International Journal of Thermal Sciences 102 (2016) 239–253

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

# Influence of thermalcapillary and buoyant forces on flow characteristics in a droplet on hydrophobic surface

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ARTICLE INFO

*Article history:*
Received 19 July 2015
Received in revised form
14 November 2015
Accepted 15 November 2015
Available online 6 January 2016

*Keywords:*
Hydrophobic surface
Droplet
Contact angle
Marangoni
Buoyancy
Heat transfer

ABSTRACT

Wetting characteristics of droplets on hydrophobic surfaces are the current interest in many fields because of necessity for self-cleaning, improving lubrication, speedy liquid separation, bacterial activity minimization, reducing fouling, etc. Therefore, we investigate flow and thermal fields in a droplet at a hydrophobic surface due to a localized heating and analyze the effects of droplet contact angle on heat and flow characteristics due to thermocapillary and buoyancy forces developed in the droplet. Trichlorooctadecylsilane coating is introduced on a smooth polycarbonate wafer to generate a hydrophobic surface and a fine sized metallic meshes is laid on the hydrophobic surface where a constant temperature heating is applied at 308 K. Flow filed is simulated numerically incorporating the experimental conditions. A droplet of a nano-fluid, consisting of water and 1% (volume) carbon nanotube mixture, is formed at the hydrophobic surface to monitor the flow velocity in the droplet, which is, then, used for the validation of velocity predictions. It is found that combination of Marangoni and buoyancy forces give rise to formation of circulation cells inside the droplet; in which case, contact angles in the range of $110^\circ \le \theta \le 150^\circ$ two counter rotating circulation cells are formed in the upper part of the droplet. The average Nusselt number increases with increasing droplet contact angle.

## 1. Introduction

Hydrophobic surfaces find interest in science, engineering, and medical applications. Hydrophobicity of a surface depends and interfacial energies of the solid and the liquid, surface texture, and Laplace pressure as demonstrated by Wenzel [1] and other researchers [2,3]. Mimicking the nature, such as lotus leaves surface, enables to create surfaces of superhydrophobic characteristics. A substantial increase in hydrophobicity can be achieved when a combination of chemical modification and surface roughness of the substrates is integrated [4–6]. Many techniques and processes have been developed to enhance the hydrophobicity of surfaces using this strategy [7–14]; however, some of these techniques involve multi-step procedures and harsh conditions, such as bio-incompatibility, or required specialized reagents and equipment. In addition, micro/nano texturing of surfaces have many challenges in terms of cost, processing time, equipment, and skilled man power requirements; however, it was demonstrated that laser controlled ablation can be used effectively to texture surfaces at micro/nano levels [15]. Thermal stress field developed in the laser textured limits the practical applications and laser processing for hydrophobic surfaces with low thermal stresses requires further research [16].

Hydrophobic surfaces can play an important role for minimizing the spreading of infected fluid in protecting environments. The surface wettability reduction is the key concern to form the liquid droplets from the infected fluid, which prevents formation of biofilm by the floating microorganisms at the surface [17]. The infected liquid droplet should be in contact with the antibacterial metallic meshes at the same time resident at the substrate surface with a high contact angle. To achieve such combination becomes a challenge. However, the flow circulation generated in the infected fluid droplet can reduce sedimentation of dead microorganisms and facilitate remaining life microorganisms reaching at the metallic mesh surface. Moreover, a combination of Marangoni flow, due to

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http://dx.doi.org/10.1016/j.ijthermalsci.2015.11.013
1290-0729/

thermally varied surface tension, and buoyancy current formed in the droplet can be considered as one of the solutions to generate circulation cells in the infected liquid droplet [18]. The generation of such circulation cells in the droplet is challenging and requires thorough investigation of the flow field in the droplet.

Considerable research studies were carried out to examine flow field and heat transfer in droplets. The flow field developed in a single droplet, due to a localized heating, at the hydrophobic surface is a challenging problem because of flow complications resulted from the Marangoni and natural convection effects. In this case, temperature gradients along the droplet free surface lead to gradients variation in the surface tension, which could cause thermocapillary Marangoni convection in the standing droplet [18]. The detailed examination of Marangoni induced flow field was presented earlier [19,20] and thermocapillary driven flows are reviewed by Schatz and Neitzel [20]. In addition, several work was reported on the droplet behavior when subjected to external heating. Bormashenko et al. [21] investigated droplet behavior on flat and textured surfaces in relation to co-occurrence of Deegan outward flow with Marangoni solute instability. They presented quantitative estimation of the wetting properties of textured polymer surface and demonstrated that wetting properties of the substrate governed the shape evolution of the evaporated droplet. Flow field inside a water droplet placed on hydrophobic surface was examined by Kim et al. [22]. They showed that the flow pattern resulted in a fluid motion demonstrating upwards along the axis of symmetry and downwards along the surface of the droplet after which it broke into a smaller vortex. Fluid motion for a water droplet during sliding on hydrophobic surfaces was studied by Sakai et al. [23]. They demonstrated that slipping and rolling controlled the droplet's velocity during sliding on a hydrophobic surface; in addition, the advancing velocity might be large when the slip velocity was large and the contact area was small. The impact behavior of water droplet on a superhydrophobic surface in the presence of stagnation flow was examined by Mohammadi et al. [24]. They indicated that the presence of the stagnation flow promoted splashing and formation of satellite droplets for a fixed impact velocity. Flow resistance of a liquid droplet confined between two hydrophobic surfaces was studied by Suzuki [25]. He indicated that the shear resistance at low shear velocities was primarily caused by asymmetrical surface tension due to the contact angle hysteresis; in addition, a droplet on a rough hydrophobic surface remained almost symmetrical under shear and exhibited extremely low friction. The high efficiency water-droplet transport in a superhydrophobic aerogel-coated channel was examined by Kim et al. [26]. Their findings revealed that the aerogel-coated surface effectively facilitated movement of water droplets. A numerical simulation of water droplet dynamics in a polymer electrolyte membrane fuel cell gas channel was carried out by Zhu et al. [27]. They demonstrated that the hydrophilic side walls of the microchannel appeared to provide some benefit by lifting the attached water from the gas diffusion layer surface; thus, freeing the gas diffusion layer-flow channel interface for improved mass transfer of the reactant. Marangoni convection in droplets on superhydrophobic surfaces was investigated by Tam et al. [28]. They showed that the internal dynamics arise due to the presence of a vertical temperature gradient; this lead to a gradient in surface tension driving the fluid away from the contact point along the interface. Thermocapillary migration of droplets under partial wetting conditions was examined by Gomba et al. [29]. The findings revealed that for large contact angles, the droplet moved as a single entity, which was weakly distorted from its static shape. Spreading and superspreading of liquid droplets on solid surfaces was investigated by Karapetsas et al. [30]. They demonstrated that the spreading rates followed a non-monotonic variation with the initial surfactant concentration; however, an accompanying feature was the formation of a rim at the leading edge of the droplet. Microhydrodynamics of superspreading of droplets were studied by Maldarelli et al. [31]. They demonstrated that the reduced concentration created a Marangoni force along the fluid surface in the direction of spreading, and a concave rim in the vicinity of the contact line with a large dynamic contact angle.

Although flow field inside the droplet and effect of thermocapillary flow on the droplet behavior were studied previously, the main focus was to demonstrate the Marangoni force in the flow field and influence of the droplet contact angle on the flow field. However, further study is required for thorough examination of flow filed and heat transfer rates inside a droplet when located on a hydrophobic surfaces; in which case, a correlation among the contact angle, the Nusselt number, and the Bond number can be sorted. Consequently, in the present study, flow field and heat transfer rates inside the water droplet subjected to a local heating from a hydrophobic surface with presence of fine sized meshes are examined. Influence of the droplet contact angle on the flow characteristics and Nusselt number is examined numerically. Simulation conditions are extended to include droplets formed from a nano-fluid, which composes of water and carbon nanotubes mixture. An experiment is carried out to measure flow velocity in the droplet at various heating durations, which, then be used to validate velocity predictions.

## 2. Experimental

Octadecyltrichlorosilane was used to hydrophobized surface of polycarbonate wafers of 3 mm thickness. Bare polycarbonate surfaces were rinsed in an ultrasonic shaker with presence of deionized water for 15 min and later they were sonicated in ultrapure water for 20 min prior to hydrophobization. A deep coating technique was applied to form an octadecyltrichlorosilane layer of 40 nm uniform thickness. The surface hydrophobized were rinsed first with chloroform, later acetone, and ultrapure water. Adhesion tests were conducted for the coated polycarbonate wafer surfaces. A linear micro-scratch tester (MCTX-S/N: 01-04300) was used to determine the friction coefficient of the laser treated and untreated surfaces. The equipment was set at the contact load of 0.03 N and end load of 5 N. The scanning speed was 5 mm/min and loading rate was 1 N/s. The total length for the scratch tests was 1 mm. Fig. 1 shows AFM images (Fig. 1a), SEM micrographs of textured surface (1b) and a plot of adhesion force versus distance (Fig. 1c) of the coated surface. The textured surface composes of micro/nano structures, which consist of spherulites, pores, cavities and nanosize fibrils (Fig. 1a and b). The roughness of textured surface varies within the order of 450 nm–360 nm. The micro/nano features of the texture give rise to hydrophobic characteristics of the surface. The adhesion of coating at the textured surface is slightly higher than that of un-textured polycarbonate surface (Fig. 1c), which eases to allocate meshes at the textured surface. Fine sized square steel meshes (55 μm × 55 μm) with nominal wire thickness of 45 μm were laid onto the coated polycarbonate surface. To achieve a strong bonding between at the interface of the steel meshes and the coated surface, a thin film of adhesive (MASTERBOND MB297) was applied prior to placing the steel meshes onto the coated polycarbonate surface. Fig. 2 shows optical and SEM images of the meshes prior (Fig. 2a) and after laid down at the coated polycarbonate surface (Fig. 2b). In order to enhance the surface hydrophobicity, polycarbonate wafer surface was textured using acetone in line with the previous studies [32]. Textured surface was coated with octadecyltrichlorosilane via applying same procedure introduced for bare polycarbonate glass. Similarly, steel meshes were placed at the textured and coated polycarbonate surface.