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Pool boiling and flow boiling on micro- and nanostructured surfaces

Mostafa Shojaeian, Ali Koşar *

Mechatronics Engineering Program, Faculty of Engineering and Natural Sciences, Sabanci University, Tuzla, Istanbul 34956, Turkey

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ABSTRACT

This study reviews recent experimental investigations performed on pool and flow boiling over nano- and micro engineered structures for enhancements in boiling heat transfer, namely heat transfer coefficient (HTC) and critical heat flux (CHF). Modified surfaces having nano/micro porous features of mainly irregular shapes through anodic oxidation processes, coating of metallic and non-metallic layers, deposition of powder materials, and roughening for improving boiling heat transfer have been of research interests of many researchers. In addition, pool boiling and flow boiling studies on artificial structures, mainly fabricated on a plain surface, such as pins, pillar fins, grooves (in different shapes, i.e. rectangular, square, cylinder, etc.) for increasing the heated surface area, or cavities created on substrates for increasing bubble nucleation sites were also considered for both micro and nano scale. The results reported in recent investigations on pool boiling and flow boiling from micro/nanostructured surfaces were included, and a comprehensive overview was provided.

1. Introduction

Boiling is considered as one of the most important phase change phenomena finding many applications. Many researchers of the heat transfer community persistently seek for techniques to improve boiling heat transfer performance in terms of fundamental science and practical applications.

While boiling is as old as humankind, first systematic and scientific studies on this subject can be traced in the 1960s [1]. Many investigations on boiling have been carried out by considering different parameters such as configuration, dimension, type of liquid, heat flux, and topography of surface. Pool boiling and flow boiling constitute significant subjects in boiling, and there already exist some reviews providing information about these specific subjects.

Related to flow boiling, for example, Cheng [2] published a review on fundamental issues of critical heat flux (CHF) and its mechanisms in microchannels. In this review, differences between boiling in macro- and micro-scale channels were distinguished and subcooled and saturated flow boiling studies were summarized. Kim and Mudawar [3,4] comprehensively reviewed databases and predictive methods for both pressure drop and heat transfer during condensation and boiling flow through mini/micro-channels. Reviews on other issues of flow boiling in small scale channels such as instabilities [5], nanofluids [6], boiling mechanisms [7] are also present.

For pool boiling, Gorenflo et al. [8] presented a review on the prediction methods for nucleate pool boiling, which were mainly empirical or semi-empirical, and compared them with the existing experimental data for 55 different fluids. They asserted that more accurate experimental data related to surface tension were required for thermo-physical interpretations, and the effect of heaters should be better understood. The fundamental issue of critical heat flux (CHF) on nucleate pool boiling in confined spaces along with the associated prediction methods was reviewed by Cheng [2], who emphasized on more need for experimental and theoretical research taking flow regimes into account. A review on numerical simulation results of pool boiling together with some validation tests with data obtained from experiments was provided by Dhir et al. [9], and encompassed single bubble, multiple bubbles, nucleate boiling, and film boiling with their relevant parameters. Kunugi [10] briefly concentrated on a review on direct numerical simulations (DNS) of pool boiling phenomena including the numerical approaches for tracking interface/surface shape such as the front tracking method, level set method, volume of fluid treatments, Marker and Cell (MAC) method, and Arbitrary Lagrangian–Eulerian (ALE) method. Nanofluids were recently recognized as an alternative for enhancement of nucleate boiling critical heat flux (CHF). A review of experimental and analytical studies on this subject was presented by Kim [11]. One of the other methods to enhance boiling heat transfer is modifying surfaces with micro-/nano structures. This subject was partially reviewed in the literature [12–14].

* Corresponding author.
E-mail address: kosara@sabanciuniv.edu (A. Koşar).

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The aim of this review is to introduce major findings of recent experimental studies on pool and flow boiling on micro-/nano structured surfaces for better understanding of boiling heat transfer performance. The pool boiling part consists of a comprehensive review on bubble formation and pool boiling heat transfer. Important parameters affecting bubble formation and pool boiling such as the geometry of micro/nanostructures were included with the summary of recent studies, and pool boiling heat transfer and critical heat flux (CHF) enhancement mechanisms were provided. Flow boiling heat transfer studies on both macro- and microchannels with micro- and nanostructured surfaces were addressed in different sections and summarized with major findings, enhancement mechanisms, and effects of major parameters.

2. Pool boiling

2.1. Bubble formation

Bubble formation from nucleation sites at discrete locations happens at a specific wall superheat for a stagnant fluid, and emerging bubbles rise through the liquid, overcoming the surface tension forces. For perfectly wetting liquids, a delay in incipience of vapor bubbles is expected. Experimental observations confirm that surface imperfections such as cavities and scratches are favorable locations for the formation of bubbles. The topology of a surface is a major parameter for the formation of vapor bubbles, which dramatically affects boiling heat transfer. Therefore, manipulation of surfaces with both random and regular configurations in micro/nano scale attracted the attention of many researchers. In the review of Kim [15], it was reported that recent experimental, numerical, and analytical studies vividly reveal that transient conduction and/or microconvection are the main mechanisms for transferring heat with isolated bubbles during boiling, while the contributions of microlayer evaporation and contact line heat transfer constitute no more than a quarter of the total heat transfer.

2.2. Coated surfaces

Many researchers mainly performed visualization studies on bubble generation on micro/nano structure coated surfaces to reveal bubble formation on them. Ahn et al. [16] investigated boiling of water on clean and reduced graphene oxide (RGO) flakes pre-coated copper surfaces near the critical heat flux (CHF) condition. They observed that for the clean surface a large mushroom of vapor formed before the appearance of a large dry patch, which finally transformed to a vapor film covering the entire heater at heat fluxes higher than CHF. On the contrary, the large dry patch entrained in the large mushroom was prolonged even at wall temperatures as high as 209 °C, when the surface was coated by graphene oxide foam. Vapor bubble release from smooth copper and porous graphite surfaces were considered in the studies of El-Genk and Parker [17–19], while graphite foam (graphite block) was utilized in the studies of Jin et al. and Pranoto et al. [20,21].

El-Genk and Parker [18] showed that discrete bubble region existed at low heat flux values for different surface orientations. As the heat flux becomes higher, the number of active nucleation sites increased followed by a steeper slope in boiling curve, and lateral coalescence of bubbles occurred near the boiling surface. They pointed out that the area covering the discrete bubbles region diminished with the increase in surface orientation, particularly for the downward orientation. In a further study of Genk and Parker [17], the images of nucleate boiling on smooth copper and porous graphite surfaces were examined. Graphite surfaces led to a much better nucleate boiling performance, regardless of subcooled or saturated conditions, and to much smaller surface superheats at a fixed heat flux (as it was also seen in [22] for saturated boiling of FC-72 with nano-porous aluminum oxide coatings on a plain aluminum surface). Compared to the smooth copper surface, porous graphite surfaces produced more bubble release into the pool of HFE-7100 liquid. Jin et al. [20] displayed the formation of bubbles on copper block and graphite-base blocks, being Kfoam and Pocofoam, at heat fluxes of 26 and 42 W/cm^2 using FC-72. The bubbles departing from graphite foams were much larger in diameter and density compared to the copper block. This finding contradicts to the observations made by Chao et al. [23], who compared bubble departure in boiling of water on copper surfaces to copper-graphite surfaces, and by Im et al. [24], who utilized flower-like Cu–O nanostructures fabricated on a copper surface.

Honda et al. [25] used a high-speed CCD camera to capture images of bubble formation on a smooth chip with a thin layer of SiO_2 of submicron size. At low heat flux, the density of vapor bubbles, increased with moving away from the lower edge of the chip. With further increase in heat flux, bubbles distributed more evenly, until they merged together to extend over the entire chip. Jo et al. [26] experimentally observed that the number of active nucleation sites and bubble size for Teflon coated nanostructures were higher than the SiO_2 surface with the deposition of Ti and Pt nanolayers. In the visualization study of Demir et al. [27], the images from the nanostructured plates having three different silicon nanorods of 850 nm diameter (Fig. 1), which were fabricated using metal-assisted chemical etching (MaCE), illustrated that the nucleation site density was greatly increased in comparison to the plain surface. As the nanorods became longer, lateral merging of individual bubbles over the surface occured along with the decrease in the bubble release frequency and the increase of the average diameter of coalesced bubbles. Some studies considered vapor bubble formation at nucleation sites, where boiling occurred on the outer side of micro/nano-structured tube surfaces [28–34]. To roughen the surface, a pocket-like sub-surface micro-structures were generated on the tube outer surface, which was submerged in refrigerant R-123 [28]. For the same heat flux, i.e. 31.5 kW/m^2, the two photograph snapshots illustrated that discrete bubbles could be viewed on the modified tube with larger bubble formation density compared to the smooth surface. The authors observed that bubbles existed and rose into the liquid at low heat fluxes and temperatures near the saturation temperature. However, at higher heat fluxes, the density of vapor bubbles increased, similar to the findings of Kulenovic et al. [29], leading to bubble agglomeration, which might cause local dry-out on the tube surface. Lee et al. [32] fabricated a nano-porous surface on a tube by degreasing aluminum tube with KOH solution and electro-polishing with $HClO_4$ and C_2H_5OH solution, and then anodizing in acidic solution in order to study pool boiling under different conditions. They reported that for the plain surface, only few large bubbles were generated, in contrast to the nano-porous surface, on which smaller size bubbles from more active nucleation sites emerged at a given heat flux condition. Copper fiber felt with random arrangement and larger porosity provided the same visualization result [35]. Zhang et al. [33] observed that the bubble release had a delay on the Alumina sponge-like nano-porous structure (ASNPS) with respect to the plain surface due to decreased interfacial contact angle on the ASNPS. In another study [36], it was seen that in comparison to the plain surface, more bubbles departed with the enhancement on the surface with sponge-like titanium dioxide for the same working fluid.

2.3. Structured surface with fins and cavities

Bubble formation in pool boiling on different types of structures such as rectangular fins [24,37–42], pyramids [43], pillars