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Pool boiling characteristics of nano-fluids

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Abstract

Common fluids with particles of the order of nanometers in size are termed as 'nano-fluids' which have created considerable interest in recent times for their improved heat transfer capabilities. With very small volume fraction of such particles the thermal conductivity and convective heat transfer capability of these suspensions are significantly enhanced without the problems encountered in common slurries such as clogging, erosion, sedimentation and increase in pressure drop. This naturally brings out the question whether such fluids can be used for two phase applications or in other words phase change in such suspensions will be assistant or detrimental to the process of heat transfer. The present paper investigates into this question through experimental study of pool boiling in water–Al_2O_3 nano-fluids. The results indicate that the nano-particles have pronounced and significant influence on the boiling process deteriorating the boiling characteristics of the fluid. It has been observed that with increasing particle concentration, the degradation in boiling performance takes place which increases the heating surface temperature. This indicates that the role of transient conduction in pool boiling is overshadowed by some other effect. Since the particles under consideration are one to two orders of magnitude smaller than the surface roughness it was concluded that the change of surface characteristics during boiling due to trapped particles on the surface is the cause for the shift of the boiling characteristics in the negative direction. The results serve as a guidance for the design of cooling systems with nano-fluids where an overheating may occur if saturation temperature is attained. It also indicates the possibility of such engineered fluids to be used in material processing or heat treatment applications where a higher pre-assigned surface temperature is required to be maintained without changing the fluid temperature.

Keywords: Boiling; Experimental; Heat transfer

1. Introduction

Heat transfer technology stands at cross roads today with ever increasing demand of cooling ultra high heat flux equipment on one hand and unprecedented pace of miniaturisation on the other. In the present day technology the different ranges of LASER applications, super conducting magnets, high power X-ray and above all super fast computing chips performing trillions of operations per second are becoming quite common. These devices are not only to operate in their respective applications with high precision but also to do so occupying minimum space. This puts a challenge not only to the core device design but also to their thermal management. While air based cooling systems are more common and reliable, they fail miserably with increasing heat flux. Therefore in almost all the high heat flux applications liquid cooling is preferred. The cooling liquids usually used are water/chilled water, common refrigerants and liquid nitrogen or similar cryogens depending on the specific application. While water is a convenient and safer medium, its relatively poor heat transfer characteristic is a major disadvantage. Usual refrigerants are hazardous to environment and cryogens are

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Nomenclature

D	diameter (m)
g	acceleration due to gravity (m/s^2)
h	latent heat for phase change (J/kg)
L	length (m)
Nu	Nußelt number
Pr	Prandtl number
q	heat flux (W/m^2)
Ra	roughness parameter (μm)
Rq	roughness parameter (μm)
Re_b	boiling Reynolds number
x	position (mm)
z	orthogonal position (μm)
Greek symbols	
α	heat transfer coefficient (W/(m^2 K))
λ	thermal conductivity (W/(m K))
μ	viscosity (kg/(ms))
σ	surface tension (N/m)
ρ	density (kg/m^3)
Subscripts	
f	fluid
g	vapour

costly not only due to their energy intensive production process but also due to whole range of costly equipment to be deployed to use them.

Under the circumstances it makes sense to look at alternatives such as fluids with suspended solid particles in them. Though the enhancement of thermal conductivity of slurries is known for more than a century, they have not been considered as a candidate for heat transfer applications in the past due to problems associated with them such as sedimentation, erosion, fouling and increased pressure drop. The recent advancement of materials technology [1] has been able to produce particles of nanometer size which when suspended in usual fluid can overcome most of the problems encountered by common slurries. Choi [2] was the first one to call such suspension 'nano-fluids' which is now widely accepted. The stability of such fluids against sedimentation is remarkably improved when very small amount of stabilising agent such as laurate salt [3] is added. The erosion and pressure drop problems are also greatly reduced due to small particles and the small volume fraction (usually <5%) required for enhancement of thermal behaviour of the base fluid. A substantial enhancement of thermal conductivity of water and ethylene glycol based nano-fluids with Al_2O_3 or CuO nano-particles ranging from 7% to 30% with only 1–5% particle volume fraction was reported by Lee et al. [4] at room temperature. A recent study by the present authors [5] shows that the enhancement of thermal conductivity of nano-fluids increases dramatically with temperature making it more attractive for cooling at high temperature and heat flux. Further enhancement of thermal conductivity of nano-fluids with pure metallic particles was reported by Xuan and Li [3] who found enhancement comparable to Lee et al. [4] using much bigger (100 nm) particles size. Finally, the enhancement of thermal property received a quantum jump when Eastman et al. [6] reported an increase of thermal conductivity by an outstanding 40% with only 0.3 vol.% of nano-particles of copper having average size <10 nm. All the above works [3–6] indicate that usual theory of suspensions and slurries such as the classical Maxwell [7] model or the extended Hamilton–Crosser [8] or Wasp [9] model fail miserably with nano-fluids. An evident theory is still missing.

However for heat transfer engineer, this enhancement of thermal conductivity is only a necessary condition for using such fluids in cooling application and not a sufficient condition. The real worth of such fluids can only be tested under convective conditions. The study of Ahuja [10], Liu et al. [11] and Sohn and Chen [12] conclusively indicate that performance of slurries under convective conditions are encouraging. Eastman et al. [13] also mention an increase of 40% in heat transfer capability for nano-fluids with 2% particle concentration under convective conditions even though no systematic study is available in this regard. The theoretical observations and proposition of dispersion model by Xuan and Roetzel [14] goes a long way in theoretical modelling of nano-fluids under convective condition the experimental validation of which is underway by the present authors.

While using nano-fluids for convective cooling, one must be aware of its boiling characteristics. This is because even if nano-fluids are unattractive with respect to two (or rather three) phase applications, during convective heat transfer with high heat flux locally boiling limit may be reached. It is important that the behaviour of nano-fluid under such conditions is accurately known to avoid unwanted effects such as local hot spot which can cause significant deterioration of reliability of components to be cooled.

The present paper is aimed at an experimental study of pool boiling characteristics of water–Al_2O_3 nano-fluid under atmospheric conditions. The thrust of the experiment is to compare the pool boiling parameters with that of pure water and thus bring out the applications and limitations of nano-fluids under the condition of phase change.

2. Production and characterisation of nano-fluid

Depending on base fluid and particle combination a number of nano-fluids can be produced. However in the present investigation, water based nano-fluids of Al_2O_3 particles have been used. The reason for this is the fact that the boiling characteristics of the base fluid water is most widely known and the thermal conductivity of water–Al_2O_3 nano-fluids for different particle concentration and the effect of temperature on it has already been studied [5]. Even though CuO–water nano-fluids have shown better thermal properties, they have not been used because CuO nano-particles have explosive characteristics at temperature more than 100 °C with moist air and they produced considerable fouling. The particles were produced (by Nanophase Technologies Corporation) by physical vapour deposition technique. In the powder state they form loose agglomerates of micrometer size as shown by transmission electron microscopy (TEM) photo given in Fig. 1. However it has been observed that the agglomerates break down to a considerable extent to produce smaller size particles and agglomerates when dispersed in water. The dispersion was carried out by using ultrasonic vibration for 4 h after making a suspension of desired concentration. Fig. 2 shows the TEM picture of dispersed particles by drying a dilute suspension on silicon wafers. The volume weighted average particle size was found to be 38 nm. However analysis showed a wide distribution of particles as typically shown in Fig. 3. It was found that the resulting suspension is quite stable at lower (1% and 2%) volume concentration and at higher concentration (3% and 4%) very nominal amount of sedimentation occurs after a time (6 h) long enough compared to the duration of the experiment. No effort was made to stabilise the solution because stabilising agents such as laurate salts are known to be surfactants and themselves have considerable effect on the boiling process [15] by reducing surface tension which may offset the main focus of the present study. However it was observed that due to turbulent mixing of the fluid by bubble movements no sedimentation takes place even for 4% volume concentration of particles during pool boiling.

To characterise the produced nano-fluid, first rheological study was made. The measurement with a disc type rotating rheometer showed that shear rate-deformation characteristics are almost linear and similar to water measured by the same instruments as given in Fig. 4. This confirms a Newtonian behaviour of the fluid between 1% and 4% particle (volume) concentration. Fig. 5 shows the values of viscosity of the fluids which are fond to be constant against shear rate but higher compared to water. Thus, it can be said that this particular nano-fluid shows an increase of viscosity with particle concentration but remains Newtonian in nature. The enhancement of thermal conductivity with particle concentration and temperature as measured by temperature oscillation technique [5] is given in Fig. 6. Since surface tension is known to be an important parameter in pool boiling, it was also measured for the present fluid using the conventional ring method. Fig. 7 shows the

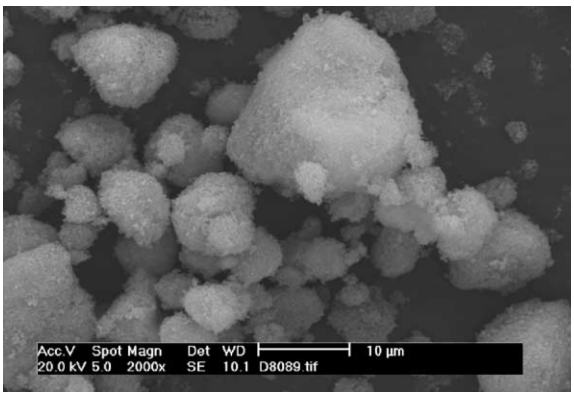

Fig. 1. TEM of agglomerated nano-aluminium oxide powder.

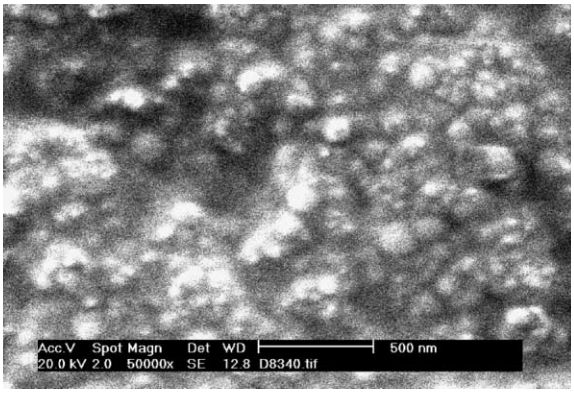

Fig. 2. TEM of dispersed nano-aluminium oxide powder.

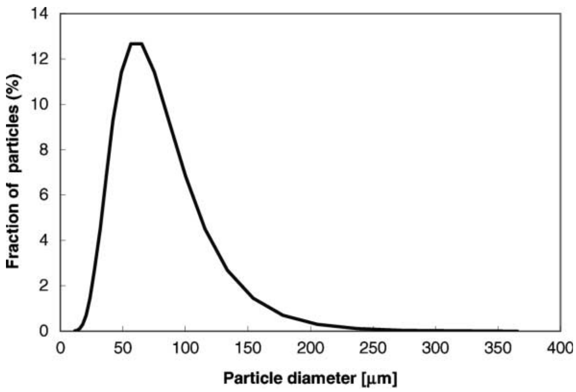

Fig. 3. Particle size distribution of the nano-powder.

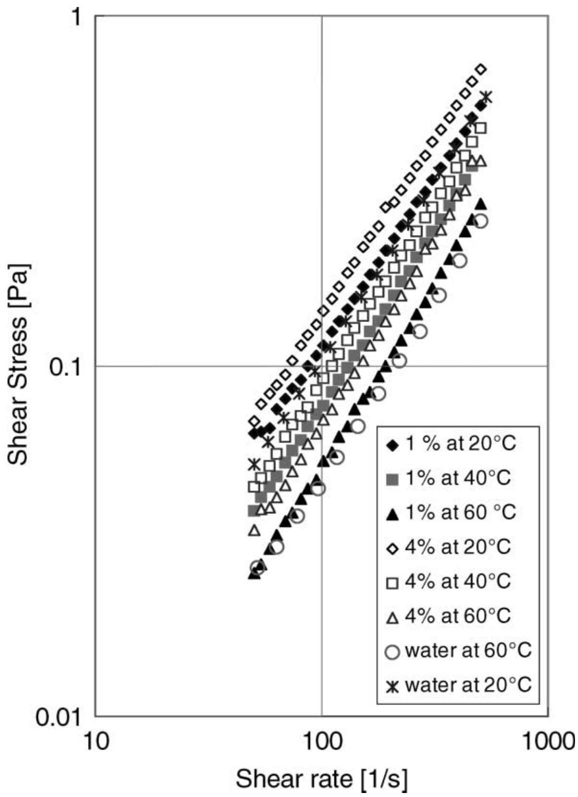

Fig. 4. Rheological behaviour of nano-fluids at 1% and 4% concentrations and pure water.

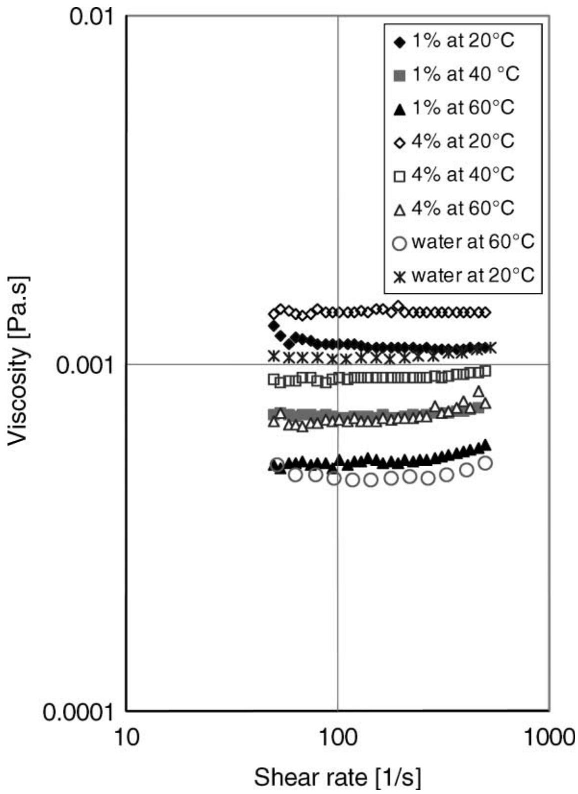

Fig. 5. Dynamic viscosity of nano-fluids and pure water at different temperatures.

variation of surface tension with particle concentration which is extremely nominal to have any surfactant effect on the boiling process.

3. Pool boiling experiment

3.1. Experimental set-up

The experimental set-up was designed keeping in mind the parameters the effects for which are required to be observed. For this reason no effort has been made to fabricate a so-called standard boiling apparatus but watch has been kept so that the experiments for different nano-fluids and water are performed under identical conditions. The test section is shown in Fig. 8. It consists of 120 mm $\times$ 100 mm $\times$ 200 mm rectangular stainless steel vessel (1) with thick insulation (2) outside. The vessel has two cooling arrangements cascaded together. The first one (3) is a counter current copper condenser which on one hand connects the vessel directly to atmosphere maintaining an atmospheric pressure in it, on the other hand it also serves the purpose of after cooling of any vapour which may try to escape as well as act as a vent to noncondensable gases. The cooling water from this vertical condenser is then circulated through an oval shaped copper coil (4) which performs the task of condensing the bulk of the vapour produced. This coil hangs from the roof of the vessel and is designed to cool the entire vapour at the maximum rate of evaporation. At the same time it is kept at sufficient distance from the top surface of the boiling liquid to avoid direct cooling which may result subcooled boiling. A pressure gauge (5) mounted at the top of the vessel checks the pressure at which boiling takes place. As boiling surface, a cylindrical cartridge heater (6) of 20 mm diameter and maximum 420 V, 2.5 kW rating is used. The voltage is regulated at appropriate values to reach prescribed heat fluxes. It is inserted from the side wall. To observe the boiling characteristics during water experiments, round windows (7), with double glass (inner 8 mm and outer 6 mm thickness) was built on both the side walls. A sheathed 0.5 mm thick chromel–alumel (K-type) thermocouple (8) was inserted to observe the bulk liquid temperature during boiling. To measure temperature on the heating cartridge 10 K type thermocouples of 0.1 mm thickness were welded at different radial and axial locations as indicated in Fig. 9. The radial locations are a, b, c

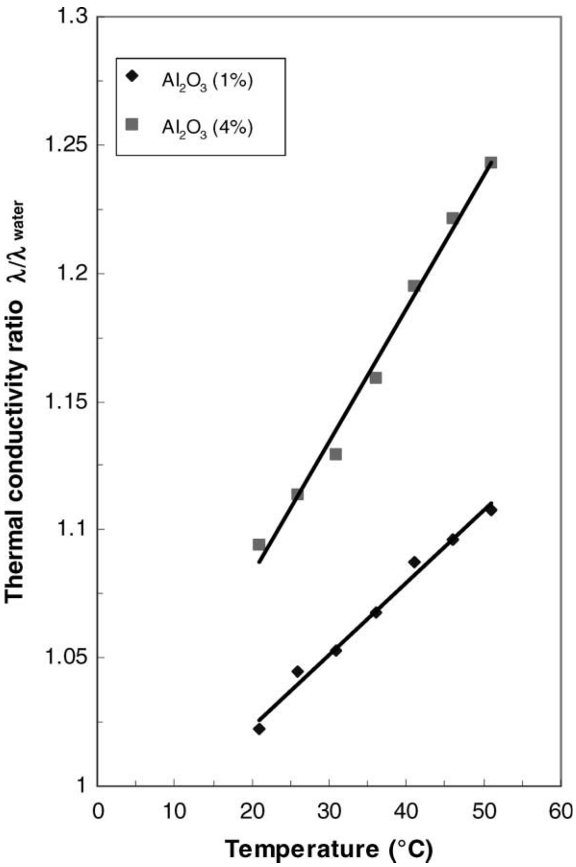

Fig. 6. Thermal conductivity enhancement of nano-fluids as a function of temperature.

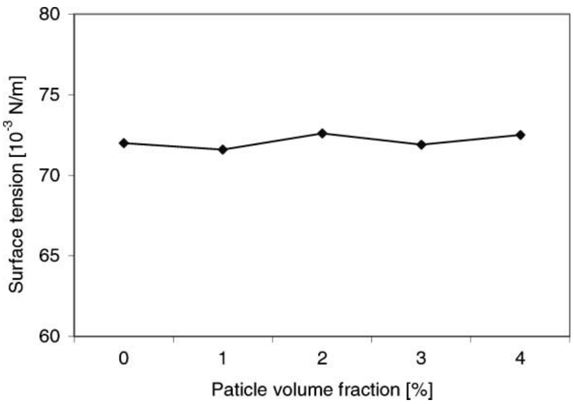

Fig. 7. Surface tension of nano-fluids.

and d and axial locations are 0, 1, 2, 3 and 4. The thermocouples were planted at locations 0d, 1a, 1b, 2a, 2b, 2c, 2d, 3c, 3d and 4a. The leads of the thermocouples were taken out from tip of the heater in a bunch (9). The power supply to the heater was varied by a transformer

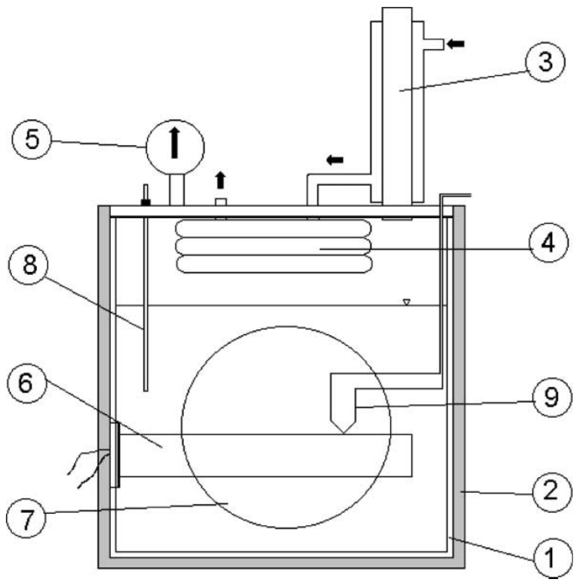

Fig. 8. The experimental cell for pool boiling.

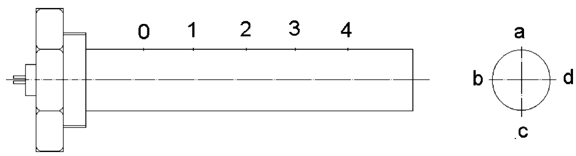

Fig. 9. The cartridge heater with thermocouple locations.

and the power was recorded with a Wattmeter. The thermocouples, pressure gauge and Wattmeter were connected to a data logger which was in turn connected to a PC for recording and storage of data.

For characterising pool boiling phenomenon it is important to know the heater geometry and surface accurately. The heater surface is machine drawn. The surface characteristics of the heater was measured using a profilometer having a diameter tip of 2 μm and a sensitivity of 0.02 μm. The major parameter for characterisation of surface roughness are *Ra* and *Rq* (DIN 4762) which are defined as

$$Ra = \frac{1}{L}\int_0^L |Z(x)|\,dx \tag{1}$$

$$Rq = \sqrt{\frac{1}{L}\int_0^L Z(x)^2\,dx} \tag{2}$$

A typical surface profile for the original heater is shown in Fig. 10. This along with other parameters characterising surface roughness were measured over a number of sample lengths. The heater surface for another set of heaters were roughened with emery paper and used for a second set of experiments. The typical measured values

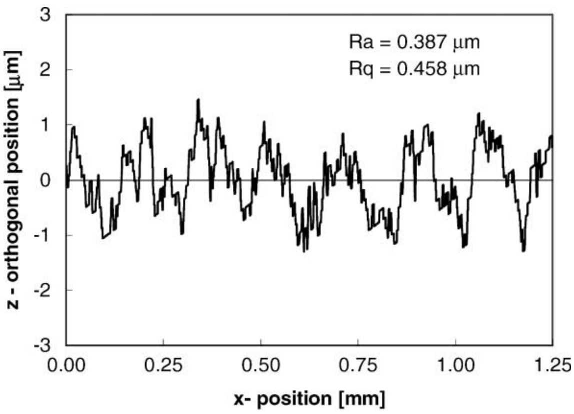

Fig. 10. Surface roughness of the smoother heater.

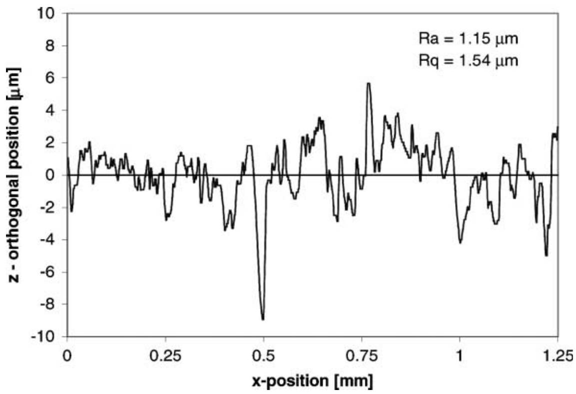

Fig. 11. Surface roughness of the roughened heater.

Table 1
Roughness of the smooth heater

No.	*Ra*	*Rq*
1	0.42	0.52
2	0.36	0.48
3	0.46	0.60
4	0.46	0.60
5	0.42	0.52
6	0.42	0.54
7	0.44	0.56
8	0.42	0.54

Table 2
Roughness of the roughened heater

No.	*Ra*	*Rq*
1	1.15	1.42
2	1.14	1.44
3	0.988	1.19
4	1.15	1.54
5	1.12	1.47
6	1.25	1.69
7	1.21	1.55
8	1.15	1.52

of roughness for the two surfaces are given in Tables 1 and 2 and typical surface profile of the roughened surface is shown in Fig. 11.

3.2. Experimental procedure and error estimates

Even though no effort was made to build standard boiling apparatus, care was taken to ensure that the pool boiling experiment are performed under standard conditions. A set of pre-experimental runs with doubly distilled demineralised water were made to ensure that the experimental results are in line with similar results available in literature for pool boiling on horizontal tubes. It was also done to check the repeatability of the experiment and to visually observe the boiling characteristics and ensure that the surface provides a fairly uniform density of nucleation sites and no local surface defect dominates the boiling process.

During these experiments check on the pressure was kept with a pressure gauge of ±0.002 bar accuracy. During this pre-experiment with water and the actual experiment, temperatures were recorded at a number of thermocouple locations and an average was taken to designate the wall temperature. The thermocouple measuring the fluid temperature was moved from the fluid surface to the bottom level of the heater to ensure that the true bulk temperature of the liquid is measured.

The projected end of the heater was insulated to avoid boiling from the end surface. Before inserting, an infrared camera was used to check the uniformity of heating by switching on the heating keeping the heater in air. Prior to each experiment, the liquid was boiled for half an hour to drive out any dissolved gases. Experiment was first performed with water from the lowest to the highest power input and then it was carried out in the reverse direction to eliminate the possibility of measuring only one part in case hysteresis exists. At each measuring condition stability of each thermocouple reading was checked by recording the mean temperature taken over a second at a sampling rate of 20 readings per second. During experiments with the nano-fluids, runs with the same nano-fluid was repeated with a run of boiling with pure water in between after cleaning the heater surface with a water jet. This is to ensure that the particles are not sticking to the heating surface to change the surface characteristics which can readily be determined from the change in the boiling curve of water.

The thermocouples are soldered on the heater surface and have a diameter of 0.1 mm. The accuracy is 0.1 °C and that for fluid temperature measurement with 0.5 mm diameter (for better stability within boiling fluid) is

0.2 °C. The mean wall temperature is assumed to be the arithmetic mean value of all 10 measuring points on the surface. The Wattmeter used for recording the power has got an accuracy of 10 W which is 1.25% at the lowest heat flux. At the highest heat flux it changes to 0.4% accuracy. Another error of the heat flux is caused by heat conduction from the electrically heated cylinder into the wall of the vessel. The vessel wall acts as a circular fin which transfers heat into the water in the vessel. This heat flow is estimated to be below 1% of the electrical heat input. The uncertainty in diameter measurement was 0.05 mm. A systematic error analysis was made to ascertain the measurement uncertainty which turned out to be 4% for surface heat flux. The uncertainty of mean temperature difference remains to be restricted to a maximum of 4%. Thus the maximum systematic error of the heat transfer coefficient is ±8%, it will have the same sign and order of magnitude for all experiments. So the effect of nano-particles on heat transfer is measured which much higher accuracy.

4. Results and discussion

Prior to the experiment the nano-fluids were separately boiled to determine the boiling point. It was observed that for nano-particle concentration from 0.1% to 4% a very nominal decrease of 0.4 °C (which is of the order of error in temperature measurement) in the boiling point occurs at atmospheric pressure.

Through the observation window it was found that for pure water at low heat flux, the flow transforms from natural convective to nucleate boiling and distinct bubbles start sliding as observed by a row of studies by Cornwell and co-workers [16–19]. As depicted in these studies, the bubble sliding mechanism gains momentum with increasing heat flux and at a high heat flux the bubbles coalesce to form bigger bubbles as observed by Chun and Kang [20]. These observations show that qualitatively the boiling behaviour in the present apparatus conforms to that reported in literature. To evaluate these pre-experimental runs with water quantitatively, the $q - \Delta T$ data of different runs for the smoother surfaced heater (Fig. 10) is plotted in Fig. 12, in terms of Nu and Re_b. $Nu = \alpha D/\lambda$ is the usual Nußelt number and $Re_b = qD/(h_{fg}\mu_f)$ is the boiling Reynolds number. Further the convective type correlation of Cornwell and Houston [21]

$$Nu = 104 Re_b^{0.67} Pr^{0.4} \tag{3}$$

is plotted in the same figure (Fig. 12). The plot shows good agreement of Eq. (3) and the measurements with water and clean heat transfer surface giving a confidence in the experimental set up and procedure. It also shows that the heat transfer coefficient decreases due to fouling

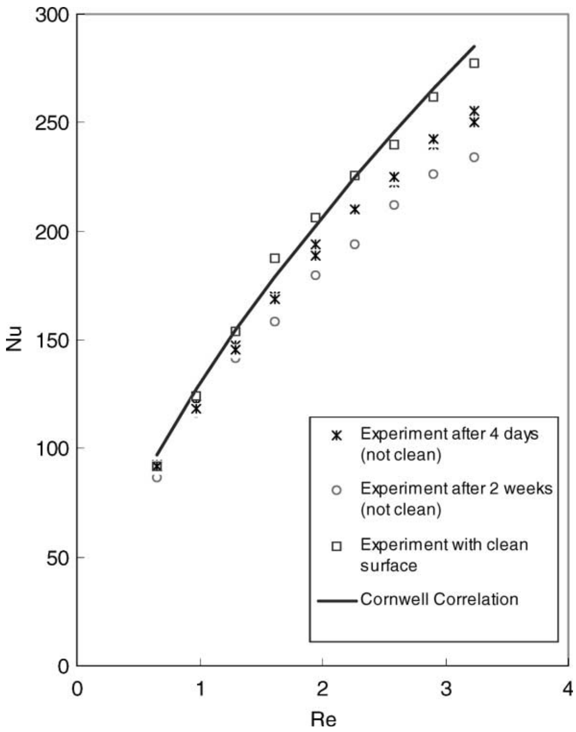

Fig. 12. Preliminary experiments: comparison of boiling of pure water in the present set-up with Cornwell–Houston correlation [18].

of the heat transfer surface, observed after four days and two weeks, respectively.

The above results clearly indicate that the present apparatus yields established boiling characteristics on horizontal tube where fluid property and boiling parameters such as surface roughness and heater diameter are found to play the expected roles.

Following the above validation, experiments were carried out to evaluate pool boiling with nano-fluids of 1%, 2% and 4 % Al_2O_3 nano-particle concentration in water. Due to opaque nature of the fluid, onset of nucleate boiling could not be accurately determined but from the surface agitation of the fluid it was ascertained to be not much different from pure water at the given surface condition. Since no significant change of surface tension with nano-particle concentration was observed, no hysteresis as described in [22] was found to exist. However it was observed that during increasing power the boiling starts at a higher heat flux than nucleation stops during decreasing power both for water and nano-fluid. After a number of runs repeatable boiling characteristics of nano-fluids were taken for which the $q - \Delta T$ from the results are shown in Fig. 13. This clearly indicates that the boiling performance of the base fluid (water) has been deteriorated with the addition of nano-particles since the boiling curves are shifted to the

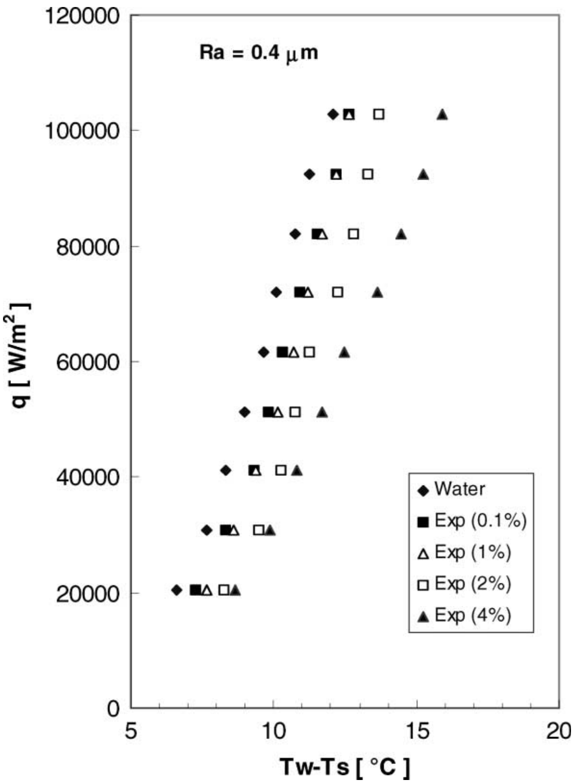

Fig. 13. Pool boiling characteristic of nano-fluids on the smoother heater.

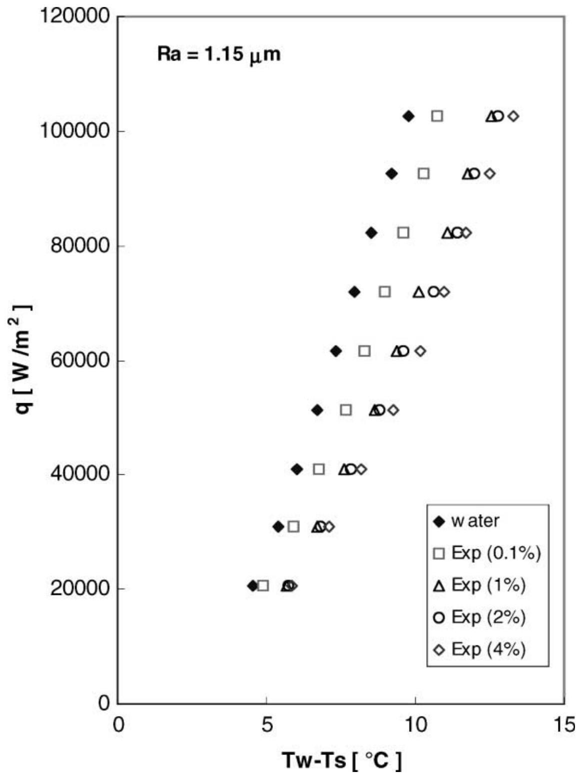

Fig. 14. Pool boiling characteristic of nano-fluids on the roughened heater.

right. This means that without changing the boiling temperature the nano-fluid can cause harm to cooled surface if boiling limit is reached because it will give a higher wall superheat meaning a higher surface temperature compared to water at the same heat flux. It has been observed that the shift of the curve to the right is not proportional to the particle concentration. For example in Fig. 13, for the case of smoother heater (surface, Fig. 10), a considerable shift of the curve was observed with only 0.1% particle concentration and thereafter from 1% to 4% concentration a regular shift of the curve was observed at lower heat fluxes. However at the upper part of the curves the difference between wall superheats for various particle concentration was fond to increase with increasing heat flux. This depicts a regular but non linear tendency of deterioration of boiling character for nano-fluids with the increase in particle concentration. In order to examine this deterioration under different heater surface conditions, the same experiments were repeated for the second (roughened, surface in Fig. 11) heater and the $q - \Delta T$ characteristics for this has been shown in Fig. 14. Here also shift of the boiling curve to the right indicating a deterioration of the boiling performance with particle concentration was observed. However, the shift was found to be different in nature compared to the smoother heater. In this case a more drastic increase in wall superheat was observed for nano-fluids up to 1% particle concentration after which it seemed to slow down up to 4% (measured range). This can be better understood from Fig. 15 where for pure water, 1% and 4% particle concentration the boiling curves for two heaters are compared. Here all the curves are shifted towards left for the roughened heater due to increase in surface roughness but the extent of shift for different particle concentrations are different and are dependent on heat flux.

The present results are somewhat contrary to expectation. Fig. 6 shows a substantial increase in thermal conductivity of fluid with nano-particles. This enhancement goes to as much as 60% at saturation temperature. The surface tension and latent heat remains unaffected and the only unfavourable change in fluid property due to presence of the particles is its increase in viscosity. Since fluid conduction in micro layer evaporation under the bubble as well as in reformation of thermal boundary layer at the nucleation site [23] plays a major role in heat transfer during pool boiling, with such a substantial increase in thermal conductivity, nano-fluids are expected to enhance heat transfer characteristic during

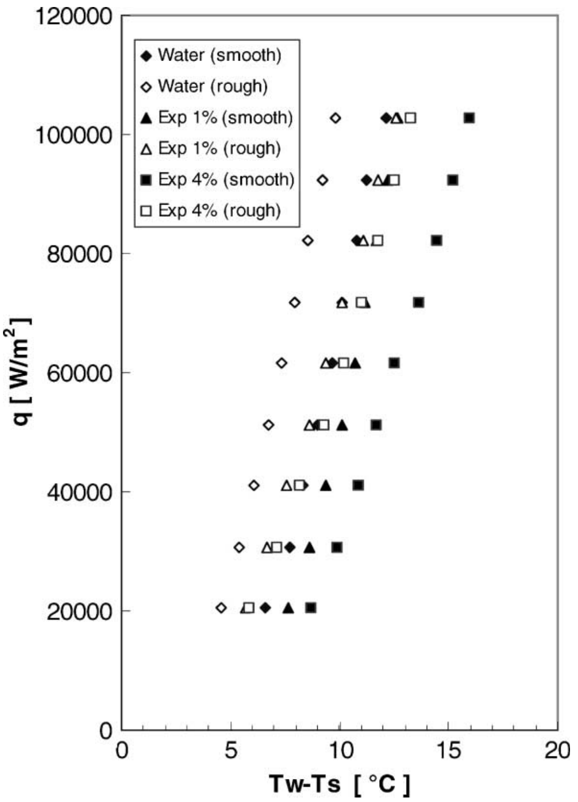

Fig. 15. Effect of roughness on the pool boiling behaviour of nano-fluids.

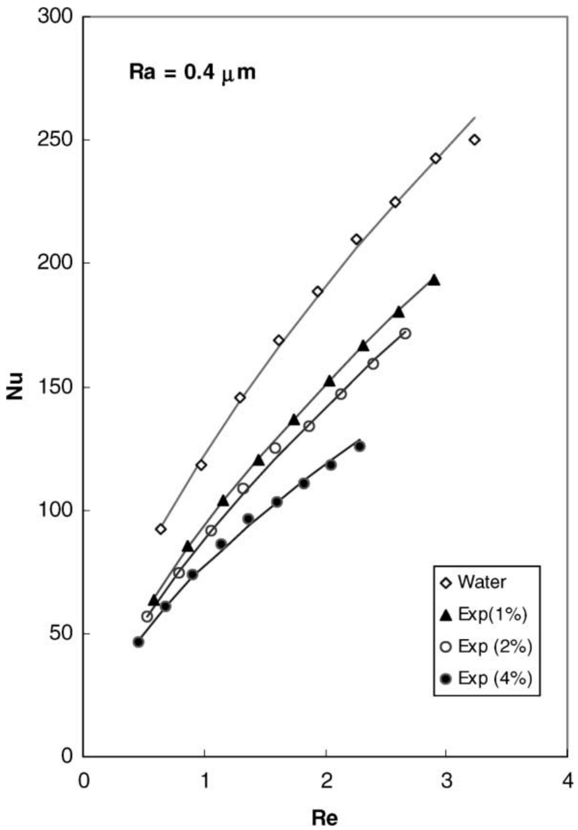

Fig. 16. *Nu–Re* plots for nano-fluids on the smoother heater.

pool boiling. In case of pool boiling on horizontal tubes at moderate heat flux, the series of works from Cornwell and co-workers [16–19] conclusively prove the importance of sliding bubbles where again conduction plays an important role. Thus both for stationary bubble development and sliding bubble mechanism, the increase in thermal conductivity is expected to enhance heat transfer during boiling which is just contrary to what has been observed in the present set of experiments. The fact, that the present increase of wall superheat in boiling and as a consequence decrease in boiling heat transfer coefficient is an additional effect, can be understood from Figs. 16 and 17. Here in keeping with Cornwell–Houston [21] type of correlation, Nu–Re_b plot for both the heaters have been presented.

It is evident that for each particle concentration the Nu–Re_b characteristics is different and shifted downwards. This conclusively brings out the fact that the change in boiling characteristics of nano-fluids cannot be explained in terms of property change alone because the Nu–Re_b correlations are altered. The following correlations were obtained for the two heaters, by regression analysis. According to Eq. (3) the exponent of Pr is taken as 0.4. The Pr number is formed with the actual fluid properties of the nano-fluid.

Heater 1 (smooth)

Pure water	$Nu = 97.9Re_b^{0.638}Pr^{0.4}$
1% Al_2O_3	$Nu = 78.84Re_b^{0.687}Pr^{0.4}$
2% Al_2O_3	$Nu = 72.39Re_b^{0.69}Pr^{0.4}$
4% Al_2O_3	$Nu = 67.56Re_b^{0.619}Pr^{0.4}$

Heater 2 (rough)

Pure water	$Nu = 137Re_b^{0.526}Pr^{0.4}$
1% Al_2O_3	$Nu = 99.48Re_b^{0.503}Pr^{0.4}$
2% Al_2O_3	$Nu = 94.63Re_b^{0.495}Pr^{0.4}$
4% Al_2O_3	$Nu = 89.12Re_b^{0.490}Pr^{0.4}$

The lines indicating these correlations are shown in Figs. 16 and 17. For smoother heating surface the shift in the boiling character was found to be more or less uniform with concentration while for the roughened surface it was found to be rapid at lower concentration and slower thereafter.

To find out which effect skirts the property variation, the surface characteristics of the heaters were re-examined after the runs with nano-fluids before jet cleaning of the surfaces. It was found that a considerable reduction in the surface roughness takes place which returns to almost the original surface after cleaning. As an example

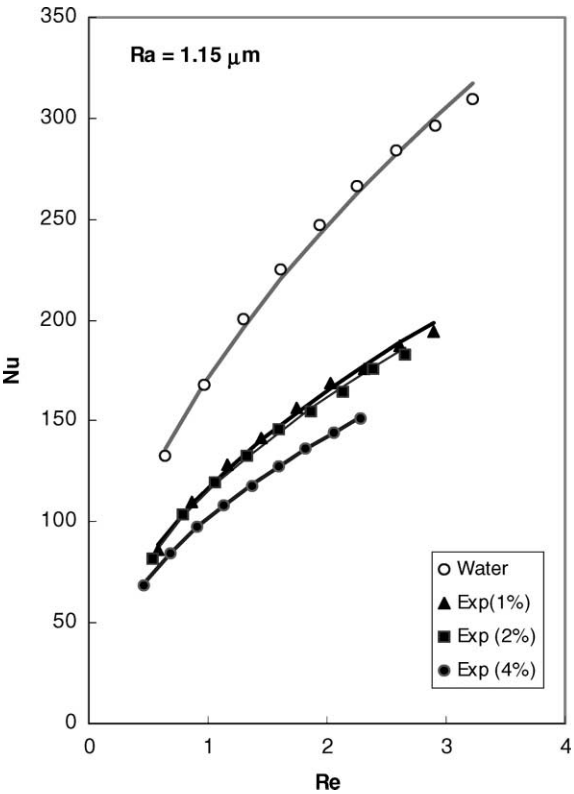

Fig. 17. *Nu–Re* plots for nano-fluids on the roughened heater.

the surface characteristics of the smooth heater (shown in Fig. 10 and Table 1) was changed to even lower value shown in Fig. 18 and Table 3 after boiling nano-fluid on it. This brings out the probable cause for the deterioration in boiling characteristics. Due to the fact that the size of the nano-particles (20–50 nm) are one to two orders of magnitude smaller than the roughness (0.2–1.2 μm) of the heating surface, the particles sit on the relatively uneven surface during boiling. These trapped particles change the surface characteristics making it smoother. This causes the degradation of the boiling characteristics. For higher particle concentration, the particles virtually form a layer on the heating surface hindering the fluid flow and heat transfer. However due to their extremely small size, they are almost completely removable by water jet cleaning. Thus the small size of the particles causes the surface skirting which overshadows the thermal conductivity enhancement of the nano-fluids.

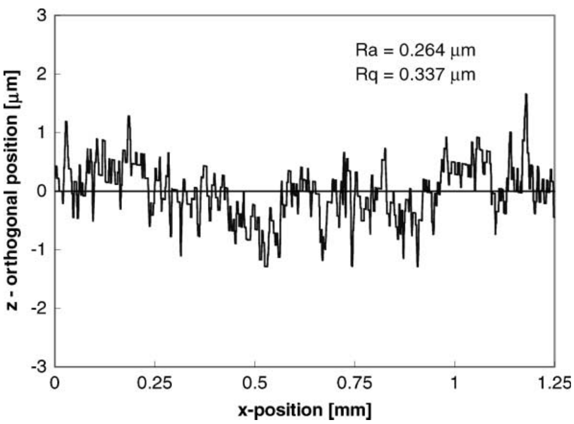

Fig. 18. Surface roughness of the smoother heater after boiling with nano-fluids (without surface cleaning).

Table 3
Roughness of the smooth heater after boiling

No.	*Ra*	*Rq*
1	0.281	0.371
2	0.264	0.337
3	0.288	0.377
4	0.358	0.439
5	0.358	0.444
6	0.347	0.445
7	0.291	0.372
8	0.299	0.377

The large change in boiling character of the roughened heater with smaller particle concentration can also be explained in a similar way. In this case due to higher surface roughness (1.15 μm) the cavities on the surface are more and as a consequence the smoothening of the surface by sitting particles is more abrupt. Thus with smaller particle concentration (<1%) enough amount of particles are deposited on the uneven surface to considerably affect the boiling character. Any additional deposit of particles from higher concentration in the fluid brings only marginal deterioration of pool boiling characteristics.

5. Conclusion

The modern electronics, computing and optical technology has brought about a stream of equipment dealing with extremely high heat flux needing more and more cooling efficiency. In recent times nano-fluids have been claimed to be a new possibility in meeting these demands due to their enhanced thermal conductivity and capability of further enhancing convective process through particle dispersion. They have been found to be much improved with respect to sedimentation, clogging and pressure drop compared to common slurries. Even though these indicate a possibility of enhancing such fluids under phase change conditions, the present study conclusively negates this possibility. Through a carefully designed series of experiments it has been shown that presence of nano-particles deteriorates boiling performance systematically with increase in particles concentration. This means with the increase in particles the wall superheat is increased at a given heat flux. Using the nano-fluid properties which were carefully obtained during characterisation of the fluid, reduction of the experimental data to conventionally used in the form of dimensionless equation reveals that there is a definite additional effect which causes this deterioration of boiling characteristic which cannot merely be explained in terms of change of fluid properties in presence of nano-particles. The additional effect which has been found to be at the root of this degradation in boiling phenomenon is the change of surface characteristics during boiling due to trapped particles on the surface which are one to two orders of magnitude smaller than the surface roughness.

On the practical aspects, the present study draws a limit for application of nano-fluids and makes it clear that while designing convective cooling systems with nano-fluids, care should be taken so that local heat fluxes do not cause boiling which will leave the heated surface temperature much above that expected for the pure fluid. In future, research may also be directed to find out whether such higher temperature of heated surface and its control by changing particle concentration (and of course other parameters such as particle fluid combination and particle size) can be used to produce engineered fluids to attained desired temperature of a surface in applications such as heat treatment or material processing.

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