Experimental Thermal and Fluid Science 38 (2012) 229–236

Contents lists available at SciVerse ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs

Studies on nanoparticle coating due to boiling induced precipitation and its effect on heat transfer enhancement on a vertical cylindrical surface

Ramakrishna N. Hegde [a,*], Shrikantha S. Rao [b,1], R.P. Reddy [c,2]

[a] National Institute of Technology, Surathkal 575 025, India
[b] Department of Mechanical Engineering, National Institute of Technology, Surathkal 575 025, India
[c] Reva Institute of Technology, Yelahanka, Bangalore 560 064, India

ARTICLE INFO

Article history:
Received 13 March 2011
Received in revised form 13 September 2011
Accepted 17 December 2011
Available online 28 December 2011

Keywords:
Nanofluid
Surface roughness
BHT
Cylindrical surface

ABSTRACT

Pool boiling experiments were conducted to study the heat transfer characteristics using low concentrations (0.1–0.5 g/l) of Alumina-nanofluid at atmospheric pressure in distilled water. The study involved investigation on the effect of nanoparticle coating on the vertical test surface exposed to multiple heating cycles, heat transfer characteristics of nanoparticle coated surface in distilled water and pool boiling behavior of Alumina nanofluid subjected to transient characteristics. In order to quantify the result, surface roughness of the cylindrical surface was measured at different concentrations of nanofluid before and after the experiments. At atmospheric pressure, different concentrations of nanofluids displayed different degrees of deterioration in boiling heat transfer. Coating of nanoparticles was observed on the heater surface due to boiling induced precipitation. The nanoparticle coated heater when tested in pure water showed significant increase in CHF comparable to CHF of bare heater tested in pure water. Study on transient characteristics of the nanofluid, keeping the heat flux constant for a specified time interval showed degradation in boiling heat transfer. The longer the duration of exposure of the heater surface, the higher was the degradation in heat transfer. Based on the experimental investigations it can be concluded that nanoparticle coating can be a potential substitute for enhancing the heat transfer.

1. Introduction

Of late, nanofluids have generated great interest with ever growing demand for new materials possessing advanced thermal properties. With increasing heat transfer rate of the heat exchanging equipment, the conventional process fluid with low thermal conductivity can no longer meet the requirements of high-intensity heat transfer. Low thermal property of heat transfer fluids is a primary limitation to the development of high compactness and effectiveness of heat exchangers. An effective way of improving the thermal conductivity of fluids is to suspend small solid particles in the fluids [1]. Traditionally, solid particles of micrometer or millimeter magnitudes were mixed with the base liquid. Although the solid additives may improve heat transfer coefficient, practical uses are limited because the micrometer and/or the millimeter-sized particles settle rapidly, clog flow channels, erode pipelines and cause severe pressure drops. The concept of nanofluids refers to a new kind of heat transport fluids obtained by suspending nanoscaled metallic or nonmetallic particles in base fluids. Some experimental investigations [2–5] have revealed that the nanofluids have remarkably higher thermal conductivities than those of conventional pure fluids and have great potential as substitute fluids for heat transfer enhancement. Nanofluids are more suitable for practical applications than the existing techniques used for enhancing heat transfer by adding millimeter and/or micrometer-sized particles in fluids. Nanoparticles used with a base fluid like water incur little or no penalty in pressure drop as they behave like a pure fluid.

Initial studies on pool boiling were mainly concerned with boiling heat transfer coefficients (BHT) and critical heat flux (CHF) values. You et al. [6] and Vassallo et al. [7] showed that BHT was unaffected but CHF increased significantly. Kim et al. [8] investigated the role of nanoparticle deposition and surface wetting characteristics by measuring the static contact angle over the heater surface. Das et al. [9] studied the role of surface roughness, particle size and nanoparticle concentration on nucleate boiling heat transfer. Sefiane [10] explained the CHF enhancement due to structural disjoining pressure and contact pinning. Kim and Kim [11] reported in their experimental findings about the modification of heater

---

* Corresponding author. Address: Department of Mechanical Engineering, M.S. Ramaiah Institute of Technology, MSR Nagar, Bangalore 560 054, India. Tel.: +91 80 23600822; fax: +91 80 23603124.

E-mail addresses: rkhegderk@gmail.com (R.N. Hegde), ssrcsr@gmail.com (S.S. Rao), principalritm@revainstitute.org (R.P. Reddy).

[1] Tel.: +91 0824 2474000; fax: +91 0824 2474033.

[2] Tel.: +91 080 65687563; fax: +91 080 2847854.

0894-1777/$ - see front matter © 2011 Elsevier Inc. All rights reserved.
doi:10.1016/j.expthermflusci.2011.12.011

Nomenclature

A	surface area (m^2)
BHT	boiling heat transfer
C_p	specific heat (J/kg K)
d	diameter (m)
g	gravitational acceleration ($m\ s^{-2}$)
h	heat transfer coefficient ($W/m^2\ K$)
h_{fg}	latent heat of vaporization ($J\ kg^{-1}$)
k	thermal conductivity ($W\ m^{-1}\ K^{-1}$)
L	length (m)
M	molecular weight
Nu	Nusselt number
Pr	Prandtl number
p	pressure (Pa)
Q	heat input (W)
q	heat flux ($W\ m^{-2}\ K^{-1}$)
Ra	roughness (μm)
T	temperature (K)
TEM	transmission electron microscopy
U	uncertainty

Greek symbols

ρ	density ($kg\ m^{-3}$)
σ	surface tension ($N\ m^{-1}$)
μ	viscosity ($m^2\ s^{-1}$)

Subscripts

CHF	critical heat flux
f	fluid
nf	nanofluid
p	particle
s	saturation
v	vapor
w	wall

surface due to nanoparticle coating which resulted in CHF enhancement of about 160%. Recently, studies have been carried out on the heat transfer coefficient of nanofluids in natural and forced flow [12–19]. Most of studies [12–19] carried out up to date are limited to the thermal characterization of nanofluids without phase change (boiling, evaporation, or condensation). As nanoparticles in nanofluids can play a vital role in two-phase heat transfer systems, there is a great need to characterize nanofluids in boiling and condensation heat transfer. Kutateladze and Barshefsky [20] and Rohsenow [21] were the pioneers who made earlier attempts, both analytical and experimental, to study boiling heat transfer using pure water.

Kutateladze and Barshefsky [20] proposed the following correlation to predict pool boiling in terms of Nusselt and Prandtl numbers.

$$\mathrm{Nu} = \frac{hd}{k} = 0.44\left[\left(\frac{10^{-4}qp}{gh_{fg}\rho_v}\right)\left(\frac{\rho_f}{\rho_f-\rho_v}\right)\right]^{0.7}\mathrm{Pr}^{0.35} \tag{1}$$

Rohsenow [21] proposed the following correlation to determine the heat transfer coefficient for pure water which is quite commonly used by researchers for experimental comparison.

$$h = \frac{1}{C_{sf}}\left[\frac{C_{pf}q}{h_{fg}}\right]\left[\frac{q}{\mu_f h_{fg}}\left(\frac{\sigma}{g(\rho_f-\rho_v)}\right)^{\frac{1}{2}}\right]^{-n}\left[\frac{\mu C_p}{k}\right]_f^{-(m+1)} \tag{2}$$

In the above correlation, m is taken as 0 and C_{sf} as 0.0015 which is the empirical constant for stainless steel and water surface-fluid combination.

Compared with the research efforts in the field of thermal properties characterization (thermal conductivity, viscosity, etc.) and convective heat transfer, relatively few studies have been carried out on boiling heat transfer. Published literatures in pool boiling heat transfer using nanofluids claim contradictory results indicating lack of consistency. Understanding of heat transfer characteristics of nanofluids, especially transient behavior in pool boiling is very much in a nascent stage. This paper intends to explore the potential of nanoparticle coating formed due to boiling induced precipitation to enhance boiling heat transfer and transient characteristics of Alumina nanofluid in pool boiling.

2. Pool boiling experiment

Before conducting the pool boiling experiment it is essential to prepare and characterize the nanofluid. Preparation and characterization of Alumina nanofluid was carried out as discussed below.

2.1. Preparation and characterization of nanofluids

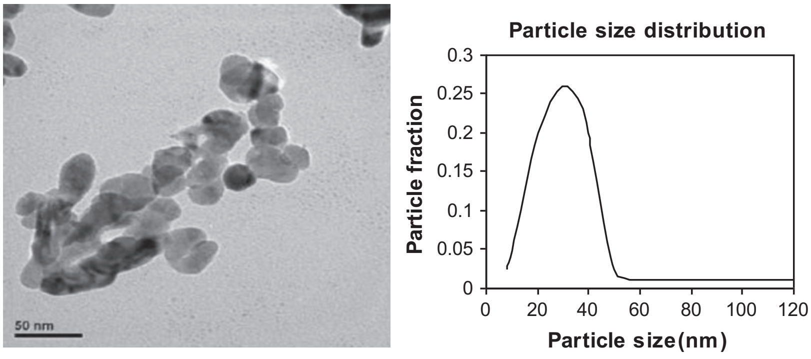
Alumina nanoparticles (purity ⩾ 99%, Average particle size = 80 nm, specific surface area = 100 m^2/g) manufactured by NaBond Technologies Corporation Limited were procured to prepare nanofluid. Nanofluid was prepared by dispersing required quantity of Alumina nanoparticles in the base fluid (distilled water). The test fluid thus obtained is considered as nanofluid only if the suspended nanoparticle did not agglomerate during experimentation and should be homogeneous. To ensure homogenization one can use dispersants or a sonicator (model Parsonic 3600 S). In this study, dispersants were not used for stabilization, as the addition of dispersants would influence the heat transfer characteristics of nanofluids. The nanofluid was stirred in a sonicator for 3 h. The test fluid sample was collected in a glass vessel and the particle size distribution was tested using a particle size analyzer. The particle size range was found to be between 10 nm and 120 nm. Fig. 1a shows the TEM image of nanoparticles dispersed in distilled water having spherical shapes (provided by the manufacturer). The particle size distribution is shown in Fig. 1b.

Fig. 2 shows the photograph of the Alumina nanofluid test samples at different mass concentrations taken 120 min after sonication. It can be observed that no agglomeration formed during this period and the fluid is homogeneous.

2.2. Pool boiling experiments

Fig. 3 shows the schematic diagram of the experimental set up. It consists of a boiling vessel of 80 mm diameter and 200 mm length made up of SS 316 fitted with flanges at the top and at the bottom. Provisions are made on the top flange for charging the nanofluid. In addition, condenser cooling water inlet and outlet pipe lines, vacuum pump line, pressure transducer and thermocouples connections also pass through the top flange with suitable openings. The bottom flange houses the test heater section and drain line. The test section is a cylindrical vertical surface of 6 mm diameter and 17 mm length with two thermocouples embedded into the surface 5 mm apart at a depth of 1 mm on the periphery. The test section is heated by an electrical heating element of 1 kW capacity. The heating element is connected to a wattmeter through a Dimmerstat (Variac) to vary the heat input during experimentation.

Saturation temperature is measured by the two thermocouples one dipped in the liquid and the other in the vapor region, at the



(a) (b)

Fig. 1. Characteristics of nanofluid: (a) TEM image of Alumina nanoparticles and (b) particle size distribution.

Fig. 2. Test samples at different mass concentrations.

vapor–liquid equilibrium condition. The boiling vessel is well insulated to ensure minimum heat loss to the surroundings. The following Fig. 4a shows the photographic view of the vertical heater surface.

Since the heating surface is completely immersed in the liquid, most of the heat input is utilized for convective pool boiling with negligible room for conduction loss into the surrounding atmosphere. The detailed cut section of the heater and the thermocouple locations are shown in Fig. 4b and c.

Heating surface contains the following components.

1. Terminal shell: the outer casing and terminal are Zinc coated to resist corrosion.
2. Insulator: the insulator has exceptional strength and thermal conductivity. It prevents short circuit. The casing provides sufficient heat resistance.
3. Rubber seal: the rubber seal prevents air from seeping through and thereby corroding the coil.
4. Insulation: electrical insulation of the coil is provided by firmly packing magnesium oxide powder which also acts as an efficient heat conductor.

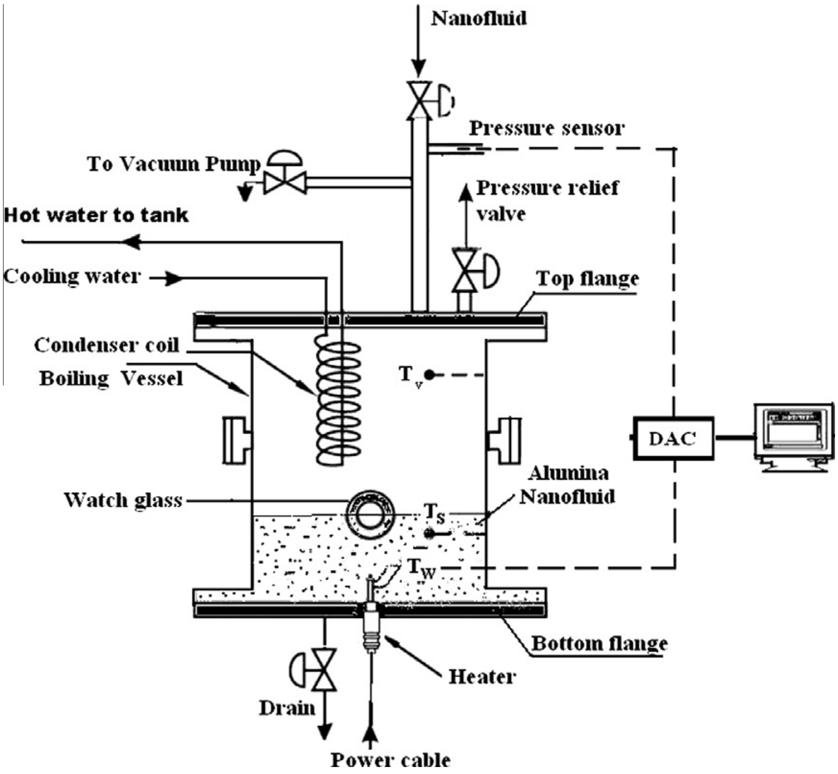


Fig. 3. Schematic diagram of experimental setup.

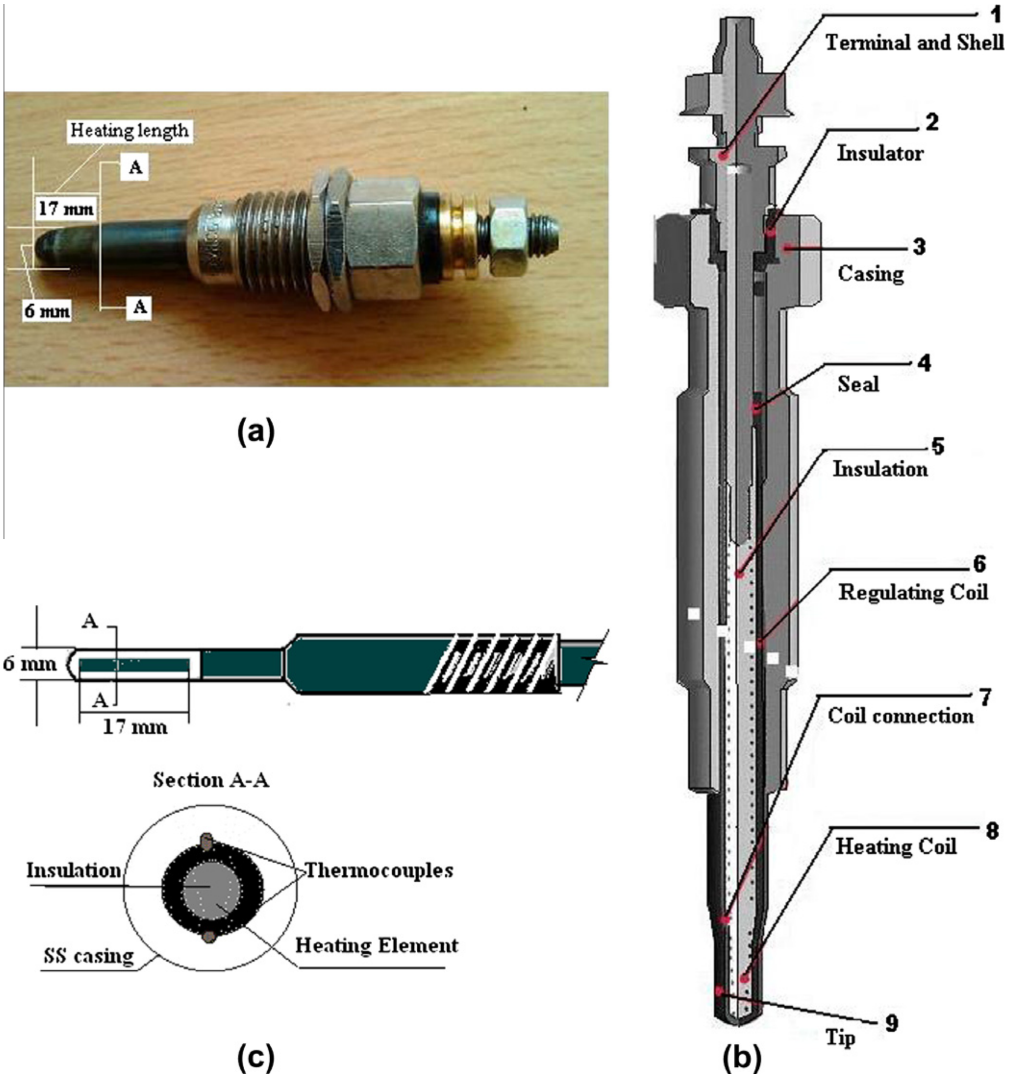


Fig. 4. (a) Photograph of heater, (b) cut section of heater, and (c) thermocouple locations.

5. Regulating coil: the main coil acts as a regulator to control and sustain temperature rise and rapid warm up.
6. Coil connections: laser welding connects the regulating and heating coil to maintain their positions at all times and maintains constant resistance characteristics.
7. Heating coil: a short tapered cylindrical end of the heater ensures quick heating while the tapered tip improves heating efficiency.

Before charging the nanofluid, the boiling chamber was evacuated using a vacuum pump. The experimentation was carried out at atmospheric conditions. Heat input to the test section was given in steps by using the Variac. The set pressure was maintained constant throughout the experiment by circulating water through the condenser coils. After ensuring the steady state condition liquid, vapor, heater surface temperatures and heat input were logged in the Data Acquisition System. Care was taken not to reach burnout point (input maintained around 850 W maximum) to avoid melting of the heater itself. The heat flux q was calculated using the following relation.

$$q = \frac{Q}{A} \tag{3}$$

Heat transfer coefficient between the surface and the liquid is calculated by applying Newton's law of cooling.

$$h = \frac{q}{T_w - T_s} \tag{4}$$

where T_w is the average of surface temperatures recorded by thermocouples embedded to the heater surface.

2.3. Experimental uncertainty

All chrome alumel K type thermocouples used in this study have an accuracy of ±0.5% full scale. The power input to the heater measured by an accurate digital power meter has an uncertainty of ±1 W. The uncertainty in temperature measurement is ±1.25 °C. Uncertainty in measurement of length and diameter of the heater is ±0.1 mm. The resulting uncertainty in the area of the heated surface is 1.74%. The uncertainty for the derived quantities can be estimated as explained by Holman [22] as follows.

Percentage uncertainty in heat transfer coefficient is given by,

$$U_h = \left[\left(\frac{U_Q}{Q}\right)^2 + \left(\frac{U_d}{d}\right)^2 + \left(\frac{U_L}{L}\right)^2 + \left(\frac{U_{T_w}}{T_w - T_s}\right)^2 + \left(\frac{U_{T_s}}{T_w - T_s}\right)^2\right]^{1/2} \tag{5}$$

The resulting maximum uncertainty in the heat flux was 4.726%. The maximum uncertainty in the heat transfer coefficient was 1.94%.

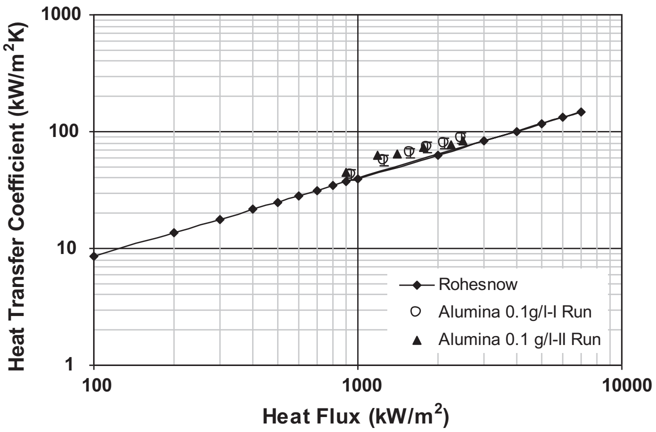


Fig. 5. Experimental reproducibility.

2.4. Experimental reproducibility

In order to verify the experimental reproducibility two trial runs were conducted using 0.1 g/l concentration of Alumina nanofluid on two different days. From the results as shown in Fig. 5 it can be seen that experimental outcome are reliable and fall within an error margin of 10%.

3. Results and discussions

As mentioned above, the main aim of present study is to investigate the pool boiling behavior of Alumina nanofluid coated heater formed due to boiling induced precipitation coating in pure water. However, it is also of great interest to make a basic study of heat flux enhancement using different concentrations of nanofluid. Based on the experimentation with Alumina nanoparticles in distilled water, boiling characteristics of water based Alumina nanofluid with changed concentrations is discussed below.

3.1. The boiling characteristics of the water based nanofluids

Fig. 6 shows the pool boiling experimental results for water based Alumina nanofluid at two different mass concentrations of 0.1 g/l and 0.5 g/l under atmospheric pressure. As reported by many previous results, there is deterioration of boiling heat transfer coefficient with increased nanoparticle concentration. From the figure it can be observed that Kutateladze and Rohsenow correlations mentioned above respectively under predict and over predict the boiling heat transfer coefficient of water which could be attributed to the different testing conditions, combination of surface (C_{sf}) characteristics of the heater and working conditions.

Comparison between experimental data using nanofluids and the Rohsenow correlation shows that the correlation has great potential to predict the pool boiling behavior with an appropriate modified liquid-surface combination and changed physical properties of the base fluid.

3.2. Effect of nanofluid concentration

Fig. 7 shows the pool boiling curve for the two concentrations of Alumina nanofluid along with distilled water. Addition of Alumina nanoparticles (0.1–0.5 g/l), results in shifting of the boiling curve to the right. This means, with nanofluids, the natural convection stage continues relatively longer and nucleate boiling is delayed due to higher degree of superheat of the boiling surface. This is because the range of the excess temperature in the natural convection regime of nanofluid is wider than that of pure water. Even though rightward shift of the boiling curve (0.5 g/l) in Fig. 7 indicates higher temperature at which nanofluid boiled, the downward shift of the curve at the same concentration as shown in Fig. 6 shows deterioration in boiling heat transfer coefficient.

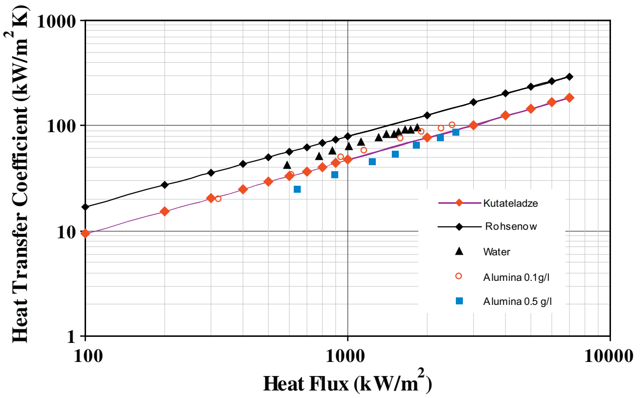


Fig. 6. Comparison of experimental data with popular correlations.

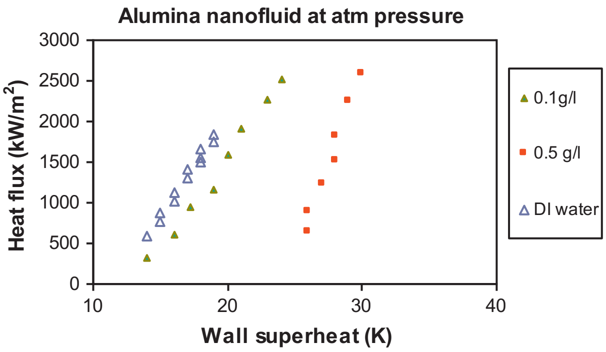


Fig. 7. Boiling curve of Alumina nanofliud.

3.3. Boiling test with nanoparticle coated heater

Many studies done in the past on CHF enhancement using nanofluids have been attributed to better wetting characteristics of nanoparticle coating which forms during pool boiling [8,23–25]. Kim et al. [8] in their investigation revealed that nanoparticles deposited on the heater surface during the boiling test can itself enhance CHF when tested in pure water. They used Ni–Cr wire in their studies and reported that nanoparticle coated heater surface can increase the CHF 1.35 times than the one tested in nanofluids. It can be noted that to have boiling induced coating of nanoparticles, it requires repeating the experiments using the same thin wire and subjecting it to multiple heating cycles and reuse it in pure water. Chances are more that any elongation or deformation of the wire surface experienced in one test might affect the subsequent tests and thereby affecting the results. Best options available is to use flat or cylindrical heater geometries. Even though Kwark et al. [25] tested this using a 10 mm × 10 mm × 3 mm flat Copper block as test surface they did not expose the surface to different heating cycles.

To investigate the effect of the nanocoated surfaces on pool boiling performance, two different concentrations of Alumina nanofluids (0.1 g/l and 0.5 g/l) were chosen and tests were conducted on a clean heater surface in nanofluid and nanoparticle coated surface in pure water. The second test was based on the

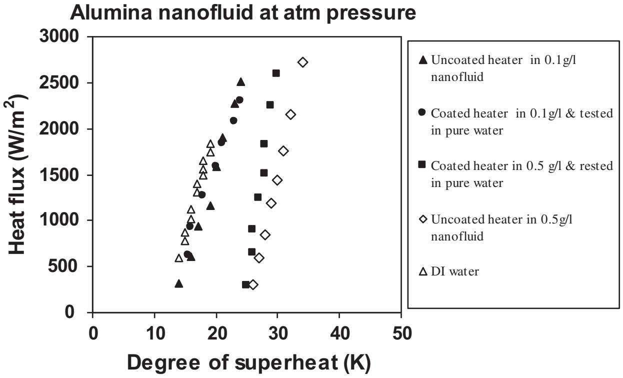


Fig. 8. Pool boiling curves tested with uncoated and nanoparticle coated heater: (a) surface roughness of clean heater and (b) surface roughness of coated heater in nanofluid (0.1 g/l) tested in pure water.

nanoparticle deposition on the heater surface formed out of the first test. Previous studies on effect of nanoparticle coating were done after removing the heater surface from the nanofluid bath and allowing it to dry. Kwark et al. [25] in their investigation have pointed that allowing the heater surface to dry would allow the nanofluid droplets to evaporate from the hot surface. This would leave additional coating on the heater surface and would influence the pool boiling performance. In this work, tests were conducted by exposing the new heater surface to three heating cycles of 120 min duration each in 0.1 g/l concentration of nanofluid. This action would result in nanoparticle coating on the heater surface due to boiling induced precipitation. Nanofluid was now drained and the second test was carried out immediately by filling the boiling vessel with distilled water. This ensured wet heater surface. The pool boiling performance of these two tests is shown in Fig. 8.

From the figure it can be observed that at lower heat fluxes the pool boiling curves for pure water and 0.1 g/l of nanofluid remain the same. But at higher heat fluxes BHT coefficient deteriorates due to boiling induced nanoparticle coating which results in thermal resistance build up. However, the boiling curve for the 0.5 g/l of nanofluid coated heater deviates from the beginning itself due to the already existing coating.

Since the nanoparticle coated heater obtained due to boiling induced precipitation in the first test was used subsequently for the second test also, it can be fairly assumed that the thickness of coating remains the same. Considering the same thickness of coating at the concentrations (0.1 g/l and 0.5 g/l) tested, it is expected that the heat flux enhancement should also be the same in case of nanoparticle coated heater tested in pure water. However, at 0.1 g/l of nanofluid concentration heat flux enhacement with nanoparticle coated heater in pure water was around 9.7% lesser when compared with clean heater surface tested in nanofluid. This indicates possibility of detachment of some nanoparticle coating from the heater surface at lower concentration of 0.1 g/l, reducing the heat flux or surface temperature. At the higher concentration (0.5 g/l), the reduction in heat flux was around 4.2% when compared with clean heater surface tested in nanofluid. In other words, at higher concentration pool boiling behavior was more or less the same. This implies that at higher concentration, the coating is thicker and even if some coating is removed from the heater surface its effect on heat flux enhancement is not significant. In order to verify the change in surface coating, surface roughness of the clean heater surface and nanoparticle coated heater surface were measured for both the concentrations tested. The modification of the heater surface due to change in surface roughness (Ra value) was measured using a surface profilometer, Mitutoyo Surftest-SJ301. The profilometer uses a diamond cone stylus of tip radius 2 μm and skid radius 40 mm with a contact force of 0.75 mN. The roughness was measured setting a cut-off length of 0.25 mm with three sampling lengths. Four measurements were taken at diametrically opposite points randomly on the heater along its length. The values indicated are average of these four measurements. After each set of measurements the profilometer was set to auto calibration mode confirming to DIN roughness standard. This is represented in Fig. 9 below. The surface roughness measurement shows that clean heater surface has an Ra value of 0.58 μm before testing in 0.1 g/l of nanofluid. After the second test with nanoparticle coated heater, the surface roughness decreased to 0.54 μm indicating a smoother surface. It can be noted that in this test the surface was not exposed to air so that it became dry.

The following Fig. 10a and b shows the surface roughness of the heater measured just after concluding the boiling experiment with 0.5 g/l of Alumina nanofluid and nanoparticle coated heater tested in pure water respectively. The surface roughness of the heater surface was 0.30 μm indicating sufficient coating formed over the surface.

SEM image of the heater surface revealed a porous layer of nanoparticles on the heater surface as shown in Fig. 11. The nanoparticles might have accumulated in the microcavities observed on the heater surface thus smoothing the surface further [9]. Same heater was now carefully mounted for the second test and pool boiling experiment was conducted in pure water. After the experiment the surface roughness of the heater was again measured which was now 0.33 μm. This indicates that some nanoparticles detached from the surface during boiling and increased the roughness of the heater surface reducing BHT. From the experiments it can be concluded that there is a minimum nanoparticle coating required to produce maximum CHF enhancement. The experimental findings here are on the similar lines with Kwark et al. [25]. However, Kim

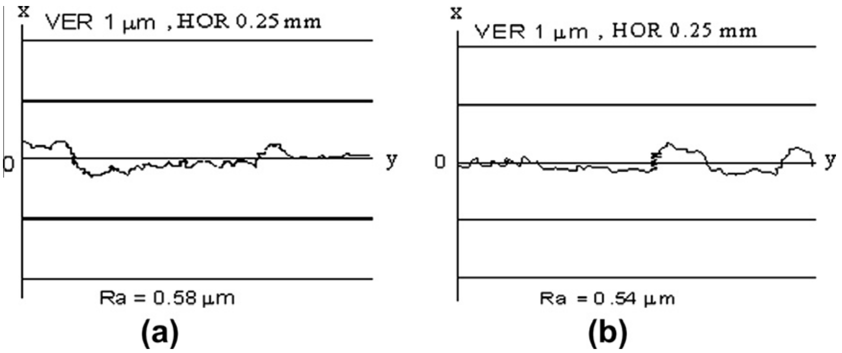


Fig. 9. Surface roughness of clean and nanoparticle coated heater with 0.1 g/l of nanofluid: (a) uncoated heater tested in nanofluid (0.5 g/l) and (b) coated heater (0.5 g/l) tested in pure water.

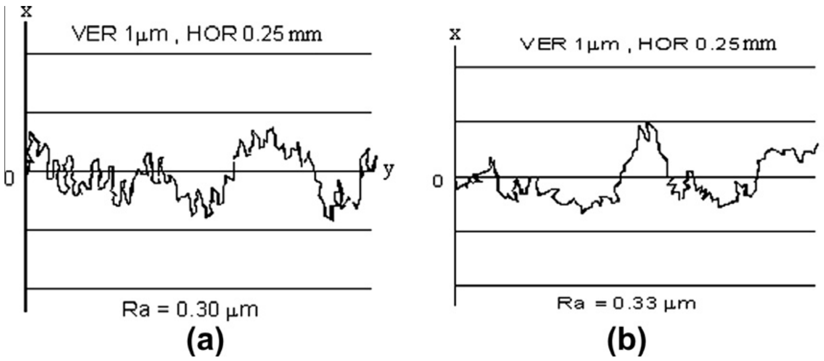


Fig. 10. Surface roughness of clean and nanoparticle coated heater with 0.1 g/l of nanofluid.

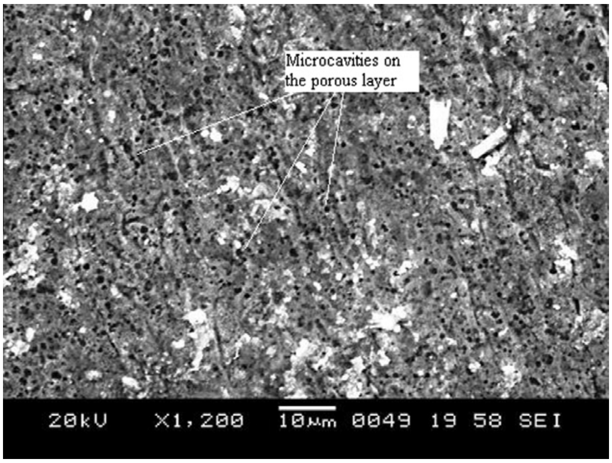


Fig. 11. SEM image of the heater surface showing porous layer.

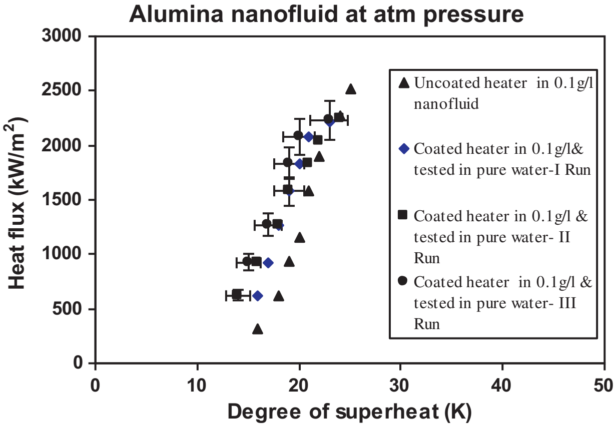


Fig. 12. Reliability test of three runs for nanoparticle coated surface in pure water.

and Kim [11] reported that nanoparticle coated heater surface tested in pure water results in CHF enhancement higher than that achieved with nanofluids.

The experimental results clearly show that modification of the heater surface associated with nanoparticle deposition is responsible for heat flux enhancement. The reliability of nanoparticle coating was tested by repeating the experiment with nanoparticle coated heater tested in 0.1 g/l of nanofluid. Since each run takes

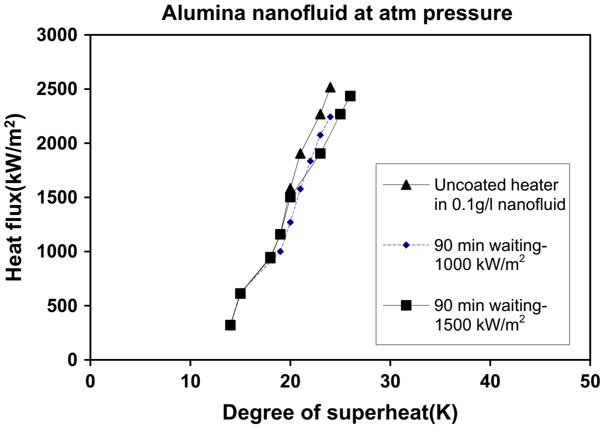


Fig. 13. Pool boiling curve-exhibition of transient characteristics at constant heat fluxes.

around 3 h, only three cycles were tested to assess the ability of the heater surface to retain the nanoparticles. The data predicted in all the three runs fall within an error margin of 6%. The results shown in Fig. 12 indicate that boiling induced precipitation results in firm coating of nanoparticles over the surface.

3.3.1. Transient characteristics

During pool boiling with nanofluid the above results showed that the heater surface modifies continuously. Hence the boiling curve may exhibit transient characteristics also. In order to investigate this, experiments were conducted using 0.1 g/l of Alumina nanofluid. Initially, the heat flux was increased at constant increments till it reached 1000 kW/m^2. Now heat flux was held constant at this value of 1000 kW/m^2 for 90 min. After a waiting for 90 min, heat flux was gradually increased till the CHF. Same procedure was repeated in the next experimental run by keeping the heat flux constant at 1500 kW/m^2. These results are presented in Fig. 13 along with the original pool boiling curve drawn without any waiting time period. As seen from the figure, initially pool boiling behavior remains almost the same and the boiling curves look identical. However, when the time limit of 90 min was imposed with constant heat flux condition of 1000 kW/m^2 and 1500 kW/m^2 respectively, the boiling curve discontinues and shifts towards right. This means prolonged exposure of the heating surface to nanofluid results in degradation of boiling heat transfer. Furthermore, the higher the time of exposure with constant heat flux, the greater will be the magnitude of degradation. Higher wall superheat resulting due to this, favors the nanoparticle deposition n on the heater surface. The reason for constant heat flux enhancement is due to other factors like surface wettability [24] governing it.

4. Conclusions

Experimental investigations of pool boiling heat transfer were carried out using Alumina nanofluid at atmospheric pressure. Investigations were primarily aimed at finding the effect of nanoparticle coating formed on the heater surface due to boiling induced precipitation and the exhibition of transient behavior of nanofluid. Pool boiling study on a vertical heating surface with nanoparticle mass concentrations ranging from 0.1 g/l to 0.5 g/l of distilled water revealed the following.

- Boiling induced precipitation of nanoparticle continuously modifies the heater surface. The surface roughness measurement showed heater surface modification during pool boiling process. The nanoparticle coated heater tested in pure water clearly shows better CHF characteristic which is nearly comparable with the performance of an uncoated heater tested in nanofluid. This suggests that a nanoparticle coated surface with some optimum thickness could be a better future option for enhancing heat transfer.
- The study also revealed that surface modification takes place due to change in nanoparticle concentration of nanofluid and leads to decreased surface roughness of the heater. The decrease in surface roughness could be due to the deposition of nanoparticles into the microcavities formed on the porous layer. The porous layer builds up due to stochastic (Brownian) motion of the particles.
- Pool boiling performance of nanofluid seems to be a strong function of time and applied heat flux. The longer the duration of exposure of the heater surface, the higher will be the degradation in heat transfer. The deterioration in nucleate boiling was due to increased particle coating. This shows transient behavior of nanofluid in pool boiling.

References

[1] R.L. Webb, Principles of Enhanced Heat Transfer, John Wiley & Sons, Inc., New York, 1993.

[2] X. Wang, X. Xu, S.U.S. Choi, Thermal conductivity of nanoparticle-fluid mixture, Journal of Thermo physics and Heat Transfer 13 (4) (1999) 474–480.

[3] S. Lee, U.S. Choi, S. Li, Measuring thermal conductivity of fluids containing oxide nanoparticles, J. Heat Transfer 121 (1999) 280–289.

[4] Q. Li, Y. Xuan, Experimental investigation on transport properties of nanofluids, in: Wang Buxuan (Ed.), Heat Transfer Science and Technology, Higher Education Press, Beijing, 2000, pp. 757–762.

[5] Y. Xuan, Q. Li, Heat transfer enhancement of nanofluids, Int. J. Heat Fluid Flow 21 (1) (2000) 58–64.

[6] S.M. You, J.H. Kim, K.H. Kim, Effect of nanoparticles on critical heat flux of water in pool boiling heat transfer, Appl. Phys. Lett. 83 (2003) 3374–3376.

[7] P. Vassallo, R. Kuman, S.D. Amico, Pool boiling heat transfer experiments in silica–water nano-fluids, Int. J. Heat Mass Transfer 47 (2004) 407–441.

[8] S.J. Kim, I.C. Bang, J. Buongiorno, Surface wettability change during pool boiling of nanofluids and its effect on heat flux, Int. J. Heat Mass Transfer 50 (19–20) (2007) 4105–4116.

[9] S.K. Das, N. Putra, W. Roetzel, Pool boiling characteristics of nanofluid, Int. J. Heat Mass Transfer 46 (2003) 851–862.

[10] K. Sefiane, On the role of structural disjoining pressure and contact line pinning in critical heat flux enhancement during boiling of nanofluids, Appl. Phys. Lett. 89 (4) (2006) 1–3.

[11] H. Kim, M. Kim, Experimental study of characteristics and mechanism of pool boiling CHF enhancement using nanofluids, Heat Mass Transfer 45 (7) (2007) 991–998.

[12] S. Lee, S.U.S. Choi, Application of metallic nanoparticle suspensions in advanced cooling systems, in: Proceedings of International Mechanical Engineering Congress and Exhibition, Atlanta, USA, 1996.

[13] K.B. Pak, Y.I. Cho, Hydrodynamic and heat transfer study of dispersed fluids with submicron metallic oxide particles, Exp. Heat Transfer 11 (1999) 151–170.

[14] Y.M. Xuan, Q. Li, Heat transfer enhancement of nanofluid, Int. J. Heat Fluid Flow 21 (2000) 58–64.

[15] Y.M. Xuan, Q. Li, Investigation on convective heat transfer and flow features of nanofluid, ASME J. Heat Transfer 125 (2003) 151–155.

[16] D.S. Wen, Y.L. Ding, Experimental investigation into convective heat transfer of nanofluid at entrance area under laminar flow region, Int. J. Heat Mass Transfer 47 (2004) 5181–5188.

[17] G. Roy, W. Nguyen, S.K. Das, Numerical investigation of laminar flow and heat transfer in a radial flow cooling system with the use of nanofluid, Superlattices Microstruct. 35 (2003) 497–511.

[18] S.E.B. Maiga, C.T. Nguyen, N. Galanis, G. Roy, Heat transfer behaviors of nanofluid in a uniformly heated tube, Perlattices Microstruct. 26 (2004) 543–557.

[19] Y. Yang, Z. Zhang, E. Grulke, W. Anderson, G. Wu, Heat transfer properties of nanoparticles-in-fluid dispersions (nanofluid) in laminar flow, Int. J. Heat Mass Transfer 48 (2005) 1107–1116.

[20] S.S. Kutateladze, V.M. Barshefsky, A Concise Encyclopedia of Heat Transfer, Pergamon Press, New York, NY, USA, 1966.

[21] W.M. Rohsenow, A method of correlating heat transfer data for surface boiling of liquids, Trans. ASME 74 (1952) 969–976.

[22] J.P. Holman, Experimental Methods for Engineers, seventh ed., McGraw-Hill, New York, 2007.

[23] I.C. Bang, J. Buongiorno, L.W. Hu, Measurement of key pool boiling parameters in nanofluids for nuclear applications, J. Power Energy Syst. 2 (1) (2008) 340–351.

[24] J.S. Coursey, J. Kim, Nanofluid boiling: the effect of surface wettability, Int. J. Heat Fluid Flow 29 (6) (2008) 1577–1585.

[25] S.M. Kwark, Ratan Kumar, G. Moreno, J. Yoo, S.M. You, Pool Boiling characteristics of low concentration nanofluids, Int. J. Heat Mass Transfer 53 (2010) 972–981.