



Heat and flow analysis of a water droplet on hydrophobic and hydrophilic phase change material

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ABSTRACT

Droplet heat transfer is examined incorporating the phase change material on the hydrophobic surface. Solvent crystallization of polycarbonate wafer is carried out and functionalized silica particles are deposited on the crystallized surface to achieve high water droplet contact angle (125°) with low hysteresis (2°). N-octadecane is used as a phase change material, which is introduced to form a thin layer on the functionalized silica coated surface. Flow and heat transfer analysis are carried out inside the droplet during the melting/solidification of the phase change material. It is found that thin layer deposition of n-octadecane on the treated surface gives rise to reversible hydrophobic-hydrophilic switching surface characteristics. In this case, the state of the treated surface becomes hydrophilic when the phase change material melts on the surface and it recoverably reverses to hydrophobic state when the surface solidifies. Inside the droplet, a single circulation cell is formed during the phase change of n-octadecane coating along the contact line at the droplet bottom. The center of circulation cell moves towards the solid phase side of the phase change material as the phase change progresses along the contact line. The Nusselt number increases with increasing size of the liquid phase on the droplet bottom. The Nusselt number demonstrates two distinguishing regions at the droplet bottom. In the first region, heat is transferred from the liquid phase of the phase change material to the droplet liquid while in the second region heat transfer reverses towards the solid phase of the phase change material, which is associated with the attainment of higher droplet fluid temperature than that of the solid phase change material surface.

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1. Introduction

Hydrophobic characteristics of the surface are critically important for self-cleaning applications. Water droplet mobility on hydrophobic surfaces is mainly influenced by adhesion of the droplet on the surface and inertia force resulted from various sources such as gravitational, magnetic, thermocapillary, etc. forces. Increasing droplet size on the hydrophobic surface enhances the adhesion force and influences the droplet mobility at the surface. Transition from hydrophobic state to hydrophilic state of the surface can alter the droplet mobility on the surface. The change of hydrophobic state to hydrophilic state requires alteration of texture and free energy of the surface. One of the methods for such alteration is to cover the hydrophobic surface with a thin layer of a phase change material with low solidus temperature. A thin layer of phase change material in solid phase may not homogeneously

cover the surface, but leaves randomly distributed islands of hydrophobic texture exposing at the surface [1]. This, in turn, does not alter the hydrophobic state of the surface when the phase change material is in solid state; however, when it melts, the liquid phase of the phase change material covers the surface because of high spreading coefficient while altering the wetting state from hydrophobic to hydrophilic [1]. This allows uniform wetting of the hydrophobic surface with a phase change material while forming a thin liquid layer at the surface [1]. One of the candidates of phase change materials having low solidus temperature is n-octadecane [2]. Since it remains in the solid phase at room temperature (297 K) and it melts once temperature increases 3 K more from the solid state temperature [2]. On the other hand, several methods were introduced to hydrophobize surfaces [3–9]. Some of these methods include phase separation [3], electrochemical deposition [4], plasma treatment [5], sol-gel processing [6], electrospinning [7], laser texturing [8], and solution immersion [9]. However, some of these methods involves with high cost hazardous chemicals, and high temperature processing. Nevertheless, these processes are adopted to reduce the free energy of the sur-

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faces through chemical changes of compositions at the surface and creating a surface texture composing of micro/nan pillars and poles. Texturing of surfaces for improved hydrophobicity has many challenges because of the requirements of precision of operation, dedicated equipment, skilled man power, and high cost. However, the recent development of dip coating by functionalized silica particles enables to texture the surface having micro/nano pillar morphology with low surface energy [10]. Therefore, the combination of surface modification incorporating functionalized silica particle deposition and coating with phase change material on the resulting surface provides thermally manipulated hydrophobic/hydrophilic surface characteristics. In this case, when the phase change material is in the solid phase, the surface is expected to act like hydrophobic and when the phase change material is in liquid form, the surface becomes hydrophilic. The thermal behavior of the water droplet on such transiently reversible hydrophobic/hydrophilic surfaces becomes important for possible self-cleaning applications. Consequently, investigation of the internal fluidity of a water droplet and heat transfer on hydrophobic/hydrophilic surfaces becomes essential.

Considerable research studies were carried out to examine flow and heat transfer behavior of water droplet on surfaces. Heat transfer analysis for a subcooled droplet falling freely in saturated steam was carried out by Luo et al. [11]. They showed that mean temperature of the droplet was the highest for the vertical velocity of steam and it remains the lowest for the horizontal velocity steam. In addition, the influence of the droplet size on the heat transfer rates was more pronounced for low velocity steam. Droplet heat transfer on the hydrophobic and superhydrophobic surfaces was investigated by Chavan et al. [12]. They indicated that setting the appropriate convective boundary conditions at the liquid vapor interface was essential to observe correct heat transfer rates along the three phase contact line; in which case, the local heat flux could be up to four orders of magnitude higher than at the droplet top. The droplet-film impact and heat transfer was studied by Jiang et al. [13]. They demonstrated that an increasing impact velocity, droplet diameter, film depth, cooling droplet, and wall temperature enhanced the heat dissipation from the film. The droplet dynamics and heat transfer in spray cooling applications were examined by Jia and Qiu [14]. They indicated that the heat transfer process in spray cooling could be divided into four regimes using the expulsion rate defined as the ratio of local outgoing to incoming mass fluxes. The slope of the droplet expulsion rate at the transition to the critical heat flux regime also changed sharply with surfactant addition. The interfacial heat transfer during cooling and solidification of molten metal droplets was examined by Wang and Matthys [15]. They observed that a high value of the interfacial heat transfer coefficient occurred when the molten splat was in contact with the substrate, followed by a smaller value during the later stages of solidification and the solid cooling phase. A numerical analysis for metal droplet cooling and solidification was carried out by Zeoli et al. [16]. They showed that the thermal history of particles was strongly dependent on initial droplet size. Large droplets did not suffer from undercooling while small droplets had identifiable stages of undercooling and recalescence. On the other hand, heat transfer pertinent to phase change material and hydrophobicity was investigated previously [17–19]. Surface hydrophobicity alteration through wax and wax blend was investigated by Lee et al. [17]. They demonstrated that the hydrophobicity in terms of chemical structure and functional groups was altered by changing the environment as well as by blending of two different waxes. The surface hydrophobicity of the wax changed for different waxes used despite the fact that the functional groups on the surfaces of all waxes under ambient atmospheric condition were similar. The varying surface hydrophobicity of coatings made of recombinant spider silk proteins were examined by

Wohlrab et al. [18]. They indicated that the engineered spider silk protein (eADF4 - C16) could be used for coating of surfaces; however, solvent and post-cast treatment showed severe impact on the silk structure and surface hydrophilicity. The nano-encapsulated n-octadecane phase change material with organosilica shell for thermal applications was studied by Zhu et al. [19]. The findings revealed that depending on the volume ratios of silane precursors, the organosilica nano-capsules with different morphologies (bowl-like and regular spherical) were obtained and the hydrophobicity of the organosilica shell materials could be facily tuned by changing the volume ratios of silane precursors.

Although surface hydrophobicity and textured silicon surface incorporating the phase change material was studied earlier [1,10], the main focus was to investigate the surface hydrophobic/hydrophilic characteristics. The transition from hydrophobic to hydrophilic characteristics and droplet heat transfer during the phase change of n-octadecane were left for future study. In addition, the water droplet behavior on the hydrophobic surface composing of a phase change material is important once the phase change is initiated. This is because of the fact that the liquefied surface alters the surface texture and surface energy while modifying the water droplet contact angle at the surface. This, in turn, influences the internal fluidity of the droplet and the heat transfer rates from the liquefied surface to the droplet. Since the heating takes place at the interface of the liquid droplet and phase change material, the values of the Nusselt and the Bond numbers changes across the mushy zone where the liquid fraction remains less than unity. This behavior complicates the internal flow inside the droplet and heat transfer rates from the phase change material. Consequently, in the present study, droplet heat transfer is considered after incorporating the n-octadecane phase change material on the hydrophobic surface. Temperature and flow fields in the phase change material and the droplet are simulated. Solution crystallization method is adopted to create surface texture on polycarbonate surface with micro/nano size spherules and fibrils. The functionalized nano-size silica particles are coated on the crystallized polycarbonate surface to increase the water droplet contact angle and lower the contact angle hysteresis. A thin layer of n-octadecane is deposited on the hydrophobic surface while sustaining the hydrophobic characteristics at the surface. The hydrophilic characteristics of the surface is achieved upon melting the n-octadecane film on the surface. Textured surface prior and after n-octadecane deposition is characterized using the analytical tools.

2. Experimental

The surface morphologies and texture characteristics of the solution crystallized and functionalized silica particles coated surfaces were characterized with a focused ion beam (FIB) field emission dual beam scanning electron microscope (FESSEM) and atomic force microscope (AFM). The AFM tip was made of silicon nitride probes ($r = 20\text{--}60\text{ nm}$) with a manufacturer-specified force constant, k , of 0.12 N/m .

A goniometer (Kyowa, model DM 501) was used to conduct sessile drop tests for the measurement of the droplet contact angle. Desalinated water was used in the sessile drop experiments, and the droplet volume was controlled with an automatic dispensing system. The images of the droplets were taken one second after deposition of the water droplet on the surface.

A polycarbonate wafer and acetone were used for solution crystallization. The polycarbonate wafers were immersed in 60% concentrated acetone in acetone-water mixture for 4 min in line with the previous study [20]. This process resulted in a hydrophobic surface ($\theta_w = 130^\circ$) with the large contact angle hysteresis (36°). In order to improve the surface contact angle and reduce

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