A study on CHF Enhancement Mechanism for Nanofluids Based on Taylor Instability

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1. Introduction

Since nanofluids, which are colloidal dispersions of nanoparticles in a base fluid such as water, were known as a way to significantly enhance the CHF, the CHF prediction models have been developed for the nanofluids [1]. The enhancement of CHF is closely related to buildup of a deposition layer of nanoparticles on the heater surface during the boiling of nanofluids. The main reason to the CHF enhancement is to increase the wettability in many experiments by observing the contact angle which indicates the degree of wetting ability on the nanoparticle-coated heater surface [2, 3]. Recently, Park et al [4] reported the reverse result about the wettability. In this work, the CHF experiments were conducted to analyze the CHF prediction mechanism based on a reduction of the Taylor instability wavelength with a relation to hydrodynamic instability.

2. Experimental Methods

2.1 Preparation of test fluids

Nanofluids were prepared with ZiO (size: 40~100nm), SiO_2 (size: <30nm), SiC (size: <100nm), Al_2O_3 (size: <50nm), graphene oxide (graphite powder, size<45μm) and CuO (size: 23~37nm) at 0.01vol% concentration. Nanoparticles are commercial products while graphene oxide nanomaterial was made by using the modified Hummers method. The prepared nanofluids were performed for 2 hours with the sonication processing for the more uniform and stable dispersion.

2.2 Experimental apparatus and procedure

A schematic diagram of the experimental apparatus is shown in Fig. 1. The pool boiling facility consists of a rectangular vessel (100 mm × 50 mm × 120 mm), copper electrodes, Teflon cover, a reflux condenser, a 1 kW DC power supply, a data acquisition system, a hot plate and a standard resistor. A concentration of nanofluid is maintained by the Teflon cover and the reflux condenser. The heating method on test heater is based on joule heating through the wire. The material of heating wire is nickel-chrome (80/20 composition, L=55 mm, D=0.49 mm). The new pure wire was replaced in every test.

The pool boiling tests were conducted to obtain the CHF value for each nanofluid when distilled water was used as a base fluid. The same heating conditions were applied to form the same order of nanoparticle-coated layer in the nanofluids because the thickness is the parameter to strongly affect CHF. Only coated test heaters were prepared with individual nanoparticles for the unique CHF experiments in R-123 refrigerant as a base fluid. The refrigerant makes it easy to individually examine and measure the distance between the bubbles formed on the heater surface. CHF could occur at low heat flux level due to the low boiling point of the refrigerant. In this experiment, it is impossible to directly use the nanofluids in R-123 refrigerant as a base fluid because the nanoparticles have bad dispersion stability in R-123 refrigerant. So, it is required to acquire the CHF data and prepare nanoparticle-coated heaters with each nanofluid in the different fluids. CHF occurrence was designed at same heat flux level by putting the uncoated part on prepared heaters.

3. Results and discussion

2.1 CHF results for nanofluids

Hydrodynamic instability theory has been known as model of Zuber who proposed initially. This model could be applicable to water and refrigerants because it is based on the properties of fluid. It is common to compare the CHF results with eq. (4) which is called as Zuber equation to determine the reliability of the data. In this work, there was an error of about 10% between the CHF result of bare wire in distilled water and Zuber equation.

$$q''_{Zuber} = \frac{\pi}{24}\rho_g^{1/2} h_{fg}[g\sigma(\rho_f - \rho_g)]^{1/4} \quad (1)$$

where h_{fg} is latent heat of evaporation, ρ_g and ρ_f are the gas and liquid density relatively. σ is the surface tension.

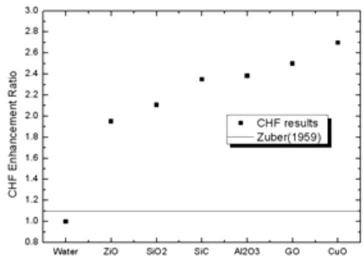
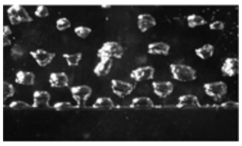


Fig. 1. Result of CHF enhancement for each test fluid compared with Zuber Eq.

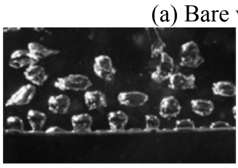
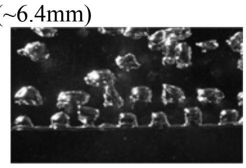
It has been known that there is no significant change in the properties of dilute nanofluid with a base fluid. But CHF of nanofluids was enhanced in comparison with distilled water and Zuber equation. Interestingly, the CHF result of each nanofluid is to show the different enhancement ratio. This enhancement is closely related to the buildup of a deposition layer of nanoparticles on the heater surface during the boiling of nanofluids.

2.2 CHF enhancement on hydrodynamic instability

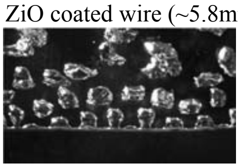
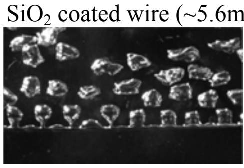
The surprising results are shown in Fig 2. Observed distance between the bubbles is individually different. In each case it is shown that the nanoparticle-coated surface has a shorter average distance compared with a bare surface. A case of high CHF enhancement has a short wavelength in this work. A short wavelength allows to the vapor to prevent the formation of bulk vapor by venting the vapor equally across the heater surface. And a short wavelength is to have the enlarged wetting surface by allowing the liquid to break through which means the enhancement of CHF.



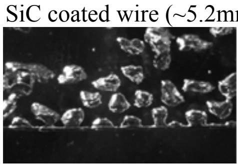
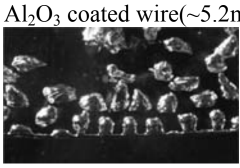
(a) Bare wire (~6.4mm)

(b) ZiO coated wire (~5.8mm) (c) SiO_2 coated wire (~5.6mm)

(d) SiC coated wire (~5.2mm) (e) Al_2O_3 coated wire(~5.2mm)

(f) GO coated wire (~4.8mm) (g) CuO coated wire (~4.5mm)

Fig. 2 Rayleigh-Taylor instability on tested wire surfaces (geometrically determined critical instability wavelength)

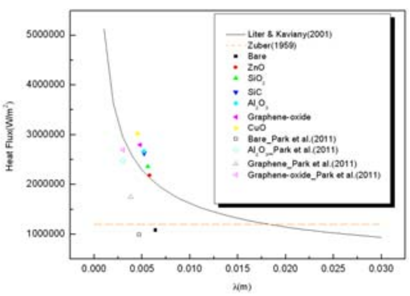


Fig. 3. Effects of a geometrically determined critical instability wavelength(Liter and Kaviany's model with modulation wavelength).

Fig 4 shows the results of the observed Taylor wavelength according to CHF for each nanofluid. The wavelength results for nanofluids are relatively well matched with Liter & Kaviany prediction equation, but there is a fairly large error in a case of bare heater wire.

2.3 CHF enhancement on nucleation site density

Nucleate-boiling heat transfer could be expressed as shown in eq. (2) based on the bubble departure. The bubble departure diameter, the departure frequency and the nucleation site density are important parameter in this equation.

$$q''_{CHF} = \frac{\pi}{6} D_b^3 \rho_g h_{fg} f_c n'' \qquad (2)$$

where D_b is the bubble departure diameter, f_c is the departure frequency, n'' is the nucleation site density.

To avoid the misunderstanding, the term is changed from the nucleation site density to the feasible departure site by coalescence of bubbles. Fig 4 shows the situation schematically in a situation that bubbles are fully developing on the surface during the nucleate boiling. A bubble coalescence and departure occur on marked point in Fig 5

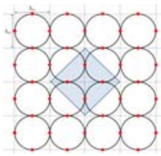


Fig. 4. Schematic bubbles formation on heater surface according to modulated surface condition

Then, eq. (2) can be written as

$$n'' = \frac{number\ of\ site}{unit\ area} = \frac{4}{2\lambda_m^2} = \frac{2}{\lambda_m^2} \qquad (3)$$

4. Conclusions

The following results are obtained.

- The wavelength results for nanofluids are relatively well matched with the modified hydrodynamic instability model.
- The increase of the nucleation site density promotes the enhanced CHF. It is related to the change of the wavelength caused by the nanoparticle-deposited layer.

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