



Analysis of fluid flow and particle transport in evaporating droplets exposed to infrared heating



Ashish Kumar Thokchom^a, Abhishek Gupta^b, Pallippadan Johny Jaijus^c, Anugrah Singh^{a,*}

^a Indian Institute of Technology Guwahati, Guwahati, Assam, India

^b Fluidyn Software & Consultancy Private Limited, Bangalore, Karnataka, India

^c Center for Bioengineering, Department of Mechanical Engineering, University of Canterbury, Christchurch, New Zealand

ARTICLE INFO

Article history:

Received 15 May 2013

Received in revised form 4 September 2013

Accepted 6 September 2013

Available online 3 October 2013

Keywords:

Evaporating droplet

Particle Image Velocimetry

Pattern formation

Marangoni flow

Computational fluid dynamics

ABSTRACT

Analysis of fluid flow and particle transport inside evaporating droplets exposed to external radiation was carried out by experiments and numerical simulations. In this study, we have shown that by altering the free surface temperature we can modify the fluid flow profile inside the droplet and hence the deposition pattern of solute particles on the substrate. The fluid velocity and particle concentration profiles inside the evaporating droplet were measured by Particle Image Velocimetry (PIV) technique. Experiments were carried out on a small sessile water droplet containing dispersed polystyrene particles. To avoid problem of image correction encountered in PIV measurements with 3D droplets, our experiments were performed on an equivalent disc shaped 2D drop sandwiched between two non-wetting surfaces, while the base of the droplet was pinned to a wetting surface. The top surface of the droplet was heated by Infrared (IR) light. The temperature of droplet surface was measured by thermocouples. The velocity field, particle concentration profile and particle deposition patterns were studied during evaporation process. We have also performed numerical simulations by solving continuity, momentum and energy transport equations. The computed velocity profiles resulting from buoyancy and Marangoni convection are in qualitative agreement with the experiments.

© 2013 Elsevier Ltd. All rights reserved.

1. Introduction

A ring shaped deposition pattern rather than uniform deposition is observed when a liquid droplet containing dispersed particles dries out (due to evaporation) on a wetting solid surface. This natural phenomenon is important in many applications such as DNA microarray [1–3], ink-jet printing [4], diseases diagnosis [5], thin film coatings [6] and manufacture of novel optical and electronic materials [7]. In these applications the phenomenon of the fluid flow inside the evaporating droplet plays a key role in deposition patterns. Deegan et al. [8–10] have extensively reported this phenomenon (commonly known as coffee-ring effect) which has received increased attention in the recent years. They explained that a ring like deposition pattern is due to the pinning of contact line, and the solvent lost from the free surface carries solute particles towards the edge during evaporation process. Buoyancy driven convection or Marangoni flow due to temperature gradient within the evaporating droplets were not considered in their works.

Nakoryakov et al. [11] have studied the behavior of evaporating droplets on a heated surface and observed strong influence of thermo-physical and geometrical parameter on the droplet evaporation. The difference in evaporation characteristics between pure and binary liquid droplet was studied by Zhang et al. [12]. Popov [13] and Fischer [14] have studied the particle deposition theoretically by considering a very thin drop and derived the expressions for height averaged radial velocity profile inside the drop. Widjaja and Harris [15] performed numerical simulations to study the deposition pattern in evaporating droplets containing solute particles. They found that the particle deposition rate on the substrate is influenced by the convection and diffusion mass transfer of the particles in the bulk liquid. They also did not consider the role of Marangoni flow in evaporating droplets. Girard et al. [16] numerically analyzed the evaporating droplet on a heated substrate under microgravity condition and investigated the role of heated substrate on flow patterns. Their numerical simulations revealed that the Marangoni convection is generated within the droplet due to temperature gradients on free surface. Recently Risenpart et al. [17] have observed that the non-uniform evaporation also produces the 'coffee-ring' effect.

Many experimental studies have shown that fluid flow within the droplet plays an important role in deposition pattern. Hu and

* Corresponding author. Tel./fax: +91 361 2582259.

E-mail addresses: a.thokchom@iitg.ernet.in (A.K. Thokchom), petro.abhishek@gmail.com (A. Gupta), jaijus.pallippadanjohny@pg.canterbury.ac.nz (P.J. Jaijus), anugrah@iitg.ernet.in (A. Singh).

Nomenclature

CCD	charge couple device
IR	infrared light
PIV	Particle Image Velocimetry
LED	light emitting diode
P	pressure (N/m ²)
C_p	specific heat of the liquid (kJ/kg °C)
u	velocity in x -direction (m/s)
v	velocity in y -direction (m/s)
T	temperature (K)
t'	dimensionless evaporation time
J	mass flux (kg/s m ²)
N	dimensionless particles concentration
h_o	initial height of the droplet
g	acceleration due to gravity (m s ⁻²)
h	height of droplet at any time

Greek symbol

θ_o	initial contact angle of the droplet
θ	contact angle of the droplet at any time
μ	droplet liquid viscosity (kg/m s)
Ω	interfacial tension
σ	local value of surface tension (N/m)
k	thermal conductivity of the liquid (W/m K)
ρ	density of droplet liquid (kg/m ³)
β	thermal expansion coefficient (K ⁻¹)
α	thermal diffusivity (m ² /s)

Subscripts

o	initial condition at $t = 0$
i	condition at any time t

Larson [18–21] using the lubrication analysis of fluid flow studied the effect of Marangoni flow inside the evaporating droplets through finite element simulations. They observed that the ring like deposition pattern is not only due to the pinning of contact line but Marangoni stress driven flow also has strong influence on particle deposition. Their experimental results indicate that the particle deposition in octane droplet can be localized predominantly at the center instead at the edge of the contact line. They believe that a non-uniformity of temperature of the surfaces leads to difference in surface tension on the interface which induces thermal Marangoni flow. This makes the fluid near the edges rise towards the top of the droplet and plunge downward to the center of the droplet. They observed qualitative agreement of experimental and simulation results for deposition pattern. The particle concentration profile showed a large peak at the edges of the water droplet when Marangoni flow was weak or absent. When the Marangoni flow was strong, a large peak was observed at the center of octane droplet. The role of surfactant on Marangoni flow was also reported by them. Zhang and Wang [22] also observed the Marangoni flow in their study of natural convection in an evaporating droplet. Savino et al. [23] and Savino and Monti [24] have experimentally shown the existence of Marangoni flow in droplets of organic fluid but not in case of water droplet. David et al. [25] investigated experimentally the role of thermal conductivities of the substrate on the evaporation of water droplet. Girard et al. [26] measured the temperature profile inside a water droplet placed on a heated substrate by infrared camera and observed that the temperature gradient within the evaporating droplet was less than 1 °C. A small temperature difference (as small as 0.5 °C) within the droplet was enough to generate the Marangoni flow. Lu et al. [27] have performed numerical investigation of the fluid flow due to temperature distribution inside the evaporating droplet placed on a heated surface. Kang et al. [28] have recently visualized the flow pattern inside the sessile droplet of NaCl solution by PIV technique and observed similar flow pattern at different concentrations. Most of these studies on evaporating droplets are for the case of pinned contact line condition. Adachi et al. [29] have observed the ‘stick slip’ motion of the contact line when there is a competition between the friction force and surface tension and this generates a stripped film composed of particles after the droplet dries out.

Quantitative visualization of fluid flow is of great interest in situations involving evaporating droplets. It is of great importance to have an accurate velocity field data inside the evaporating droplet. Besides the fluid flow, the deposition pattern is also influenced by the nature of the substrate surface. Xu et al. [30] have shown that nanoparticles can be self-assembled by allowing a solution of

nanoparticles to evaporate on a sphere-on-flat geometry. This self-assembly of particles on a substrate is of great importance in many micro level applications. It is a great challenge to control this phenomenon in small droplets. Hong et al. [31,32] were able to get ordered polymers pattern of concentric ring and punch-like shape by interacting the polymer and the substrate. Marin et al. [33] observed the ordered particles arrangement at the early stage while disordered arrangement were observed at the end of the evaporation of droplet. Wong et al. [34] used this phenomenon to separate the biological entities in a liquid droplet with an aim to develop low cost technologies for disease diagnostics in resource poor environment. Majumder et al. [35] found that the phenomenon of evaporating droplet can be used for depositing catalyst nanoparticles to form a single walled carbon tubes as well as to manufacture plasmonic films of well-spaced, un-aggregated gold nanoparticles.

Despite their importance, there are very few works on the analysis of fluid flow and the particles transport inside the evaporating droplets due to inherent problem encountered in imaging a small droplet. Understanding the proper mapping of fluid flow inside the evaporating droplet can help to manipulate the particles transport, so that highly ordered structures in micro-devices can be produced in large scale. In one of the earlier studies, Yarin et al. [36] have analyzed the velocity inside the levitated evaporating droplet. Savino et al. [23] carried out experimental measurements and numerical simulation to study the Marangoni and buoyancy effect on velocity field inside the hanging evaporating droplet. They observed that n -octane droplet exhibit Marangoni convection whereas pure water droplet does not. Savino and Monti [24] solved the steady state velocity field inside the evaporating droplet by considering a Marangoni stress on air–liquid interface. Due to the wrong velocity mapping during the measurement of the velocity field their experimental results did not match with the theoretical predictions. Without a proper image correction it is very difficult to analyze the velocity field in 3D droplets. This problem was overcome by Kang et al. [37] who developed correlations to map the image in the velocity plane to that of image plane. Minor et al. [38] reported that the ray tracing algorithm by Kang et al. is valid only for hemispherical shape and needs correction for droplet having the shape of a sphere. Recently, Saha et al. [39] used the ray tracing method and improved algorithm of Minor et al. [38] to correct the optical distortion during the measurement of velocity vectors in a levitated evaporating droplet. Yan et al. [40] have also measured the velocity field inside the levitated drops by tracking the displacement of tail or front end of streamlines in the recorded digital images. Ueno and Kochiya [41] and Pereira et al. [42] have

Download English Version:

<https://daneshyari.com/en/article/658027>

Download Persian Version:

<https://daneshyari.com/article/658027>

[Daneshyari.com](https://daneshyari.com)