Visualization of water droplet dynamics on the heated nanostructure surface

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1. Introduction

Spray cooling, an efficient method of cooling down heated nuclear rods when LOCA (Loss of Coolant Accident) occurs, has been researched for its important role in severe accident scenario of the nuclear engineering. [1, 2] The cooling performance of sprayed droplet shows directive relations with how the droplet behaves on the heating surface, and the dynamics of droplet is also affected by surface characteristics. [3] Furthermore, the visualization of droplet also may cover understanding of CHF mechanism in a pool boiling situation. [4] In this study, water droplet behaviors were visualized by high speed camera on several heating points (Room Temperature and 250ºC ~ 500ºC), and its dynamics on nano-modified and bare zircaloy surface were compared and interpreted.

2. Experiments

2.1 Surface Preparation

Rectangular plates of zircaloy (20 × 25 × 0.7 mm) were used as test section, and the surfaces were modified through HF (Hydrofluoric acid) anodic oxidation. [5] First, the surface was mechanically polished by silicon carbide abrasives (# 1200). Then, the surface was anodic-oxidized by applying electric potential (20V) with HF solution (0.5 wt %), and these surfaces was heated through 300C over 6hr to remove any fluoride residue. Furthermore Rinsing procedure with deionized water was implemented between every steps of fabrication. The Fig. 1 shows SEM (Scanning Electron Microscopy) image of test surfaces and their wetting conditions. Nano structured surface indicate a morphology scaled by nanometer- structures (rods, tubes and bundles), as shown in Fig 1 (b). While bare surface has 50º of contact angle, nano structured surface shows complete wetting characteristics (~10º). The spreading feature on the nano structured surface was studied, and there are many research reports about relations between spreading and CHF. [5,6]

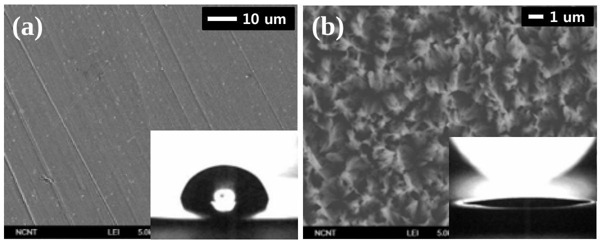

Fig 1. SEM image & Contact angle, (a) Bare & (b) Nanostructured surface

2.2 Visualization

Deionized water droplets were fallen from 1.0 cm height to zircaloy test surface (nanostructured or bare surface), where is heated on brass block with inserted cartridge heaters. Accurately, 6 μL of water volume were controlled by micro syringe, and the momentary behaviors of the droplet contacting the heated surface were captured by high speed camera (ReDLAKE) with 5000~10000 frms (frames per second). The water droplet shows 8.7 of We (Webber Number). In addition, in order to get temperature from the test surface, very thin thermocouple (100 μm TC) was inserted at the bottom the zircaloy surface.

3. Results & Interpretation

Basically, according to the images captured by high speed camera, water droplet on the nano-structured surface experienced more vigorous movements and delayed cutback phenomena. In this article, these two obvious different trends of droplet dynamics between bare and nanostructure surface would be discussed.

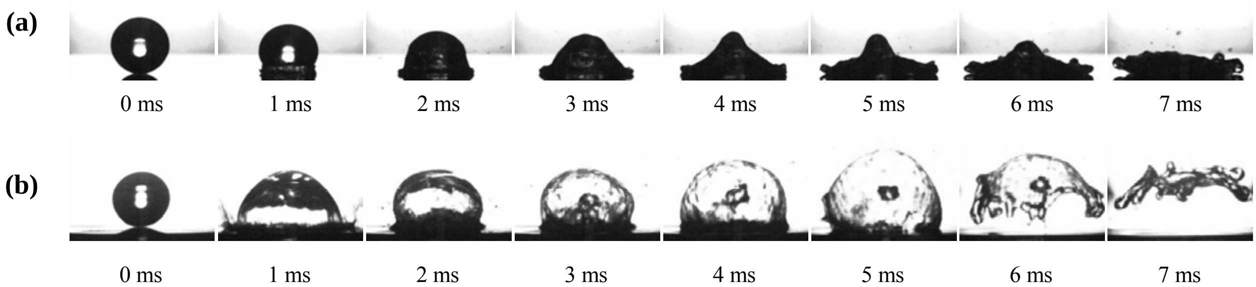

Fig 2. Water droplet behavior at 350^{o}C, (a) Bare & (b) Nanostructured surface

3.1 Bouncing up & Explosion-like behavior of droplet

Fig. 2 shows the different behavior of water droplet on each test surface of 350ºC. Simply, the water droplet on nanostructured surface shows more dynamical behavior and bouncing up from the test surface within 6~7 ms. At the temperature (350ºC), both case must have strong nucleation on the surface within a few ms, and the nucleate boiling and evaporation of water affect the water behavior. Especially, the nano structured surface, in which featured the strong spreading and complete wetting condition, has more chance to be affected by nucleation and evaporation of the liquid, due to the its spreading features and large meniscus of water droplet on to the surface. More spreading and larger meniscus takes more evaporating, and it cause more vigorous and bouncing up dynamics on the droplet.

3.2 Delayed cutback phenomena

Cutback phenomena, that a rapid evaporation at the interface near the meniscus causes liquid-vapor interface to tend backward steps, were observed in this experiment. Fig. 3 shows each cutback points on the test surface, and nanostructured surface (450^{o}C) indicated delayed cutback phenomena compared to bare surface (330^{o}C). This phenomena could be explainable with applying force balance between evaporation recoil force ($F_V \sim 1/2\rho_v V_v^2$, where ρ and *V* are density and velocity respectively) and surface force ($F_S = \sigma / \gamma$, where σ and γ are surface tension and interface curvature respectively). The recoil force acts as a counterforce of the surface force which tends to hold the liquid meniscus on surface. Since nanostructured surface has complete wetting and spreading condition, [7] it presents more surface force with Eq. (1).

$$\gamma = \sqrt{\frac{\sigma}{g\left(\rho_l - \rho_v\right)}} / \sqrt{1 - \frac{\sin\theta}{2} - \frac{\pi/2-\theta}{2\cos\theta}} \qquad (1)$$

Since the structured surface shows higher surface force, so it requires higher evaporation recoil force with higher wall temperature. [8,9]

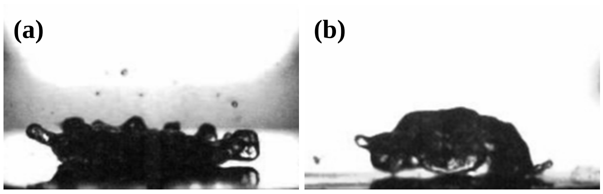

Fig 3. Cutback Phenomena, (a) 330 C (Bare) & (b) 450 C (Nano)

4. Conclusion

In this study, behaviors of water droplet on heated nanostructured surface were visualized by high speed camera, and its dynamics reflecting the surface wetting characteristics could be interpreted with the following description.

- Due to a strong spreadable feature of water droplet on nano-structured surface, the more vigorous and bouncing up dynamics was observed. The spreading water meniscus on the structured surface experienced more chance to evaporate and brought about bouncing up behavior.
- Cutback phenomenon on the nanotubes surface delayed with the stable and larger liquid meniscus. The more stable liquid meniscus with the larger spreading diameter could endure the stronger evaporation recoil force at higher wall superheat due to the improved wettability and the liquid spreading ability.

ACKNOWLEDGEMENTS

This research was supported by WCU (World Class University) program through the National Research Foundation of Korea funded by the Ministry of Education, Science and Technology (R31 – 30005)

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