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Modeling of the evaporation rate of liquid droplets on anodized heated surfaces

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ABSTRACT

The present study investigates the sessile droplet evaporation and mass transfer characteristics on the anodized hole-patterned surfaces and proposes a theoretical model based on the experimental data. Polished aluminum specimens and oxalic acid are utilized to generate anodized surfaces with three cases by changing area fractions and hole diameter. The anodized hole surface contributes to enhancing surface wettability with higher capillary force inside the holes on the surface. The droplet evaporation rate increases with a reduction in the hole diameter. It is found that the previous models of the evaporation heat transfer rate on the bare surface do not fit well with the experimental results for the anodic oxidation surface. The solid-liquid-air interfacial equations involving the Gibbs energy are newly established for development of a new evaporation model that considers of the liquid displacement length. The results are validated against the previous results, showing that the new model has an error range of 6%. From the results, the smaller the hole diameter, or the deeper the hole depth, the capillary force increases, thereby widening the surface area of the droplet and promoting the evaporative heat transfer of the droplet.

1. Introduction

As the thermal management becomes more important within the battery and fuel cell industry, demand for studying heat transfer phenomena using phase change is increasing because the latent heat is much greater than the sensible heat. In particular, the evaporation phenomenon is one of the important issues in the phase change applications. In recent decades, many researchers have studied the evaporation of sessile droplets with a spherical cap shape, through numerical simulations and visualization techniques [1–3]. Researchers have identified that key parameters, such as the contact area and the apparent contact angle, vary with time. Mostly, these parameters have been used for making the useful correlation of the droplet evaporation rate, especially characterizing the Marangoni flows inside the droplet [4].

Various theoretical attempts have been made for evaporative heat transfer of sessile droplets on heated bare substrates. Chandra et al. [5] conducted experiments on droplet evaporation cooling of a hot solid surface. They examined the effect of contact angle on droplet evaporation and suggested their model for estimating the evaporation rate. Lower contact angles with higher contact diameters on bare surfaces contribute to a faster evaporation rate for apparent contact angles from 90° to 20°. Theoretical and experimental studies of droplet evaporation have been conducted for heated substrate [6]. Crespo and Linan [7] carried out asymptotic analysis for droplet evaporation under an inert atmosphere with the quasi-steady evaporation theory. They also conducted a transient analysis for vaporization rates and total evaporation times [7].

Aluminum has been used in many industrial applications, including automobile construction, civil engineering, architecture, shipbuilding, chemical manufacturing, and food applications because aluminum protects the base material from oxidation [8,9]. In particular, anodic aluminum oxide (AAO) surfaces have been widely used for coating applications through electrochemical oxidation. Moreover, AAO surface wettability can be changed depending on the manufacturing process, which contributes to heat transfer enhancement due to the change of surface energy [8,10]. Several previous studies have reported that surface wettability is affected by different hole configurations on the surface. For instance, Ran et al. [11] showed that the liquid displacement on anodized surfaces changed according to different hole diameters and depths; they also suggested a liquid displacement length model with pressure balance between air compression and capillary pressures. Leese et al. [12] used various hole configurations with apparent contact angles ranging from 10° to 100° by using surface

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anodization, and obtained a useful model focusing on the contact angle. Hsu et al. [13] studied the effect of surface anodization on droplet evaporation. They observed a substantial change in heat and mass transfer at the interface between two dissimilar phases on the anodized surfaces and provided the relation between surface wettability and temperature of textured surfaces.

Indeed, the above-mentioned works have focused mainly on the interfacial phenomena and heat transfer on manufactured hydrophobic surfaces. Generally, lower wettability decreases the contact area between liquid and solid phases, subsequently decreasing the heat transfer area. Thus, there remains a need for better understanding of the effect of the anodized surfaces with high wettability on droplet evaporation, specifically regarding heat transfer enhancement. The main purpose of the present study is to examine the evaporative heat transfer characteristics of a sessile droplet deposited on anodized aluminum surfaces with different configurations. Also, the present study suggests a new model of the evaporation rate based on the experimental data, by considering the liquid displacement on the hole-patterned, anodized surface. We also examine variation of the apparent contact angle for different hole diameters and area fractions and investigate the change in interfacial contact areas between two dissimilar phases during evaporation.

2. Experiments

Bare aluminum 6061 surfaces were first polished to generate a target apparent contact angle of 80.15° and were then used to generate the anodized surfaces. This aluminum surface shows excellent weldability and corrosion resistance, and it has been widely used in many thermal applications [14]. Each aluminum 6061 cylindrical specimen has a 12.5 mm radius and a height of 20 mm. The anodized surfaces were manufactured when a voltage of 50 V was induced for 4 h with the use of an oxalic acid solution of 0.3 M. The measured contact angle was similar to that reported by Leese et al. [12]. The voltage was applied by using a DC power supply (Digital Electronics Co., DRP-42305DU). The current and voltage were maintained over time. By connecting an electrode to oxalic acid, the current decreases when the hole starts to be created on the surface during the etching. By observing the plateau pattern of the current signal, the stable conditions for generating holes can be found.

We used a fixed voltage of 50 V in the first anodization stage. Then, the wet chemical etching process was needed to form the alumina layers on the surface for approximately 4 h. This etching process was followed by the widening process in which the hole size on the surface could be controlled with an oxalic acid solution of 0.3 M, depending on the wet etching time. The maximum widening time was 120 min in the present study. During the processes, the hole diameter and the area fraction could be changed. The surface morphologies were monitored with FE-SEM for different hole diameters and depths. The averaged hole diameter was in the range from 44.5 nm to 74.0 nm, with the area fraction in the range from 0.119 to 0.155.

Fig. 1 shows the schematic of the experimental set-up. The acrylic chamber enables control of the humidity; relative humidity was maintained at 20.1% ± 3.6%. Environmental temperature was maintained at 22.5 °C ± 2.9 °C, measured by a thermometer (TH-100 V). A telecentric lens (TML-HP, Edmond) and a CMOS camera (XLI, Meyer) were utilized to get a resolution of 2048 × 1536 pixels to process images. We mounted three calibrated RTD sensors (SA100S, J&S) into the specimen to measure the surface temperature with a deviation of about 1.5 °C in the case of a surface temperature of 150 °C. ImageJ software was used for image analysis of the anodized surfaces; diameter, depth, area fraction, and the pitch [15] were measured. The LB-ADAS plugin in ImageJ was utilized for measuring the contact angle [16].

3. Results and discussion

3.1. Wettability and heat transfer on anodized surfaces

Hole diameter and area fraction increase with the widening time, due to the increase in hole size that occurs from the use of oxalic acid [11,17]. With the increase in the time of the widening process, the hole diameter increases because the energy of the oxide layer is minimized. As shown in Fig. 2, the apparent contact angle of the anodized surface becomes lower than that of the bare aluminum surface, which is measured to be 80.15°. As the bare surface is anodized, the apparent contact angle drops to 35.8° because of the high liquid displacement into the anodized hole. The apparent contact angle increases with the widening time because of the reduced displacement. Because of the increased liquid displacement length underneath the droplet, the increase in the surface energy for the anodized surface leads to increasing wettability. The liquid displacement length decreases when the hole diameter becomes larger, because of the lower liquid capillary pressure, leading to decreased surface energy.

Fig. 3 shows the total evaporation times for evaporating droplets on bare and anodized aluminum surfaces. The total evaporation time is defined as the time at which the apparent contact angle becomes 0° [18–20]. Compared to the bare surface, the total evaporation time decreases because of the higher wettability, showing the increase in the heat transfer rate. This supports the theory that the anodization process would be useful in enhancing the heat and mass transfer during evaporation. As the surface temperature increases, a rapid decrease in the total evaporation time is also observed. When the hole diameter increases, the total evaporation time shows an increasing tendency due to a decrease in the capillary pressure, leading to a decrease in the liquid displacement.

Meanwhile, Fig. 4 shows that the evaporation rate increases with an increase in the surface temperature. The mean evaporation rate of the sessile droplet over time is expressed by [1,18–21].

$$\frac{dm}{dt} = \frac{1}{t_f}\int_0^{t_f}\frac{dm}{dt}dt = -\frac{m_0}{t_f} \tag{1}$$

where m_0 means an initial mass of the sessile drop, and t_f indicates the total evaporation time. This assumption is valid because the droplet volume decreases linearly during evaporation on hydrophilic surfaces [22]. As shown in Fig. 4, the evaporation rate increases with the surface temperature up to 37 times, and compared to the bare surface, it increases slightly for the anodized surfaces.

3.2. Surface energy modeling on anodized surfaces

The surface energy can be estimated by the contact of the static droplet on solid surfaces [23]. Prior work has studied the wetting transitions from surface energy [23]. Surface energy G in a thermodynamic state is given by:

$$G = \gamma_{LV}A_{LV} - \cos\theta_Y\gamma_{LV}A_{SL} \tag{2}$$

where θ_Y is the contact angle at a flat surface, and A_{LV} and A_{SL} are the interfacial area of the liquid–air and solid-liquid, respectively [23]. For the spherical cap shape of a droplet, A_{LV} on bare surfaces can be governed by:

$$A_{LV} = \frac{2\pi R^2}{1+\cos\theta_Y} \tag{3}$$

where R is the contact radius. The interfacial energy can be expressed with interfacial areas between liquid-air-solid phases and the contact angle [23]. As the interfacial area between liquid and solid increases, the surface energy can be increased, showing that the contact line is prone to be maintained [23].

The wettability increase of the anodized surfaces is associated with increased surface energy by the existence of nano-sized holes, leading