, methanol) into the base fluid.

Many studies have investigated the effect of the surfactant-dependant Marangoni flow on the pattern formation of particles [7-13]. There have been some studies dedicated to the effect of the temperature-dependant Marangoni flow on the particles deposition, but most of them investigated the evaporation of sessile drops on nonheated substrates, rather than heated ones [6,9,15–17]. It is worth mentioning that the aforementioned studies are about the evaporation of drops with single component base fluids (i.e., pure water). There is also a very limited number of studies available regarding the effect of the binary base fluids on the nanoparticles deposition [18,19]. In spite of numerous studies on the pattern formation, investigations on the nanoparticles deposition caused by the dryout of binary-based drops are still scarce, particularly on heated substrates.

Here, the evaporation of binary-based nanofluid sessile drops on substrates heated at a wide range of temperatures has been investigated. The internal flow field throughout evaporation is visualized by reflection optical microscopy. The dried deposit pattern is related to the dynamics of evaporation. Infrared thermography is employed to visualize the temperature distribution along the drops free surface.

2 RESULTS AND DISCUSSION

It has been found that the internal flows within an evaporating drop can be divided into the three stages. The first stage was associated with the chaotic and vigorous motion of nanoparticles. This behavior can be due to the concentration gradients at the free surface of the drops caused by the evaporation of a more volatile liquid. Using infrared thermography, multiple vortices were observed at the free surface arisen from the nonuniform evaporation along the air-liquid interface. During the second stage, the flow slows down and a rapid transition to the third stage occurs. The infrared thermography results have also shown that there is a fewer number of vortices throughout this stage. The third stage is identical to the experimental observations of Parsa et al. [6] who investigated the evaporation of water-based nanofluid drops at the same substrate temperatures. Unlike the first and second stages, infrared thermography does not show any vortices at the free surface during the last stage. In this stage, the tracking

of nanoparticles shows that some of the solutes move toward the contact line due to the outward capillary flow , and deposit there. On contrary, some of the nanoparticles change their direction from the near regions of the contact line, and move inwardly along the air-liquid interface. The change in the direction of the nanoparticles is caused by the temperature gradients at the free surface. Infrared thermography showed that the drop apex has the lowest temperature, and the edge is the warmest position, leading to the surface tension gradients at the free surface. Thus, the temperature-dependant Marangoni flow is the mechanism behind the change in the direction of the nanoparticles. These repelled nanoparticles form a ringlike cluster at the top of the evaporating drop. The existence of the ringlike cluster on the top of the drop has an important role in the final deposit pattern. At the substrate temperatures between 47 and 81 °C, the dual ring pattern was left after the complete evaporation. For higher temperatures, the stick-slip pattern was formed on the solid surface. Parsa et al. [6] reported the similar deposit patterns for the water-based nanofluid drops evaporating at the same temperatures of the present study. This reveals that having the chaotic and vigorous internal flow at the beginning of the evaporation process does not lead to a significant change in the final dried deposit patterns.

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