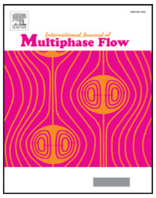
International Journal of Multiphase Flow 84 (2016) 165–175

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

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



Numerical approach to the suppression of film boiling on hot-spots by radial control of patterned wettability

Jung Shin Lee, Joon Sang Lee*

School of Mechanical Engineering, Yonsei University, 50 Yonsei-ro, Seodaemun-gu, Seoul, Republic of Korea

ARTICLE INFO

Article history:
Received 8 December 2015
Revised 13 April 2016
Accepted 29 April 2016
Available online 2 May 2016

Keywords:
Critical heat flux
Patterned wettability
Boiling heat transfer
Pool boiling
Radial area fraction control
Hot-spot

ABSTRACT

This paper proposes a novel method for controlling the boiling phenomena of a thermally heterogeneous field on a surface. To achieve thermal heterogeneity, we used a heat flux gradient. The control method is based on radial pitch control of the patterned wettability using hydrophobic dots. The area fraction of the hydrophobic dots was set to be small near the center of the hot-spot and large in the marginal region. Consequently, the boiling phenomena at the center changed from a film boiling regime to a nucleate boiling regime. Compared with an uncontrolled surface, the critical heat flux was enhanced at the center region, and the heat transfer rate was enhanced at the marginal region. Pitch control prevents film generation at the center and film propagation over the whole surface, thus enhancing the overall critical heat flux of the whole surface.

1. Introduction

Patterned wettability, which derives from the control of boiling phenomena by uniform wettability, is a popular optimization scheme for boiling heat transfer (Nam and Ju, 2008; Betz et al., 2010; Jo et al., 2011, 2014). Takata et al. (2003) demonstrated that hydrophilic surfaces enhance the critical heat flux (CHF) and superheat and lower the heat transfer rate. In a later study, they reported the opposite effects on hydrophobic surfaces (Takata et al., 2006a). Therefore, both hydrophobic and hydrophilic surfaces have advantages and disadvantages for boiling heat transfer.

Patterned wettability was proposed by Takata et al. (2006b), who pioneered the pool boiling experiment using a checkerboard arrangement of square hydrophobic dots. The hydrophobic parts of the checkerboard pattern act as nucleation sites, decreasing the superheat and increasing the heat transfer rate. The nucleated bubbles are prevented from merging by the intervening hydrophilic surfaces. Other researchers have since applied checkerboard or similar wettability patterns to pool boiling (Nam and Ju, 2008; Betz et al., 2010; Jo et al., 2011, 2014).

Nam et al. (2008) showed that bubbles can nucleate on the hydrophobic dots with low superheat, thus suppressing the overall superheat. Nucleation can then be prompted by a hydrophobic surface that covers a small fraction of the whole surface area (Nam and Ju, 2008). Betz et al. investigated the critical heat flux and heat transfer rate of pool boiling with two wettability patterns. A hydrophobic surface arrayed with hydrophilic dots generated a higher heat transfer rate and a lower critical heat flux than a bare hydrophilic surface. The second pattern, consisting of hydrophobic dots on a hydrophilic surface, enhanced the heat transfer rate and the critical heat flux by 100% and 65%, respectively, relative to a bare hydrophilic surface (Betz et al., 2010). This suggested that both the heat transfer rate and the critical heat flux could be enhanced by optimizing the patterned wettability. However, Jo et al. (2011, 2014) altered the pitch of the hydrophobic dots in a patterned wettability study, and obtained contrary results for the critical heat flux. They found that on a hydrophilic surface arrayed with hydrophobic dots, the critical heat flux approached that of a bare hydrophilic surface (Jo et al., 2011). In their later study, Jo et al. (2014) integrated the known variables in the area fraction of the hydrophobic dots over the total surface area, and demonstrated that this area fraction was correlated with the critical heat flux. Consequently, the critical heat flux can be optimized by varying the area fraction of the hydrophobic dots. However, the critical heat flux of the patterned wettability could not exceed the critical heat flux of a bare hydrophilic surface (Jo et al., 2014).

Whether the critical heat flux in patterned wettability can exceed the critical heat flux of a bare hydrophilic surface remains unclear (Betz et al., 2010; Jo et al., 2011, 2014). At present, we know that the critical heat flux can be optimized by varying the area fraction, and can at least approach that of a bare hydrophilic surface (Jo et al., 2011, 2014). An equidistant square array

---

* Corresponding author.
E-mail address: joonlee@yonsei.ac.kr (J.S. Lee).

http://dx.doi.org/10.1016/j.ijmultiphaseflow.2016.04.021
0301-9322/

of hydrophobic dots can optimize the heat flux under uniform or quasi-uniform thermal conditions, but the applicability of this strategy to non-uniform thermal conditions remains unresolved. In particular, the critical heat fluxes, superheats, and heat transfer rates of equidistant wettability patterns under heterogeneous thermal conditions have not been reported. Even on surfaces with small thermal heterogeneity, a film initiates from the site of peak temperature and eventually covers the whole surface (Chu et al., 2014). As the boiling crisis of a specific area determines the boiling crisis of the entire system, film boiling arising from local thermal deviations must be suppressed by a localized wettability control.

The boiling crisis over a specific area can be changed by a conjugate heat transfer. Zhang et al. (2015) observed bubble nucleation on single nucleation sites. Because the thermal diffusivity of a heat plate depends on its composite materials, the temperature gradient (and hence the bubble waiting period) can be altered by changing the heat-plate material. This modification simply changes the bubble departure frequency of single bubble nucleation (Son et al., 1999). However, this modification changes the entire boiling behavior of a system with multiple nucleation sites, because the temperature gradient and waiting period of the bubbles affect the bubble nucleation at their neighboring nucleation sites. Sultan et al. (1983) observed bubble nucleation on multiple neighboring nucleation sites. They found that the thermal diffusivity of a solid substrate affects the interference between neighboring bubbles. This phenomenon can change the merging behavior of the bubbles.

In this paper, we propose radial pitch control of a hydrophobic dot array. First, we investigate the boiling characteristics of an equidistant square array of hydrophobic dots on a radial heat flux field, which mimics a hot-spot. Next, we control the pitch of the hydrophobic dot arrays and compare the resulting boiling phenomena with those of the equidistant square array. In our radial pitch control design, the pitch of the hydrophobic dots is gradually decreased with the radial distance from the center, so that the fraction of hydrophobic dots in the center region was lower than that in the marginal region. The pitch is controlled by the pitch modification parameter (*Mp*). The most important criterion of a boiling regime is film formation. Therefore, bubble merging behavior and film formation are observed in this study. To investigate the effects of bubble formation on boiling heat transfer, we correlate the surface temperature and local heat flux profiles with the bubble formation. As noted above, the onset of the boiling crisis must be investigated with reference to location. Therefore, to investigate the effect of a local boiling crisis on the overall boiling phenomena, we calculate the local heat flux, the local critical heat flux, and the critical heat fluxes of the overall system. Next, we compare the positive and negative effects of radial pitch control on the calculated heat transfer rates. Finally, we investigate the effect of thermal diffusivity of the solid substrate on the boiling phenomena with different *Mp* values.

2. Numerical method

We applied the modified pseudopotential lattice Boltzmann model developed by Gong and Cheng (2012). In this model, the body force term that delivers the interparticle force, wettability and buoyancy to the density distribution function f_i is computed by the exact difference method (Kupershtokh and Medvedev, 2006).

The interparticle interaction force F_{int} is given by

$$F_{\mathrm{int}}(x) = -\beta\psi(x)\sum_{x'} G(x,x')\psi(x')(x'-x) - \frac{1-\beta}{2}\sum_{x'} G(x,x')\psi^2(x')(x'-x), \qquad (1)$$

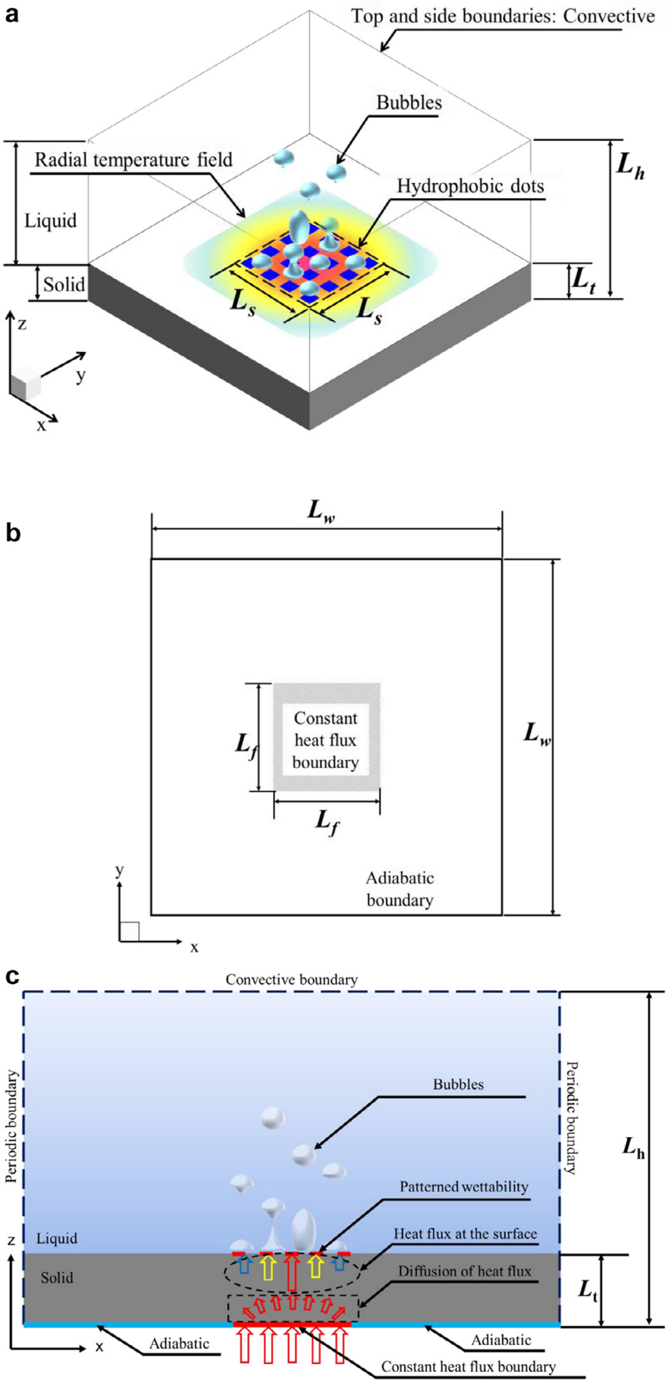


Fig. 1. Simulation description: (a) outline of the whole domain, (b) x–y plane at $z = 0$ and (c) schematic of the heat flux gradient developed at the top surface of the solid substrate.

where β is an arbitrary value. The effect of β on the phase change is derived from the numerical work of Gong and Cheng (2012). $G(x, x')$ is given by

$$G(x,x') = \begin{cases} g_1, & |x-x'| = 1 \\ g_2, & |x-x'| = \sqrt{2} \\ 0, & otherwise \end{cases}, \qquad (2)$$

where $g_1 = g_0$, $g_2 = g_0/2$ is selected for the three-dimensional lattice Boltzmann method using the (D3Q19) model with 19 directions of distribution functions. The effective mass $\psi(x)$is based on the Peng–Robinson (P–R) equation of state.