Pool boiling CHF enhancement on modified zirconium alloy

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1. Introduction

The critical heat flux (CHF) is the maximum heat flux at which nucleate boiling heat transfer sustains high cooling efficiency. After a surface heat flux reaches the CHF, it becomes coated with a vapor film that interferes with the contact between the surface and the ambient liquid, decreasing the heat transfer efficiency. The system temperature rises, and a system failure occurs if the temperature exceeds the limits of the materials in the system. For this reason, every system incorporates a safety margin by operating at a heat flux much lower than the CHF, even though this reduces the system efficiency. This compromise between safety and efficiency is an important issue in thermal systems such as nuclear power plants. A large number of investigations for the argumentation of boiling heat transfer and CHF using surface modification have taken place since the 1950s. Recently, POSTECH [1] engineered the silicon-ZnO surfaces using micro fabrication in order to imitate the micro/nanostructures of the nanoparticles deposition layer that resulted in the significant CHF enhancement of the nanofluid boiling. The various surfaces with flat, micro, nano, micro/nano-patterned ZnO structures showed quite significant but diverse CHF increase results, which could be correlated using a combination of the surface roughness and surface wettability. Besides the wettability effect of CHF enhancement, the liquid spreadability of the micro/nano-patternd surface resulted in the highest CHF increase. This result was quite significant, although a ZnO structure is not very robust. In addition, POSTECH [2] conducted the CHF enhancement experiment using zirconium alloy (nuclear cladding material) by anodic oxidation method. The wettability and spreading of modified zirconium alloy with micro and nano sized structures had a good CHF enhancement in pool boiling.

2. Experimental results and discussion

An anodic oxidation method [2] was simple method to change the surface characteristics of metal like zirconium alloy. Fig. 1 shows SEM images that modified zirconium alloys have micro and nano scale structures like a valley and a nanotube. They have the enhanced wettability and the liquid spreading ability as increasing anodic oxidation time as shown Fig. 2 and Fig. 3. As the anodic oxidation time increased, the surface of zirconium alloy was more wettable. Finally, the development of surface modification with specific size was fully developed at 10 minutes.

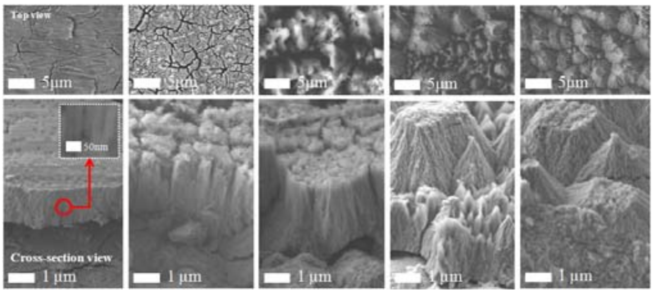

Fig.1. SEM images of modified zirconium alloy

Fig.2. Contact angles of modified zirconium alloy

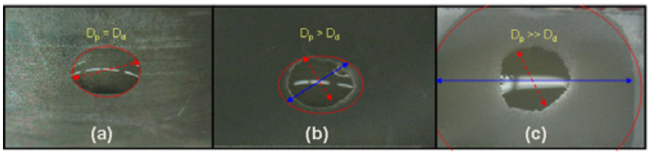

Fig.3. The liquid spreading abilities of each treated zirconium alloy (D_p: the precursor line of droplet, D_d: the contact line of droplet) (a): non-spreading, (b): small-spreading and (c): large-spreading [2]

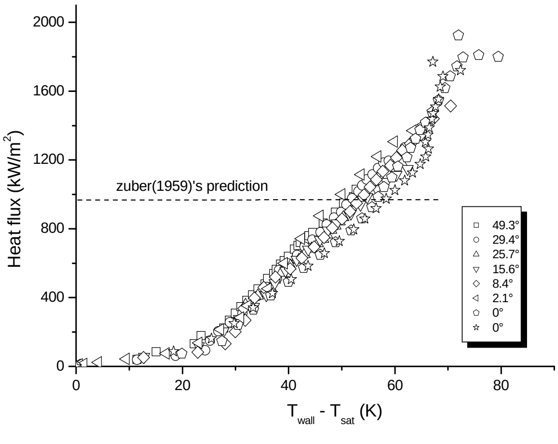

Fig.4. Boiling curve on the modified zirconium alloy [2]

2.1 Pool boiling experiment

Fig. 4 shows the boiling curve of test samples. It is noteworthy to increase CHF, not decrease boiling heat transfer. We conjectured that micro sized structure played a role as active nucleate site and helped spreading phenomenon. *Fig. 5* shows the CHF enhancement ratio (%) versus the bare case which was non-modified (bare) zirconium alloy with the contact angle of 49.3°.

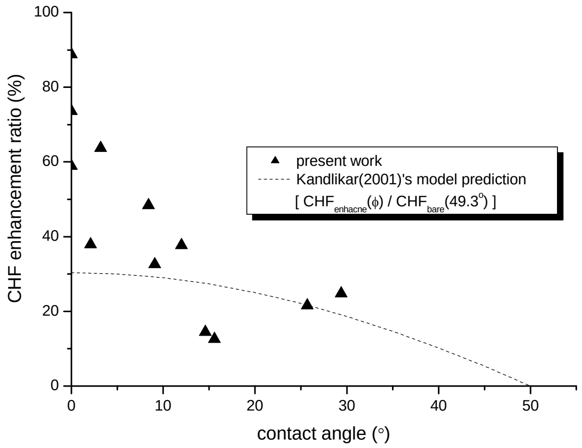

Fig.5. CHF enhancement ratio on the treated zirconium alloy (CHF$_{enhance.}$/CHF$_{bare}$) [2]

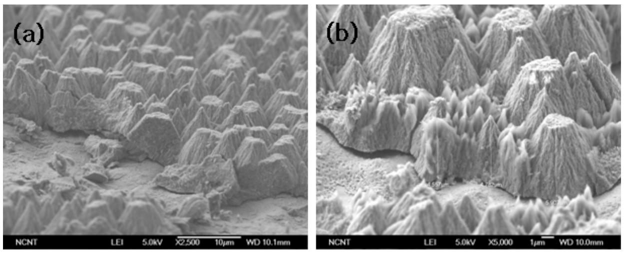

Fig.6. SEM images of modified zirconium alloy with large CHF enhancement. (a): 74% enhance., (b) 90% enhance.

In addition, Kandlikar[3]'s prediction was used to present the CHF enhancement ratio (%) as the reference data with the contact angle of 49.3°. The modified zirconium alloy with contact angles from 10° to 49.3° enhanced the CHF in a manner quite close to Kandlikar[3]'s correlation. On the other hand, for contact angles less than about 10°, the CHF enhancement related to the contact angle change was greater than that predicted by Kandlikar[3]. However, we have one question about significant CHF enhancement of test samples with 0° of contact angle (complete wetting, large spreading). With same contact angle (0°), CHF enhancement ratio of test samples was different from each other. In next section, we conducted a new observation to investigate the liquid spreading ability of samples.

2.2 Liquid spreading ability with micro/nano structures

The amount of CHF enhancement was different for various samples with large spreading ability. Fig. 6-(b) shows nanosized tubes with small spreading ability formed between nano/micro multiscale structure valleys with large spreading ability, which have already been described; for this case, the CHF increased by about 90%. Fig. 6-(a) shows only nano/micro multiscale structures of various valleys; here, the CHF increased by about 74%. These results (i.e., the CHF enhancement data and the SEM observations) indicate that it is not only the nano/micro multiscale structures that significantly influence the CHF enhancement, but also the combination of the two different nano/micro structures. Moreover, we contend that the latter could affect the CHF enhancement more significantly than the former because of the combined effects of these multiple structures. In addition, we conducted the measurement of capillary wicking height of modified zirconium alloys with 74% and 90% CHF enhancement. Capillary wicking height represented the quantitative liquid supply ability on heating surface with porous medium to prevent CHF occurring like liquid spreading ability [4]. The capillary wicking height with 90% enhancement was higher than it with 70% enhancement.

3. Conclusions

Pool boiling CHF enhancement by anodic oxidation of zirconium alloy surfaces was investigated under saturated and atmospheric conditions. Zirconium alloy was selected to be relevant to real application because it is used as cladding material of fuel rods in nuclear power plants. The anodic oxidation of the zirconium alloy surfaces decreased contact angle of a water droplet by creating micro/nanostructures from 49.3° to 0°. Liquid spreading phenomenon was observed on the surfaces with contact angles less than 10°. The experimental results above the CHF prediction with the wettability effect could be interpreted with liquid spreading ability on the surfaces: (a) Non-spreading regime: the CHF increased as the contact angle decrease; (b) Small spreading regime: the CHF enhancement was greater than could be predicted by the wettability effect; (c) Large spreading regime: the combination of different micro/nano multiscale structures on the zirconium alloy surface contributed to greater CHF enhancement than non-combined multiscale structures. These results showed that the surface multiscale structures in the low-contact angle regimes of less than 10°, which had large effects on the liquid spreading ability, were the main influence on the CHF enhancement. In addition, these results suggested that the micro/nano multiscale structures of the surface promoting liquid spreading would be another main factor for the significant CHF enhancements.

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