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EFFECTS OF NANOPARTICLES-COATED SURFACE ON FLOW BOILING CHF USING FC-72

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1. Introduction

Critical Heat Flux (CHF), where a sudden and drastic reduction in the heat transfer coefficient, is the essential limiting parameter of the systems adopting boiling heat transfer mode. In most of power generating systems, especially in nuclear reactor, CHF becomes very important because it determines the safety limit in the operation resulting in economic limit. CHF mechanism in flow boiling can be distinguished into two types. One is liquid film dryout (LFD) developed at smaller heat flux with higher vapor quality, which occurs in BWR. The other is departure from nucleate boiling (DNB) occurring in PWR with relatively higher heat flux at lower vapor quality. Many studies have focused on the physical understanding for the CHF phenomenon, clear explanation for CHF, especially DNB, which isn't achieved yet. The present study aims to investigate feasibility of DNB enhancement and promising mechanisms for the nanotechnology-engineered surfaces. In general the widely accepted DNB models are proposed from Weisman and Pei [1] and Lee and Mudawwar [2]. One is near-wall bubble crowding model based on the enthalpy transportation through the interface between boundary layer and the bulk core. The other is liquid sublayer dryout model introducing liquid sublayer located between vapor blanket and heated surface. By using highly wettable refrigerant FC-72 as a working fluid, the study focuses on the effect of porosity and roughness from nanoparticles-formed porous structure on vertical heated surface.

2. Experimental Setup

The experimental facility is shown in Fig. 1. The flow loop consists of a test section, a pump, a flow meter, a preheater, a heat exchanger, and fluid reservoir. Controlled volume pump is used for small mass flow rate range in 0.046 ~ 0.070 kg/s. Corresponding mass flux is the range of 2000 ~ 3000 kg/m^2s. The gear flow meter measures mass flow rate using rotating gears in liquid flow. After the mass flow meter, the coolant flows to the preheater to maintain constant inlet temperature. A 3kW preheater is capable to maintain maximum subcooled temperature 25℃. Condenser has capacity of 11kW enough to remove applied heat from test section. 1/4 inch Stainless Steel 316L tubes of 5.45 mm inner diameter were used as test heaters. The heating length is 280 mm. The temperatures of fluid at the inlet and outlet of test section were measured by thermocouples of K-type, which were obtained by a data acquisition system. Another five K-type thermocouples are installed to measure the outside wall temperatures of tube. All the experiments are conducted at atmosphere pressure.

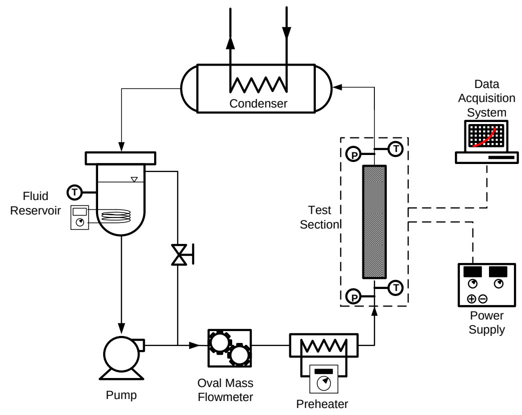


Fig. 1. Schematic diagrams of flow boiling loop

The uncertainties in the electrical voltage, current, inner diameter and length of test section are estimated to be 0.3%, 0.08%, 0.1%, 1%, respectively. Finally, the uncertainty in critical heat flux is less than 1.05%.

3. Preparation of Nanoparticles-Coated Surface

In this study, nanoparticles were coated on the inner surface of tube through a UNIST quenching facility. The 0.01 vol% Al_2O_3/water nanofluids were injected at 3 cm/s flow rate into preheated test section (600 – 650 ℃) to deposit the nanoparticles on the inner surface of the test section. The circulation of nanofluids last for 900 s. The uncertainties of thermocouple and flow rate are less than 0.1℃, 5% respectively. The boiling process induces the nanoparticles-coating on the test section.

Figure 2 shows SEM images of the bare and nanoparticle-coated test sections. Compared to the bare surface like Fig. 2(a), the nanoparticles-coated surface shows a number of pores on the surface as shown in

Fig. 2(b) and (c). The roughness of nanoparticles-coated surface is higher than that of bare surface. Also, from Figs. 2(b) and 2(c), one can ensure the deposited nanoparticles almost remained for all the experiments. The FC-72 droplets on the bare and nanoparticles-coated surfaces as specimens were used to measure the static contact angle. The static contact angle for bare surface is 20.5° while that for nanoparticles-coated surface is 22.3°. It shows that there is no meaningful difference in terms of wettability between two surface conditions. Furthermore, low static contact angles were measured by both cases indicating very high wetting performance of FC-72 working fluid on both bare and nanoparticles-coated tubes. The measured static contact angles are shown in Fig. 3.

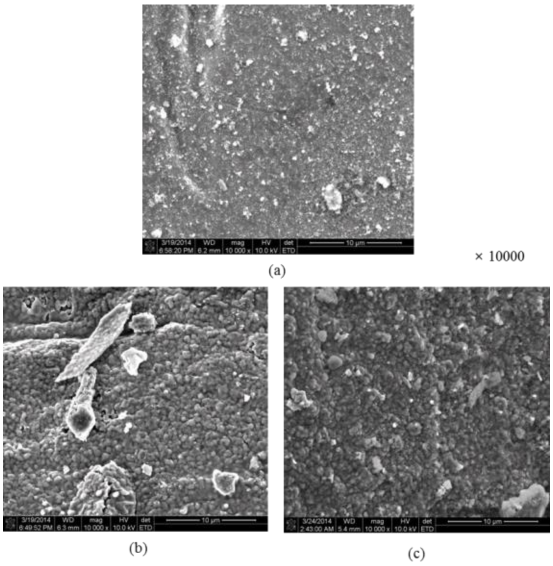


Fig. 2. SEM images of heater surface: (a) bare surface; (b) nanoparticles-coated surface before experiments; (c) nanoparticles-coated surface after experiments.

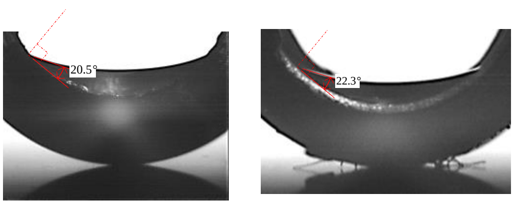
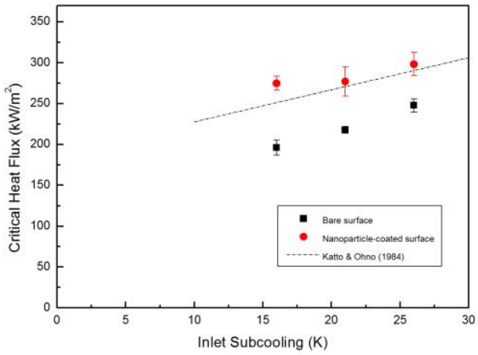


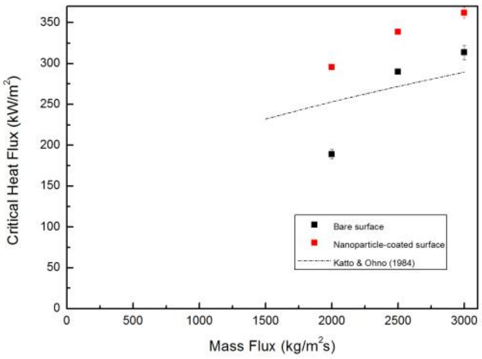
Fig. 3. Static contact angle of FC-72: (a) bare surface; (b) nanoparticles-coated surface.

4. Results and Discussion

The inlet temperature and mass flux are controlled for the parametric studies; subcooling of 16℃, 21℃ and 26℃, mass fluxes of 2000 kg/m^2s, 2500 kg/m^2s and 3000 kg/m^2s. The parametric studies of CHF data were investigated on bare and nanoparticles-coated surfaces according to subcooling and mass fluxes, shown in Fig. 4. With increasing inlet subcooling and mass flux, CHF increases similar to previous reports with FC-72 on short heater [3-5] and heater chips [6] in rectangle channel. The parametric trend is also shown for the nanoparticle-coated surface. Both experimental data roughly agree with predictions of the CHF correlation by Katto and Ohno [7] for vertical round tubes, showing less than 20% deviation.



(a)



(b)

Fig. 4. Critical heat flux of FC-72 on the bare and nanoparticles-coated test section: (a) with inlet subcooling; (b) with mass flux.

The nanoparticles-coated surface shows CHF enhancement compared to bare surface for each corresponding subcooling and mass flux condition. For all the cases on nanoparticles-coated surface, CHF enhancement was observed. Furthermore, CHF enhancement by nanoparticles-coated surface decreases with increasing inlet subcooling and mass flux, similar to those reported in Al_2O_3-coated surface with water at low mass flux [8].

Considering negligible wettability effect, the remaining parameters for CHF enhancement are porosity and roughness differences resulted from nanoparticles deposited on the surface. The porosity and roughness effects can be explained by the enhancement of rewetting process induced by increased capillary action.

Based on the sublayer dryout model, interruption of liquid supply to sublayer enlarges the dry patches leading to CHF. Maintenance of liquid supply to sublayer after detaching of the vapor bubble, called rewetting process, can delay CHF. Higher porosity increases the liquid velocity induced by capillary force, resulting in more liquid supply to the liquid sublayer. At higher mass flux, the relatively less liquid velocity induced by capillary force compared to large bulk liquid velocity can explain the decreasing enhancement ratio [9]. That is, as the mass flux increases, the influence of capillary force induced liquid becomes smaller leading less CHF enhancement. Furthermore, the thickness of liquid sublayer becomes larger due to the additional liquid in the cavity of the nanoparticles-coated surface. The thicker sublayer also enhances liquid supply to the liquid sublayer.

5. Conclusions

The CHF enhancement phenomena in FC-72 refrigerant on a bare and a nanoparticles-coated heater were investigated according to inlet subcooling. The nanoparticles-coated surface shows CHF enhancement up to 40% compared to bare surface, while the enhancement ratio decreases as the inlet subcooling increases. Due to the high wettability of FC-72 working fluid, only the porosity and roughness are the key parameters for CHF enhancement. Increased porosity and roughness by nanoparticles deposited on the surface provide the enhancement of rewetting process induced by increased capillary action. Based on the momentum balance, liquid velocity to the sublayer is related to porosity. Then increasing porosity supplies more liquid to the sublayer delaying CHF.

REFERENCES

[1] J. Weisman, B. S. Pei, Prediction of critical heat flux in flow boiling at low qualities, Int. J.Heat Mass Transfer, 26 (10), p.1463–1477, 1983.

[2] C. H. Lee, I. Mudawwar, A Mechanistic Critical Heat Flux Model for Subcooled Flow Boiling based on Local Bulk Flow Conditions, Int. J. Multiphase Flow, 14 (6), p.711-728, 1988.

[3] D. E. Maddox, I. Mudawar, Single- and Two-Phase Convective Heat Transfer From Smooth and Enhanced Microelectronic Heat Sources in a Rectangular Channel, Int. J. Heat Transfer, 111, p.1045-1052, 1989.

[4] J. C. Sturgis, I. Mudawar, Critical heat flux in a long, rectangular channel subjected to one-sided heating- I. flow visualization, Int. J. Heat and Mass Transfer, 42, p.1835-1847, 1999.

[5] J. C. Sturgis, I. Mudawar, Critical heat flux in a long, rectangular channel subjected to one-sided heating- II. Analysis of critical heat flux data, Int. J. Heat and Mass Transfer, 42, p.1849-1862, 1999.

[6] C. P. Tso, K. W. Tou, G. P. Xu, Flow boiling critical heat flux of FC-72 from flush-mounted and protruded simulated chips in a vertical rectangular channel, Int. J. Multiphase Flow, 26, p.351-365, 2000.

[7] Y. Katto, H. Ohno, An improved version of the generalized correlation of critical heat flux for the forced convective boiling in uniformly heated vertical tubes, Int. J. Heat Mass Transfer, 27, p.1641-1648, 1984.

[8] T. I. Kim, Y. H. Jeong, S. H. Chang, An experimental study on CHF enhancement in flow boiling using Al2O3 nano-fluid, Int. J. Heat and Mass Transfer, 53, p.1015-1022, 2010.

[9] J. Yang, F. B. Cheung, A hydrodynamic CHF model for downward facing boiling on a coated vessel, Int. J. Heat and Fluid Flow, 26, p.474-484l, 2005.