A Review of Wettability Effect on Boiling Heat Transfer Enhancement

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1. Introduction

Critical heat flux (CHF) and nucleate boiling heat transfer coefficient (NBHTC) are the key parameters characterizing pool boiling heat transfer. These variables are complicatedly related to thermal-hydraulic parameters of surface wettability, nucleation site density, bubble departure diameter and frequency, to mention a few. In essence, wettability effect on pool boiling heat transfer has been a major fuel to enhance the CHF. Often, however, the improved wettability effect hinders the nucleate boiling. Thus a comprehensive review of such wettability effect may enlighten a further study in this boiling heat transfer area. Phan et al. described surface wettability effects on boiling heat transfer as shown in Fig. 1 [1].

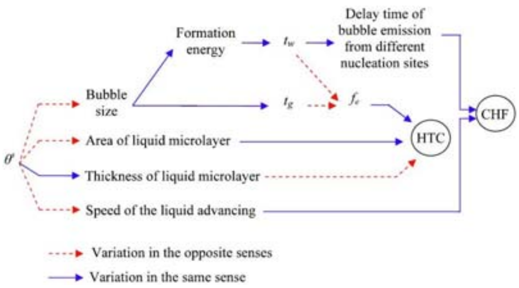

Fig. 1. A logical diagram describing the effects of the contact angle on the nucleated boiling parameters [1].

2. Review of recent research

Recently many researchers have studied a boiling enhancement technique using nanofluids. After observing a considerable surface modification with the nanofluid boiling, more sophisticated coating techniques have been explored to draw an equivalent enhancement in boiling heat transfer. In this section studies on wettability change to enhance boiling heat transfer are reviewed.

2.1 Wettability change during nanofluids boiling

Heat transfer enhancement in nanofluids is achieved by nanoparticle deposition [2-4]. Kim et al. found a considerable enhancement in CHF and suggested that such improvement was caused by nanoparticle deposition (Fig. 2) rather than physical or chemical properties of the nanofluids [3]. They studied the pool boiling characteristics of dilute dispersions of alumina (Al_2O_3), zirconia (ZrO_2) and silica (SiO_2) nanoparticles in water. In this study buildup of a porous layer on the heater surface was formed during nucleate boiling. The porous coating layer increased the wettability, which was confirmed as a consequence of the nanoparticle deposition.

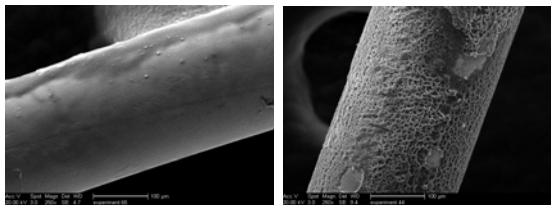

Fig. 2. SEM images of steel wires taken after boiling pure water and 0.01%v alumina nanofluid [3].

2.2 Wettability enhancement techniques using dry-coating techniques

Boiling heat transfer can also be enhanced by dry-coating techniques to change surface wettability. Different from the surface modification during nanofluid boiling, various micro/nanocoating techniques on a heated surface allow a more systematic design of the nano-structured surfaces.

Kim et al. used four artificial surfaces (F, M, N, NM) to the substrate silicon plate to observe the effect of surface modification [5]. It was found that the surfaces with nanorods (N, NM) showed better wettability than those without (F, M) as presented in Fig. 3. In addition, the higher CHF enhancement was observed in the surfaces with improved wettability. They concluded that major parameters to enhance CHF are wettability, spreadability, and surface geometry.

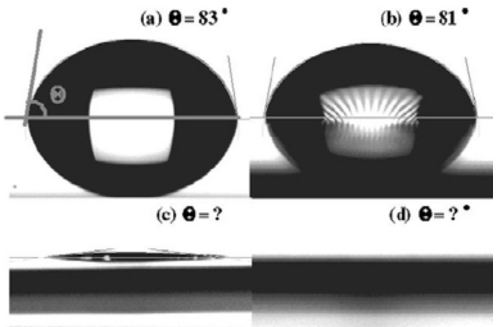

Fig. 3. Mean (n=5) contact angles images of various test surfaces. (a) F surface, (b) M surface, (c) N surface, (d) NM surface. The contact angle value of each test surface is marked on the upper right of each image. Uncertainty is about (+/-) 3 ° [5].

Phan et al. conducted experiments to investigate the influence of surface wettability on nucleate boiling heat transfer [6]. They investigated various coating techniques of chemical vapor deposition (CVD), physical vapor deposition, and nanofluid boiling. Fig. 4 shows the static contact angle ranging from 22º to 112º, which correspond with hydrophilic and hydrophobic surfaces. It was found that, for hydrophobic surface, bubble cannot detach from the surface resulting in damage to the wall. On the other hand, for hydrophilic surface, bubble departure diameter increases and bubble emission frequency decreases. Moreover, HTC is dependent on the ranges of the contact angles. The enhancement of the HTC was observed at very high surface wettability ($\theta \leq 45º$). However, the HTC deteriorated at low surface wettability ($45º < \theta < 90º$).

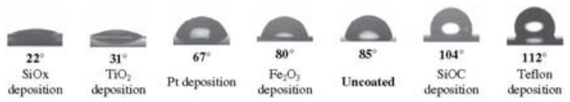

Fig. 4. Static contact angles of 2-μl sessile water droplets on stainless steel surfaces with and without nanoparticle deposition [6].

Surface modification to change surface wettability can be achievable using an electroetching process. Chen et al. studied the effects of nanowire arrays made of Si and Cu [7]. The Si nanowires were obtained through an aqueous solution of electrolyte, $AgNO_3$ and HF acid. Experiencing continuous oxidation and etching process, the Si nanowire arrays were developed in the unetched region. Fig. 5 presents the nanowire arrays and the coated surfaces with the corresponding contact angles. A superhydrophilic surface (very low contact angle) was shown for the surfaces coated with Si or Cu nanowires. It was found that boiling heat transfer was considerably enhanced in both CHF and HTC by more than 100%. They suggested that the enhancement can be affected by high nucleation site density, superhydrophilicity, and enhanced capillary pumping effect of nanowires, which are the unique properties of nanowires.

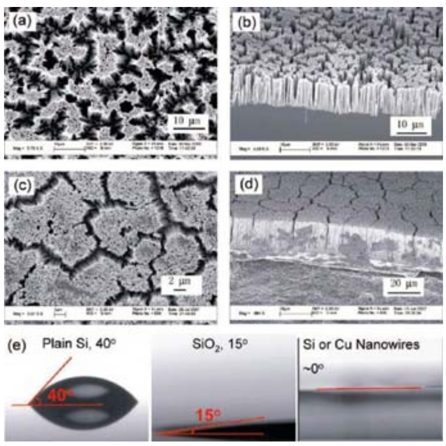

Fig. 5. SEM images of (a) top view of Si Nanowires, (b) cross section of Si Nanowires, (c) top view of Cu Nanowires, (d) cross section of Cu Nanowires, (e) static contact angle of a water droplet on surfaces of Si, SiO_2, and Si and Cu nanowires [7].

3. Conclusions

The recent researches were reviewed in light of the wettability effect on boiling heat transfer enhancement. In general wettability change during nanofluid boiling shows significant heat transfer enhancement, especially of the CHF. It has been well-known that the nanoparticle deposition on the heated surface affects the improvement. To obtain favorable nano-structured surfaces resulting in wettability change, dry-coating techniques have been developed. In many cases, similar CHF enhancement is reported. However, prediction of HTC enhancement is not in a comprehensive step. It depends on various boiling and surface conditions including surface wettability. Therefore, a further study on wettability effect is required with integrated consideration of CHF and HTC together at various experimental conditions.

REFERENCES

[1] Hai Trieu Phan, Nadia Caney, Philippe Marty, Stéphane Colasson, Jérôme Gavillet, How does surface wettability influence nucleate boiling?, Comptes Rendus Mécanique, Vol. 337, pp. 251-259, 2009.
[2] S.J. Kim, I.C. Bang, J. Buongiorno, L.W. Hu, Effects of Nanoparticles Deposition on Surface Wettability Influencing Boiling Heat Transfer in Nanofluids, Applied Physics Letter, Vol. 89, p. 153107, 2006.
[3] S.J. Kim, I.C. Bang, J. Buongiorno, L.W. Hu, Surface wettability change during pool boiling nanofluids and its effect on critical heat flux, International Journal of Heat and Mass Transfer, Vol. 50, pp. 4105-4116, 2007.
[4] Hyungdae Kim, Ho Seon Ahn, Moo Hwan Kim, On the Mechanism of Pool Boiling Critical Heat Flux Enhancement in Nanofluids, Journal of Heat Transfer, Vol. 132, pp. 061501-11, 2010.
[5] Seontae Kim, Hyung Dae Kim, Hyungmo Kim, Ho Seon Ahn, Hangjin Jo, Joonwon Kim, Moo Hwan Kim, Effects of nano-fluid and surfaces with nano structure on the increase of CHF, Experimental Thermal and Fluid Science, Vol. 34, pp. 487-495, 2010.
[6] Hai Trieu Phan, Nadia Caney, Philippe Marty, Stéphane Colasson, Jérôme Gavillet, Surface wettability control by nanocoating: The effects on pool boiling heat transfer and nucleation mechanism, International Journal of Heat and Mass Transfer, Vol. 52, pp. 5459-5471, 2009.
[7] Renkun Chen, Ming-Chang Lu, Vinod Srinivasan, Zhijie Wang, Hyung Hee Cho, and Arun Majumdar, Nanowires for enhanced boiling heat transfer, Nano Letters, Vol. 9, pp. 548-553, 2009.