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Evaporation of nanofluid sessile drops: Infrared and acoustic methods to track the dynamic deposition of copper oxide nanoparticles

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ABSTRACT

In this work, we investigated the precipitation of 0.05%wt copper oxide nanoparticles in a sessile droplet during the evaporation process. We used two complementary methods to analyze the precipitation process of the nanoparticles at the solid/liquid interface: an optical one coupled to an infrared thermography method and an acoustic method. From the optical observation, using a Keyence microscope on the rear side of a transparent glass substrate coated with a silane layer, the precipitation process of the nanoparticles was successfully monitored by measuring the mean intensity density ($\overline{ID}$) above the substrate by using ImageJ software. The acoustic method, based on a high frequency echography principle, allowed to monitor the deposition phenomenon of the particles above a non-transparent silicon substrate having similar silane coating as the glass substrate at room temperature. The time from which the nanoparticles begin to settle at the bottom of the substrate, obtained from the acoustic method, corroborated the one obtained from the optical one. Moreover, an estimate of the particles concentration throughout the process was deduced. The effect of substrate temperature and substrate wettability have also been studied experimentally and investigated using only the optical method and the infrared thermography one. An infrared camera from the top was employed to observe the temperature effect on the precipitation of the nanoparticles. Furthermore, when the substrate temperature exceeded 60 °C, co-existence of the thermal Marangoni flows was observed. It is expressed as a temperature gradient at the droplet liquid/air interfaces. The result showed the effect of these cells due to Marangoni effect on the nanoparticles' stability.

1. Introduction

Fluids containing suspended nanoparticles are called nanofluids, a term coined by Choi et al. [1] in 1995. Nanofluids as a new and innovative class of heat transfer fluids represent a rapidly emerging field where nanoscale science and thermal engineering meet. Nanofluids, engineered by dispersing nanometer-sized solid particles in conventional heat transfer fluids, have been found to possess superior thermal performance compared to their base fluids [2]. A solid metal has a larger thermal conductivity than a base fluid. Suspending metallic fine particles into the base fluid is expected to improve the thermal conductivity of the fluid [3–6]. As such, nanofluids would be useful as coolants in the automobile, electronics industries, fuel cells, etc. [7] Droplet evaporation is a very important phenomenon for industrial applications using atomized liquids such as fuel spray and spray cooling [8,9]. Several researchers conducted experimental studies to understand the heat transfer mechanism during droplet evaporation [10,11] and how to improve the evaporative heat transfer using enhanced surfaces. Many experiments suggested that thermal conductivity of a nanofluid could be enhanced compared to pure liquid, and studies on the application of nanofluids in phase change heat transfer (evaporation, etc.) have been conducted [12,13].

Several studies were performed to analyze and observe the evaporation process of nanofluid sessile droplets and to visualize the final shape pattern of nanoparticles due to change in surface temperature [14–17] but without monitoring the time at which nanoparticles start to deposit on the surface during the evaporation process. This study focused on the evaporation of droplets

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Nomenclature

%wt	weight concentration, %	ρ_{nf}	density of nanofluid, kg·m^{-3}
$\overline{ID}$	mean intensity density	ρ_p	density of CuO particles, kg·m^{-3}
|R|	amplitude reflection coefficient	ρ_ω	density of water, kg·m^{-3}
Z	mechanical impedance, kg·s·m^{-2}	E_{nf}	Young Modulus, Gpa
nf	nanofluid	E_ω	Young Modulus of Water, Gpa
p	particles	E_{eff}	effective Young Modulus, Gpa
w	water	c	acoustic velocity, m·s^{-1}
Z_{nf}	mechanical impedance of nanofluid, kg·s·m^{-2}	c_{nf}	acoustic velocity of nanofluid, m·s^{-1}
Z_s	mechanical impedance of Silicon, kg·s·m^{-2}	$\upsilon_{\%}$	particles volume fraction concentration, %
CA°	droplet contact angle, °	t^* (%)	nanoparticles relative time percentage to deposit, %
γ	surface tension, mN·m^{-1}	D* (%)	percentage area distribution of dried nanoparticles, %

containing copper oxide nanoparticles in order to monitor the deposition process. From the results, a clear information on the heat transfer efficiency could be optimized due to the decrease in the nanoparticles inside the droplet, which leads to a decrease in the thermal conductivity.

Non uniform evaporative cooling at the free surface of a liquid droplet induces temperature gradients along the air/liquid interface of the drop and further results in surface tension gradients, which drive a convective Marangoni flow [18,19]. The Marangoni convection flows from regions of lower surface tension to those of higher surface tension. The flow fundamentally exists at the air/liquid interface of evaporating droplets. Therefore, depending on surface tension gradient direction, the Marangoni effect can either counteract the outward capillary flow or enhance it.

It is worth stressing that the Marangoni effect in general can have a significant role in many practical applications such as heat and mass transfer, coatings, and production of materials [20,21]. This phenomenon has a significant importance on the nanoparticles deposited during the evaporation of the droplets and on the final shape pattern of the dried nanoparticles.

In this work, experiments on the evaporation of nanofluid sessile droplets on heated hydrophobic surfaces are conducted using optical and infrared measurements. To validate the deposition process of the nanoparticles, highlighted by the optical method, an acoustic method is used at room temperature. Wetting properties of the substrates (Glass and Silicon here) are very important in fluidic systems to have a low surface energy (low wettability- big contact angle). A glass transparent substrate is used for the optical and the infrared thermography study, whereas a silicon substrate is used for the acoustics measurements. To insure the same evaporation conditions, the glass and the silicon substrates underwent the same surface treatment using silane to render them hydrophobic. Silane is a colorless chemical liquid whereas the bond onto surfaces terminated with hydroxyl (-OH) groups forming a regular covalent bond. It anchors on oxide surfaces with its tricholoro-silane group and attaches covalently. Due to its heavily fluorinated tail group, a silane monolayer reduces surface energy as a result (less wettability) [22]. A monolayer Silane coating is achieved by a relatively simple process, also known as a liquid-based process. All reactions were performed in a glove box under dry nitrogen atmosphere at room temperature from 2 to 3 h. Prior to the coating process, silicon and glass surfaces were cleaned using acetone and isopropanol placed in ultrasonic bath and then oxidized, due to the ozonolysis action inside the UV-Ozone chamber, to remove all the impurities and the molecules before starting the reactions. Perfluorodecyltrichlorosilane, (PFTS) was used in solutions of hexane to create the monolayer on the substrate surfaces. Monitoring nanoparticles' deposition at the liquid–solid interface is carried out by fixing the Keyence microscope at the rear side of the glass substrate. The acoustic method, developed in our laboratory, was used to characterize solid–liquid interfaces at micro-/nanometer scales [23]. This method is highly sensitive to events that take place at the interface and reveals the dynamic deposition of copper oxide nanoparticles as a function of time. The method is based on a high-frequency reflectometry principle. The amplitude of the reflection coefficient is exploited to monitor the deposition process of the nanoparticles.

The experiments, consisting of heating the glass substrate, contribute to the comprehensive understanding of the influence of both temperature and internal flows on the delay in nanoparticles deposition during the evaporation of nanofluid drops and on the resulting deposition patterns. By recording the liquid–vapor interface using infrared camera, a link between the phenomena observed and the time at which nanoparticles started to deposit is achieved. Copper oxide (CuO) nanoparticles (diameter < 50 nm) at a concentration of 0.05% wt in water were investigated in this study. CuO nanoparticles have a good thermal conductivity for heat transfer in energy systems.

2. Experimental setup

In this work, the studied nanofluid consists of copper(II) oxide (CuO) nanopowder (Sigma Aldrich, molecular weight = 79.55, diameter < 50 nm with a mass concentration of 0.05 wt%) dissolved in distilled water using the two-step method [24] and then stabilized through ultrasonication (Elma, S 10/H) for at least 1 h before use.

To analyze the dynamic of the droplet evaporation and particles deposition, two different methods are used, one using optical and infrared thermography measurements and the other one using acoustic reflection coefficient measurements at room temperature. For the optical observation, a transparent substrate is required (Glass substrate) whereas a silicon substrate is used for the acoustics measurement. The two substrates were modified with a perfluorodecyltrichlorosilane (PFTS) layer to achieve hydrophobic surfaces. In that case the two substrates were at the same surface temperature. Then, optical measurements were achieved increasing the temperature substrate. First, the substrates are cleaned through ultrasonication in acetone and ethanol for 5 min each then the polished face was cleaned by ozonolysis for 15 min in a UV/ozone cleaner to remove all the physisorbed organic molecules. This step gives a zero contact angle. The silanization of the cleaned substrates with PFTS was carried out in a glovebox under nitrogen atmosphere. The cleaned substrates were immersed for 2 h at room temperature in a hexane solution of PFTS (50 μL of PFTS in 50 mL hexane). The substrates were then removed, rinsed with hexane and blown with dry nitrogen. The droplet contact angle