Critical heat flux enhancement by single-layered metal wire mesh with micro and nano-sized pore structures

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ABSTRACT

This study reports the results of critical heat flux (CHF) enhancements by using single-layered metal wire mesh with micro/nano-sized pore structures with no modification of the original heating surface. Pool boiling tests with the wire mesh showed a significant CHF increment of up to 84% compared with that recorded on a bare surface. And, we investigated the dynamic behavior of the liquid and vapor phases on the boiling surfaces using an IR thermometry technique. From the quantitative measurements of liquid–vapor-solid phase distribution on the heating surface, it was revealed that the presence of the wire mesh and its hydrophilic nature play a role in sustaining a liquid phase inside the heating area that prevents the excessive expansion of the dry spot, and strongly disseminates thermal energy generated by the heater. In other words, the thermal energy generated inside the heater is dispersed more uniformly under the existence of the wire mesh. Using this type of mesh with the micro-sized pore structures for CHF enhancement intrinsically can mitigate changes in thermos-physical and chemical properties, and losses in structural durability for original heating surface. We expect that the meshes can be exploited in applications to several thermal systems.

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1. Introduction

Critical heat flux (CHF) specifies the upper limit of thermal energy that can be reached in boiling. At this heat flux, the two-phase fluid consisting of liquid and vapor fails to cool the heating surface, and the surface temperature rapidly and irreversibly increases. Hence, a substantial part of research on boiling is devoted to enhancing the CHF and enlarging the range for which nucleate boiling heat transfer occurs. During the past decades, the CHF triggering mechanisms and several enhancement methodologies have been presented involving a change in surface wettability [1–4], capillary wicking behavior [5–14], thermal behavior of dry spot on surface [12,15–21], hydrodynamic instability [22–29], and relationship between vapor recoil and liquid adhesion mechanisms near the triple contact line [30–34]. Most of these studies modified the heating surface using various techniques, such as physical or chemical coatings of hydrophilic materials,

microstructures fabrication in the range of 10 nm–100 μm, and nanoparticle coatings.

Despite some significant improvements in CHF results on modified surfaces, drawbacks exist and they impact on real applications of the technologies. Generally, most surface modification techniques can inherently transmute the chemical properties or the physical morphology of the material of the heating surface. However, in practical applications of boiling heat transfer, such as coal-fired and nuclear power plants, cooling systems of electronics circuits, and refrigeration and air-conditioning systems, the material of the boiling surface are selected carefully considering thermal and mechanical strength, chemical and physical durability, and thermo-physical properties. Therefore, the surface modification for CHF enhancement can result in unfavorable changes in structural characteristics of the heating materials. In addition, because these previous surface modification techniques are tailored to some specific materials, such as silicon wafer and glass, which can be processed on scales smaller than 10 μm with photolithography, chemical etching, and MEMS technologies, they are difficult to apply to heating materials commonly used, such as metals.

In this study, we propose a distinct CHF enhancement technique that requires no heating surface modification. Enhancement can be

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achieved simply by improving the supply of liquid to the boiling surface, enabling vapor to escape more easily, and reducing dry spot regions on the surface which are closely related to the supply of liquid. To satisfy the above criteria, we prepared metal wire meshes made of stainless steel (STS 304) with micro- and nano-sized structures on their surfaces. Originally, this type of mesh had been developed and studied for its waterproofing applications exploiting the mesh's hydrophobicity [35–41]. A water droplet on a completely dry wire mesh has a high contact angle (CA) of $> 150°$, which means that the droplet and the surface configuration is in the Cassie-Baxter state that results when air pockets are present around the surface microstructures. However, in this study, we demonstrate that for a slightly wetted wire-mesh surface, a water droplet exhibits hydrophilic wetting on the surface, i.e., the droplet and surface configuration convert to the Wenzel state with water molecules sticking to the microstructures. During boiling, wetting of the wire mesh can induce capillary liquid flow along the wire surface, and may improve liquid supply to the heating surface.

During the past two decades, some previous studies for the effects of metal mesh on boiling and evaporator for heat pipe applications had been reported [42–46]. In those studies, mainly, multi-layered metal meshes were utilized to induce capillary wicking liquid flow through the several micro-sized gaps ($\sim 10 \mu m$) [43–45]. On a thin copper foil surface covered with multi-layered copper wicks, the CHF for water at atmospheric condition was enhanced by 145% compared to it on a plain copper surface [44,45]. And, the multi-layered stainless steel 304 wire meshes on an aluminum surface increased the CHF for HCFC141b at atmospheric condition by 30–40% [43]. However, in the experiments with single-layered metal meshes [42,45], the CHF values decreased rather compared to the plain surfaces. To the our knowledge, the CHF enhancement result by using single-layered metal wire mesh has not been reported yet.

In this work, we fabricated micro-structured stainless-steel wire meshes using electrochemical etching and examined them in experiments on boiling. From the results, the wire meshes clearly provided a CHF enhancement. To explain this acquired attribute, the underlying physical mechanism was analysed in high-speed infrared (IR) thermometry.

2. Experimental methods

2.1. Electrochemical etching of stainless steel wire mesh

For etching the steel wire meshes, 3.6% (1 N) HCl and 1.2% HNO$_3$ solutions were prepared and mixed in a 1:1 ratio to make a dilute 500-mL Aqua Regia solution in a Pyrex beaker (see Fig. 1). The solution was mixed immediately before the etching procedures because of its self-decomposition characteristics. Stainless steel 304 wire mesh was prepared as target material, cut into $35 \times 30 \ mm^2$ size. Carbon plate (cathode) and the wire mesh (anode) are immersed in the solution and immobilized using two alligator clips attached under the top cover plate (made of polyether ether ketone, PEEK) of the beaker. The wire mesh was placed parallel to a carbon plate electrode ($15 \times 50 \ mm^2$), 7 cm apart. Then, a constant DC electric current was applied to start electrochemical etching; the wire mesh and the carbon electrode had positive and negative polarities. During etching, the solution is continuously mixed using a rotating magnetic stirrer (60 rpm rotation) on the bottom of the beaker. Immediately after the current is supplied, hydrogen bubbles are generated on the carbon plate by electrolysis of the solution. From the wire mesh, etched particles were observed with the naked eye. Different electric current values were applied to the various wire meshes to establish identical current densities in the meshes. The current values were determined
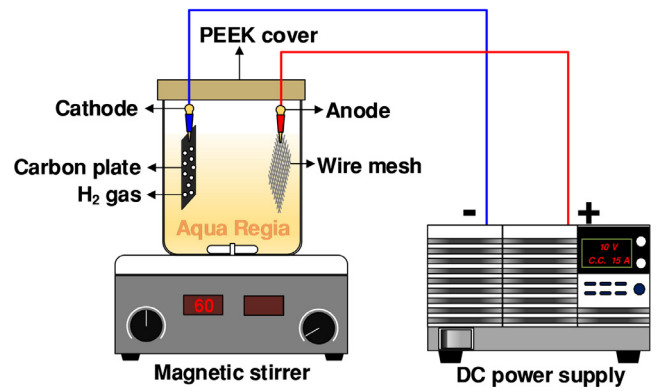

Fig. 1. Electrochemical etching setup for fabricating wire meshes with micro/nano-sized pores.

considering the total surface area of each etched wire mesh (EWM). For EWM #1, EWM #2, EWM #3, and EWM #4 (see Table 1 for geometry of each wire sample), the current values of 15.0, 10.0, 11.6, and 14.0 A, respectively, were inputted and as a result, the current density values were identically 0.972 A/cm^2. The EWMs were rinsed in DI water immediately after etching and completely dried for the experiments on boiling.

2.2. Pool boiling experimental setup

Optical grade silicon wafer, which is semi-transparent to IR light ($\langle 1\,0\,0 \rangle$ orientation; P/Boron-doped; double-side polished; 1–10 Ω cm in electrical resistivity; 500 ± 25 μm in thickness) was used as the boiling heater material. Whereas 500-nm-thick silicon dioxide (SiO$_2$) layer was thermally grown on the upper surface of the boiling heater for electrical insulation against the working fluid, a thin Au film (100 nm thick) and a Ti film (6 nm thick. adhesion layer) were deposited on the back surface of the silicon heater for electrical connection to the DC power supply. The boiling surface temperature was measured from the IR radiation intensity from four high-emissivity black dots painted on the back of the heater as shown in Fig. 2(a); the IR intensity values with temperature variations were pre-calibrated (see Fig. 3). A high-speed IR camera (FLIR systems, SC6000, $\lambda = 3-5 \mu m$) and an IR-reflective gold mirror were located below the pool boiling chamber (Fig. 2 (a)) to image the liquid–vapor phase distribution on the boiling surface using detection-of-phase by IR thermometry [21,47,48]. In this technique, liquid, vapor and the triple contact line can be clearly distinguished by detecting the IR intensities emitted from the liquid and vapor permeating the IR-transparent silicon heater. The IR emissivity of liquid water is much larger than that of vapor. For all heat flux steps, IR images were captured at 1000 frames per second to visualize the phase distribution on the boiling surface.

The fabricated wire meshes were attached directly to the top surface of the boiling heaters; the wire mesh covered the whole area of the effective heating region, $20 \times 10 \ mm^2$ (Fig. 2(a)). The experiments were conducted with de-ionized water as working fluid, which saturates at atmospheric pressure conditions. The surfaces were electrically heated using a DC power supply connected to the Au electrodes. The boiling surface heat flux (q) was calculated from the values of electrical voltage (V_h) and current (I) applied to the silicon heater using $q = (V_h \times I)/A_s$ with A_s the heating area. The CHF value in each experimental run was determined from the point where the surface temperature abruptly increases, i.e., the electrical resistance of the heater suddenly increases. In the boiling tests, additional heat was generated on the side-heating region due to direct joule heating. We conducted heat loss calculation by solving three-dimensional heat conduction problem