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THE EFFECT OF NANOSCALE SURFACE MODIFICATION ON BOILING HEAT TRANSFER AND CRITICAL HEAT FLUX

Moo Hwan Kim
POSTECH
Pohang, Republic of KOREA

ABSTRACT

Recently, there were lots of researches about enormous CHF enhancement with the nanofluid in pool boiling and flow boiling. It is supposed the deposition of nanoparticles on the heated surface is one of main reasons. In a real application, nanofluid has a lot of problems to be used as the working fluid because of sedimentation and aggregation. The artificial surfaces on silicon and metal were developed to have the similar effect with nanoparticles deposited on the surface. The modified surface showed the enormous ability to increase CHF in pool boiling. Furthermore, under flow boiling, it had also good results to increase CHF. In these studies, we concluded that wetting ability of surface; e.g. wettability and liquid spreading ability (hydrophilic property of surface) was a key parameter to increase CHF under both pool and flow boiling. In addition, using wettability difference of surface; e.g. hydrophilic and hydrophobic, we conducted some tests of BHT (boiling heat transfer) enhancement using the oxide silicon which have micro-sized hydrophobic islands on hydrophilic surface. By using both of these techniques, we propose an optimized surface to increase both CHF and BHT. Also, the fuel surface of nuclear power plants is modified to have same effect and the results shows a good enhancement of CHF, too.

INTRODUCTION

The problem of cooling reactors has become increasingly critical in the nuclear industry. The most effective way to cool a nuclear power plant running at high temperatures is boiling heat transfer (BHT), which exploits the latent heat of vaporization during the phase change from liquid to gas. However, BHT has an inherent limitation: the critical heat flux (CHF), i.e., the maximum heat flux at which BHT has a high cooling efficiency. When a surface reaches CHF, it becomes coated with a vapor film that interferes with the contact between the surface and the ambient liquid, and decreases the heat transfer efficiency. The system temperature increases and failure occurs if the temperature exceeds the thermal limits of the system's constituent materials. For this reason, every system incorporates a safety margin by running at a heat flux much lower than CHF; this approach reduces the system efficiency. This compromise between safety and efficiency is an important problem in the nuclear industry.

Nanofluids

Nanofluids are engineered heat transfer fluids consisting of nanometer-sized particles (nanoparticles) dispersed in a base liquid. These fluids have been studied in various fields of thermal engineering since Choi [1] began research with nano-sized particles well dispersed in engineered fluid.Adding tiny amounts (< 0.001% by volume) of alumina nanoparticles to a conventional cooling liquid can increase CHF by 200% [2]. During pool boiling, the same magnitude of CHF increase observed in a nanofluid can also occur when a nanoparticle-fouled surface is submerged even in pure water [3],[4]. This result suggested that the CHF increase in nanofluids is caused by the altered surface characteristics due to the surface deposition of nanoparticles during boiling. The same results were recently obtained by Golubovic et al. [4]. This suggests in turn that changes in interfacial parameters due to nanoparticle fouling could be a key factor in the significant increase in the nanofluid CHF.

Nanoparticle-fouled surfaces had significantly greater wettability measured by a reduction in the static contact angle, than do clean surfaces [5]. This suggestion was based on a review of the prevalent CHF theories, which state that the improved wettability caused by the nanoparticle layer could predict CHF enhancement. In pool boiling experiments with water-based and alcohol-based nanofluids on a plain heated surface, the deposition of the nanoparticles on the boiling surface changed its microstructure and physicochemical properties [6], [7]. Such changes in the heat transfer surface significantly influenced the boiling phenomena by changing nucleation site density, bubble departure diameter, bubble frequency, and evaporation of the microlayer and macrolayer beneath the growing bubbles. However, the concentrations of nanoparticles in a nanofluid can change due to agglomeration and settling; this phenomenon could limit the usefulness of nanofluids in cooling systems.

Surface modification for enhancing the CHF

The nanofluid experiments indicated that the heating surface characteristics significantly affect the nucleate boiling phenomenon. Flat surfaces, and surfaces with micrometer-size (micro-scale), nanometer-size (nano-scale) and both micro-scale and nano-scale (micro/nano-scale) structures formed on a silicon wafer using microelectromechanical systems (MEMS) techniques have different CHF values; the effects of surface structure and surface wettability were dominant factors affecting this change. The liquid-spreading effect of nano-scale rods on the micro/nano-scale surface included the wettability effect and produced a greater increase in CHF than the other factors.

Zircaloy-4 was used as the test material for the pool boiling CHF experiment in this study; results are valuable because Zircaloy-4 is often used as the cladding of nuclear fuel rods. We tested whether CHF on a Zircaloy-4 surface can be increased using non-traditional metals such as copper or stainless steel. In this study, various methods of treating Zircaloy-4 were tested, with the aim of achieving a more-wettable surface.

Surface wettability can be increased by several methods. Because the wetting phenomenon is governed by the surface energy and surface morphology, modification methods can be classified into two corresponding categories: ultraviolet irradiation and thermal oxidation.

Ultraviolet irradiation uses high-energy radiation to modify the surface energy of materials; it can even produce a super hydrophilic (contact angle < 5°) state. This method increases both the wettability and the heat flux of materials [10], but it is not practical for industrial use because the effect is not permanent.

Thermal oxidation is a simple and easy method of modifying the surface energy to increase the wettability because metal oxide is more hydrophilic than pure metal. Thermal oxidation has been used to make hydrophilic heater surfaces [9]. However, simple thermal oxidation has certain limitations and is not capable of producing highly wettable surfaces. By optimizing the anodic oxidation, procedure, we can increase the CHF on a modified surface which is well-wetted and has strong liquid spreading ability. Therefore, we concluded that anodic oxidation is the appropriate method to modify Zircaloy-4.

Surface modification for enhancing the boiling heat transfer

Increasing nucleate BHT is also an important goal, because it enables equipment to transfer heat more effectively under the same limitations. To achieve this increase, the effects of heating surface characteristics are very important. The boiling condition has been improved by coating the porous media [11], creating micro-structures on surfaces [12], [13] and changing the roughness [14], [15] Among those methods, the change of wettability is regarded as a powerful method. Reducing the contact angle of the heating surface using surface oxidation reduces the nucleate boiling density [16], [17]. Nucleation site density is dominantly correlated with the wettability of the heating surface [18]. In this respect, high CHF and high nucleate BHT during pool boiling could be achieved by modifying the surface to optimize its wettability. Results of pool boiling on surfaces marked with checked and spotted patterns made of a super-hydrophobic material [19] provided new approaches to understanding the wettability effect on boiling phenomena, but the experiment involved two limitations: (1) the micro-scaled height difference between the super-hydrophobic material and the bare surface affected the boiling phenomena; and (2) the experiments were conducted using millimeter-size dots (3 mm – 5 mm). A special surface has been developed which consists of hydrophobic dots and a hydrophilic basic surface without any micro-geometry [20]; Even though they reported interesting result that earlier bubble inception is induced by hydrophobic dot, the experiment couldn't cover the total nucleate BHT performance. Therefore, we conducted heat transfer pool boiling experiments to study the effect of wettability on total nucleate BHT on several kinds of wettability surface without micro structure.

NOMENCLATURE

q”	Heat flux (w/m^2)
h	Latent heat (kJ/kg)
g	Gravity acceleration (m/s^2)

Greeks symbols

σ	Surface tension (N/m)
ρ	density (kg/m^3)

subscripts

l	liquid state
g	vapor state

NANOFLUIDS EXPERIMENTS

Using nanofluids as working fluids in boiling applications can greatly increase CHF [1-3]. In this paper, the nanofluid experiments used several types of experimental apparatus to reveal the reason for increased CHF in boiling nanofluids.

Pool boiling experiment with nanofluids

In pool boiling experiments using nanofluids with various concentrations of TiO_2 or Al_2O_3 nanoparticles on Ni-Cr wire under atmosphere, the CHF increased [5], [21]; scanning electron microscopy (SEM) revealed that a nanoparticle coating was generated on the wire surface during pool boiling of nanofluids (Fig. 1). The similarity between the CHF of nanoparticle-fouled surfaces in pure water and that of a clean surface in nanofluids (Fig. 2), suggests that the CHF of nanofluids is related to modification of surfaces immersed in the fluid [5], [12].

This research examines plate pool boiling to develop understanding about the dominant factor which affects CHF. In plate boiling experiments, the thermal heating method is used to preclude any interaction between the nanoparticles and the electrical field. Detailed information about the plate pool boiling facility and test sample is in [22]. The results of plate pool boiling experiments confirmed that nanofluids can significantly increase CHF, and that surface modification due to nanoparticle deposition results in the same magnitude of CHF increase in pure water as occurs in nanofluids. That result corresponds well with previous experimental results.

To analyze the CHF on a surface modified by nanoparticle fouling, the recoil force is regarded as the factor that most strongly influences the increase in CHF. After visualizing the dynamic wetting motion of an evaporating water droplet, we conjectured that the nanoparticle layer increases the stability of the evaporating microlayer underneath a bubble growing on a heated surface, and thus that the irreversible growth of a hot/dry spot is inhibited even at superheated wall temperatures, resulting in the CHF increase observed when boiling nanofluids [22].

These experimental results indicate that a surface modified by nanoparticle fouling has significant influence on the amazing increase in CHF that is obtained using nanofluids. Among many surface properties, we concluded that dynamic wetting and liquid capillarity are the most important factors that affect CHF increase on nanoparticle-fouled heating surfaces.

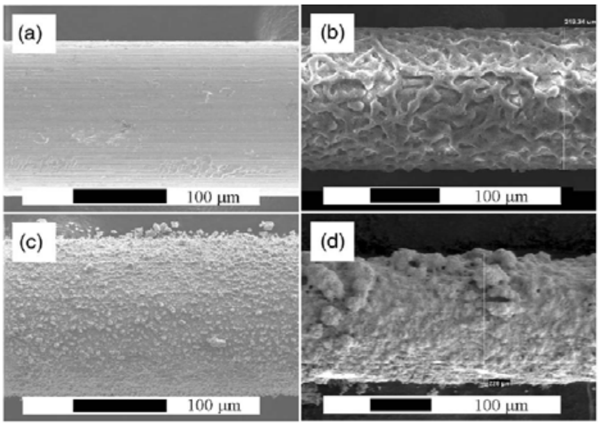

FIG. 1 SEM IMAGES OF (A)BARE WIRE AND (B) TiO_2, (C)SiO_2 AND (D)Ag NANOPARTICLES DEPOSITED ON WIRE AFTER BOILING [5]

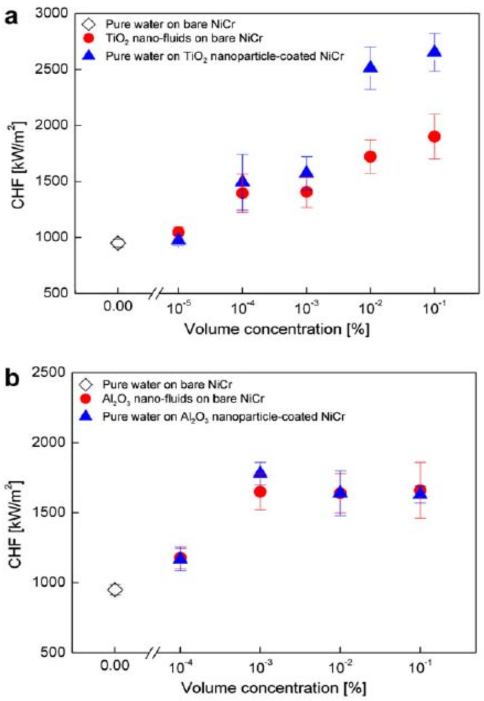

FIG. 2 COMPARISION OF CHF INCREASES OF NANOFLUIDS ON A BARE HEATER AND OF PURE WATER ON NANOPARTICLE-COATED HEATERS: (A) TiO_2; (B) Al_2O_3 [21]

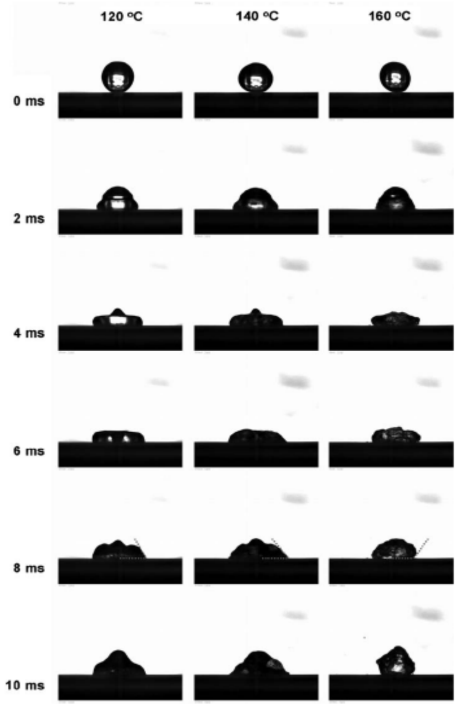

FIG. 3 WETTING OF A WATER DROPLET ON A WATER-BOILED COPPER SURFACE AT 120 ºC, 140 ºC, AND 160ºC [22]

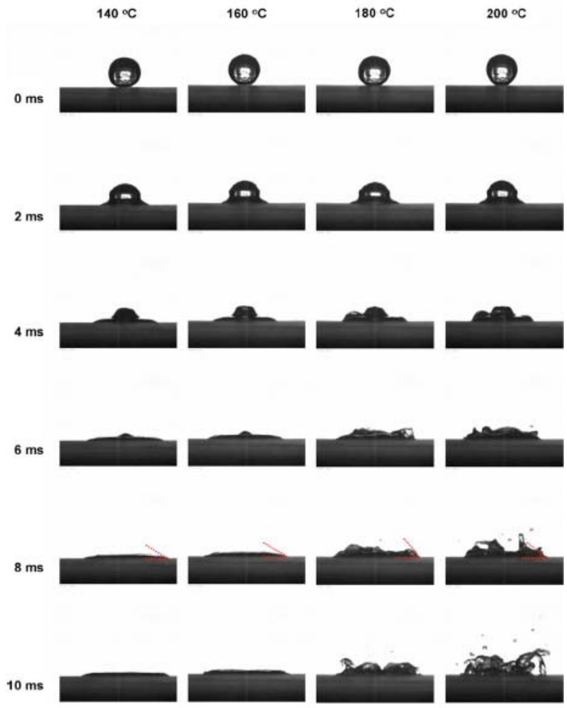

FIG. 4 WETTING OF A WATER DROPLET ON A TITANIA NANOPARTICLE-FOULED COPPER SURFACE AT 140ºC, 160ºC, 180ºC, AND 200 ºC [22]

Flow boiling experiment with nanofluids

Previously nucleate boiling experiments in nanofluids reported increased CHF during pool boiling due to modification of surfaces by nanoparticle fouling. Considering the importance of flow BHT in various practical applications, an experimental study on CHF enhancements of nanofluids on convective flow conditions was performed. A rectangular channel (10 mm wide, 5 mm deep) was used to confine the flow. Thermal heating was used to preclude the effect of electric fields. Detailed information and schematic diagram are given in Ahn et al. [23]. Aqueous nanofluids with alumina nanoparticles (0.01% volume fraction) were investigated. At that volume concentration incredible increase in CHF was observed in plate boiling and wire boiling experiments. Flow boiling CHF in nanofluids was distinctly increased during forced convective flow compared to that in pure water. The heating surfaces were then examined using SEM and by measuring contact angle; results suggested that the flow boiling CHF increase in nanofluids is mostly caused by deposition of nanoparticles on the heater surface during vigorous boiling of nanofluids, and by the consequent wettability increases. [23]

And now we conduct the internal flow boiling experiment with nanofluids to reveal the effect of nanofulids.

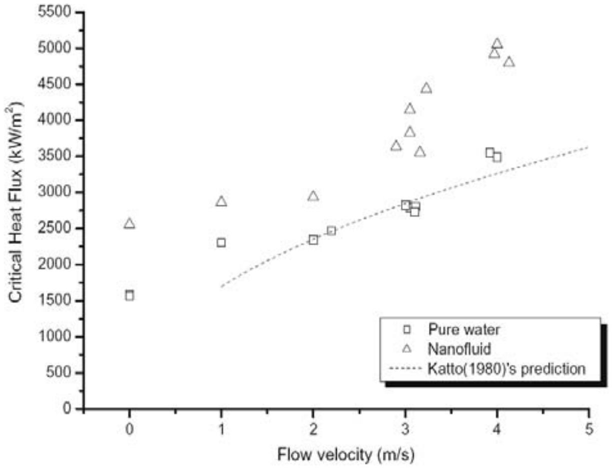

FIG. 5 CRITICAL HEAT FLUX VS FLOW VELOCITY OF PURE WATER AND NANOFLUIDS [23]

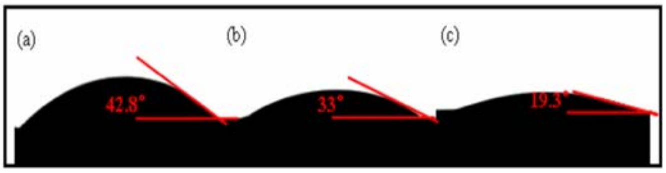

FIG. 6 CONTACT ANGLES OF WATER DROPLETS ON THE NANOPARTICLE-DEPOSTIED SURFACES AT 3 m/s CHF: (A) 3638 kW/m^2; (B) 4147 kW/m^2; (C) 4435 kW/m^2 [23]

ARTIFICIAL SURFACE MODIFICATION

Micro, nano, Micro/nano strcutrue on ZnO for CHF

Although the boiling nanofluids can give high CHF, they are not appropriate for use in real heat transfer devices because of aggregation and deposition of nanoparticles. So researchers in our lab suggested using MEMS techniques to create an artificial surface which mimics the property of a nanoparticle-fouled surface.

To facilitate both CHF test and surface modification, we embedded a thin film heater on one side of a silicon wafer and created artificial surfaces on the other side of the wafer. Although the fabrication processes of the film heater side and surface modification were conducted simultaneously, we will describe them separately for convenience.

The test heater was fabricated on a rectangular (25 mm x 20 mm) silicon wafer plate (Fig.7). Joule heating was selected for this experiment, so an SiO_2 layer for electrical insulation was fabricated on both the top and bottom to preclude the possibility of electrical interference on the modified surface structures and on the hydrodynamics on top of the heater. As a heater, a titanium thin film (~1000 Å thick) was layered on the bottom of the substrate using an E-beam evaporator. The completed titanium film heater has 'H' shape. The center bar of 'H' is 15 mm x 10 mm; it is the main heat generating area; we confirmed by simple calculation that it generates more < 99 % of the total heat. The vertical bars at ends of the 'H' are used for wire connection. Because connecting copper wires to a titanium film using lead solder is impossible, an additional gold (Au) film (1500 Å thickness) was deposited on each vertical bar using an E-beam evaporator. With lead soldering and Au film on the vertical bars, their resistance becomes smaller than that of the center bar and guarantees that heat generation is focused in the center bar.

To increase CHF during pool boiling, the surfaces of test specimens were modified to be microstructured, nanostructured, or micro/nano structured (Fig. 8). The surface material is ZnO on a silicon wafer. Detailed procedure and surface characteristics are in [8].

All experiments were conducted under saturated pool boiling at atmosphere pressure (101.3 kPa); applied heat flux ranged from the convective heat transfer regime to CHF. The uncertainty analysis of all data is also in previous study [8]. Every modified surface SiO_2 showed noticeable CHF increase compared with the reference bare surface (Fig. 9). The average CHF was 1121 kW/m^2 for bare, 1652 kW/m^2 for microstructured, 2003 kW/m^2 for nanostructured, and 2326 kW/m^2 for micro/nano structured surfaces. Differences in CHF estimates on samples of the same surface differed by < 15%. The micro/nano structured surface showed the greatest increase (107 %) in CHF compared to the bare surface, followed by the nanostructured surface (79 % increase) and the microstructured surface (47 % increase).

We concluded that the wettability, liquid spreading and multi-scaled geometry separately affect the CHF increase. The wettability effect confirmed (Fig. 10) by comparing Kandlikar's CHF correlation [16] (Equation 1) which considers the receding contact angle effect.

$$q''_{CHF} = h_{fg}\rho_g^{1/2}\left(\frac{1+\cos\beta}{16}\right)\left[\frac{2}{\pi}+\frac{\pi}{4}(1+\cos\beta)\cos\phi\right]^{1/2}\left[\sigma g(\rho_l-\rho_g)\right]^{1/4} \qquad (1)$$

From the experimental results, the effects of wettability and liquid spreading were associated with CHF increase in nanostructured and micro/nano structured surfaces, compared to those on flat surfaces. The effect of liquid spreading was shown as the CHF increase difference between nanostructured and micro/nano structured surfaces. The effect of multi-scaled geometry was shown as difference between liquid spreading characteristics of nanostructured and micro/nano structured surfaces; this effect indirectly affected CHF increase. [8]

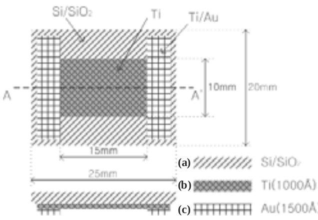

FIG. 7 TEST HEATER FABRICATION OF SILICON SURFACE [8]

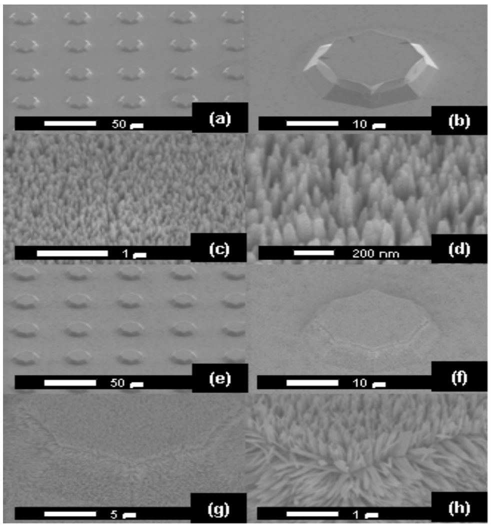

FIG. 8 SURFACE MODIFICATION BY MEMS FABRICATION ON SILICON OXIDE WAFER:
(A) AND (B) MICROSTRUCTRED;
(C) AND (D) NANOSTRUCTURED;
(E),(F),(G) AND (H) MICRO/NANO STRUCTURED [8].

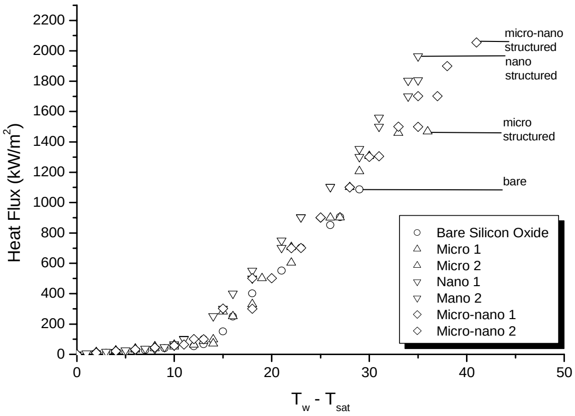

FIG. 9 BOILING CURVES OF MODIFIED SILICON SURFACES [8]

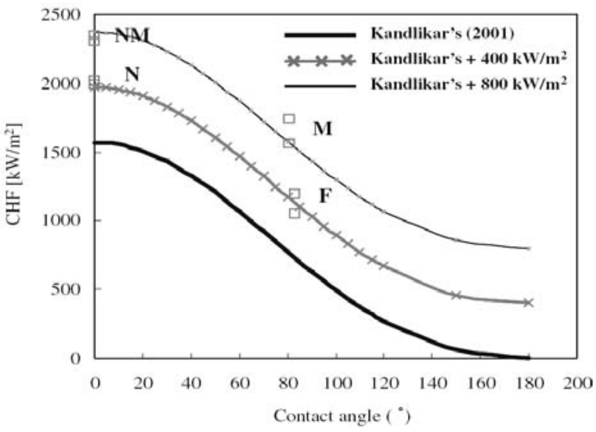

FIG. 10 PLOT OF CHF CORRELATION OF KANDLIKAR[16] AND EXPERIMENTAL DATA OF VARIOUS SURFACES. [8]

Surface modification on Zircalo-4 for CHF

Using ZnO surfaces fabricated with microscale, nanoscale or micro/nano scale geometry, we could estimate the effect of surface characteristics on the CHF. However the existing technique is not suitable for use in real industry because the quality of the modified surface and fabrication method depend delicately on the surface material and the on the fabrication procedure. So we decided to develop a surface treatment method that is suitable for realistic applications, such as in nuclear power plants.

In a nuclear power plant, Zircaloy-4 was used as the test material for the pool boiling CHF experiment in this study; this material is often used as the cladding of nuclear fuel rods. However, we wondered whether the CHF on a Zircaloy-4 surface could be increased by other some method, perhaps using non-traditional metals such as copper or stainless steel. In this study, various methods of surface treating Zircaloy-4 were tested to achieve a more-wettable surface.

Anodic oxidation was used to modify the metal surface. Anodic oxidation is an electrochemical fabrication technique in which an external applied electric potential is used to accelerate the chemical reaction at the interface between an electrolyte and the target material. The reaction rate can be very easily controlled by adjusting the applied voltage; this control is as sensitive as a 108-fold increase of the reaction rate per volt of increased potential [24]. Varying other parameters such as current density, type of electrolyte, and acid strength also affects the reaction, and result in different end products. The final product of anodic oxidation is a generally a thick oxide layer. However in certain materials and under certain conditions, unique ordered nanostructures occur instead of randomly formed oxide structures; anodic aluminum oxide (AAO) [25] and titania nanotubes [26] are two well-known examples. Because of their nanoporous surface morphologies and the chemical nature of the metal oxide, these examples are very hydrophilic. Anodic oxidation of Zircaloy-4 has already been attempted and the results have been observed by microscopy [27]. However, no ordered nanostructures have been found and few studies have attempted to measure the resulting wetting properties.

Zirconia nanotubes were subsequently reported [28], and we later succeeded in fabricating zircaloy nanotubes. We then conducted wettability studies on these nanotubes as well as the associated micro/nano-scale mountain-like structures that were subsequently discovered. Rectangular zircaloy-4 plates (20 × 25 × 0.7 mm) were used as test samples. They were mechanically polished with #1200 silicon carbide abrasive to remove impurities and to produce a uniform surface. The polished samples were cleaned with a 1:1 mixture of acetone and methanol in an ultrasonic bath. After rinsing in deionized water, the samples were completely dried [29]. The detailed process of anodization is in [30], along with surface characteristic of a metallic heater Fig. 11).

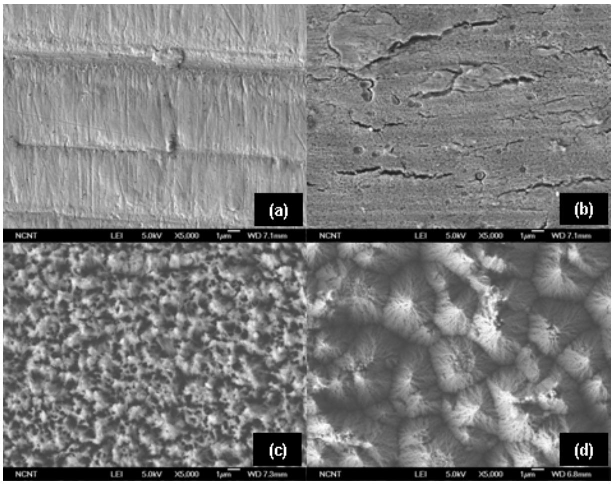

FIG. 11 SURFACE OF MODIFIED ZIRCALOY-4: (A)BARE; (B)OXIDIZED MEANINGLESS STRUCTURE; (C)NANOSTRUCTURE; (D)MICRO/NANO STURCTURE [30]

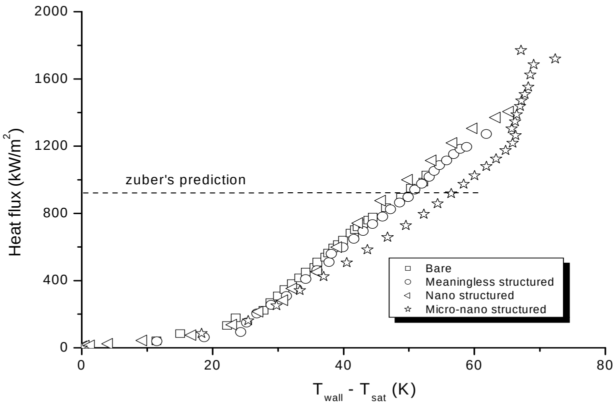

FIG. 12 BOILING CURVES OF MODIFIED ZIRCALOY-4 SURFACES [30]

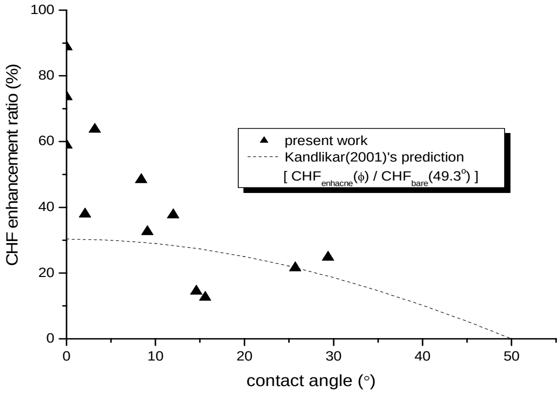

FIG. 13 CHF ENHANCEMNET FRATIO ON THE MODIFIED ZIRCALOY-4 ($CHF_{enhance}/CHF_{bare}$) [30]

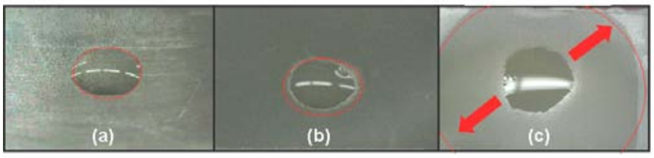

FIG. 14 THE LIQUID SPREADING ABILITIES OF MODIFIED ZIRCALOY-4; (A)NON-SPREADING (B)SAMLL-SPREADING (C)LARGE-SPREADING [30]

In boiling curves of modified zircaloy-4 surfaces (Fig. 12), nanostructured and micro/nano structured surfaces have higher CHF that bare and meaningless structures. Various parameters could influence CHF directly and indirectly. Among these parameters, wettability and spreading ability of surface influenced CHF increase. Kandlikar [31] analyzed the mechanism of CHF phenomena using a balance of the recoil force and the surface tension on the heating surface. The recoil force was generated by fast evaporation into the liquid-vapor interface and the surface tension was provided by a single bubble. He suggested a correlation model (Eq. 1).

However, the CHF increases on modified surfaces with contact angles < 10° exceeded those predicted using the wettability effect alone (Fig. 13). Surfaces of modified silicon oxide water and modified zircaloy-4 are each more wettable and spreadable than the corresponding bare surface. Nanotube-like nanostructures were observed on the zircaloy-4 surface (Fig. 11). These nanostructures increased the ability of liquid to spread on modified zircaloy-4 to some extent and contributed to the CHF increase. The same surfaces also contained valley-like microstructures (Fig. 11). Microscale structures can increase both capillary wicking and capillary-driven flow [32]; they can also influence liquid capillary wicking on the surface [33], and the liquid spreading ability can be characterized by the diameter of the wetted zone that surrounds the liquid droplet [33]. Liquid spreading was observed on the zircaloy-4 surfaces with contact angles < 10°. CHF increases that exceed Kandlikar's prediction (Fig. 13) that considers the wettability effect could be interpreted to result from liquid spreading ability on the surfaces: (a) in the non-spreading regime, the CHF increased as the contact angle decreased; (b) in the small spreading regime, the CHF incerease was greater than could be predicted by the wettability effect; (c) in the large spreading regime, the combination of different micro/nano multiscale structures on the Zircaloy-4 surface contributed to greater CHF increase than did the individual multiscale structures (Fig. 14, 15). These results indicate that surface multiscale structures that cause contact angle < 10°, which had large effects on the liquid spreading ability, were the main contributor to CHF increase. Kim *et al*. [8] also reported that nanostructures could facilitate liquid spreading and delay the CHF (Figs. 8, 9), and that the combination of nanostructures and microstructures had the best liquid spreading ability and the most-increased CHF.

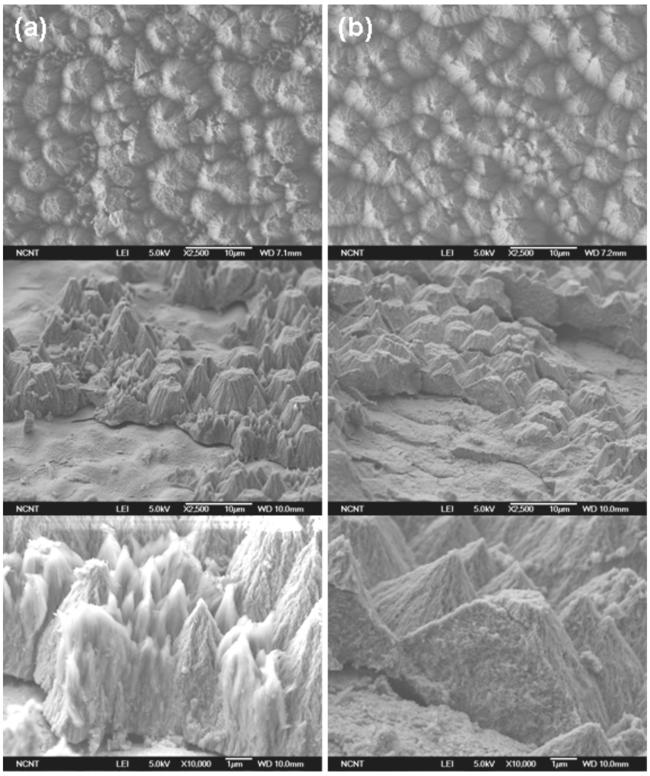

FIG. 15 SEM IMAGES OF LARGE SPREADING; (A)CHF: 1924kW/m^2 (B)CHF: 1770kW/m^2 [30]

Based on these experimental results and fabrication method, we then conducted internal pool boiling experiments with modified Zircaloy-4 surfaces.

Surface modification for nucleate boiling heat transfer

Until now, we have focused on how to increase the CHF by modifying surfaces. In this part, we will propose a fabricated surface which has higher total nucleate BHT than a bare heating surface. According to preceding surface parametric studies,

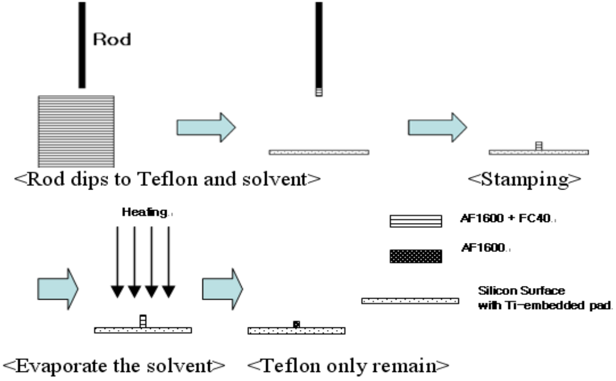

FIG. 16 THE PROCESS TO FABRICATE A HYDROPHOBIC DOT ON A SILICON SURFACE [34].

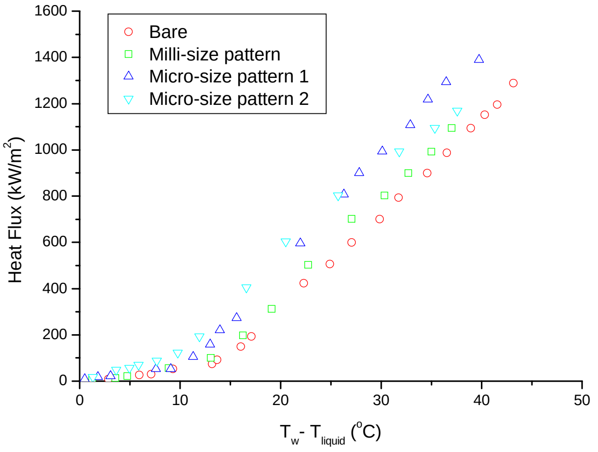

FIG. 17 BOILING CURVES OF HYDROPHOBIC DOT SURFACE [34]

wettability can influence both CHF and the total nucleate BHT coefficient. The wettability is directly related to the nucleate boiling site density. A hydrophobic material induces earlier bubble initiation than a well-wetted surface. But the CHF on a hydrophobic surface decreased greatly because induced bubbles can easily coalesce into a large bubble mushroom which is the former sign of the CHF.

Therefore, we tried to create a surface with a hydrophobic pattern that only increases nucleate BHT and does not affect CHF (Fig. 16). A Ti film was used as the heater. All experiments were conducted during pool boiling under an atmospheric pressure condition. The hydrophobic components were made of Teflon; the hydrophilic components were made of SiO_2. Detailed information is in [34].

Boiling curves were obtained on a bare silicon surface, and on silicon surfaces with millimeter-size dots (milli-dots), and on silicon surfaces with micrometer-size dots (micro-dots) (Fig. 17). The surface with the hydrophobic dot has a higher nucleate heat transfer than the surface without it, probably because the hydrophobic dots cause early onset of nuclear boiling (ONB). The increase in nucleate heat transfer is greatest on the surface with micro-dots, because a dot smaller than millimeter-size causes a higher bubble frequency at a given heat flux than large dots, and thus the total volume of bubbles on the micro-dots will be larger than that on milli-dots when all hydrophobic dots are activated on the same total area of Teflon. Actually the difference of nucleate heat transfer between the milli-dot on silicon and bare silicon is not distinctly large because the ratio of the total area of the hydrophobic material to total heating area is large. This observation suggests that further experiments with milli-dots are needed.

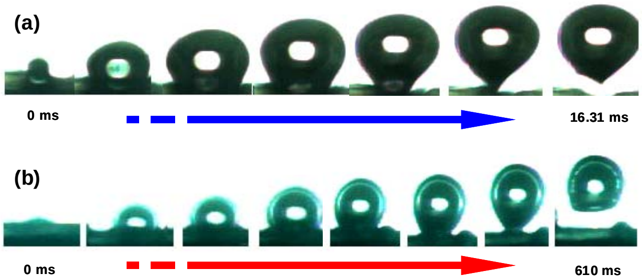

FIG. 18 BUBBLE GROWTH AND DEPARTURE: (A)BARE SILICON OXIDE; (B)TEFLON MILLI-DOT [34]

The milli-dot on the silicon gives a lower CHF than does bare silicon. We conjecture that the center dot may influence CHF. In contrast, micro-dots gave a range of CHFs; those from some micro-dot experiments are comparable to that of the bare silicon, while those from other micro-dot experiments are almost the same as that from the milli-dot experiments, i.e., lower than on a bare silicon surface. The result is most likely due to the uncertainty in producing micro-dots which can affect the bubble inception without changing CHF significantly. So we then attempted to develop new fabrication method which can realize an exact pattern of hydrophobic dots.

A high speed camera was used to capture images (Fig. 18a) of bubble inception near ONB (wall temperature near 112°C ~115°C) in on bare silicon (Fig. 18a) and on a Teflon milli-dot (Fig. 18b). On silicon, a bubble grows on a cavity, elongates for a short time, then smoothly departs from the cavity.

On the Teflon milli-dot, the bubble appears earlier than on bare silicon when the wall temperature approaches 101~106°C. The size of the first bubble initiated on the Teflon dot seems to be related to the dot's size. The heat flux at ONB on the Teflon milli-dot is so small that bubble frequency is very low. The bubble on the Teflon dot is that the bubble sustains a saturated state for a certain time and then departs suddenly. The saturated bubble state means that bubble does not grow and does not depart from the Teflon dot. The sudden departure occurs when the buoyancy force on the bubble overcomes the strong force of the triple line at the liquid/vapor boundary of the bubble. Because the size of the bubble incepted on the Teflon dot is determined by the size of the dot, the bubble frequency is only dependent on the heat flux: as more heat is supplied, the bubble frequency increases.

CONCLUSION

Thermal systems that use BHT are limited by the CHF phenomenon and therefore require more-efficient heat transfer. Surface effects are important determinants of CHF and BHT. We reviewed methods of increasing CHF by increasing surface wettability and spreadibility, and of increasing BHT using surfaces with combinations of the different surface wettability (e.g. hydrophilic and hydrophobic). If a surface can be prepared which combines these surface properties appropriately, boiling performance of this surface is expected to make it appropriate for real applications. We outlined a plan to design such a surface.

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