International Journal of Heat and Mass Transfer 102 (2016) 826–832

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Determination of the adhesion energy of liquid droplets on a hydrophobic flat surface considering the contact area

Yong Hwan Kim, Kiwook Kim, Ji Hwan Jeong *

School of Mechanical Engineering, Pusan National University, Jangjeon-Dong, Geumjeong-Gu, Busan 609-735, Republic of Korea

ARTICLE INFO

Article history:
Received 26 December 2015
Received in revised form 25 June 2016
Accepted 27 June 2016
Available online 9 July 2016

Keywords:
Contact angle
Dropwise condensation
Adhesion energy
Hydrophobic surface

ABSTRACT

The formation of liquid droplets on a hydrophobic surface and continuous droplet removal is beneficial in the design of various engineering devices. A liquid droplet on an inclined hydrophobic surface may roll down or attach to the surface depending on the balance among the associated forces. A series of experiments is performed in order to measure the inclination angle of a hydrophobic surface that makes a liquid droplet begin to slide or roll down. Various sizes of sessile drops of deionized water, ethylene glycol, and methylene iodide are examined. The existing adhesion force models have not been successful in predicting the sliding angle because they do not consider the area where the liquid droplet and solid surface are in contact with each other, but rather they consider the length of the periphery of the contact area. In this study, a new method to predict the adhesion energy of a droplet on a flat solid surface is proposed. The proposed method is based on the relationship between the solid and liquid contact area using moment of force analyses. Analyzing the experimental data using the proposed method, the adhesion energy per unit area is evaluated to have a constant value regardless of the droplet volume. The new definition of adhesion energy per unit area is appropriate for describing the movement of a liquid on a hydrophobic solid surface.

1. Introduction

The Rankine cycle for power plants and the refrigeration cycle for air conditioners, refrigerators, and heat pumps use heat exchangers to remove latent heat [1]. Heat exchangers have a heating surface for the phase change heat transfer between the hot and cold source working fluids that enter in a counter or parallel flow. At the heating surface, the hot and cold source working fluids circulate continuously. When the vapor contacts the cooling surface during the working fluid circulation, it condenses and changes to the liquid phase as the temperature decreases below the saturation temperature. This phenomenon is referred to as condensation.

The condensation mode is classified as dropwise condensation (DWC) or filmwise condensation (FWC) depending on the condensate flow behaviors on the heating surface. In the DWC process, droplets that nucleate, grow, and coalesce on the surface are removed from the surface quickly. Condensate water functions as thermal resistance during the heat transfer between the water vapor and a cold surface. DWC provides a small coverage area of condensate water compared with FWC. Therefore, if dropwise condensation is realized, the heat exchanger performance can be increased with a reduction in the exchanger size.

Previously, various studies have been performed in efforts to reduce the surface energy of metallic surfaces, because metallic surfaces have a high surface energy and are easily oxidized. As a result of these properties, FWC occurs on metallic surfaces [2–7]. In order to decrease the surface energy for the realization of DWC, polymer coating, electroplating, and other methods have been used. However, sustained dropwise condensation is difficult to achieve due to the surface damage resulting from oxidation, contamination, and deterioration.

With advanced manufacturing methods, hydrophobic surfaces with nano- and micro-structures have been manufactured [8,9]. Kim et al. [10] fabricated a super-hydrophobic surface with microstructures on a nickel surface in order to improve the heat transfer performance using micro electro mechanical system (MEMS) technology. However, the condensation mode changed from DWC to FWC. They observed condensate droplets nucleate and grow on the bottom surface and on the pillar side walls, but the droplets would not detach from the surface due to the large adhesion energy.

Since the first reports on FWC on nano- and micro-structured hydrophobic surfaces, other researchers have reported hybrid surfaces that are hydrophobic on the top and hydrophilic on the

* Corresponding author. Fax: +82 51 512 5236.
E-mail address: jihwan@pusan.ac.kr (J.H. Jeong).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.06.096
0017-9310/

Nomenclature

Bo	bond number
b_1, b_2, b_3	constants
F	force (N)
g	gravitational acceleration (m s^{-2})
H, h	droplet height (m)
l	length of the contact area (m)
l_c	capillary length (m)
R	radius (m)
V	volume (m^3)
x, y, z	rectangular coordinates (m)
α	surface inclination angle (°)
ζ	ellipse radius (m)
θ	contact angle (°)
ϕ	azimuthal angle (°)
ω	width, or diameter of the contact area (m)

Subscripts

a	advancing
adhesion	adhesion
Base	base of an extended surface
CA	static contact angle
COM	center of mass
gravity	gravitational
r	receding
l	saturated liquid conditions
lg	liquid to gas interface
wet	wetted

bottom that prevent the adhesion energy effect by droplet growth and coalescence [11]. However, commercialization of these advanced technologies has proven to be difficult due to the high manufacturing cost and because they are unprofitable for large area manufacturing applications. In order to address the fundamental problems for successful DWC and droplet adhesion on the surface, a better theoretical understanding of droplet mobility on plane surfaces is required.

Furmidge et al. [12] sprayed a water and cetylpyridinium chloride mixed solution to measure the retention force on plant leaves. In order to predict the retention force, they considered the droplet size, tilting angle, air/liquid surface tension, and advancing and receding angles. Extrand and Kumagai [13] proposed a retentive force predictive equation considering the advancing and receding angles where a droplet slides on a tiltable surface and an elliptical shape is assumed. ElSherbini and Jacobi [14] investigated a method to predict the adhesion force using the contact angle considering the azimuthal angle when a droplet slides on an inclined surface.

Fig. 1 illustrates a droplet on an inclined surface with an inclined angle α. The adhesion force, $F_{adhesion}$, is calculated as follows:

$$F_{adhesion} = -2\sigma_{lg}\int_0^{\pi} \zeta \cos\theta \cos\phi d\phi, \quad (1)$$

where σ_{lg} is the liquid–air surface tension, ζ is the ellipse radius, θ is the contact angle, and ϕ is the azimuthal angle. The contact angle hysteresis on the inclined surface denotes a function of the azimuthal angle ϕ, as follows:

$$\cos\theta(\phi) = b_1\phi^3 + b_2\phi^2 + b_3, \quad (2)$$

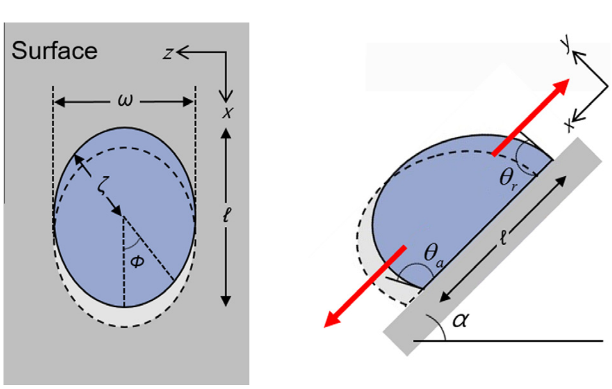

Fig. 1. Droplet on an inclined surface.

where

$$b_1 = 2\frac{\cos\theta_a - \cos\theta_r}{\pi^3}, \quad (2\text{-a})$$

$$b_2 = -3\frac{\cos\theta_a - \cos\theta_r}{\pi^2}, \quad (2\text{-b})$$

$$b_3 = \cos\theta_a, \quad (2\text{-c})$$

where θ_a and θ_r are the advancing and receding contact angles, respectively. If the droplet contour approximates the shape of a circle, the ellipse radius ζ is equivalent to the radius R_{Base}. Then, Eq. (1) becomes

$$F_{adhesion} = \frac{48}{\pi^3}\sigma_{lg}R_{Base}(\cos\theta_r - \cos\theta_a). \quad (3)$$

When the droplet adhesion force on the surface is equal to or less than the external force, including gravitational force, the droplet begins to slide on the surface.

Previous studies predicted the adhesion force using the liquid–air surface tension, droplet geometry, and contact angle hysteresis. However, they only considered the contact line at the liquid–air interface. They did not consider the relationship between the solid and liquid contact area. In this study, a method is proposed that predicts the adhesion energy of a droplet considering the contact area between the solid surface and liquid droplet. The behaviors of various liquid droplets on a hydrophobic surface are experimentally measured and analyzed in order to validate the proposed concept of the adhesion energy definition. In order to minimize the effects of unexpected factors, experiments are performed with a well-known hydrophobic surface made from an aluminum substrate coated with plasma-polymerized fluorocarbon (PPFC). Aluminum has a high surface energy and its contact angle is well known. The PPFC thin film has a hydrophobic characteristic. The adhesion energy is calculated through determining the contact area between the solid and liquid with the droplet geometry and the reaction force on the surface.

2. Experimental method

2.1. Experimental apparatus

Using gravitational force, the droplet easily slides from the surface. The reaction force on the droplet varies depending on the droplet size and the inclination angle of the horizontal axis. When measuring the droplet volume and the inclination angle, the