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Near-wall fluid flow near the pinned contact line during droplet evaporation

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ABSTRACT

Drop evaporation is a fundamental and complex phenomenon in nature and industrial processes. For the case of pinned contact line mode, however, we still lack a comprehensive understanding of the near-wall fluid flow during drop evaporation. In this paper, we measure the in-plane average velocities near the pinned contact line during evaporation of deionized water and aqueous ethanol solutions by the multilayer nano-particle image velocimetry (MnPIV) technique. The results show that the Marangoni convection near the triple-phase contact line is negligible for the flow pattern during the natural evaporation process without heat source being applied. The near-wall velocity profiles experience the decrease of thin film thickness just before the droplet shrinking process. The thin film thickness in the ethanol solution appears to decrease earlier than that in deionized water and the total shrinking time is much shorter than water. The thin film thickness decreases linearly before decreasing exponentially in about the first 100 nm. The transition time also becomes earlier for the high-concentration solutions due to higher evaporation flux, while the transition thickness is larger for ethanol solutions with higher concentrations due to the inverse relation between the transition thickness and the surface tension.

1. Introduction

Drop evaporation is a fundamental and complex phenomenon in nature and industrial processes, due to the coupling between hydrodynamics, heat and mass transfer in the solid, liquid and gas phases. It is essential to understand the basics of drop evaporation that will encounter in engineering applications such as spray cooling, dropwise cooling, and fuel injection. Previous investigation has been focused on various aspects including surface wettability [1], fluid thermophysical properties [2], contact line movement [3,4], substrate heat conduction [5–7], self-cooling on the drop surface [8], natural convection in the vapor phase [9], and also the resultant mass flux and Marangoni flows during drop evaporation [10–13]. It was shown that the mass flux which increases along the drop surface from the apex to the contact line generates an internal flow inside the drop, making the thin liquid film evaporation near the contact line an important role in drop evaporation [13,14]. However, in the case of pinned contact line during drop evaporation, only limited study which is about the substrate heat conduction and self-cooling on the drop surface can be found in the literature [7–9]. Therefore it is necessary to complete this by studying the fluid flow near the pinned contact line during drop evaporation.

The contact line itself can usually be divided into three regions: the adsorption layer region, which consists of a thin liquid film adsorbed onto the solid surface; the evaporating thin film region, where the attractive forces of the solid are much weaker, the effects of long-range molecular forces (disjoining pressure) are felt, and the liquid–vapor interface has measurable curvature; and the intrinsic meniscus region, where the capillary forces dominate and the curvature of the interface becomes nearly constant [14]. Enormous researches have proved that a strong evaporating process happens in the evaporating thin film region and the internal flow in this region is crucial for revealing the mechanism of drop evaporation [15]. The disjoining pressure, along with the capillary pressure, was believed to be crucial for liquid supply into the thin film region [16]. These forces are closely related to the thin film thickness profile which is influenced by factors such as superheat, liquid polarity, slip boundary and thermocapillary effects [17–19]. For binary fluids, the solutocapillary effect can also attribute to the variation of thin film thickness [20]. However, although many theoretical predictions and numerical simulations for this region have been performed, high resolution measurements of the flow pattern and the thin film thickness variation are quite rare due to the small size and the near wall characteristics.

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Nomenclature

A	Hamaker constant (J)
I	intensity (cd)
n	refractive index
P	pressure (Pa)
r	radius (m)
R	film radius (m)
t	time (s)
u	velocity (m/s)
V	thinning velocity (m/s)
z	depth (m)

Greek symbols

δ	thickness (m)
λ	wavelength (m)
μ	dynamic viscosity (Pa s)
θ	incident angle (°)
θ	contact angle (°)
σ	surface tension (N/m)

subscripts

0	adsorption layer
0	initial
0	wall
1	medium 1
2	medium 2
a	contact
av	average
c	critical
c	capillary
d	disjoining
f	drying
p	penetration
t	transitional

Taking advantage of various optics to monitor tracer particles, instantaneous, whole field and non-intrusive approaches to flow profiling has been possible. Among these methods, the micro particle image velocimetry (μPIV) and the nano-particle image velocimetry (nPIV) techniques can be utilized for microflow visualization [21,22]. The resolution of these methods can be further improved by utilizing the unique characteristics of evanescent wave illumination, the intensity of which decays exponentially with the distance normal to the wall [23,24]. Particularly, the multilayer nPIV (MnPIV) method was proposed for measuring the two velocity components parallel to the wall averaged over the first few hundred nanometers next to the wall and the spatially averaged velocities at different distances normal to the wall, using the nonuniform illumination characteristics of evanescent wave by classify each tracer image into different layers on image intensity [24]. In this paper, we employ the evanescent wave based MnPIV to quantitatively measure the internal flow pattern in the extended meniscus of evaporating droplets and further analyze the variation of thin film thickness using the intensity information of the images.

2. Experiment

2.1. Method

An evanescent wave can be created when a light beam traveling through a medium with a refractive index n_1 into another transparent medium with a lower refractive index of n_2 at an angle exceeding the critical angle $\theta_c = \sin^{-1}(n_2/n_1)$. According to the continuous condition of electromagnetic equation, the electromagnetic field penetrates into the lower refractive index region and propagates for a small distance parallel to the interface. This indicates that an evanescent wave is totally reflected at the interface [25]. The intensity of evanescent wave decays exponentially with the distance normal to the wall and can be expressed as:

$$I = I_0 \exp\left(-z/z_p\right) \tag{1}$$

where I is the intensity of evanescent wave, I_0 is the maximum intensity at the wall, z is the distance normal to the wall, and z_p is the penetration depth which can be decided by the following equation:

$$z_p = \frac{\lambda_0}{4\pi n_1}\left[\sin^2\theta - \left(\frac{n_2}{n_1}\right)^2\right]^{-1/2} \tag{2}$$

where λ_0 is the wavelength of the light and θ is the incident angle.

Employed the exponentially decaying nature of the evanescent-wave illumination, the tracer nanoparticles in a typical nPIV image can be divided into sublayers based on the tracer intensity that can be correlated to the distance between the particle center and the wall. By processing these sub-images using standard method of particle tracking velocimetry, one can thus determine the velocities at different distances from the wall and hence the flow pattern in the near wall region, viz., the extended meniscuses of deionized water and ethanol solutions in this investigation. This method was named as MnPIV and its effectivity and accuracy were first validated by prior researches on many aspects, including the electro-osmotic flow, near-wall flow, microscale Poiseuille flow, and nanoscale contact line visualization [23,24,30–34]. The experiment in this work applies the MnPIV technique and the measured data also shows good agreement with related simulation [35].

In this experiment, the cover slip that holds the water droplet is made of borosilicate with a refractive index of $n_1 = 1.52$, therefore the light will be totally reflected at the interface of the borosilicate glass and water ($n_2 = 1.33$) at a critical incident angle $\theta_c = 61.04°$. For dilute aqueous ethanol solutions, which will also be tested in the experiment, the critical incident angle changes slightly. Here the incident angle of excitation light is 68° and thus the calculated penetration depth z_p is about 86 nm. Normally the region beyond $4z_p$ is considered to be out of illumination field, therefore the depth of illumination field is about 340 nm. Although z_p varies with fluid temperature, the penetration depth varied by no more than 1 nm for the range of temperatures investigated here. We divided the illuminated region into four sublayers and the thickness of each layer is 90 nm. Fluorescent polystyrene nanoparticles with radius of 50 nm are used as tracer. Every tracer nanoparticle is assigned into one layer based on their distance to the cover slip, then the velocity profile of liquid flow is obtained by averaging all the particle velocities in each layer.

The non-uniform illumination and shape of the tracer particles, however, may produce errors for the measurement of z, which is the distance between the solid surface and the tracer particle. From Eq. (1), one can derive $z = z_p \ln(I_0/I)$ and further obtain $\Delta z = z_p \ln(1 + \Delta I_0/I_0)$, where Δz and ΔI_0 are the deviations of z and I_0, respectively. The measured I_0 in this experiment is 811, the maximum ΔI_0 is 279, and $z_p = 86$ nm calculated from Eq. (2), thus the maximum Δz is about 25 nm which is considered acceptable. The study on the accuracy of MnPIV method using Monte Carlo simulation indicated that the time interval within one image pair has different effects on different sublayers, i.e., the calculated velocity is bigger than the real velocity in the layer near the wall, is smaller than