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International Journal of Heat and Mass Transfer 48 (2005) 2407–2419
International Journal of HEAT and MASS TRANSFER
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Boiling heat transfer performance and phenomena of Al_2O_3–water nano-fluids from a plain surface in a pool

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Received 24 August 2004; received in revised form 31 December 2004
Available online 16 March 2005

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 smooth horizontal flat surface (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. On the other hand, CHF has been enhanced in not only horizontal but also vertical pool boiling. This is related to a change of surface characteristics by the deposition of nano-particles. In addition, comparisons between the heat transfer data and the Rhosenow correlation show that the correlation can potentially predict the performance with an appropriate modified liquid-surface combination factor and changed physical properties of the base liquid.

Keywords: Nano-fluid; Nano-particle; Boiling; CHF; Visualization

1. Introduction

During the past five decades rapid advances in engineering technology related to nuclear energy, fossil energy, electric power generation, ink-jet printers, and electronic chips cooling have expedited research in a variety of subjects related to heat transfer. Among the subjects, many engineering systems include problems related to boiling. In this regard, associated phase change heat transfer has been used extensively to acquire good heat transfer performance. Accordingly, various techniques for enhancement of the boiling heat transfer have been proposed and studied. Typical approaches that have been considered to enhance ‘‘pool’’ boiling and critical heat flux (CHF) in particular include [1]: (a) oxidation or selective fouling of a heater surface to increase the wettability of the liquid; (b) vibration of heaters to promote the departure of bubbles from a heater surface; (c) coating or extended heater surface to increase the heat transfer area; (d) heater rotation to promote bubble departure from and liquid deposition onto the heater surface; (e) fluid vibration to promote bubble departure and liquid supply; and (f) application of electric fields to promote bubble departure from the surface by dielectrophoretic force to increase liquid renewal.

In addition to these methods, nano-fluid technology has emerged as a new technique in recent years.

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0017-9310/$ - see front matter
doi:10.1016/j.ijheatmasstransfer.2004.12.047

Nomenclature

A	heated surface area
C_p	specific heat capacity
C_{sf}	liquid-surface combination factor
C_{CHF}	pool boiling CHF orientation coefficient
g	gravity
f	orthogonal position
h	heat transfer coefficient
I	electric current
i_{fg}	latent heat of vaporization
k	thermal conductivity
l	wall thickness of heater
m	constant
n	constant
NF	nano-fluid (4NF:4 vol.% alumina nano-fluid)
Nu	Nusselt number
Pr	Prandtl number
q	heat flux
R_a	roughness parameter, $R_a = \frac{1}{L}\int_0^L \mid f(x) \mid \mathrm{d}x$
Re	Reynolds number
R_q	roughness parameter, $R_q = \sqrt{\frac{1}{L}\int_0^L f(x)^2 \mathrm{d}x}$
T	temperature
t	time
V	voltage
x	wall thickness position

Greek symbols

ϕ	particle concentration
μ	viscosity
ρ	density
θ	orientation angle
σ	surface tension

Subscripts

f	saturated liquid or base liquid
g	saturated vapor
m	mass
v	volume
p	particle
sat	saturation
w	wall or boiling surface

Nano-fluid was created by Choi [2] as a next-generation fluid that may revolutionize heat transfer. By adding tiny particles to a conventional fluid, up to 40% of the fluid's capability to transfer heat can be improved. That is, the dispersion solution, (i.e., the nano-fluid), which is produced by dispersing nano-particles into fluids, is known to significantly enhance the poor thermal conductivity of the water [2,3]. The original concept of nano-fluid is that suspensions that contain solid particles have effective thermal conductivity by their mixing effects. In the past, particles of millimeter or micron scale have been added to fluids to enhance thermal conductivity; however, all of the studies using the concept have been faced with severe problems including sedimentation, abrasion and clogging due to the large size of the particles [2,7]. The nano-particles used in nano-fluids commonly have a small average size, below 100 nm in diameter Therefore, nano-fluid technology has succeeded in the enhancement of thermal conductivity without the aforementioned problems.

Xuan [7] summarized the main factors that enhance heat transfer as follows: (a) the nano-particles' increased surface area; (b) increased interaction and collisions among the particles and fluid; and (c) increased mixing fluctuation and turbulence of the fluid. Owing to these attributes, it is expected that the heat transfer performance of water, the most widely used coolant, can be improved. Naturally, many researchers first expected the augmentation of boiling heat transfer performance and the deterioration of CHF limit due to an earlier boiling crisis resulting from the coalescences of too many produced bubbles by enhanced boiling. However, two recently published papers provided interesting results in relation to boiling heat transfer and CHF. One work shows that nano-particles of Al_2O_3 deteriorate boiling heat transfer performance [4]. In particular, Das et al. [4] insisted that the degradation of boiling heat transfer is due to trapped particles on the surface, which are smaller than the surface roughness. On the other hand, another recent study shows that nano-particles of SiO_2 outstandingly increase CHF [5]. However, they could not precisely account for the enhancement of CHF, conjecturing that the effect was related to the surface coating of the silica affecting the nucleation site density of the surface.

In this regard, studies and understanding of the boiling heat transfer characteristics of nano-fluids are very much in an infant stage. In order to understand the characteristics more extensively, the boiling heat transfer characteristics for Al_2O_3–water nano-fluids are studied on a horizontal flat surface with highly smooth roughness in a pool to a higher heat flux level. Their boiling phenomena are also investigated using a visualization technique in order to elucidate the mechanisms and the differences between the fluids. In addition, CHF characteristics are investigated for both a horizontal flat surface and a vertical flat surface.

2. Experiment

The experiment is divided into four sub-tests: preparation of nano-fluids; boiling heat transfer measurement; visualization of boiling phenomena; and CHF measurement.

2.1. Preparation and properties of nano-fluids

Alumina nano-fluids are prepared by dispersing alumina nano-particles into water as a base fluid. The reasons for using Alumina nano-fluids are that they are widely used in this research area owing to requirements such as stable, uniform, and continuous suspension without any outstanding chemical change of the base fluid and also that the physical properties of alumina nano-fluid have been well documented. Alumina nano-particles used in this work are manufactured by the patented physical vapor synthesis (PVS) Process of Nanophase Technologies Corporation and have the following properties: bulk density = 260 kg/m^3, true density = 3600 kg/m^3, specific heat = 765 J/kg K, melting point = 2046 °C.

Generally, the properties of the nano-fluid depend on the properties of the nano-particles, 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.

As shown in the photo of Fig. 1(a) taken by transmission electron microscopy (TEM), alumina nano-particles have a spherical shape. The size has a normal distribution in a range from 10 nm to 100 nm (47 nm avg. diameter is given from the manufacturer). In order to ensure a stable, uniform, continuous suspension, the dispersion solutions are vibrated in an ultrasonic bath for about 8 h just before the boiling test is performed. Through this preparation, the solution temperatures increase from 20 °C to approximately 55 °C. Four alumina nano-fluids with different mass concentrations for the experiment are prepared by controlling the amounts of the particles.

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

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

This equation leads to the next density expression for a solution of liquid–solid.

$$\rho = \rho_f(1 - \phi_v) + \rho_p\phi_v \tag{2}$$

This equation can easily derive the next relation for heat capacity [6].

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

The thermal conductivity of the solution can be easily calculated through a simplified Hamilton and Crosser model without considering the temperature effect of Das et al. [12] as the following equation [2].

$$k/k_f \approx 1 + n\phi_v \tag{4}$$

Actually, though a dramatic increase in the enhancement of conductivity takes place with temperature, rough estimation using the model is meaningful in our description of Section 3.1 as an indication of enhancement of the thermal conductivity by nano-particles.

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

In a fluid, viscosity and surface tension are also considered important properties. Das et al. [4] have performed a rheological study on alumina nano-fluids. With increasing particle volume fraction, viscosity displayed higher values than that of water. Also, the following equation may be applied in the prediction of viscosity of nano-fluids [8].

$$\mu = \mu_f(1 + 2.5\phi_v) \tag{5}$$

Surface tension has only changed slightly in their results. Therefore, the change of the properties of water should have a negligible effect on the present heat transfer results.

2.2. Boiling experimental facility and procedure

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

A test plane heater with copper electrodes is heated by a DC power supply of HP 6680a with a maximum capacity of 4.375 kW(5 V, 875 A). The boiling surface of the test plane heaters is 4×100 mm^2 rectangular with a depth of 1.9 mm. At the back of the boiling surface, four holes are machined where 4 K-type thermocouples are imbedded at a depth of 1 mm with silver welding to measure the boiling surface temperature. The surface roughness of the boiling surface is controlled by sandpaper of grade #2000. The signals of the 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 a 1 kW pre-heater. In the case of the horizontal test, water in the outer isothermal vessel is preheated to saturation temperature using the 1.5 kW pre-heater in order to keep the inner fluid temperature saturated. The exterior of the experimental facility is insulated by thermal insulating materials.

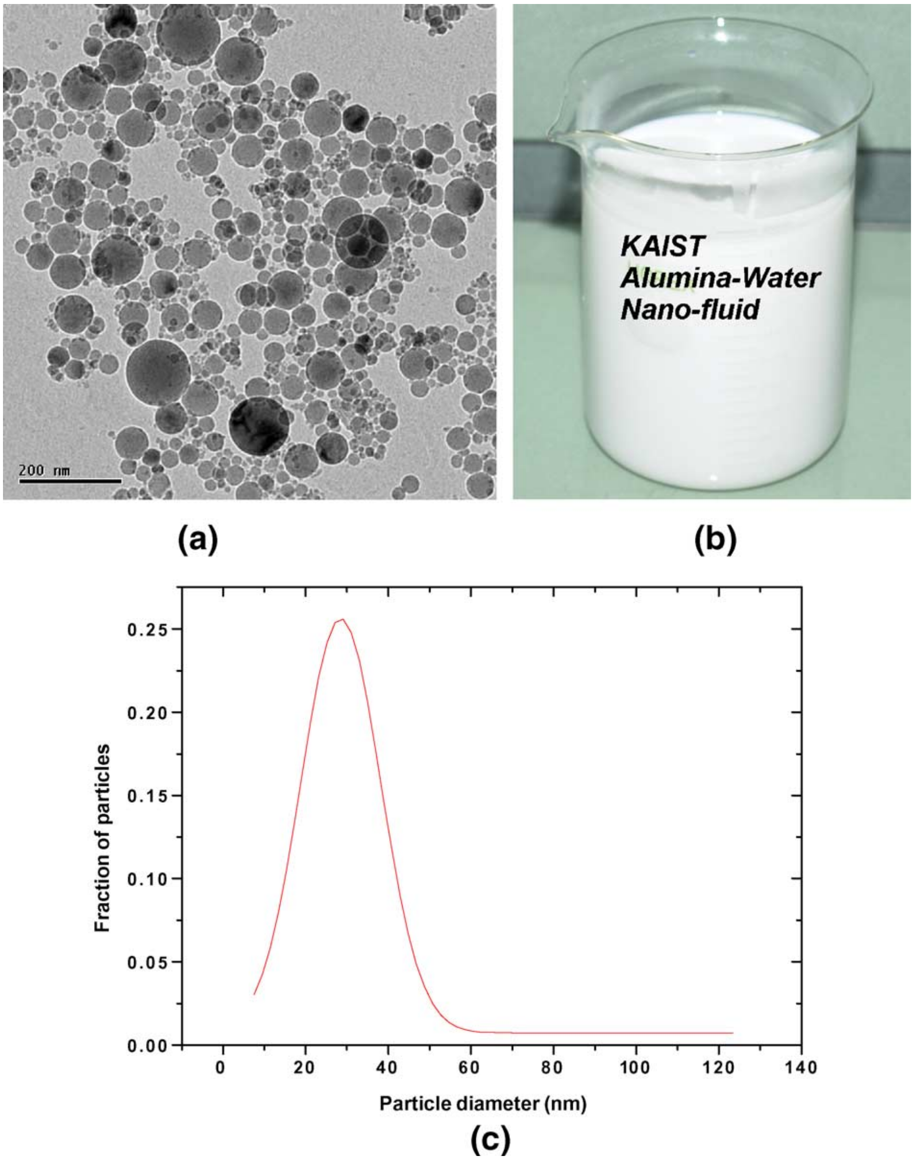

Fig. 1. Characteristics of nano-fluid: (a) TEM photograph of Al_2O_3 nano-particles, (b) photograph of Al_2O_3 nano-fluid, (c) size distribution of the nano-particles.

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

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

$$q = \frac{VI}{A} \tag{6}$$

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

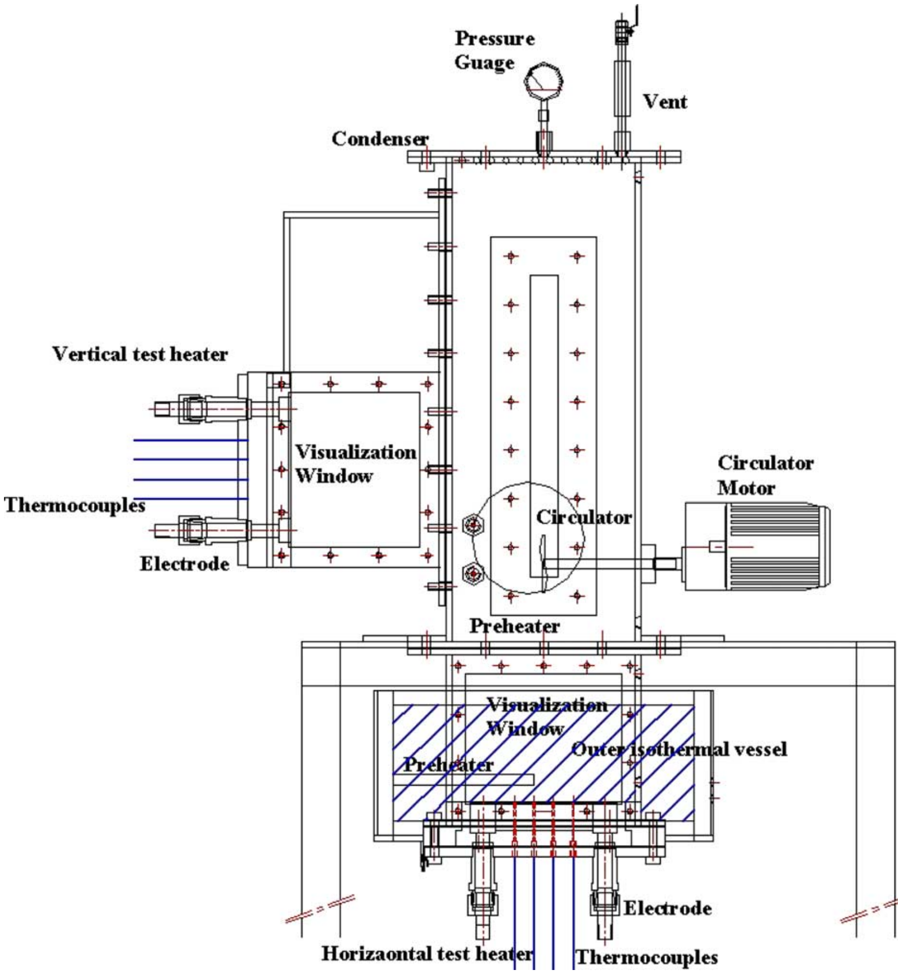

Fig. 2. Nano-fluid boiling experimental facility.

$$T = \frac{1}{At}\int_A \int_t T\,dA\,dt \tag{7}$$

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

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

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

$$h = q/\Delta T_w, \tag{9}$$

$$\Delta T_w = T_w - T_{sat}. \tag{10}$$

2.3. Uncertainty analysis

The uncertainties of the measurement parameters are analyzed by the error propagation method [11]. The uncertainties of the heated area and the applied heat flux are less than ±5% and ±5.2%, respectively. The uncertainty associated with the temperature is ±0.5 °C. The difference in the wall superheat attributable to the uncertainties is 2 °C at a heat flux of 604 kW/m^2, depending on the heat flux and the embedding distance of thermocouples. The uncertainty for the boiling heat transfer coefficient is about 7.5%.

3. 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 determine the reasons of the deterioration of the boiling heat transfer, surface roughness of identical samples as those used in the test heater is measured using a non-contact coordinate measuring machine, NanoScan of Intekplus company for pure water and 0.5% and 4% alumina nano-fluids.

Also, the boiling phenomena of pure water and the nano-fluids are compared through a visualization test using a Kodak motion coder SR-1000 high-speed camera and a Nikon D1 digital camera. In addition, CHF enhancements are identified through the performance tests.

3.1. Pool boiling heat transfer coefficient

The measurements of the temperature of the boiling surface are shown in Fig. 3(a). The addition of alumina nano-particles caused the water boiling curve to shift to the right, i.e. a decrease of pool nucleate boiling heat transfer. Compared with that for low volume concentrations, the temperature of the boiling surface was increased at the same heat flux for 2% and 4% nano-fluids. This shows that the heat transfer coefficient was decreased by increasing particle concentration.

Fig. 3(a) also shows clear distinctions between the natural convection stage and nucleate boiling stage. In the case of nano-fluids, the natural convection stage continues relatively longer and nucleate boiling is delayed or higher superheat of the boiling surface is needed for boiling.

The above results appear inconsistent with the increased thermal conductivity of nano-fluids.

For pool nucleate boiling correlation considering surface characteristics, Rhosenow [9] proposed the following equation

$$Nu = \frac{1}{C_{\mathrm{sf}}} Re^{(1-n)} Pr_{\mathrm{f}}^{-m} \tag{11}$$

or

$$h = \frac{1}{C_{\mathrm{sf}}} \left[\frac{c_{\mathrm{pf}} q}{i_{\mathrm{fg}}}\right] \left[\frac{q}{\mu_{\mathrm{f}} i_{\mathrm{fg}}} \left(\frac{\sigma}{g(\rho_{\mathrm{f}} - \rho_{\mathrm{g}})}\right)^{1/2}\right]^{-n} \left[\frac{c_p \mu}{k}\right]_{\mathrm{f}}^{-(m+1)} \tag{12}$$

This can be used for two objectives. One use is to determine if our pool boiling characteristics for pure water are reasonable. Fig. 4(a) shows that the data for pure water correspond closely with the correlation. The other use is to predict some effects of nano-fluids. In Section

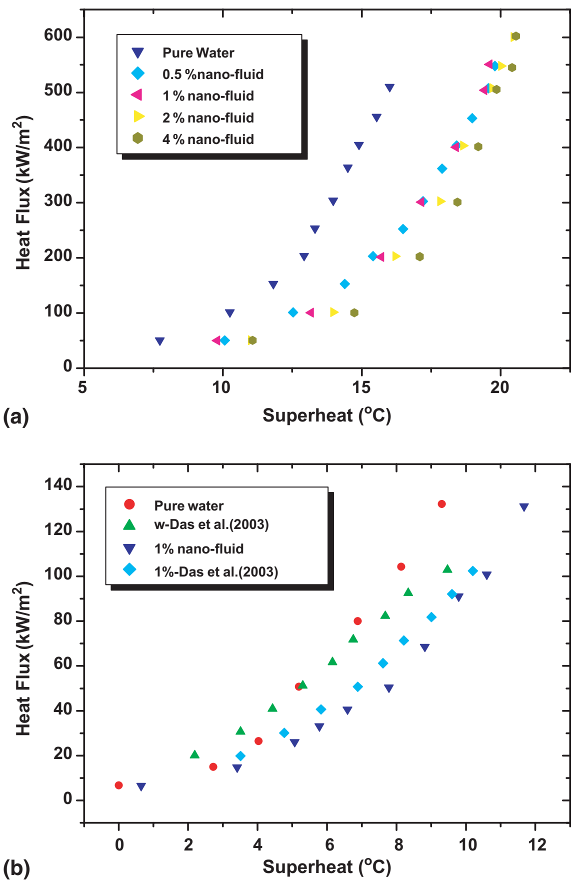

Fig. 3. Boiling curves of pure water and nanofluids & characteristics at low heat flux of natural convection.

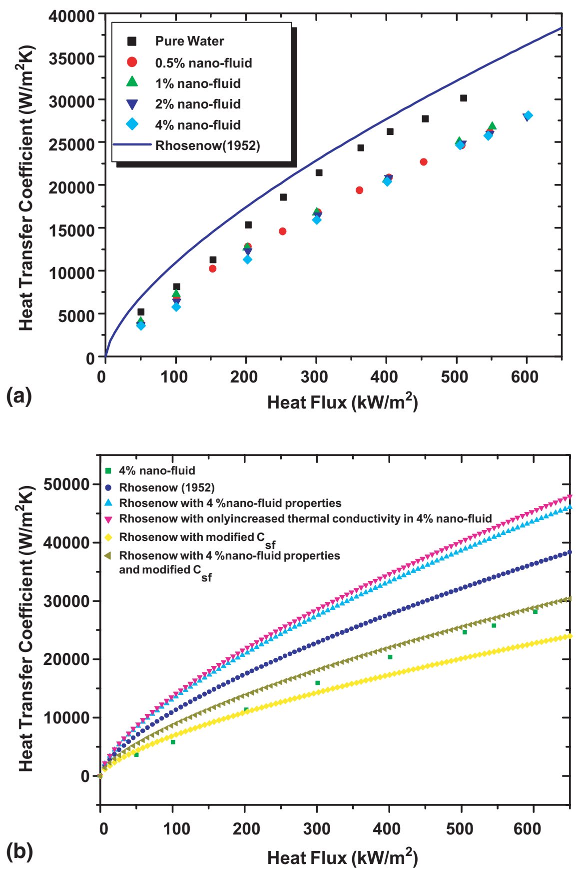

Fig. 4. Boiling heat transfer coefficients and applicability of Rhosenow's [9] correlation.

2.1, almost all properties of the nano-fluids are predicted. If these properties are used for calculation of the heat transfer coefficient, the value can be acquired as shown in Fig. 4(b). Various applications for the correlation have been attempted in the present study with variation of the property values. The results indicated that the thermal conductivity (or the conductivity by extrapolations from the temperature effect of Das et al. [12], roughly ~20% more increased) or other properties varied in the nano-fluids does not affect the boiling heat transfer whereas the altered surface characteristics does impact the heat transfer. Comparisons between the experimental data and the Rhosenow correlation show that the correlation can potentially predict the performance with an appropriate modified liquid-surface combination factor and changed physical properties of the base liquid. Further discussion of this is provided in Section 3.3.

In addition, Fig. 3(b) shows that the experiment yielded different rates of heat transfer from that of

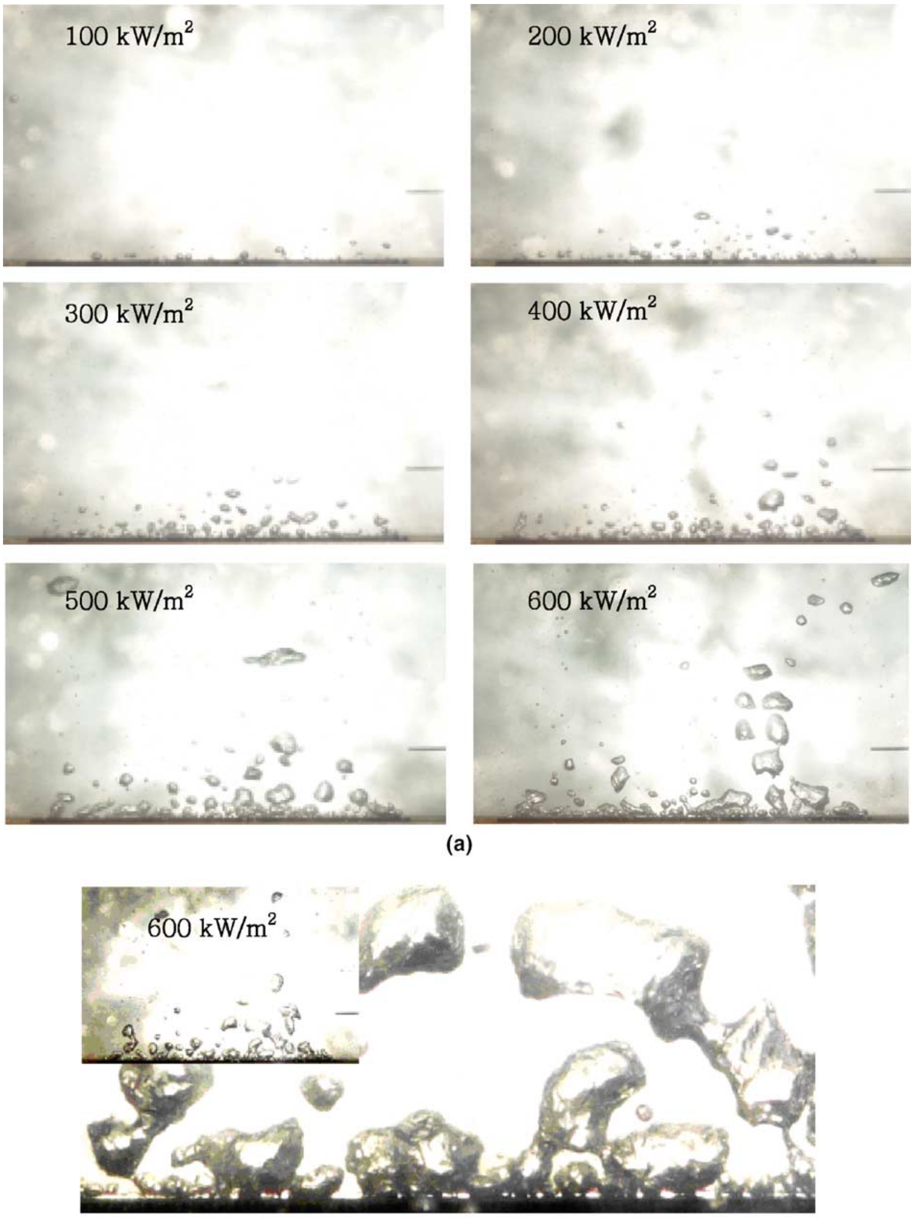

Fig. 5. General pool boiling phenomena of pure water: (a) with heat flux, (b) near-wall magnification.

Das et al. [4], because of the geometrical features, i.e., a rectangular channel. The present results show a clear distinction between natural convection and a nucleate boiling well.

3.2. Visualization of pool boiling phenomena

In this work, pool boiling phenomena are observed in order to elucidate the nano-fluid heat transfer mechanism. Fig. 5 shows the main regimes in nucleate boiling, a discrete bubble regime and a coalesced bubble regime in pure water. The phenomena correspond to the boiling curve of Fig. 3(a). The slope of the boiling curve is changed below 100 kW/m^2 with the onset of nucleate boiling, and at higher heat flux, more active nucleate boiling is shown on the boiling surface.

Fig. 6 shows the results observed by a high speed camera with an interval of 0.004 s. # denotes the original record sign from the tests. The water–Al_2O_3 nano-fluids have the same color (white) as the nano-particles. With increasing particle concentration, the color becomes much deeper. As such, the bubbles cannot be clearly observed in general boiling tests. Visualization of the nano-fluid boiling phenomena is only possible at high heat flux over 500 kW/m^2 and at a low particle concentration of 0.5% volume fraction.

The pictures with #9 signs show the sequential bubble behavior in pure water whereas those with #12 signs show the sequential bubble behavior in the nano-fluid. Overall nucleate boiling phenomena are similar in the two fluids. However, there is a large difference in the amount of vapor and the number of bubbles observed. This is apparently a result of the poor visualization conditions of the nano-fluid. However, it may also be due to less active nucleate boiling than that in pure water. This corresponds to the boiling curve characteristics of the nano-fluids. The surface characteristics are discussed in this regard in the next section.

3.3. Discussion on changed boiling performance

The unexpected heat transfer performance of nano-fluids is opposite to their properties as a fluid. Therefore, the reasons for this conflicting performance may be related to differences in the surface characteristics between the boiling surface and nano-fluids. Das et al. [4] found that the surface roughness considerably decreased. They contend that the reduction is the cause of the boiling characteristics. However, it should be noted that their smooth heater has a roughness that is much larger than the size of nano-particles. In the case of the present study, the test heater has a 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 on average with increasing

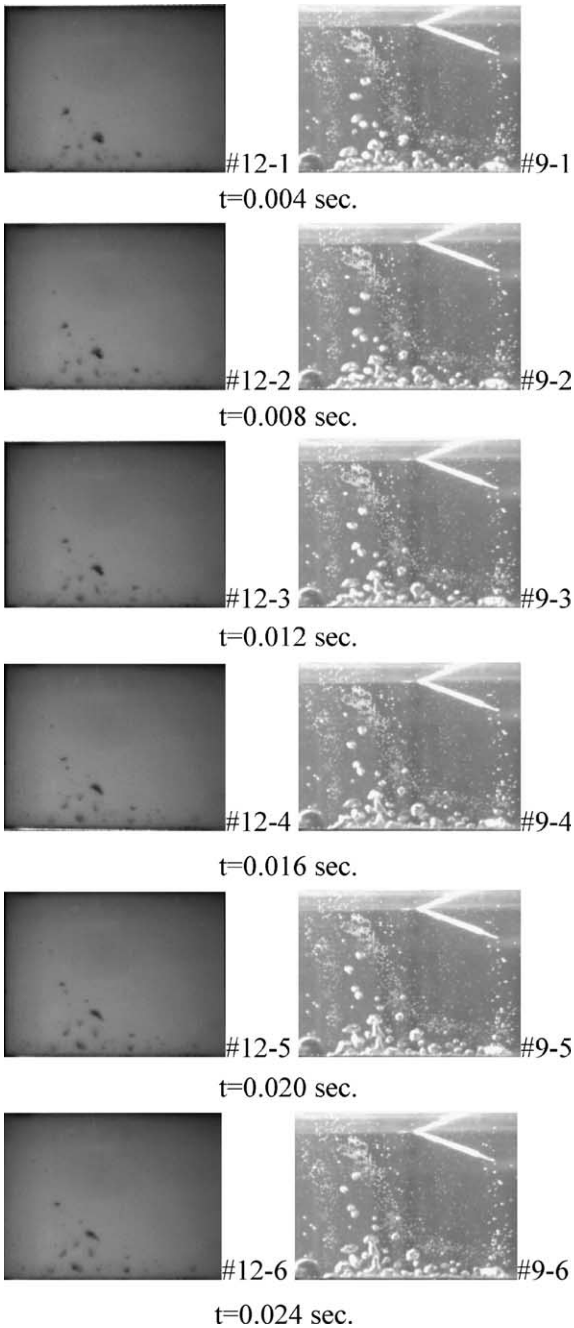

Fig. 6. Comparison of boiling behaviors (0.5% vol. water–Al_2O_3 nano-fluid(#12), q = 550 kW/m^2; pure water(#9), q = 500 kW/m^2; using high speed camera).

particle concentration, as shown in Fig. 7. High concentration means that the nano-fluid contains more nano-particles. Therefore, in higher concentrated nano-fluid, more particles move around themselves or heated surface, which is thought as the stochastic

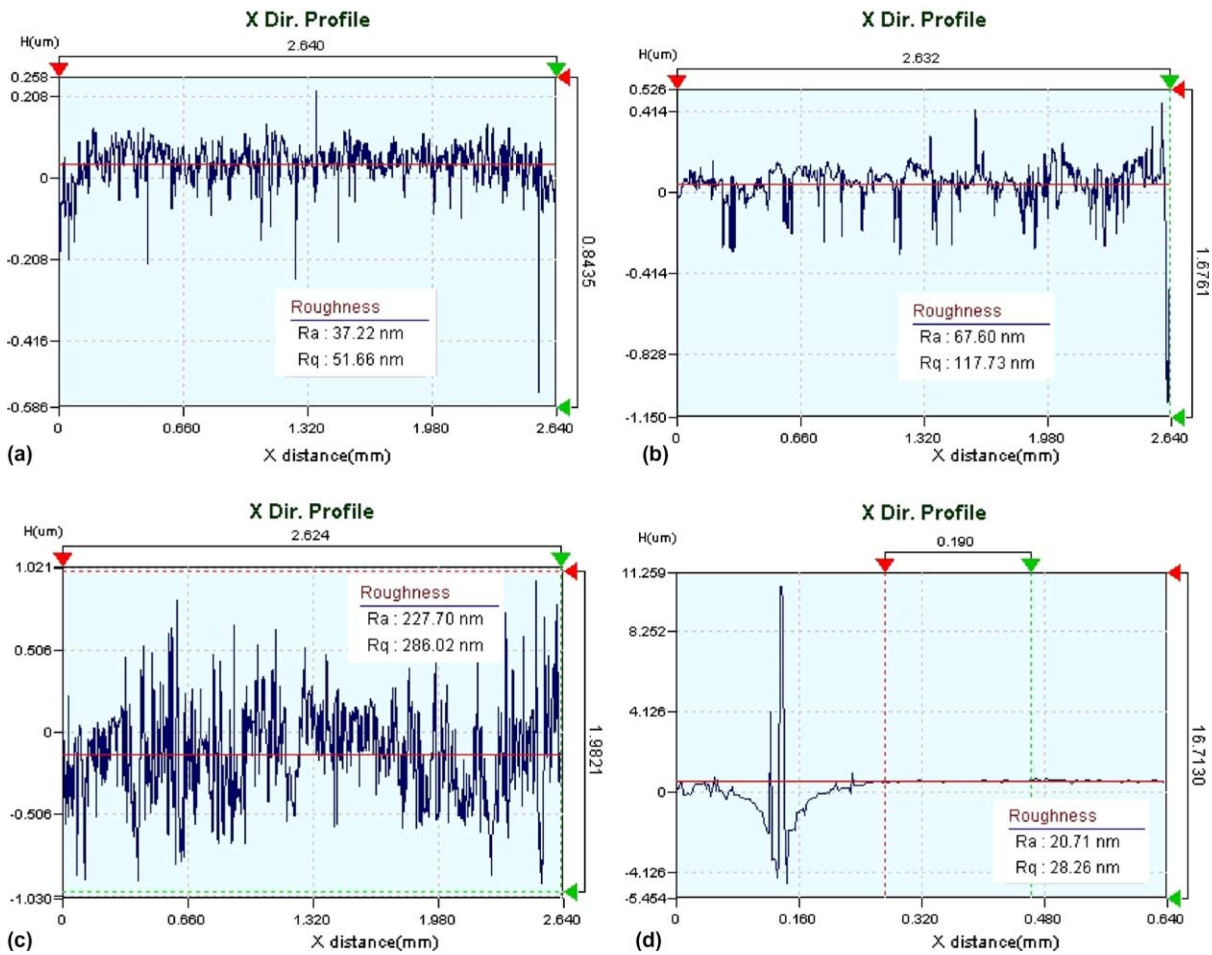

Fig. 7. Representative surface roughness: (a) clear heater, (b) heater submerged in 0.5% alumina NF, (c) 4% alumina NF, (d) locally smoothed heater in 0.5% NF.

(Brownian) motion of the particles [12] and then, more agglomerates form and attach to the heated surface, which is considered as a kind of fouling. As actually an indication of the result, the roughness value was changed with increasing concentration.

In addition, in order to investigate the surface coating effect, we have performed roughness measurements before and after submersion in the nanofluid for various samples with differently roughened surfaces processed by different sandpapers (#2000, 300, and 100). Fig. 8 shows the roughness changes in various samples. Here, the measured roughness values are shown with each confidence interval. The coating is not so firm. However, it is hard to remove the coating fully by water-jet. The large change of the roughness after CHF is due to the burn-out of the heater metal.

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 an important factor. Both factors

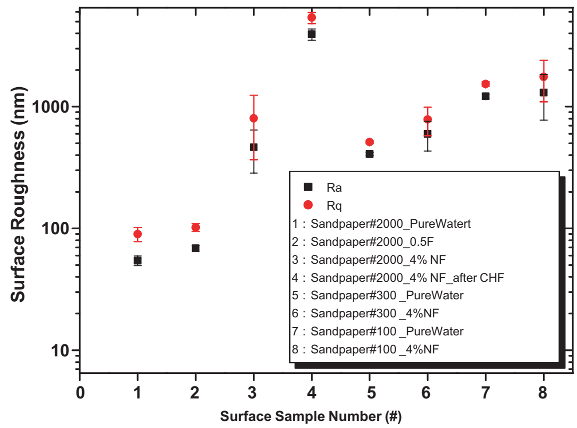

Fig. 8. Surface roughness change of samples.

of roughness and particle size are simultaneously considered in the effects. Fig. 7(d) shows the locally smoothed roughness in the present study. It appears to agree with the results of Das et al. [4]. In here, our consideration is that the surface roughness can be increased and decreased by nano-fluid (nano-particles) depending on both original surface condition and the size of nano-particles. If the original surface roughness is smaller than nano-particles, it can be increased as our results. Reversely, if the original surface roughness is larger than nano-particles, it can be decreased as Das et al's results and local observation of our results. Measurement of surface roughness is just one method for identifying that surface is coated by the nano-particles (fouling effects). On the other hand, for a relatively 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. 9. This figure presents surface images reconstructed by image software with the roughness values.

In Fig. 9, the first image shows a magnified surface of a sample on which scratched roughness can be identified.

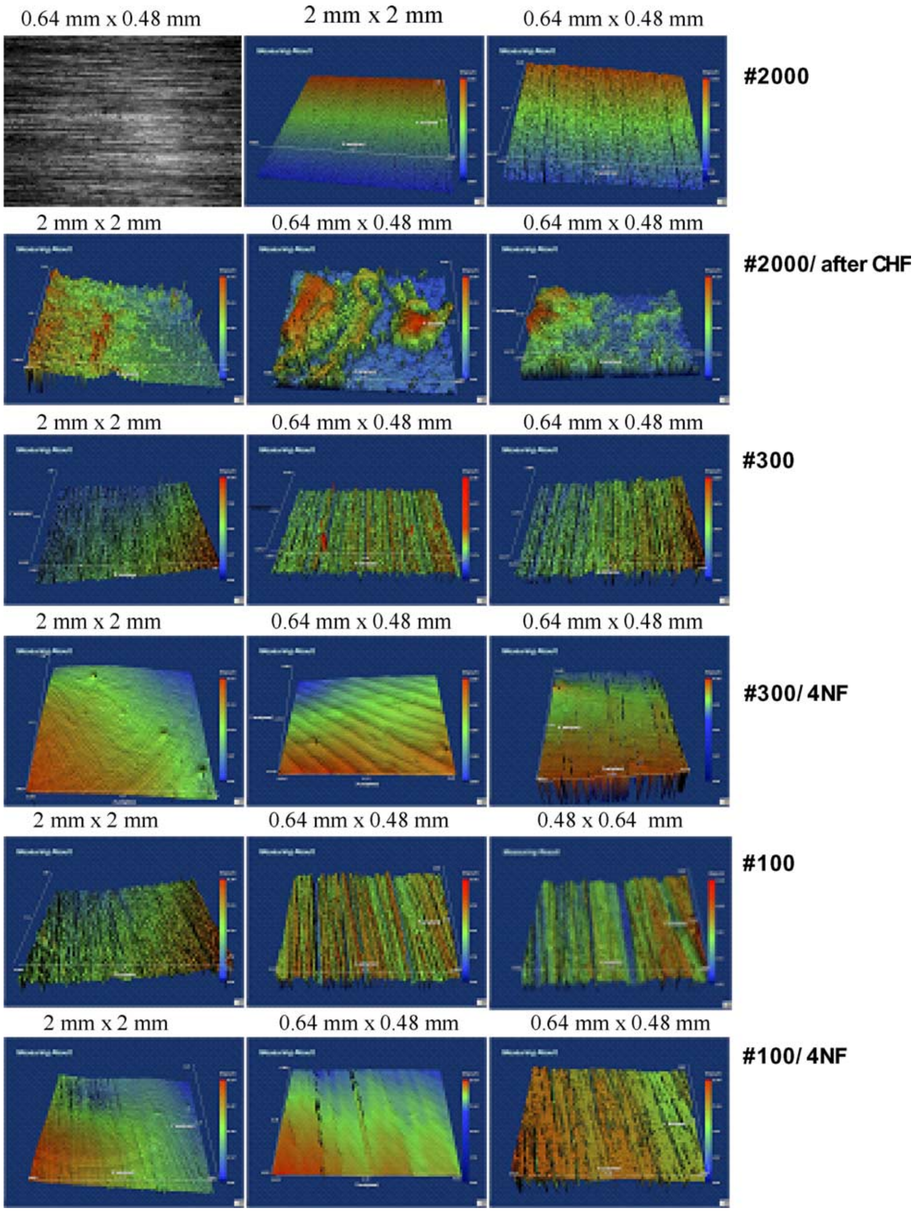

Fig. 9. Visualization of the surface roughness (#2000/after CHF, #300/submersion, #100/submersion).

The surface image for #2000 after CHF is shown, which indicates that the nano-fluid can have a surface coat.

Conclusively, it is reasonable that the nano-particles reduce the number of active nucleation sites with variation 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 relatively small heat transfer difference among the nano-fluids with different particle concentrations, shown in Fig. 3, because the concentration effect is smaller than the coating effect.

3.4. CHF performance

In the previous section, boiling heat transfer characteristics of nano-fluids with nano-particles suspended in water were studied using four different volume

Table 2
Critical heat flux enhancement

	Prediction for water	Pure water	0.5% NF	1% NF	2% NF	4% NF
Horizontal test Section (θ = 90)	1.22 MW/m^2	1.74 MW/m^2	2.30 MW/m^2	2.64 MW/m^2	2.57 MW/m^2	2.4 MW/m^2
Vertical test Section (θ = 0)	0.88 MW/m^2	1.2 MW/m^2	1.36 MW/m^2	1.36 MW/m^2	1.36 MW/m^2	1.36 MW/m^2

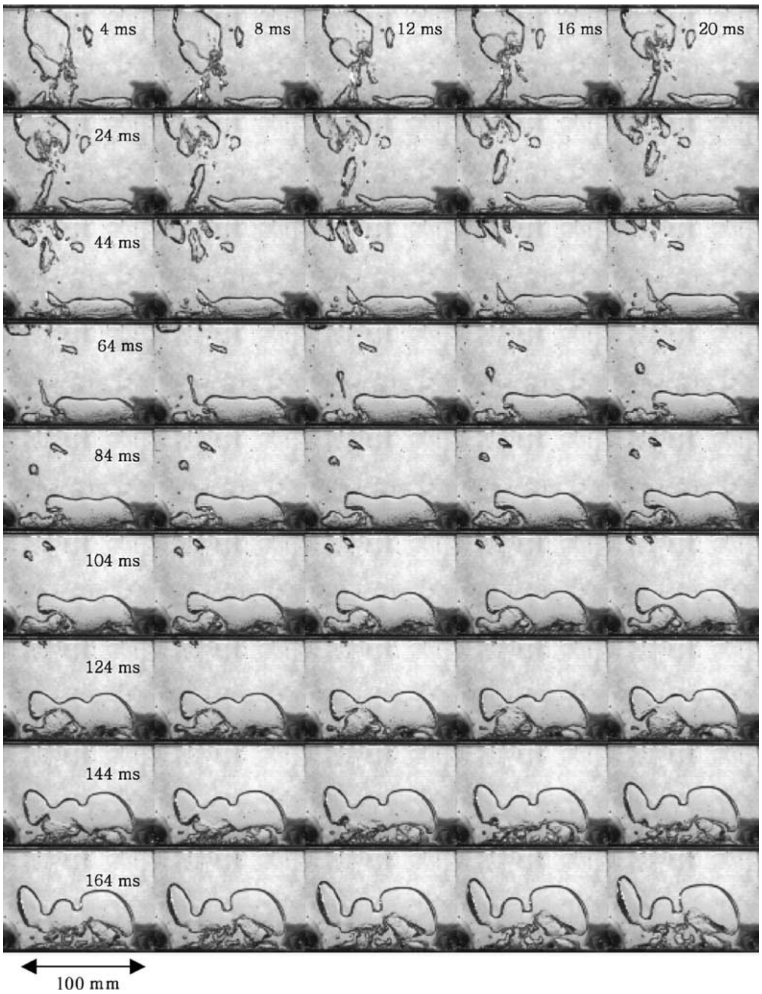

Fig. 10. Flow pattern at a high heat flux in pure water (lateral view from horizontal heater at 90% CHF).

concentrations of alumina nano-particles on a flat surface of a pool. In this section, CHF characteristics are investigated in both horizontal and vertical pool boiling.

Generally, the following CHF prediction correlation is used in pool boiling [10]

$$q_{\mathrm{m}} = C_{\mathrm{CHF,f}}(\theta)\rho_{\mathrm{g}} i_{\mathrm{fg}} \left[\frac{\sigma(\rho_{\mathrm{f}} - \rho_{\mathrm{g}})g}{\rho_{\mathrm{g}}^2}\right]^{1/4}, \tag{13}$$

$$C_{\mathrm{CHF,water}}(\theta) = 0.034 + 0.0037(180 - \theta)^{0.656}, \tag{14}$$

For a heater with narrow width, increase of CHF is reported [13]. Therefore, in this work, CHF data is significantly higher than that obtained with a flat wide heater. Table 2 shows the results of the CHF tests. For the horizontal test section, ~32% of CHF increased while for a vertical test section ~13% of CHF increased. Each CHF value is the average value of three repeated measurements.

Figs. 10 and 11 show boiling phenomena near CHF of pure water and 0.5% nano-fluid in the horizontal geometry. Each image with a large growing vapor bubble is acquired by a high speed camera with a time interval of 0.004 s. A flow pattern characterized by a vapor mushroom in high heat flux boiling phenomena is observed commonly in both cases. In the previous section, the addition of alumina nano-particles caused a decrease in the pool nucleate boiling heat transfer of pure water. This is attributed to the coating of the surface by nano-particle sedimentation. In this regard, the causes for CHF enhancement are similar to those of the boiling heat transfer. Otherwise, the change of CHF is due to a possible surface coating effect that would change with the nucleation site density. Less active nucleation will generate less bubbles and, in turn, less coalescence or large vapor blankets to interfere with the supply of liquid to the surface. In addition, the nano-coating also can give the causes of the

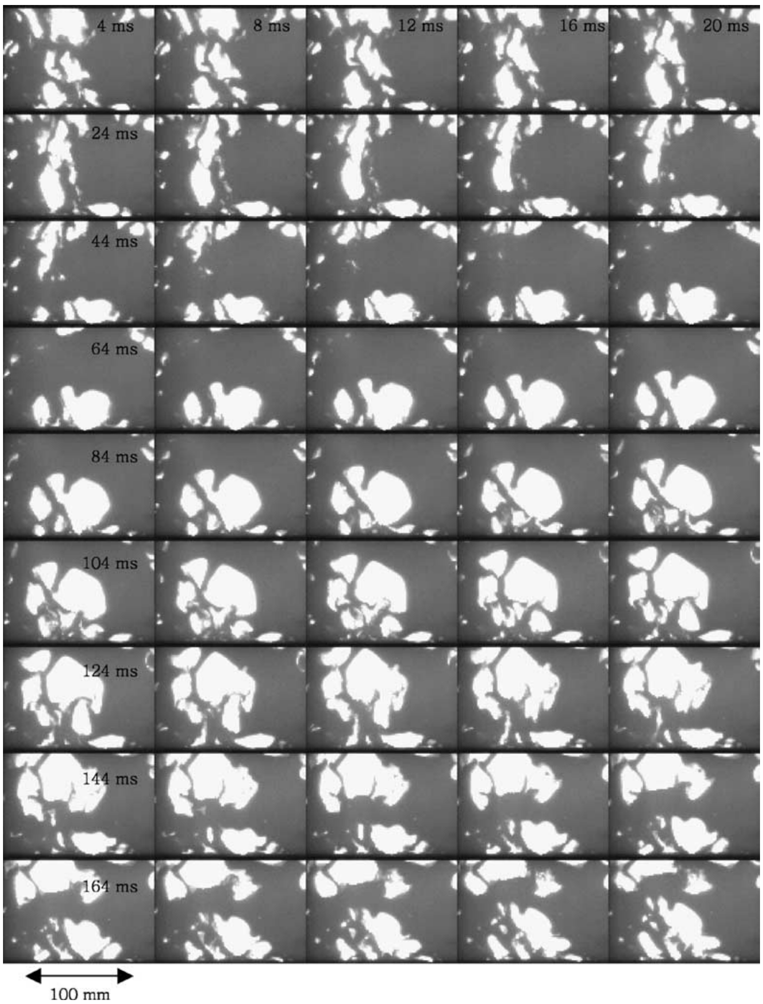

Fig. 11. Flow pattern at a high heat flux in 0.5% alumina nano-fluid (lateral view from horizontal heater at 90% CHF).

enhancement such as trapping of liquid near the surface due to porous characteristics of the coating, breaking up the voids near the surface and preventing blanketing from occurring as easily.

The enhancement of the critical heat flux observed are much lower than that observed in Vassallo et al. [5]. In relation to the reason for this difference, in pool boiling CHF, generally CHF conditions are affected according to various factors such as surface conditions (roughness or nucleation site density) of the heater, geometry, geometry orientation, impurities, liquid subcooling and so on. In here, actually, we used alumina nano-particles different from silica nano-particles in Vassallo et al.'s work and also used other geometry of heated surface. We insisted that the reason on CHF performance change might be due to surface coating effect. We considered that the difference in surface coating (for example, coating thickness or effect on nucleation site density) due to particles with different properties and size between two nano-fluid could give the CHF performance distinction between those fluids.

4. Conclusions

Boiling heat transfer characteristics of nano-fluids with nano-particles suspended in water were studied using four different volume concentrations of alumina nano-particles. Pool boiling heat transfer coefficients of nano-fluids measured on a flat surface in pool were compared to the coefficient of pure water. Alumina-water nano-fluids show different performance and phenomena compared to pure water in terms of natural convection and nucleate boiling. The addition of alumina nano-particles caused a decrease of the pool nucleate boiling heat transfer. The heat transfer coefficient was decreased by increasing particle concentration. On the other hand, CHF performance has been enhanced to $\sim$32% and $\sim$13%, respectively, for both horizontal flat surface and vertical flat surface in the pool due to delayed boiling activity. A flow pattern characterized by a vapor mushroom in high heat flux boiling phenomena is observed in both pure water and nano-fluid. Conclusively, it is reasonable that the nano-particles reduce the number of active nucleation sites with variation 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 can potentially predict the performance with an appropriate modified liquid-surface combination factor and changed physical properties of the base liquid.

Acknowledgments

The financial support from the Korea Atomic Energy Research Institute(KAERI) is appreciated. Special thanks are also given to Dr. S.Y. Chun, Dr. S.K. Moon, Dr. S.H. Kim, Dr. J.H. Song, Dr. B.T. Min of KAERI.

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