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Numerical simulation of boiling enhancement on a microstructured surface☆

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ABSTRACT

Significant efforts have been made to augment nucleate boiling by surface modification with micro-machined structures, but a general predictive approach for heat transfer enhancement has not yet been developed. In this work, complete numerical simulations are performed for boiling enhancement on a microstructured surface by employing the sharp-interface level-set method, which is modified to handle the contact angle and the evaporative heat flux from the liquid microlayer on an immersed solid surface. The effects of cavity diameter and surface modification such as concentric grooves and multi-step cavities on bubble growth and boiling heat transfer are investigated.

1. Introduction

Nucleate boiling is a liquid–vapor phase-change process associated with bubble formation at discrete cavities and is a very efficient mode of heat transfer. The boiling process has recently received new attention as a promising way for thermal management of high-powered microelectronics. With an increasing demand for higher cooling capacity, the boiling heat transfer has been enhanced by employing several techniques such as surface modification with micro-machined structures, surface treatment in a submicron scale by spraying, painting and sintering micro or nano particles, addition of surfactant, and application of electric field or mechanical force, which were reviewed by Bergles [1], Honda and Wei [2], and Khan et al. [3]. In this work we focus on boiling enhancement by surface modification, which is one of the most suitable techniques for electronics cooling application [3]. Using advanced microscale machining and MEMS techniques, various microstructures have been fabricated and tested for boiling enhancement.

Anderson and Mudawar [4] experimentally studied boiling of saturated dielectric fluid FC-72 on various microstructured surfaces with fins, studs, grooves and drilled cavities. Low-profile microstructures of the order of bubble departure diameter were found to significantly improve nucleate boiling whereas large cavities of the order of 0.3 mm diameter are not effective for boiling enhancement. Subsequently, using hexagonal dimples of 9.4 μm diameter and 3.3 μm depth, Miller et al. [5] reported a better performance than other enhanced surfaces.

Reentrant cavities with different sizes and shapes were tested by Phadke et al. [6] for boiling of R-113. The experimental data for saturated boiling showed that the performance of all the cavity surfaces is better than that of the plain surface, but the neck diameter of the cavity is not significant in the size range of 0.23–0.49 mm.

Guglielmini et al. [7] used finned copper surfaces for heat transfer enhancement in nucleate boiling of saturated Galden HT-55. Straight fins with a square cross-section of 0.4 and 0.8 mm widths were tested in horizontal and vertical orientation. The finned surfaces provided much higher heat fluxes compared with a plain surface. They also reported that the vertical orientation has a better heat transfer performance than the horizontal orientation.

Recently, Shoji et al. [8] investigated boiling phenomena of saturated water on a thin copper plate with a single artificial cavity. Three types of cavities, which are conical, cylindrical and reentrant, were tested with diameters of 0.05 and 0.1 mm. The conical cavities showed intermittent bubbling with large temperature oscillations and required high superheat for bubble generation while the cylindrical and reentrant cavities showed continuous and stable bubble generation from low superheat.

Square micro-pin-fin structures with different thicknesses of 30–50 μm and heights of 60–270 μm were tested by Wei and Honda [9] for boiling of FC-72. The microstructures showed a very sharp increase in the heat flux with increasing wall superheat when compared with a smooth surface. A considerable enhancement in the critical heat flux was also observed on the microstructured surface.

Yu et al. [10] performed a nucleate boiling experiment on a thin silicon plate with artificial cavities of 0.05–0.2 mm diameters and 0.11–0.2 mm depths. The effect of number density of cavities was included in their study. The experimental data showed that the heat transfer coefficient increases with cavity density, but the critical heat flux is suppressed by denser cavities. A larger cavity diameter reduces the heat transfer coefficient in moderate and high heat flux regions, but the effect of cavity diameter can be ignored in a low heat flux region.

Despite a number of experimental studies, the boiling enhancement on microstructured surfaces is far from being understood due to

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