Transactions of the Korean Nuclear Society Autumn Meeting
Gyeongju, Korea, October 25-26, 2012

Critical heat flux enhancement mechanism on nanoparticle-coated surfaces

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1. Introduction

It is well known that the critical heat flux (CHF) on nanoparticle-coated surfaces is significantly enhanced compared with that on flat surfaces. Several physical mechanisms have been proposed to explain this phenomenon. However, all studies so far have been qualitative, and a generalized theory has not yet been established. In this study, we present a quantitative mechanism for CHF enhancement on nanoparticle-coated surface based on the vapor recoil and surface adhesion forces. We focus on the length increase of a triple contact line due to nanoparticle deposition and the adhesion force between nanoparticles and liquid.

2. Previous Researches

A theoretical explanation of CHF phenomena was first presented based on the Kelvin–Helmholtz instability using Zuber’s hydrodynamic theory [1]. The theory regarded the CHF as occurring when the surface–fluid interface was broken due to the velocity difference between the ascending vapor column and the liquid descending due to gravity. In Kandlikar’s research [2], CHF phenomena were defined as occurring when a vapor bubble spreads on the surface due to the vapor recoil force, and the CHF value was theoretically predicted. The recoil force pushes the interface in the direction of the liquid, and when the force exceeds the surface tension that adheres the liquid molecules on the triple contact line (vapor, liquid, and solid), vapor spreads on the heater surface (see Fig. 1(a)). Vapor spreading can be observed in visualization studies of the bottom of a boiling heater [3] (see Fig. 1(b)). However, the theoretical model of Kandlikar does not predict the CHF results of recent nanofluid boiling experiments accurately [4,5]. It significantly underestimates the CHF values on heater surfaces coated with nano-sized porous structures. To reasonably explain CHF phenomena on nanoparticle-coated surfaces, a macrolayer dry-out model [6], the effect of thermal conduction on heat surface [6] and capillary wicking [4] have all been presented as key mechanisms. However, these are qualitative ideas, and a generalized theory has not yet been established. In this study, we therefore present a quantitative theory of CHF enhancement on a heater surface coated with nano-sized porous structures, based on the vapor recoil mechanism.

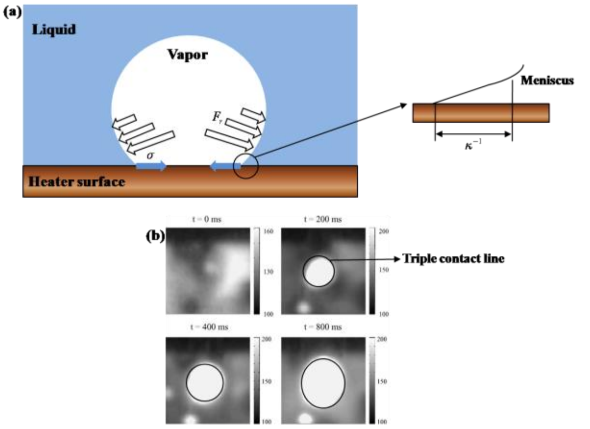

Fig. 1. Vapor spreading mechanism due to the relation between vapor recoil force and surface adhesion force. (a) In the evaporating vapor-liquid interface, vapor recoil force (F_r) and surface tension (σ) and their directions. (b) Vapor spreading phenomena in the visualization study of the bottom of boiling heater (See Ref. 3).

3. Model Development and Results

We assume a spherical liquid–vapor interface evaporating on the surface coated with nanoparticles (see Fig. 2(a)). If we identify the instant of vapor spreading due to the CHF phenomena, a force balance equation on the left side of the sphere cut symmetrically can be obtained:

$$F_r = F_G + F_{\sigma,l} + F_{\sigma,w}\,, \quad (1)$$

where F_r is the vapor recoil force, F_G is the force due to gravity, $F_{\sigma,w}$ is the surface adhesion force on the triple contact line, and $F_{\sigma,l}$ is the adhesion force between liquid and liquid. The vapor recoil force is

$$F_r = \frac{D_b^2}{4}\left(\frac{q''}{h_{fg}}\right)^2\left(\frac{\rho_l-\rho_v}{\rho_v\rho_l}\right)(\pi-\theta_A+\cos\theta_A\sin\theta_A)\,, \quad (2)$$

where D_b is the bubble diameter, θ_A is the dynamic receding contact angle of the liquid on the heater surface, ρ_v and ρ_l are the densities of the vapor and liquid, respectively, q'' is the heat flux and h_{fg} is latent heat. Next,

$$F_G = \frac{D_b^3}{16}(\rho_l - \rho_g)(1+\cos\theta_A)(\pi - \theta_A + \cos\theta_A \sin\theta_A) \,. \quad (3)$$

In addition, $F_{\sigma,l} = \sigma \times \pi D_b \times (2\pi - 2\theta_A)/2\pi = \sigma D_b(\pi - \theta_A)$.

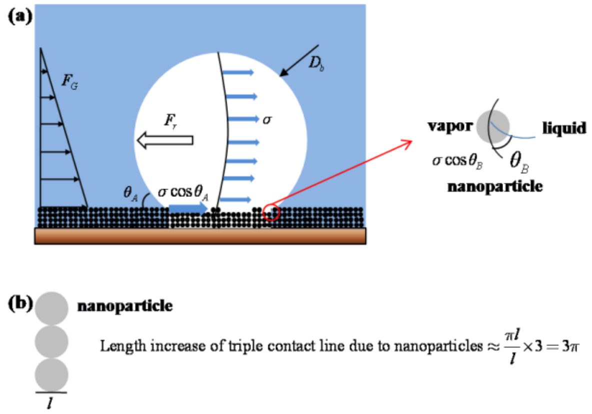

Fig. 2. Schematic model of the evaporating interface on nanoparticle coated heater surface. (a) Force components acting on a evaporating vapor bubble. (b) An example of length increase of triple contact line due to nanoparticles.

And, on a surface coated with nanoparticles, the length of triple contact line may increase significantly (Fig. 2(b)). Therefore, $F_{\sigma,w}$ can be written as

$$F_{\sigma,w} = \sigma\cos\theta_A \times \frac{\pi D_b \sin\theta_A}{2} + \sigma\cos\theta_B \times \frac{\pi D_b \sin\theta_A}{2} \times R_{triple-line} \,, \quad (4)$$

where θ_B is the the dynamic receding contact angle of the liquid on the nanoparticle material, and $R_{triple\text{-}line}$ is the length ratio of the triple contact line created by the nano-structures on a flat surface. Finally, using Eq. (1)-(4), we can obtain an equation for the CHF:

$$q''_{CHF} = \frac{1+\cos\theta_A}{16}\left[\frac{\rho_l \rho_v}{\rho_l - \rho_v}\right]^{1/2} h_{fg} \left[\frac{\pi(1+\cos\theta_A)}{4} + \frac{4}{\pi}\frac{\pi - \theta_A + \pi\sin\theta_A(\cos\theta_A + R_{triple-line}\cos\theta_B)/2}{\pi - \theta_A + \sin\theta_A\cos\theta_A}\right]^{1/2} \times[\sigma g(\rho_l - \rho_v)]^{1/4} \quad (5)$$

We can explain the CHF enhancement mechanism on nanoparticle-coated surfaces using (5). On the surface coated with one-layered ZnO nanorods described by Kim et al [7], $R_{triple\text{-}line}$ can be calculated approximately as 35.3 (see Fig. 3(b)). Eq. (5) gives a CHF value of 1910.4 kW/m^2. This agrees closely with the experimental value of 2003 kW/m^2 reported by Kim et al [7]. And, as described by Kim and Kim [4] and Park et al. [5] (Fig. 3(a)), when $R_{triple\text{-}line} = 0$, the CHF values for surfaces with nano-sized porous structures are clearly much higher than the predictions of Eq. (5). However, a significant CHF enhancement can be predicted when the length increase of the triple contact line and the adhesion force between the nanoparticles and liquid θ_B are considered (See Fig. 3(a)).

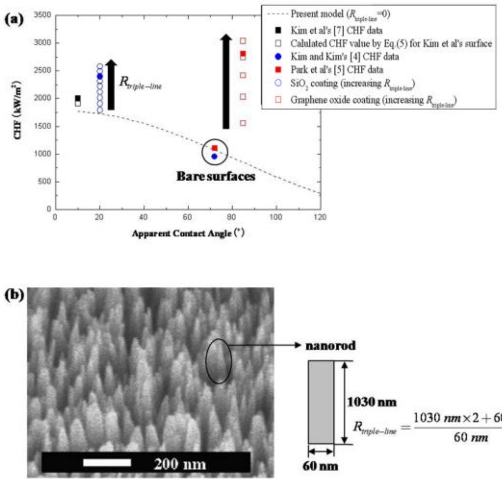

Fig. 3. Comparison between the present model and existing experimental CHF data [4,5,7]. (a) Experimental CHF data and predictions of Eq. (5). (b) Scanning Electron Microscope image of the Kim et al's [7] surface coated with ZnO nanorods and the estimation of $R_{triple-line}$.

4. Conclusions

We conclude that our CHF model based on the force balance between the vapor recoil and surface adhesion reasonably explains the CHF enhancements on heater surfaces coated with nanoparticles. For accurate validation, an assessment of the increase of triple contact lines on surfaces coated with nano-sized porous structures is required.

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