

Critical Heat Flux Enhancement in Pool Boiling Using Alumina Nanofluids

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The pool boiling characteristics of dilute dispersions of alumina nanoparticles in water were studied. Consistent with other nanofluid studies, it was found that a significant enhancement in critical heat flux (CHF) can be achieved at modest nanoparticle concentrations (<0.1% by volume). During experimentation and subsequent inspection, formation of a porous layer of nanoparticles on the heater surface occurred during nucleate boiling. This layer significantly changes surface texture of the heater wire surface which could be the reason for improvement in the CHF value. © 2010 Wiley Periodicals, Inc. Heat Trans Asian Res, 39(5): 323–331, 2010; Published online 13 May 2010 in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/htj.20301

Key words: nanofluids, nanoparticle deposition, critical heat flux, pool boiling

1. Introduction

To increase the critical heat flux (CHF) addition of solid nanoparticles to common fluids such as water is an effective method. The resulting colloidal suspensions are popularly known as nanofluids. Materials used for nanoparticles include some noble metals (e.g., gold, silver, platinum) and metal oxides (e.g., alumina, zirconia, silica, titania). Previous studies of CHF in nanofluids [1–3] have established the following facts: 1. Significant CHF enhancement (up to 200%) with various nanoparticle materials, e.g., silicon, aluminum and titanium oxides. 2. Enhancement occurs at low nanoparticle concentrations, typically less than 1% by volume. 3. During the nucleate boiling process some nanoparticles precipitate on the surface and form a porous layer. In other words, nanofluids can improve the thermal performance of any engineering system that is limited by CHF. To explore the CHF enhancement mechanism of nanofluids, a pool boiling experiment was conducted using a 0.15-mm diameter NiCr wire held in a horizontal position.

Nomenclature

A: surface area of the test wire
D: wire diameter
g: acceleration due to gravity
h: enthalpy

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- I : current
- L : length of the test wire
- q : heat flux
- U : uncertainty in measurement
- V : applied voltage
- ρ : density
- σ : surface tension of the liquid

Subscripts

- CHF: critical heat flux
- f : fluid
- fg : liquid–gas phase
- g : gas
- max: maximum value

2. Pool Boiling CHF Experiments

The pool boiling CHF experiment is divided into two steps viz. preparation and characterization of the nanofluids and the experimental procedure.

2.1 Preparation and characterization of nanofluids

For the experiments, an alumina (Al_2O_3) nanoparticle of 20 nm in size supplied by NaBond Technologies Co., Limited was selected. The reasons for using alumina nanofluids are that they are widely used in this research area due to desired features such as they are stable, uniform, and form continuous suspension without any outstanding chemical change of the base fluid and also that the physical properties of alumina nanofluid have been well documented. Alumina nanoparticles used in this work have the following properties: bulk density = 260 kg/m^3 , true density = 3600 kg/m^3 , apparent density = 0.9 g/cm^2 , purity = 99%, specific heat = 765 J/kg K , melting point = $2046 \text{ }^\circ\text{C}$.

Generally, the properties of the nanofluid depend on the properties of the nanoparticles, and the surface molecules taking part in the heat transfer procedure depend on the size and shape of the particles themselves, which are also affected by the agglomeration of the particles. The nanofluids were then prepared ranging in concentrations, from 0.01% to 1% by volume with deionized water. With these low concentrations, the boiling point of the dilute nanofluids was measured with a thermocouple and found to be within $\pm 1 \text{ }^\circ\text{C}$ of pure water while the surface tension, thermal conductivity, and viscosity of the nanofluids were found to differ negligibly from those of pure water, i.e., within $\pm 5\%$. At the low concentration of interest, also the fluid density and the heat of vaporization can be considered unchanged [4]. In summary, as per the studies, the transport and thermodynamic properties of the dilute nanofluids used in the experiment are very similar to those of pure water [4].

In order to ensure a stable, uniform, continuous suspension, the dispersion solutions are vibrated using a high-speed mixer/homogenizer for about 1 hour just before the boiling test is performed. It was observed that the nanoparticles did not settle at least for the next hour as shown in the photo of Fig. 1 taken by transmission electron microscopy (TEM). Alumina nanoparticles have a spherical shape with a size that has a normal distribution in a range from 10 nm to 80 nm as shown

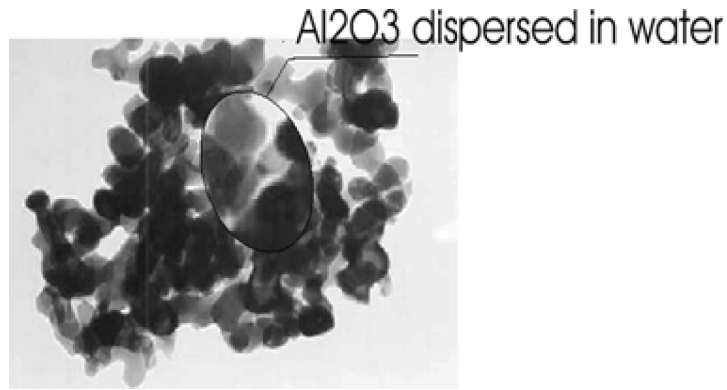


Fig. 1. TEM image of nanofluid with volume concentration of 0.5% by volume.

in Fig. 2. Through this preparation, the solution temperatures increase from 25 °C to approximately 61 °C. Alumina nanofluids with different mass concentrations for the experiment were prepared by controlling the amounts of the particles.

2.2 CHF experiments with NiCr wire

The CHF of deionized (pure) water and Al_2O_3 nanofluids was measured with a NiCr wire heater of 0.15-mm diameter, horizontally submerged in the test fluid at atmospheric pressure. A simplified line diagram of the experimental setup is shown in Fig. 3.

The main test pool consists of a 250-mm diameter, 150-mm-high Pyrex glass vessel and a 30-mm-thick Bakelite cover. The simple geometry and glass material of the test chamber ensured clean conditions that could be maintained for each experiment. The working fluid was pre-heated using a 1 kW heating coil wound around a metallic strip of tungsten material. The pool surface temperature was measured with a K-type RTD thermocouple. A provision is made at the top of the Bakelite cover plate (10-mm diameter hole) to insert the thermocouple lead wire into the boiling

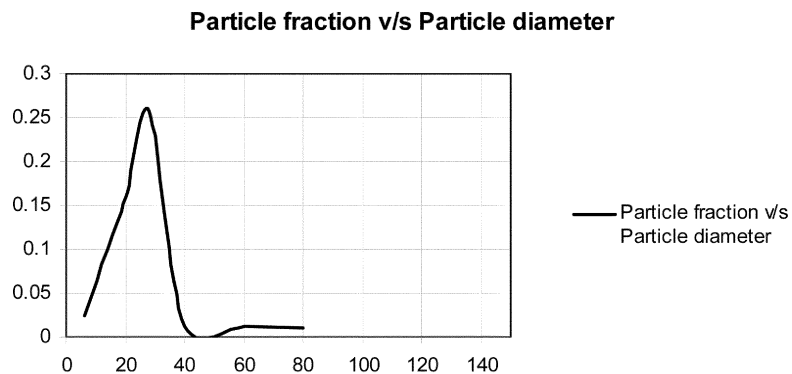


Fig. 2. TEM image of nanofluid with volume concentration of 0.5% by volume.

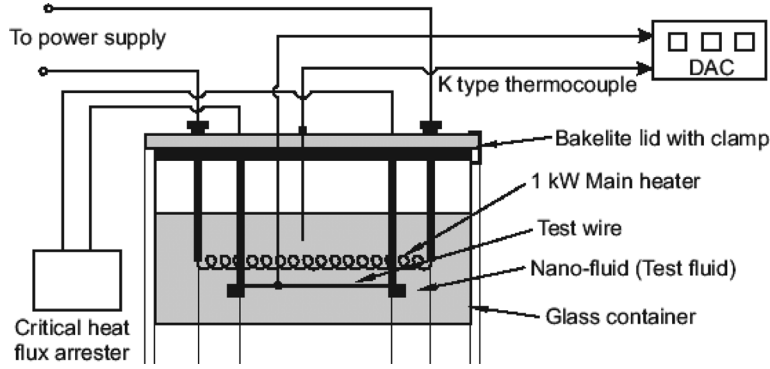


Fig. 3. Experimental setup.

liquid. The cover plate can be secured firmly on the glass vessel containing the nanofluid. The hole on the cover ensures atmospheric conditions inside the vessel. The loss due to evaporation and liquid leakage from the plate was estimated to be 1.33%. This loss was compensated by adding the makeup fluid before the next run. Due to this, the volume concentration of the working fluid did not change during the pool boiling. A horizontally suspended smooth NiCr wire (test wire) of 0.15-mm diameter was used as a boiling surface. Both ends of the NiCr wire heater were tightly secured to the clamps of the tungsten electrodes. The heat input to the test wire was measured by a digital Watt meter incorporated with a “critical heat input sensor.” A DC power supply (60 V/20 A) was used for this purpose. After filling the vessel, all fluids were preheated to a saturated temperature using a 1-kW pre-heater. All pool boiling experiments were conducted after the bulk temperature of the working fluid was stabilized at the saturated temperature (100 °C). The experiments were performed by increasing the electric power supplied to the wire heater. The electric power/heat input was increased in small steps using a variac until the critical value is reached due to increased resistance of the wire heater, and the heater was instantaneously broken. This peak value was recorded in the digital wattmeter with a peak value locking arrangement. The CHF was calculated using data obtained just before the steep increase of heater resistance. All tests were performed under atmospheric pressure. Data from all tests were deduced using the following equations. The voltage and electric current supplied to the NiCr heating wire heater are used to compute the heat flux as

$$q = \frac{VI}{A} \quad (1)$$

The main sources of uncertainty of the applied voltage and current are due to contact resistance between the wire heater and electrodes which are connected with only mechanical clamps. In addition, there is uncertainty associated with the length and diameter of the NiCr wire heater. The experimental uncertainty mainly including the parameters like applied voltage and length of the wire is calculated using the following relation proposed by Holman [5] as follows:

$$U_{q_{CHF}} = q_{CHF} \left\{ \left(\frac{U_{V_{\max}}}{V_{\max}} \right)^2 + \left(\frac{U_{I_{\max}}}{I_{\max}} \right)^2 + \left(\frac{U_D}{D} \right)^2 + \left(\frac{U_L}{L} \right)^2 \right\}^{1/2} \quad (2)$$

The uncertainties of the applied voltage and the length of wire heater are less than 3.96% and 0.7%, respectively. From the above analysis, the maximum uncertainty for pool boiling CHF was estimated to be 4.96%.

3. Results and Discussion

Figure 4 shows the measured CHF values of the alumina nanofluid at different volume concentrations.

Significant CHF enhancement is observed for all nanofluids, up to 48% with alumina nanofluids as shown in Fig. 5. The CHF dependence on nanoparticle concentration is erratic, but not unprecedented for nanofluids [3]. Since the study is mainly focused on CHF enhancement, no detailed discussion is made on effect on heat transfer coefficient using nanofluids.

Typical boiling curves for pure water and two concentrations of nanofluids are shown in Fig. 6. The nanofluids have a higher CHF and lower boiling heat transfer coefficient, which is consistent with the findings of Das et al. [6] and Bang and Chang [3].

The deterioration of nucleate boiling may be due to a surface effect. To ascertain the change in surface roughness, the wire surface was exposed to three continuous heating cycles for the same heat input but at a point below the critical value by slowly varying the heat input and maintaining it at the same value. This was possible by initially heating the test wire to the burn out point and noting the CHF value for a given concentration. Now a fresh wire was mounted and was exposed to three heating cycles below the critical value and for a fixed time period of 120 s. The surface roughness of the specimen was measured using the Surf Test and the results clearly indicate that the surface roughness decreases due to building up of a layer with the increase in concentration of the nanofluid as shown in Fig. 7. This is because the size of the nanoparticles used are much smaller in magnitude than the Al_2O_3 nanoparticles used for testing. Due to this, the nanoparticles deposit on relatively uneven surfaces and formed a coating on the wire surface.

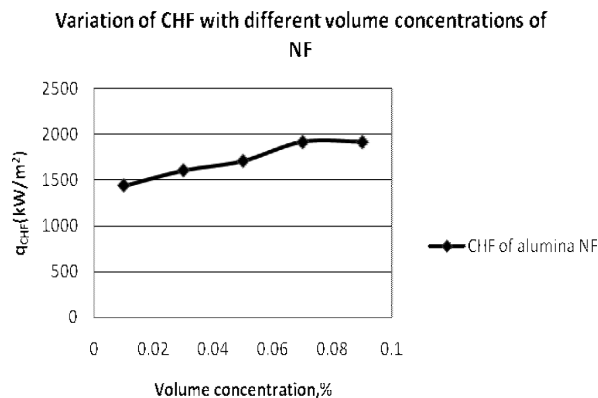


Fig. 4. Variation of CHF with different volume concentrations of alumina nanofluid.

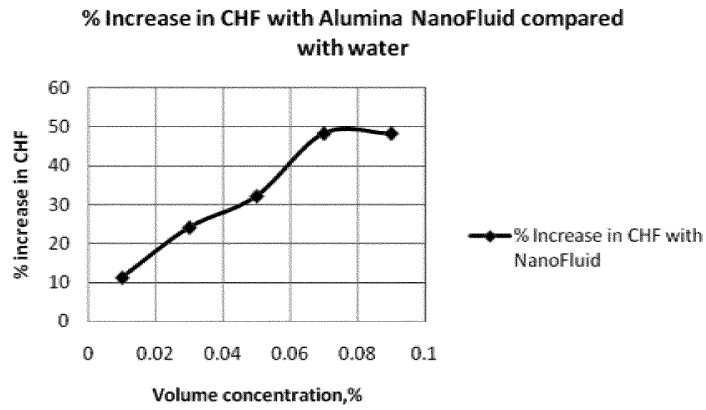


Fig. 5. Percentage increase in CHF with Al_2O_3 compared with pure water.

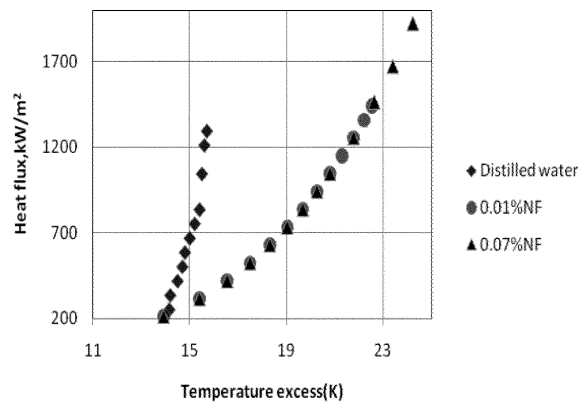


Fig. 6. Boiling curve for two different concentrations of Al_2O_3 .

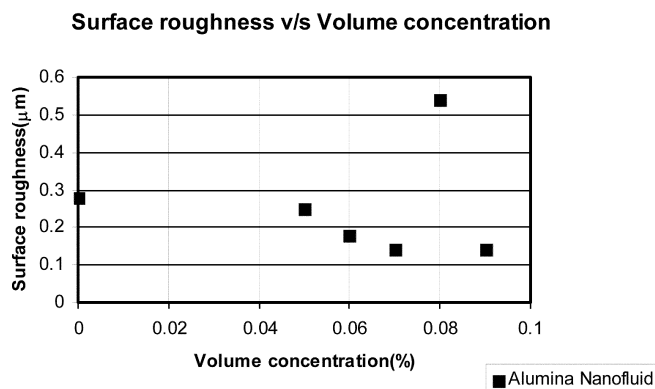


Fig. 7. Effect on surface roughness with change in concentrations of Al_2O_3 .

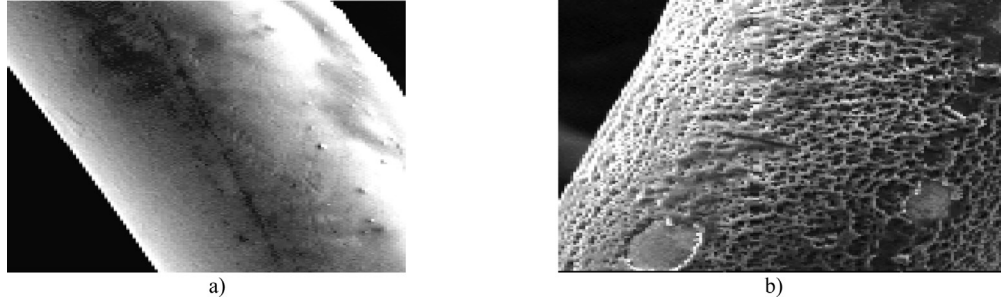


Fig. 8. Comparison of wire surface (a) before experiment, (b) after experiment.

Scanning electron microscope (SEM) analysis of the wire surface revealed that the surface is clean during pure water boiling [Fig. 8(a)], but a porous layer builds up over the wire surface during nanofluid boiling [Fig. 8(b)].

The subsequent images of the surface of NiCr wire after reaching the burnout point with 0.01% and 0.1% alumina nanofluid is shown in Fig. 9. Most probably this layer is formed due to boiling induced precipitation of nanoparticles which was confirmed by surface testing. The presence of a porous layer on the surface definitely plays a major role on boiling heat transfer through changes in roughness and wettability, the detailed study of which will be made in due course of time. It can be observed that the deposition is more pronounced on the heater surface with the 0.1% alumina nanofluid.

According to Zuber [5], which has been widely used to predict pool boiling CHF we have

$$q_{CHF} = \frac{\pi}{24} \rho_g^{1/4} h_{fg} [g \sigma (\rho_f - \rho_g)]^{1/4} \quad (3)$$

As reported by Barkhu and Lienhard [7], the prediction of CHF by Eq. (3) is not valid and experimental data of previous studies have shown large deviation for a small horizontal 0.15-mm NiCr wire used in this experiment. Since the main focus of the present work is to investigate CHF

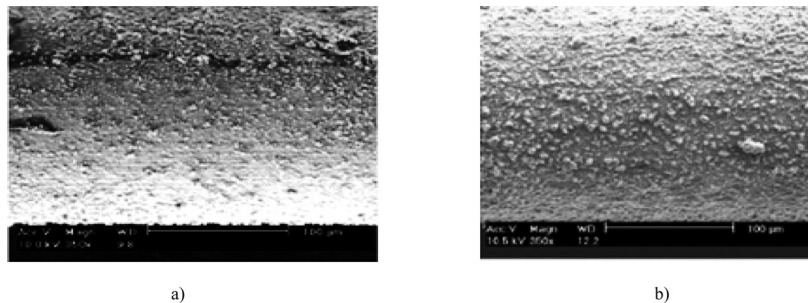


Fig. 9. SEM image of NiCr wire surface after the burnout point with 0.01% alumina and 0.1% alumina with $\times 350$ magnification.

Comparison of CHF of alumina Nanofluid with CHF of water

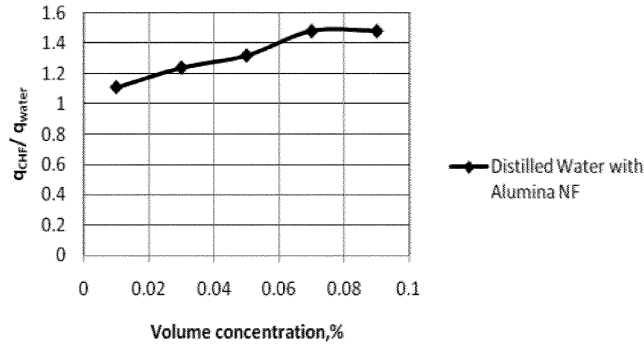


Fig. 10. Ratio of CHF data of Al_2O_3 nanofluid and water.

enhancement using nanofluids relative to the CHF of pure water, the experimental CHF value of pure water in the present work can be used as a standard for subsequent CHF comparisons of nanofluids. Figure 10 shows pool boiling CHFs of water– Al_2O_3 nanofluids with different particle volume concentrations at atmospheric pressure when compared with pure water. It is clear that alumina nanofluid’s CHF ability is 1.5 times that of water even used in small concentration.

For nanofluids with a minimum concentration of 0.01% used for the pool boiling experiment, the CHF was enhanced by only 10% of the value of pure water while the CHF sharply increased up to 48% of the value of pure water at particle concentrations of 0.09%, and then became saturated at about 48% at 0.1%. Similar saturation phenomena were reported by You et al. [1] from the results of pool boiling CHF experiments of water– Al_2O_3 nanofluids under reduced pressure ($P_{sat} = 2.89$ psia) but with the CHF increase being approximately 200%. For a comparison of the present results with data from previous research, CHF values in nanofluids normalized [3] by CHF of pure water in each work are shown in Fig. 11. Significant CHF enhancement is observed in all works, but there are quantitative differences due to the variation of experimental parameters, such as the material and

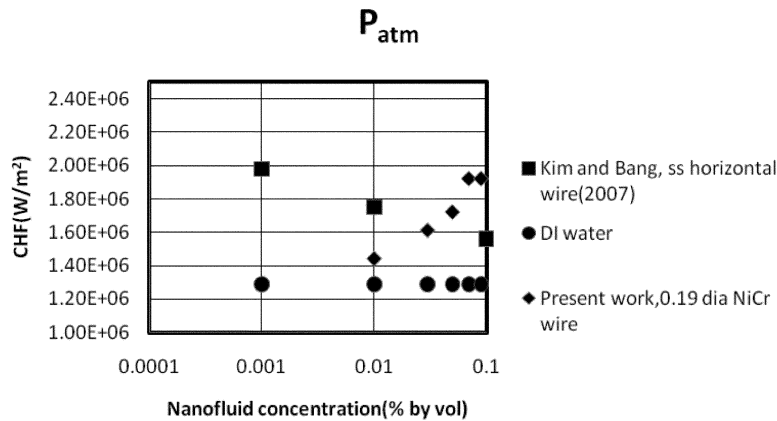


Fig. 11. Comparison of CHF of nanofluid with CHF of pure water.

dispersion conditions of the nanoparticles, as well as the heater geometry, all of which can affect the CHF.

In terms of CHF enhancement by the usage of nanofluids instead of pure water as a cooling liquid, the results of the present study are consistent with those of other works under atmospheric pressure. Modification of the heater surface by the nanoparticle surface coating was dependent on the particle concentration of the nanofluids.

4. Conclusions

Pool boiling CHF characteristics in nanofluids were investigated with five volume concentrations of Al_2O_3 nanofluid ranging from 0.01% to 1%, and the effect of nanoparticles in pool boiling CHF of Al_2O_3 nanofluids for each concentration was studied experimentally. During the experimentation, the pool boiling CHF of Al_2O_3 nanofluids on a bare heater of NiCr wire was enhanced to ~48% compared to that of pure water by increasing nanoparticle concentration. It was observed that with low concentration of Al_2O_3 the dispersion was homogeneous while higher concentration of Al_2O_3 resulted in the formation of a coating over the heater surface and fouling of the vessel inner surface. The SEM images of the heater surface taken after pool boiling CHF tests revealed that CHF enhancement of nanofluids was closely related to the surface microstructure and enhanced topography resulting from the deposition of nanoparticles. This study clearly shows that the main cause of CHF enhancement of nanofluids has a definite connection with the change of surface microstructure and topography of the NiCr heater due to the nanoparticle surface coating formed during pool boiling.

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