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Applicability of Nano-fluids for a Thermal Hydraulic System : Boiling Heat Transfer Characteristics of Al_2O_3 Nano-fluids

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Abstract

Boiling heat transfer characteristics of nano-fluids with nano-particles suspended in water are studied using different volume concentrations of alumina nano-particles. Pool boiling heat transfer coefficients and phenomena of nano-fluids are compared with those of pure water, which are acquired on a horizontal flat surface with highly smooth roughness of a few tens nano-meters. The experimental results show that these nano-fluids have poor heat transfer performance compared to pure water in natural convection and nucleate boiling. This is related to a change of surface characteristics by the deposition of nano-particles. Comparisons between the experimental data and the Rhosenow correlation show that the correlation has a possibility to predict the performance with an appropriate modified liquid-surface combination factor and changed physical properties of a base liquid

I. Introduction

Many engineering systems include the problems related to boiling. In a power system, the associated phase change heat transfer has been used extensively to acquire good heat transfer performance of the system. In recent years, various boiling heat transfer enhancement techniques have been proposed and studied. In particular, the dispersion solution called nano-fluid which produced by dispersing nano-particles into fluids is known to significantly enhance the poor thermal conductivity of the water [1,2]. Therefore, it is expected that heat transfer performance of water can be improved. Naturally, many researchers firstly expected the augmentation of boiling heat transfer performance and the deterioration of Critical Heat Flux value resulting in an earlier boiling crisis.

However, recently published two papers give interesting results in relation to boiling heat transfer and CHF. One latest work shows that nano-particles of Al_2O_3 deteriorate boiling heat transfer performance [3] and the other latest note shows that nano-particles of SiO_2 outstandingly increase CHF [4]. In this work, the boiling heat transfer characteristics for Al_2O_3-water nano-fluids are studied on a horizontal flat surface with highly smooth roughness in pool to a higher heat flux level. In addition, boiling phenomena are visually investigated using a visualization technique.

II. Expreiment

The experiment is divided into three sub-tests. One is the preparation of nano-fluids and another is boiling heat transfer measurement. The other is visualization of boiling phenomena.

II.A. Preparation and Properties of Nano-fluids

In this work, the alumina nano-fluids are prepared by dispersing alumina nano-particles into water as a base fluid. The reasons for using the nano-fluids are that it is widely used in this research area depending on requirements for nano-fluids such as stable, uniform and continuous suspension without no outstanding chemical change of the base fluid and also that physical properties of the alumina nano-fluid are most well known. Alumina nano-particles used in this work are manufactured by patented Physical Vapor Synthesis (PVS) Process of Nanophase Technologies Corporation.
Generally, the properties of a nano-particle determine those of a nano-fluid and the one's surface molecules actually taking part in heat transfer procedure depend on the size and shape of the particle itself which are also related to agglomeration of particles affecting stable suspension.

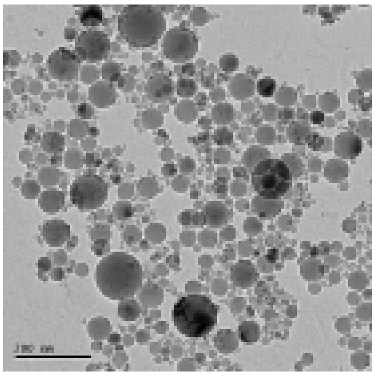


Fig. 1 TEM photograph of Al_2O_3 nano-particles

As shown in the photo of Fig. 1 taken by transmission electron microscopy(TEM), alumina nano-particles have spherical shape. The size has normal distribution in a range of from 15 nm to 124 nm (47 nm avg. diameter is given from the manufacturer). In order to make sure on stable, uniform and continuous suspension, the dispersion solutions are vibrated in ultrasonic bath for about 8 hours just before a boiling test is performed. Through this preparation, their temperatures increase from 20 ^oC to about 55 ^oC. Four alumina nano-fluids with different mass concentration for the experiment are prepared by controlling the amounts of the particles.

It is known that a flow phenomenon of the liquid-solid solution depends on the hydrodynamic force acting upon surface of solid particle. Therefore, volume fraction of the solution is considered as more important factor than mass fraction. Also, following conversion formula is used conventionally because it is very difficult to measure the exact true volume of nano-particles.

$$\phi_v = \frac{1}{\left(\frac{1-\phi_m}{\phi_m}\right)\frac{\rho_p}{\rho_f}+1} \quad (1)$$

The equation leads the next density expression for a solution.

$$\rho = \rho_f(1-\phi_v)+\rho_p\phi_v \quad (2)$$

This equation can easily derive the next relation for heat capacity [5].

$$\rho c_p = \rho_f c_{pf}(1-\phi_v)+\rho_p c_{pp}\phi_v \quad (3)$$

The thermal conductivity of the solution can be calculated easily through simplified Hamilton and Crosser model as the following equation [1].

$$k/k_f \approx 1+n\phi_v \quad (4)$$

Table 1 shows the nano-fluid properties of this work.

In a fluid, viscosity and surface tension are also considered as important properties. Das et al. [3] have performed rheological study on the alumina nano-fluids. With increasing particle volume fraction, viscosity had higher values than that of water. Also, the following equation may be applied in prediction of viscosity of nano-fluids [6].

$$\mu = \mu_f(1+2.5\phi_v) \quad (5)$$

Surface tension has changed very slightly in their results. Therefore, the change of the properties of water might hardly have made any effects on the present heat transfer results.

Table 1. Major properties of nano-fluids

Al_2O_3 nano-fluid	#1	#2	#3	#4
ϕ_m (%)	2.06	3.88	7.5	14.19
ϕ_v (%)	0.5	1	2	4
ρ/ρ_{f0}	1.01	1.03	1.06	1.12
C_p/C_{p0}	0.98	0.97	0.94	0.88
k/k_0	1.13	1.15	1.18	1.25
μ/μ_0	1.01	1.03	1.05	1.1

II.B. Boiling Experimental Facility and Procedure

The pool boiling test facility is shown in Fig. 2. The facility consists of main vessel, horizontal test heater part with visualization windows, vertical test heater part with visualization windows, outer isothermal vessel, pre-heater, circulator and condenser. The pure water and nano-fluids are filled in a main vessel.

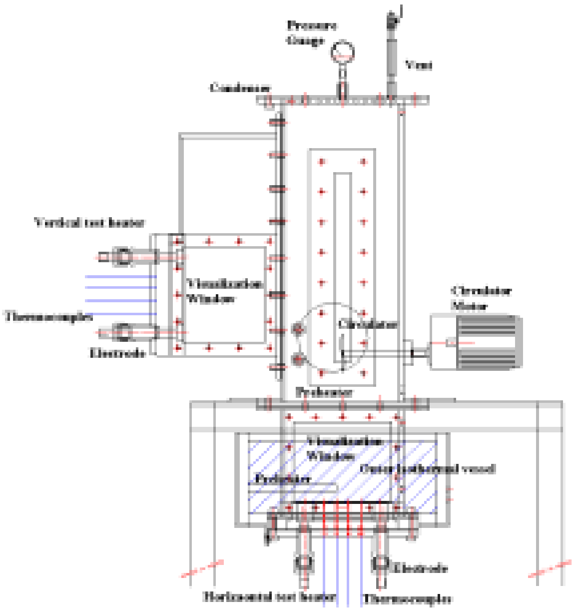


Fig. 2 Nano-fluid boiling experimental facility

A test plane heater with copper electrodes is heated by DC power supply of HP 6680a with the maximum capacity of 4.375 kW(5 V, 875A). Boiling surface of the test plane heaters is 4 x 100 mm^2 rectangular, with depth of 1.9 mm. At the back of the boiling surface, four holes are machined where 4 K-type thermocouples are imbedded with depth of 1 mm with silver welding to measure boiling surface temperature. The surface roughness of the boiling surface is controlled by sand paper of grade #2000. The signals of the all thermocouples are acquired by a HP 3852a Data Acquisition System.

All tests were performed under atmospheric pressure. After being filled into the vessel, all fluids are preheated to saturated temperature using 1 kW pre-heater. In case of a horizontal test, water in outer isothermal vessel is preheated to saturation temperature in order to keep the inner fluid temperature saturated using 1.5 kW pre-heater. All outsides of the experimental facility are insulated by thermal insulating materials.

Data from all tests are deducted using the following equations. The voltage and electric current supplying to the plain heater are used to compute the heat flux as:

$$q = \frac{VI}{A} \qquad (6)$$

As the temperature distribution on the boiling surface is not uniform spatially and not constant with time, the following time-space averaged temperature was used.

$$T = \frac{1}{At}\int_A \int_t T dA dt \qquad (7)$$

The heat diffusion equation is adopted to acquire the boiling surface temperature, or

$$T_w = T(x) - \frac{ql}{2k}\left(1 - \frac{x^2}{l^2}\right) \qquad (8)$$

Therefore, the average boiling heat transfer coefficient is calculated as followings:

$$h = q / \Delta T_w \ , \qquad (9)$$

$$\Delta T_w = T_w - T_{sat} \qquad (10)$$

III. Results and Discussion

The results of the heat transfer test show that boiling heat transfer coefficients in the nano-fluids are lower than that in pure water.
In order to find out the reasons of the deterioration of boiling heat transfer, surface roughness of same samples as test heater is measured using non-contact coordinate measuring machine, NanoScan of Intekplus company for pure water, 0.5% and 4% alumina nano-fluids.
Also, the boiling phenomena of pure water and the nano-fluids are compared through the visualization test using the high-speed camera of Kodak motion coder SR-1000 and digital camera of Nikon D1.

III.A. Pool boiling heat transfer coefficient

The measurements of the temperature of the boiling surface are shown in Fig. 3. The addition of alumina nano-particles caused the water boiling curve to shift to the right, i.e. decrease of pool nucleate boiling heat transfer. Compared with that for low volume concentrations, the temperature of the boiling surface was increased at same heat flux for 2% and 4% nano-fluids. This shows that the heat transfer coefficient was decreased by increasing particle concentration.
Figure 3. also shows obvious distinctions between the natural convection stage and nucleate boiling stage. In case of nano-fluids, natural convection stage continues relatively longer and nucleate boiling is delayed or for it, higher superheat of the boiling surface is needed.

Above results ignored general prediction on effects of nano-fluids with increased thermal conductivity.
For pool nucleate boiling correlation considering surface characteristics, Rhosenow[7] proposed the following equation.

$$Nu = \frac{1}{C_{sf}} \mathrm{Re}^{(1-n)} \mathrm{Pr}_f^{-m} \quad (11) \text{ or}$$

$$h = \frac{1}{C_{sf}} \left[\frac{c_{pf} q}{i_{fg}} \right] \left[\frac{q}{\mu_f i_{fg}} \left(\frac{\sigma}{g(\rho_f - \rho_g)} \right)^{1/2} \right]^{-n} \left[\frac{c_p \mu}{k} \right]_f^{-(m+1)} \quad (12)$$

It can be used for two objectives. One is to be used in order to know if our pool boiling characteristics for pure water are reasonable. Fig. 4 shows that the data for pure water has good approaches with the correlation. The other is to predict some effects of nano-fluids. In Section II.A, almost all properties of nano-fluids are predicted. If they are used for calculation of a heat transfer coefficient, the value can be acquired as shown in Fig. 5. Various applications for the correlation are tried with changing the property values. As the result, it is considered that the nano-fluids of the experiment do not affect the boiling heat transfer with changed thermal conductivity or other properties but affect with changed surface characteristics. Comparisons between the experimental data and the Rhosenow correlation show that the correlation has a possibility to predict the performance with an appropriate modified liquid-surface combination factor and changed physical properties of a base liquid. Further discussion with the consideration will be given in section III.C.

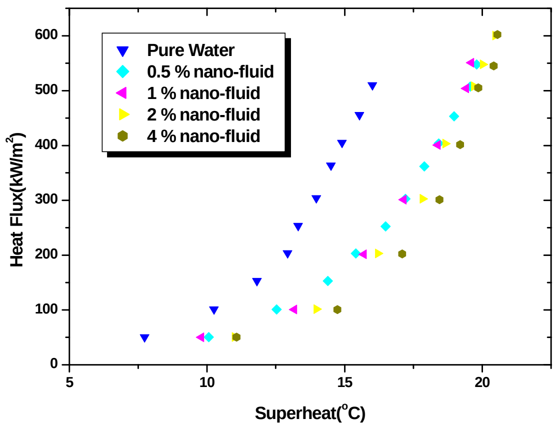


Fig. 3 Boiling curves of pure water and nanofluids

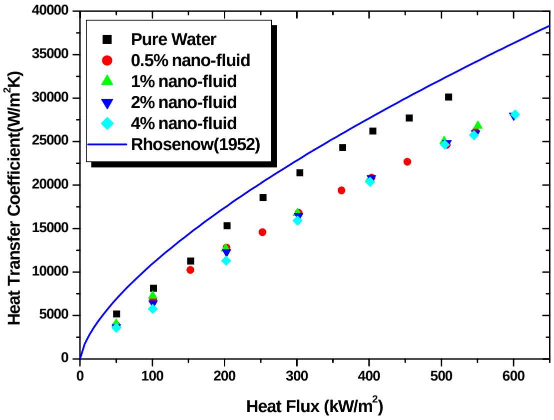


Fig. 4 Boiling heat transfer coefficients of nano-fluids

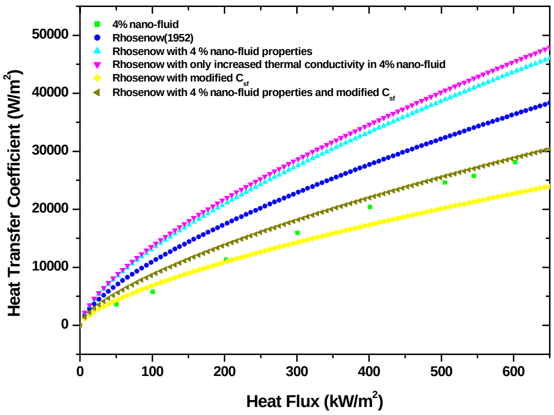


Fig. 5 Applicability of Rhosenow[7]'s correlation

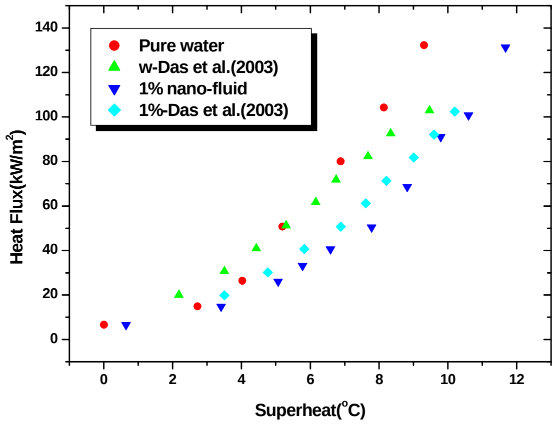
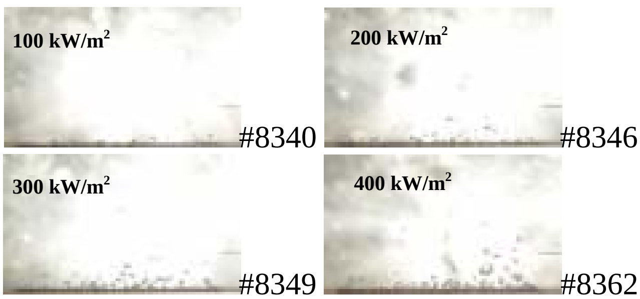


Fig. 6 Characteristics at low heat flux of natural convection

Figure 6 shows the characteristics of natural convection stage. It is thought that the natural convection of the experiment has different rates with that of Das et al.[3] because of geometrical features with rectangular channel. Actually, the present results show obvious distinction between natural convection and nucleate boiling well.

III.B. Visualization of pool boiling phenomena

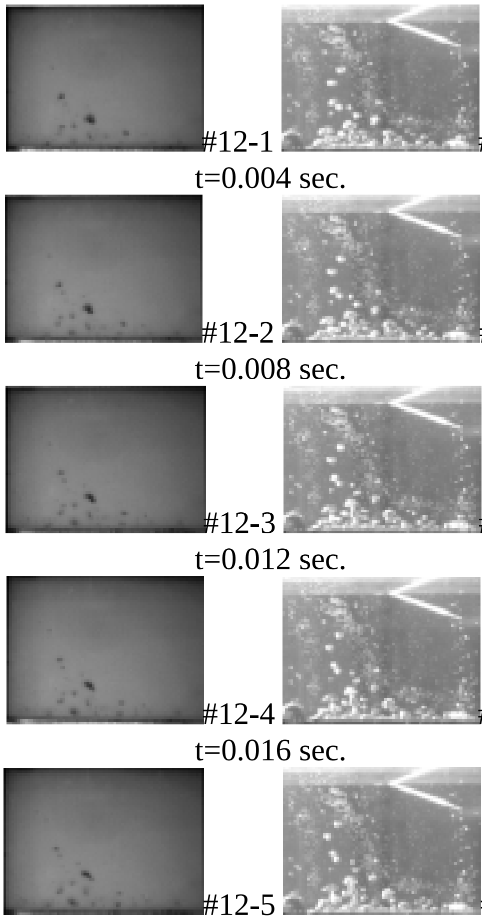
In this work, pool boiling phenomena are observed to understand the nano-fluid heat transfer mechanism. Figure 7 shows the main regimes in nucleate boiling such as discrete bubble regime and coalesced bubble regime in pure water. The phenomena can be corresponded to the boiling curve of Fig. 3. Actually, the slope of boiling curve is changed below 100 kW/m^2 with onset of nucleate boiling and at higher heat flux, more active nucleate boiling decreases the temperature of the boiling surface.



#8378 #8394

Fig. 7 General pool boiling phenomena of pure water

Figure 8 shows the results observed by the high speed camera with an interval of 0.004 seconds. # means the original record sign from tests. Actually, water-Al_2O_3 nano-fluids have the same color of white as the nano-particles. With increasing particle concentration, the color is getting much deeper. Therefore, the bubbles cannot be observed obviously in general boiling tests. The visualization of the nano-fluid boiling phenomena only succeeds in high heat flux over 500 kW/m^2 and at low particle concentration of 0.5 % volume fraction.



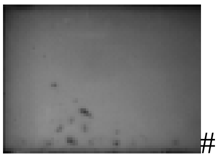
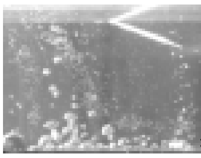
#12-1 #9-1
t=0.004 sec.

#12-2 #9-2
t=0.008 sec.

#12-3 #9-3
t=0.012 sec.

#12-4 #9-4
t=0.016 sec.

#12-5 #9-5
t=0.020 sec.

#12-6 #9-6

t=0.024 sec.

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0.5 % vol. water-Al_2O_3 nano-fluid(#12), q=550kW/m^2

Pure water(#9), q=500kW/m^2

Using high speed camera

Fig. 8 Comparison of boiling behaviors

The pictures with #9 signs show the sequential bubble behavior in pure water. Compared to that, the pictures with #12 signs show the sequential bubble behavior in the nano-fluid. Overall nucleate boiling phenomena are similar in two fluids. However, there is a large difference of the amount of vapor or the number of bubbles observed in those pictures. It apparently seems to be poor visualization condition of the nano-fluid. However, actually it might be due to less active nucleating boiling than that in pure water. This corresponds to the boiling curve characteristics of the nano-fluids. Therefore, the consideration leads to discussion on surface characteristics of the next section.

III.C. Discussion on changed boiling performance

The unexpected heat transfer performance of nano-fluids is opposite to their properties as a fluid. Therefore, the reasons of this conflictive performance can be related to surface characteristics between the boiling surface and nano-fluids. Das et al. [3] found that the surface roughness considerably decreased. They insisted that the reduction is the cause of the boiling characteristics. This is a very natural and interesting fact. However, their smooth heater has the roughness much larger than the size of nano-particles. In case of the present study, the test heater has the roughness smaller than the size of nano-particles. The measurement results of the present work show that the surface roughness values of test heaters submerged in nano-fluids are increased in average with increasing particle concentration as shown in Fig. 10 through 12.
The result with increased roughness indicates that with surface roughness values, the average size of nano-particles with normal distribution in a range of 10 to 100 nm can be important factor. Both factors simultaneously are considered in the effects. Actually, Figure 13 shows the locally smoothed roughness in the present study. It seems to be agreed to the result of Das et al. [3]. On the other hand, for more roughened surface with higher particle concentration, less heat transfer is due to the originally poor thermal conduction of alumina in surface coated or deposited with those as shown in Fig. 14.

Conclusively, it is reasonable that the nano-particles reduce the number of active nucleation sites with change of surface roughness values in nucleate boiling heat transfer. Roughness change causes a kind of fouling effect with poor thermal conduction in single phase heat transfer.

This is closely related to the relative small heat transfer difference among the nano-fluids with different particle concentrations of Fig. 3 because the concentration effect is small than the coating effect. Related to that, Fig. 15 shows the distinction between single phase heat transfer region and nucleate boiling region near the boiling surface in pure water. In near-wall region, the liquid-layer below bubbles may play an important role on slightly different heat performance among the nano-fluids because of direct interactions with the surface.

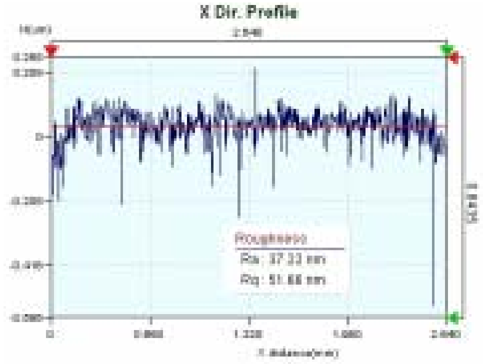


Fig. 10 Surface roughness of clear heater

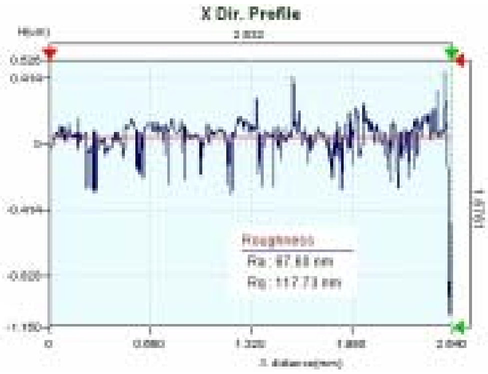


Fig. 11 Surface roughness of the heater submerged in 0.5 % alumina nano-fluid

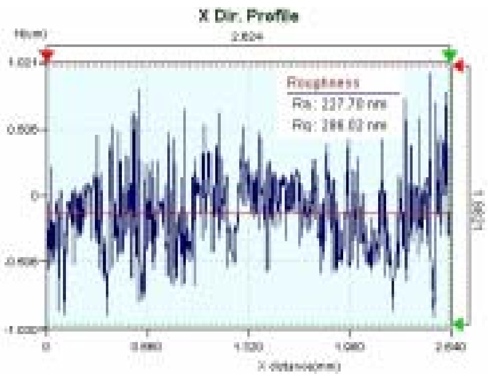


Fig. 12 Surface roughness of the heater submerged in 4 % alumina nano-fluid

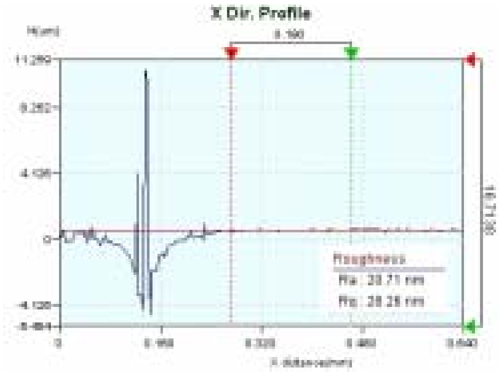
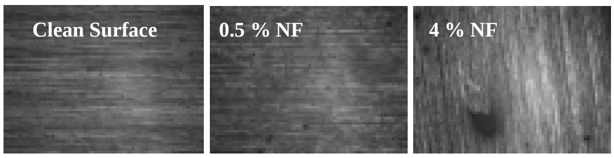


Fig. 13 Locally smoothed roughness in 0.5% nano-fluid



(Magnified surface images)

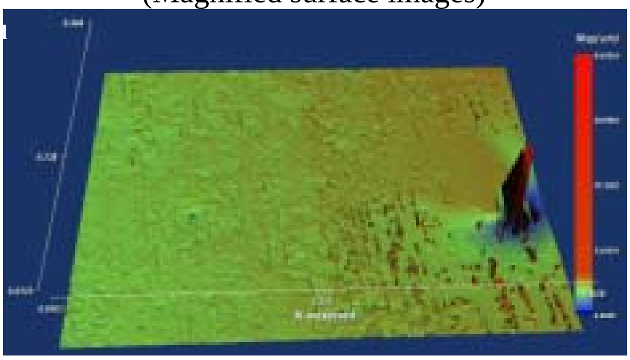


Fig. 14 Direct magnification of the surface roughness

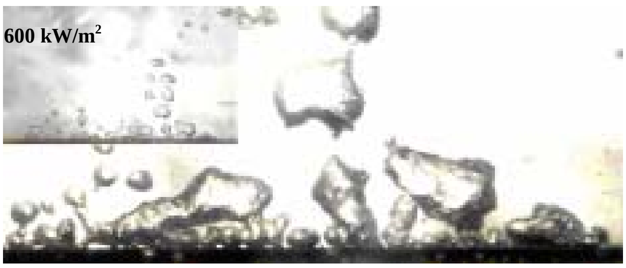


Fig. 15 Heat transfer mechanism near boiling surface in pure water

IV. Conclusions

Boiling heat transfer characteristics of nano-fluids with nano-particles suspended in water was studied using 4 different volume concentrations of alumina nano-particles. Pool boiling heat transfer coefficients of nanofluids was compared to the coefficient of pure water, which are measured on a flat surface of pool. Alumina-water nano-fluids show different performance and phenomena compared to pure water in natural convection and nucleate boiling. The addition of alumina nano-particles caused the decrease of pool nucleate boiling heat transfer. The heat transfer coefficient was decreased by increasing particle concentration. Conclusively, it is reasonable that the nano-particles reduce the number of active nucleation sites with change of surface roughness values in nucleate boiling heat transfer. Roughness change causes a kind of fouling effect with poor thermal conduction in single phase heat transfer.

Comparisons between the experimental data and the Rhosenow correlation show that the correlation has a possibility to predict the performance with an appropriate modified liquid-surface combination factor and changed physical properties of a base liquid.

The unexpected heat transfer performance of nano-fluids is causing the problem that many research motives in this area can be frustrated. However, the possibility of CHF enhancement is still opened. As the further studies, vertical boiling test will be performed to find out an effect of settlement of nano-particles. And then, finally, CHF test will be performed to identify the possibility of application to nuclear power plant.

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Nomenclature

ϕ	particle concentration
C_p	specific heat capacity

C_{sf}	liquid-surface combination factor
n	constant
m	constant
h	heat transfer coefficient
k	thermal conductivity
Nu	Nusselt number
Pr	Prandtl number
Re	Reynolds number
q	heat flux
V	voltage
I	electric current
A	heated surface area
T	temperature
t	time
l	wall thickness of heater
x	wall thickness position
μ	viscosity
density	
i_{fg}	latent heat of vaporization
g	gravity

Subscripts

v	volume
m	mass
p	particle
f	base fluid
g	gas
w	wall or boiling surface
sat	saturation

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