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Effect of surface orientation on pool boiling heat transfer of nanoparticle suspensions

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Abstract

Several investigators have found that there is a significant effect of surface orientation on pool boiling performance and mechanisms, when a pure liquid is boiled over tubular heating surfaces. However, there is no similar study reported in literature for pool boiling of nanoparticle suspensions. This paper investigates the effect nanoparticles, suspended in pure liquids, can have on nucleate pool boiling heat transfer at various surface orientations. Systematic experiments were conducted on a smooth tube (average surface roughness 48 nm) of diameter 33 mm and length 170 mm at various inclinations (0°, 45° and 90°). Electro-statically stabilized water-based nanoparticle suspensions containing alumina nanoparticles (primary average sizes 47 nm and 150 nm) of concentrations 0.25%, 1% and 2% percent by weight were used. It has been found that there is a significant effect of surface orientation on the heat transfer performance. Horizontal orientation gave maximum heat transfer and the heating surface, when inclined at 45°, gave minimum heat transfer. Further, it was observed that surface–particle interaction and modified bubble motion can explain the behavior.

Keywords: Pool boiling; Nanoparticles suspensions; Surface orientation; Surface–particle interaction; Bubble sliding

1. Introduction

Due to its wide range of applications in areas such as that in advanced light water nuclear reactors (ALWRs), pool boiling of pure liquids on inclined tubes has been widely investigated. In fact, the first classical study of pool boiling on inclined surfaces was conducted by Nishikawa et al. (1984). Their experimental results showed that the heat transfer coefficient increases with the increase of angle of inclination under low heat flux conditions or in partial nucleate boiling regime. The heat transfer coefficient for surfaces with 90° angle of inclination (i.e., vertical positions) is about two to three times higher than that for horizontal surfaces (0° angle of inclination) in the partial nucleate boiling regime. It was further observed that the effect of inclination reduces with the increase of heat flux and beyond a certain value of heat flux the inclination has got no influence at all.

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Jung et al. (1987) conducted experiments on flat copper surfaces using R-11 subjected up to 180 kW m^{-2} for angles varying from 0° to 180°. They reported similar results as Nishikawa et al. (1984). They observed that there is a bubble agitation mechanism, which is a strong function of the surface orientation. As the surface is inclined, there is a bubble flow over the surface, which causes the surrounding fluid to be more turbulent resulting in an enhanced convection. Fujita et al. (1988) conducted experiments to study the affects of gap width and surface inclination on pool boiling. Their results were similar to those of the studies discussed above but as gap width was reduced there was no effect of tube inclination. All these studies were on either flat heaters or on thin wires.

Cornwell and Houston (1994) proposed that pool boiling on horizontal tubes leads to a bubbly flow layer around the lower periphery of the tube in which bubbles slide around the surface. They also showed that heat transfer was influenced greatly by rapid evaporation of a thin layer under the sliding bubble.

Chun and Kang (1998) and Kang (1998, 2000a,b, 2003) have conducted several studies on pool boiling over tubes. They have investigated the affects of several parameters like tube diameter, length, surface roughness and inclination. Kang (2000a) conducted experiments at three inclinations 0°, 45° and 90° and showed that there is a pronounced effect of inclination but only for smoother tubes (average surface roughness 60.9 and 15.1 nm). He observed that if the tube is inclined (at 45°), bubbles move upward and depart before getting to the top regions of tube circumference and the tube upper side. This leads to higher liquid agitation and smaller bubble travelling time and also decreases bubble slugging on the surface of the heater. This, he explained, is why there in an improved boiling performance on inclined tubes compared to vertical or horizontal tubes. Later he (Kang, 2003) showed that the combined effects of surface inclination and diameter of the tube. His results regarding the inclination effect were the same as already reported and he also observed that with increase in diameter of tube the heat transfer coefficient decreased but for 15° and 30°.

From the brief review of literature of the affect of surface inclination on pool boiling over tubes it is clear that there is a consensus among researchers that boiling over inclined tubes is advantageous because of higher heat transfer rates. Reasons for which are reportedly twofold (1) bubble slugging is reduced and (2) shorter bubble path in the bulk fluid.

Suspensions of nanoparticles in common liquids, widely known as nanofluids, have created considerable interest in recent times for their improved heat transfer properties. There have also been several investigations (Das et al., 2006) carried out in pool boiling of nanofluids, which have been briefly reviewed below.

The Pioneering work in pool boiling of nanofluids was by Das et al. (2003a) who investigated nucleate pool boiling characteristics of Al_2O_3–H_2O nanofluids on a cylindrical cartridge heater. They conducted experiments with high solid particle concentrations of 4–16% by weight. In this work the nanofluids were neither electrostatically stabilized nor was surfactant used to stabilize the nanofluid. The nanoparticles where found to sediment on the heater, thus making it smoother and deteriorating the boiling performance. The higher the concentration, the greater the sedimentation, and hence the boiling performance worsened.

Das et al. (2003b) also studied the boiling behavior of nanofluids on narrow tubes and observed that the deterioration of heat transfer performance was lesser on narrow tubes. Bang and Chang (2005) studied pool boiling characteristics of Al_2O_3–H_2O nanofluids at higher heat fluxes and smoother heaters. Their experiments were also with 4–16 wt% nanofluids. Here again nanoparticles were found to foul the surface causing a decrease in the pool boiling heat transfer coefficient. Even though they found that the fouling layer gave higher wall surface roughness readings, when it was locally cleaned, the heater was found to be smoother than before the experiment.

You et al. (2003) performed experiments with silica–water and alumina–water nanofluids of very small solid particle concentrations (0.0001–0.005% by weight) on a 10 mm square heater in sub-atmospheric conditions. They found no significant change in nucleate pool boiling. However, they observed a very significant enhancement (~200%) in critical heat flux (CHF). Vassallo et al. (2004) conducted experiments with silica–water nanofluids (2% by weight) of different particle sizes, ranging from 15 nm to 3000 nm on a NiCr wire heater and found no significant change in the boiling performance at low and medium heat fluxes but CHF limit was found to have been increased for the nano-solutions. Also, 3 μm particles were found to give an enhancement in heat transfer coefficient and they suggested that this was because of particles settling on the surface and changing the nucleation site density. Witharana (2003) carried out experiments using gold–water nanofluids of very low solid particle concentrations (0.001% by weight) on plate heater. An enhancement of 11–21%

in heat transfer coefficient was found. With increasing particle concentration the percentage enhancement in the heat transfer coefficient also increased.

Wen and Ding (2005) conducted experiments with aqueous alumina nanofluids at lower particle concentrations (0.32–1.25% by weight) on 3 mm disc heaters. They showed that alumina nanofluids of these concentrations significantly enhance boiling heat transfer and with increase in particle concentration, the heat transfer coefficient was found to increase.

From the above summary of literature it is clear that a complete understanding of pool boiling process in nanofluids has not yet emerged. There is an acceptance that nanoparticles affect pool boiling performance profoundly. However, there is no unanimity on the nature of this effect and its cause. In view of the projected application of nanofluids in areas such as boiling nuclear reactors, the effect of orientation on the boiling of nanofluids is of importance. In general, although some studies on the effect of orientation on boiling of pure fluids are available, a comprehensive view on boiling on inclined tubes surfaces particularly with respect to bubble sliding has not been arrived at. This makes it even more complicated to understand the overlapping effects of inclination and nanoparticles on boiling of nanofluids on inclined tubes. This paper presents an investigation into the question of how the nanoparticles will affect bubble slugging and whether it will impede bubble sliding bringing out the effect of surface orientation in the boiling of nanofluids. Also it is important to know whether it is advantageous to suspend nanoparticles in base fluids for boiling on an inclined tube.

2. Experimental details

2.1. Preparation of stable suspensions

This study was carried out using stable suspensions of Al_2O_3 nanoparticles in de-ionized water. Alumina nanoparticles were used because they are easier to suspend in water and also form uniform and continuous suspensions due to their relatively low densities. Two different alumina nanoparticles of primary sizes, 47 nm and 150 nm, manufactured by physical vapour synthesis (PVS) process, were procured from Nanophase Technologies Corporation and Inframat Corporation, respectively. Fig. 1(i) shows the TEM image of the 47 nm alumina nanoparticles and Fig. 1(ii) shows the SEM image of the 150 nm alumina nanoparticles. It can be seen that the particle morphology is spherical and the nominal sizes match the specifications provided by the manufacturers.

It is well established that nanoparticles have a strong tendency to agglomerate due to the relatively more predominant van der Waals forces between the particles, especially in dry environments. As it is imperative

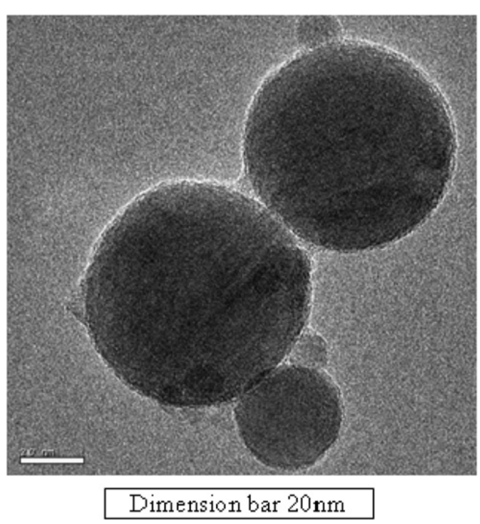

Fig. 1(i). 50 nm alumina particles TEM image.

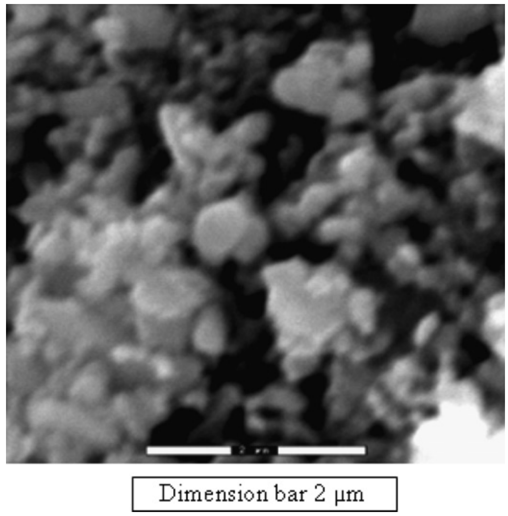

Fig. 1(ii). 150 nm alumina particles SEM image.

to the objective of the experiments to have very stable solutions, these agglomerates were broken using prolonged ultrasonication. This dispersed the nanoparticles uniformly in the base liquid. But, it was found that after 5–6 h, a solution thus prepared sediments rapidly (Fig. 2(i)). Adding surfactants is a known way of keeping the solution from settling for a prolonged period. But, surfactants have been shown to affect the thermo physical properties of the dispersed fluid (Masuda et al., 1993;) and also the boiling process (Wu et al., 1995; Wasekar and Manglik, 1999, 2000, 2002), which complicates our investigation of the affect of nanoparticles on the boiling performance.

In this study the solution was stabilized by creating electrostatic repulsive forces between particle surfaces. When the alumina nanoparticles comes in contact with water, a hydroxyl radical (OH^-) is formed at the surface of the particle. When water is acidic, with excess H^+ ions, the surface of the particle is positively charged. Similarly, the surface of the particle in an alkaline base fluid is negatively charged. However, at a certain pH value the mixture reaches an equipotential point in which the positive and negative ions are balanced. Hence, the solution was made acidic in order to make it stable. The authors have found that at a pH of 3, the solution is absolutely stable. But, at such pH values the heater surface will get altered and hence the solution was main-

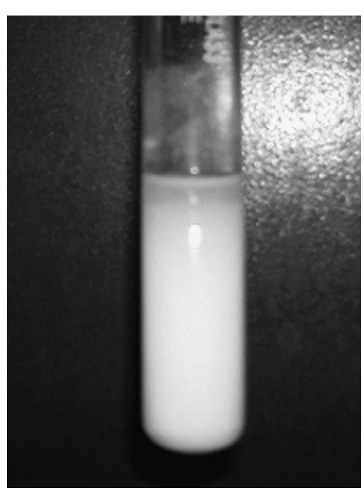

Fig. 2(i). Sedimented water–Al_2O_3 nanofluid.

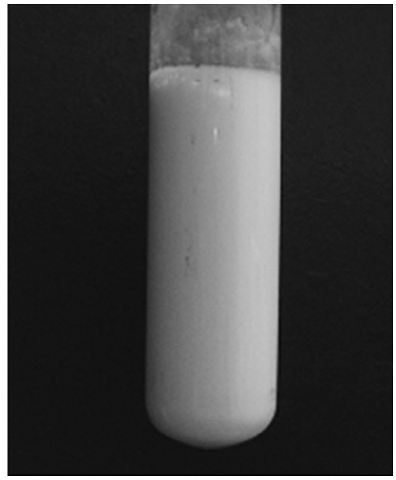

Fig. 2(ii). Electro-statically stabilized water–Al_2O_3 nanofluid suspension.

tained at a pH of 5.5 for the boiling experiments as a compromise. A highly acidic solution will react with the surface of the metal heating surface and alter the surface features of the heating surface which in turn will affect nucleation and hence the boiling performance. Even at these pH values the solution was found to be stable for weeks (Fig. 2(ii)).

2.2. Measurement of fluid properties

2.2.1. Viscosity measurements

The relative viscosities of water-based nanofluid were measured using an Ubbelohde viscometer, as the viscosity values were smaller for applying the rheometer with sufficient accuracy. The above comparative viscometer had a capillary bore of 0.5 mm. The ratio of efflux time of nanofluid, t_{nano} to that of base fluid t_{bf} was regarded as the experimental relative viscosity ratio i.e,

$$\eta_{\mathrm{r}} = \frac{t_{\mathrm{nano}}}{t_{\mathrm{bf}}}$$

The time was measured with an accuracy of 0.5 second the total experimental time involved was 50–100 s, thus the inaccuracy involved in the determination of viscosity ratio was approximately 0.5–1%.

2.2.2. Transient hot wire (THW) equipment

The measurement cell of the experimental set-up consists of a 15 cm long, 100 μm diameter platinum wire which acts as both a heater as well as a thermometer, which is kept in a glass container filled with test liquid and forms an arm of a Wheatstone bridge. Analytical solution for temperature distribution for an infinitely long, line heat source, heating continuously in a semi-infinite medium is used to find the conductivity of the test liquid. The platinum wire is insulated electrically. The instrument has been validated against water, ethylene glycol, transformer oil, xylene and toluene and found to be giving thermal conductivity values within 0.8% of literature values. By error propagation analysis, the theoretical uncertainty of the Transient Hot Wire instrument was found to be ±1.6%.

2.3. Experimental set up

The experimental circuit, as shown in Fig. 3, consists of a boiling vessel, a condenser with cooling water circulation and an auto-transformer regulated power supply. The boiling vessel is made of double-walled high temperature toughened glass with stainless steel (316) supports at four corners. The inner dimensions of the

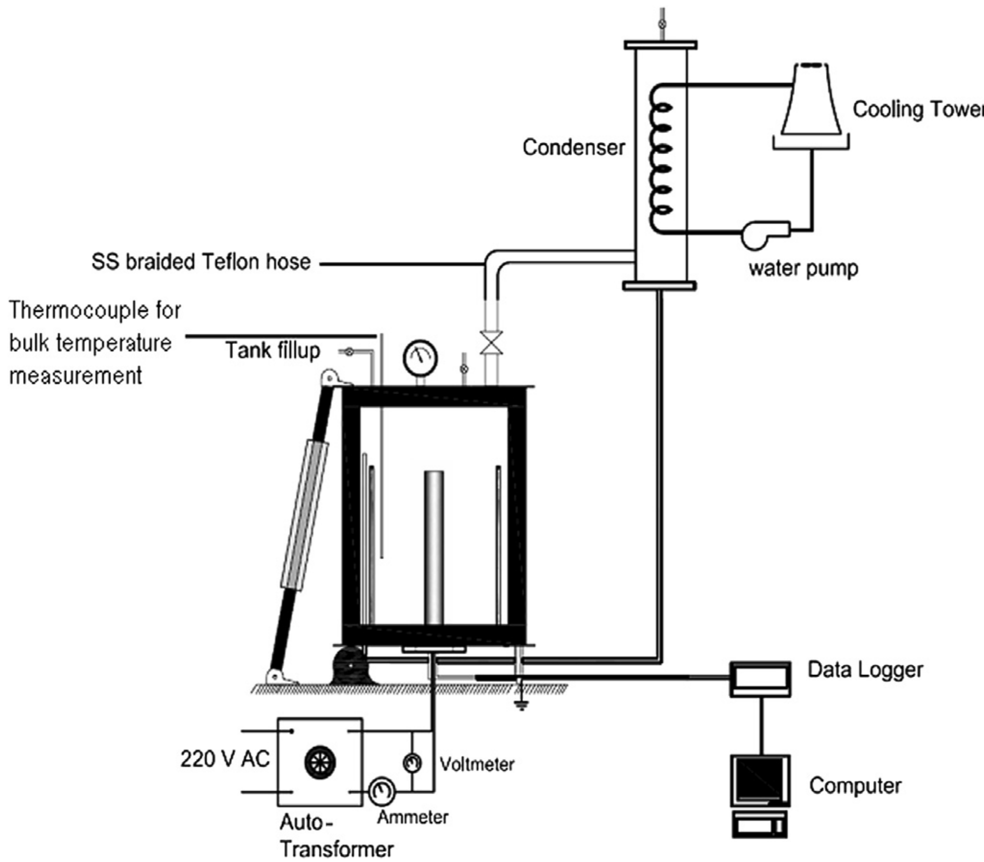

Fig. 3. Experimental circuit.

glass vessel are 12 cm × 12 cm × 30 cm. Foam insulation was applied to the exterior of these four stainless steel supports to reduce heat loss. Stainless steel bolts were screwed to these supports both at top and bottom for fixing stainless steel plates. A stainless steel plate of 3 mm thickness was fixed to the bottom of the glass vessel. This plate has a hole and a nut welded at the centre for fixing the main heater. Two secondary heaters, sufficiently away from the main heater, were fixed to the bottom plate at two corners diagonally opposite to each other. These heaters are used for preheating the boiling liquid, degasification, and to ensure saturated boiling.

All the literature available on nanofluid boiling is on boiling using flat plate or NiCr wire heaters. The problem of sedimentation, which is inherent to these experiments, causes the particles to settle on the heater surface thus affecting the boiling performance. For this reason, in the present study vertical tubular heating surfaces, shown in 4(i), were used. Stepped holes (5 mm/3 mm) were drilled into the tube at six different locations as shown in Figs. 4(i) and 4(ii). K-type fiberglass insulated thermocouples with copper buttons (1.5 mm thick and 4.6 mm diameter) were placed in the holes and silver brazed from outside. By a stepped hole we mean a hole with two different diameters. Five millimeter is the diameter of the larger hole, and 3 mm is the diameter of the smaller hole. The depth of each of these holes is 2 mm. Then bulges arising from these brazings were shaved off with very smooth file and then also buffed. To get a smoother surface, the tube was then diamond polished. The average roughness (R_a) obtained was 48 nm respectively. Wen and Ding (2005) had pointed out that if the thermocouple buttons are on the outer part of the heating surface, it would inevitably influence surface characteristics of the boiling surface as bubbles have a tendency to nucleate at these positions and the measured temperature may not be representative of the boiling surface. Hence, the copper buttons were also polished to the same roughness as the heating tube and it was observed during the experiments that these posi-

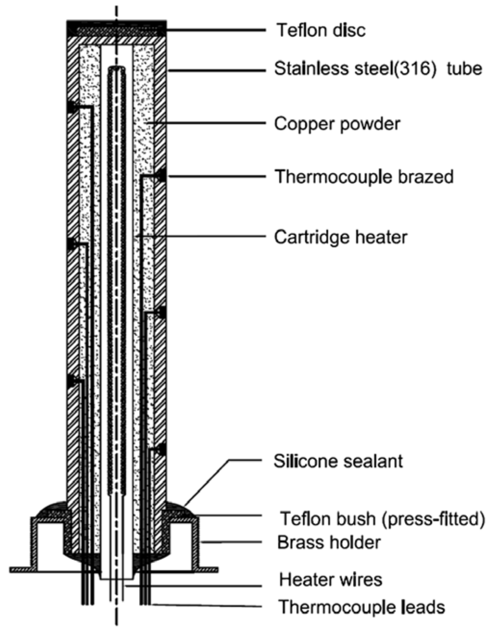

Fig. 4(i). Cross sectional view of the main heater.

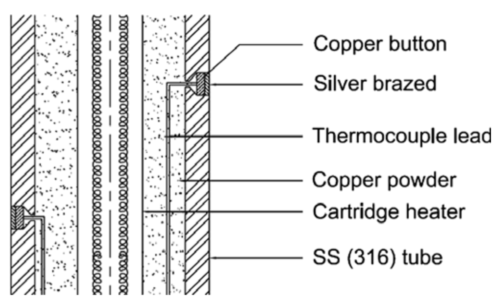

Fig. 4(ii). Close-up view of the thermocouples placement.

tions did not act as extra nucleation sites. The results of Kang (2000a,b) for horizontal tubes show that middle wall or sidewall (at 90° from top) superheat temperature equals the average of top and bottom wall superheats. Also according to him the heat transfer coefficient equals the average of two local heat transfer coefficients measured at the top and bottom wall temperatures. The results of Cornwell and Einarsson (1990) for horizontal tube and zero liquid velocity (pool boiling) show that the average heat transfer coefficient equals the average of the local heat transfer coefficients at the top and bottom of the tube. So in the present case, thermocouples were fixed (brazed) at three different axial locations but at the same azimuthal position. The other three thermocouples were brazed exactly at 180° opposite to the former, but at different axial locations as shown in Fig. 4(i).

A K-type Teflon coated thermocouple was inserted into the glass vessel from the top plate (as shown in Fig. 3) to measure the bulk liquid temperature. The boiling vessel was connected to an external condenser by a stainless steel braided Teflon hose of 20 mm diameter for carrying vapor from the boiling vessel to the condenser and an SS braided Teflon hose of 8 mm diameter for carrying condensate from the condenser to the glass vessel. The vapor enters the condenser from the bottom where the condensate is also collected. The condenser is cooled by water circulating in the copper coils. So as to maintain atmospheric pressure while boiling, a valve at the top of the condenser is kept partially open to the atmosphere.

A link (with left hand threaded bolt and right hand threaded bolt connected by a sleeve) and a hinge at the bottom of the glass vessel facilitate tilting the whole boiling vessel to different angles of inclination (from 90° to 0° from horizontal). The power to the main heater and the secondary heaters are adjusted by auto-transformers (for main heater: 220 V, 30 A; secondary heaters 220 V, 15 A). A voltmeter, ammeter, and digital multimeter are used to measure the power supplied to the main heater. Thermocouples are connected to the data logger (HP34901A), and the readings are monitored using a computer with HP Benchlink data logger software.

2.4. Experimental procedure

First, the liquid is heated to the boiling point by two secondary heaters. Once the boiling point is reached, the liquid is allowed to boil (by secondary heaters) for about one hour to release the dissolved gases. During this time, the valve at the top of the condenser is kept partially open so as to maintain atmospheric pressure in the boiling vessel. When the volume of the liquid being boiled by the secondary heaters reaches steady state, thermal equilibrium between the SS tube and the boiling liquid is achieved. At this time, the thermocouples brazed to the SS tube (main heater) are calibrated with respect to the boiling point. Once the boiling for 1 h is completed, the main heater is switched on and the power is slowly increased to the maximum heat flux possible with the heater. Once the maximum heat flux is reached, thermocouple readings are monitored to determine steady state. Readings are scanned over an interval of thirty seconds. Once the steady state is reached, ammeter, voltmeter and thermocouples readings are recorded. Then the vessel is tilted, maintaining the same power (and hence heat flux). The same process (measurement) is followed for different angles of inclination. Then, the vessel (and hence the tube) is brought back to the vertical position and the power is decreased. The same procedure is repeated for different power levels in the decreasing direction.

2.5. Experimental uncertainty

Uncertainty of the thermocouple was found to be ±0.1 °C. Uncertainties of the extreme cases were determined and it was found that the uncertainties in the wall superheat was limited to 3.5% and that in the heat flux obtained from the current and voltage measured was limited to 1% as calculated using error propagation analysis.

3. Experimental results

3.1. Validation with a standard correlation

Fig. 5 shows a validation curve for the experimental apparatus used in the present study. A convection-based correlation given by Cornwell and Houston (1994) for saturated, nucleate pool boiling on horizontal tubes is used here for comparison with experimental data. The experimental data shown in the validation curve is that of pure water whereas the data shown in the subsequent sections are of the base fluid (water + very low concentration of HCl). The correlation applies to pool boiling of water, refrigerants, and organic fluids on tubes of 8–50 mm in diameter. Here, the boiling Reynolds number is plotted with respect to Nusselt number. The boiling Reynolds number is defined as

$$Re_{\mathrm{b}} = G_{\mathrm{g}}D/\mu_{\mathrm{f}} = qD/\mu_{\mathrm{f}}h_{\mathrm{fg}}$$

It can be observed that there is an agreement within 7.5% (*Nu* number values for same values of boiling Reynolds numbers) between the experimental values recorded with decreasing heat flux and the Cornwell–Houston correlation. It can also be observed that there is a discernible difference in Nusselt number values for experiments with increasing and decreasing heat flux. This is known as "boiling hysteresis". The nucleation sites that are activated as we increase the heat fluxes from lower to higher values fail to deactivate when we are decreasing the heat flux from higher to lower values. Hence, higher heat transfer is obtained for boiling experiments with decreasing heat fluxes.

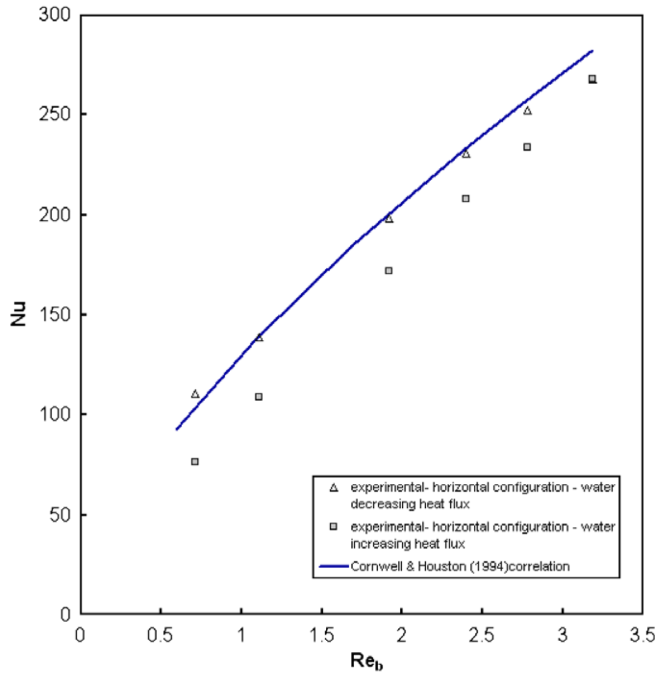

Fig. 5. Non-dimensional validation curves for boiling of water.

Kenning (1999) ascertained that experiments for laboratory purposes should be conducted with decreasing heat fluxes and hence in the present work, heat flux in the decreasing direction is considered for analysis.

3.2. Effect of surface orientation

Fig. 6 shows the nucleate boiling curve (heat flux vs. liquid super heated) of water–alumina nanoparticle suspension (2 wt%, 47 nm average particle size) at various inclinations (0°, 45°, 90°). It can be observed that

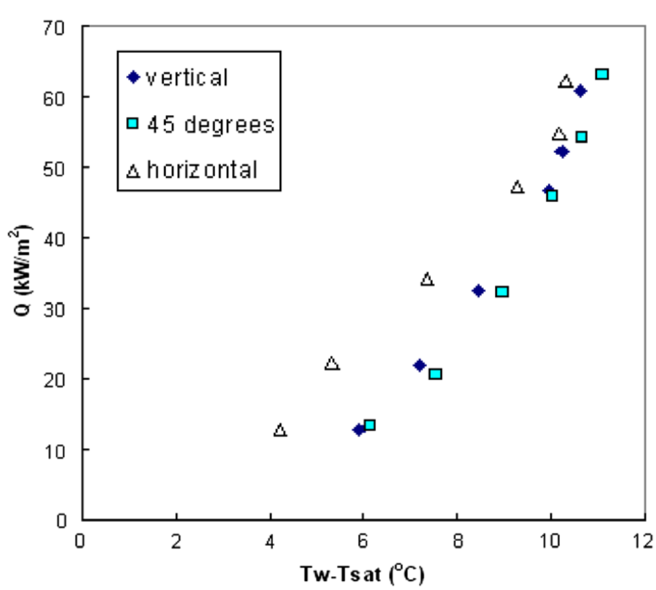

Fig. 6. Nucleate boiling curve for boiling on tube of water–Al_2O_3 nanofluid (2 wt%, 47 nm particle) at various inclinations.

boiling with the heating surface in a horizontal configuration provides higher heat transfer compared to vertical and 45° inclined configurations. However, the difference decreases as heat flux increases. A similar trend has been observed with other concentrations of nanofluids. It is also to be noted that the range of heat fluxes given was 10–70 kW/m^2 for which the liquid superheat ($T_w - T_{sat}$) was between 2 °C and 12 °C.

3.3. Effect of volume concentration

Fig. 7 shows non-dimensional nucleate boiling curves (Nusselt number vs. boiling Reynolds number) for boiling of water–alumina nanofluids (47 nm APS) at various surface orientations and volume concentrations. It is advantageous to use Nusselt number–Reynolds number plots to study pooling boiling heat transfer of nanofluids. Let us consider the correlation given by Rohsenow (1952) for nucleate pool boiling to study this point. It is understood that the Rohsenhow correlation is for pure fluids but since, it is a widely accepted correlation and also since, there is no such correlation for two phase fluids we are considering it.

$$\frac{c_p(T_w - T_s)}{h_{fg}Pr^s} = C_{sf}\left[\frac{q}{\mu h_{fg}}\sqrt{\frac{\sigma}{g(\rho - \rho_v)}}\right]$$

where $Pr = \mu c_p/k_L$ and h_{fg} is the latent heat of the fluid, σ is the surface tension, ρ_v is the vapor density, g is gravitational acceleration, and Pr is the Prandtl number ($s = 1$ for water).

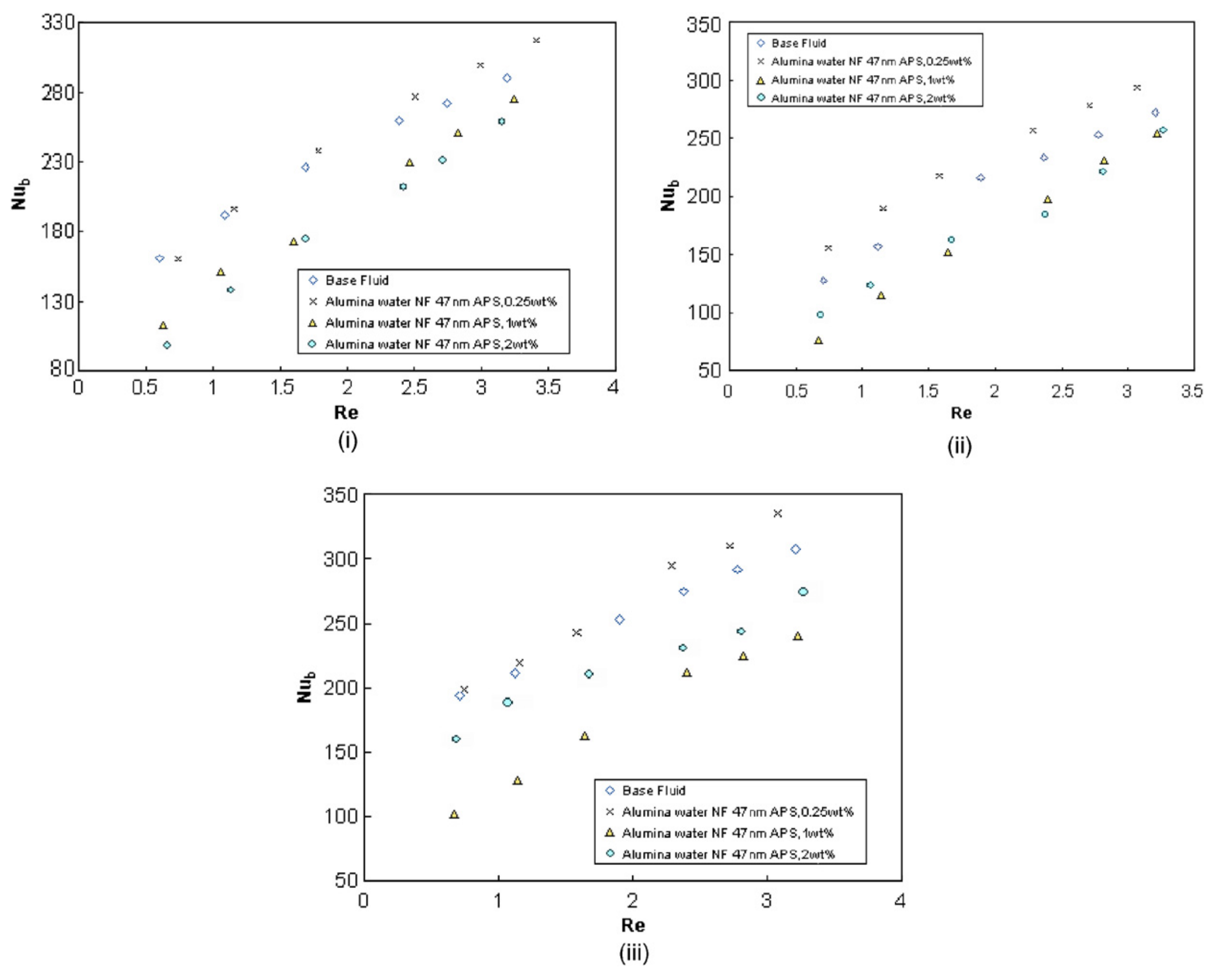

Fig. 7. Non-dimensional nucleate boiling curves for boiling of water–Al_2O_3 nanofluid (47 nm APS) on (i) vertical, (ii) 45° inclined (iii) horizontal tubes.

It is clear that the heat transfer coefficient is directly proportional to third power of thermal conductivity and that it also depends on viscosity. It is well documented that there is an appreciable change in these fluid properties when nanoparticles are suspended in base fluids (Choi, 1995; Eastman et al., 1996, 2001; Lee et al., 1999; Xuan and Li, 2000). By introducing them in the variables plotted, we are accounting for these changes, and will get a clearer picture of the actual nanoparticle effect in the boiling process.

3.3.1. Effect of concentration for the vertical configuration

Figs. 7(i) and 8(i) show the effect of concentration of the nanofluid on pool boiling heat transfer with the tubular heating surface in a vertical configuration. It can be seen that there is a monotonous variation; the boiling performance deteriorates with increase in nanoparticle concentration.

For the 47 nm particle size nanofluids, there is an enhancement of pool boiling heat transfer at 0.25 wt% over the base fluid. For the same range of heat fluxes, the heat transfer coefficient for the base fluid varied from 5900 W/m^2 K to 3300 W/m^2 K whereas, for 0.25 wt% nanofluid it varied from 6750 to 3400 W/m^2 K (3–14.5% increase). It is to be noted that the base fluid used for comparing the boiling heat transfer is water with the same pH as that used to stabilize the suspension.

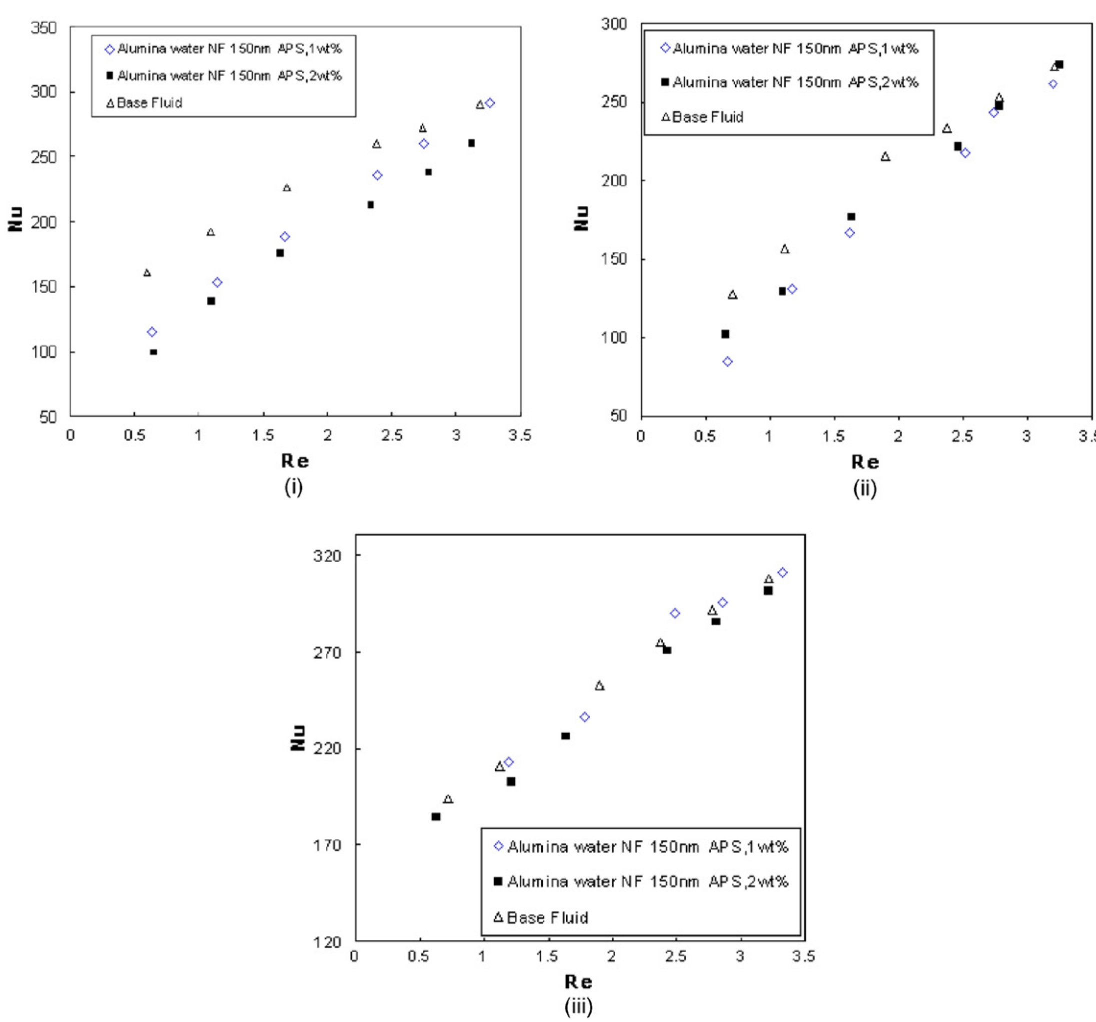

Fig. 8. Non-dimensional nucleate boiling curves for boiling of water–Al_2O_3 nanofluid (150 nm APS) on (i) vertical, (ii) 45° inclined (iii) horizontal tubes.

It can be asserted from Fig. 7(i), that there is significant deterioration for 1 and 2 wt% nanofluids. For 1 wt%, deterioration of heat transfer coefficient is up to 26.1% and for 2 wt%, up to 34.7%.

For the nanofluid with the larger particles (average particle size 150 nm), experiments were conducted with 1 and 2 wt% nanofluid. It is obvious, from Fig. 8(i), that there is a similar trend as observed for the smaller particles. With respect to heat transfer coefficient, the deterioration is up to 25.1% for 1 wt% and 28.2% for 2 wt%.

3.3.2. Effect of concentration for the inclined configuration

Figs. 7(ii) and 8(ii) show the effect of concentration of the nanofluid with the tubular heating surface in an inclined configuration. There is a decrease in heat transfer with increase in concentration. But, for smaller particles (average size 47 nm) at higher concentrations (1 wt% and 2 wt%), this trend is not followed at high heat fluxes and also, for the larger particles (average size 150 nm) at higher concentrations (1 wt% and 2 wt%), this trend is reversed.

As was observed for the vertical configuration, the nanofluids provide an enhancement in pool boiling behavior only at lower concentration (0.25 wt%). For higher concentrations (1 wt% and 2 wt%) the heat transfer is deteriorated.

3.3.3. Effect of concentration for the horizontal configuration

Figs. 7(iii) and 8(iii) show the effect of concentration of the nanofluid with the tubular heating surface in a horizontal configuration. There is a decrease in heat transfer with increase in concentration. But, for smaller particles (average size 47 nm) at higher concentrations (1 wt% and 2 wt%), this trend is reversed.

3.4. Effect of particle size

Fig. 9 shows the effect of particle size on pool boiling heat transfer of the suspensions at different orientations. The figure is shown for 1 wt% nanofluids. In the figure, the ordinate is the ratio of Nusselt numbers for larger and smaller particles (150 nm average particle size and 47 nm average particle size respectively). It is clear that there is a discernible effect of the particle size for the horizontal orientation and for the inclined configuration. For the horizontal arrangement the percentage increase in heat transfer for the larger particles (150 nm average particle size) is from 29.7% to 66.7% and for inclined it is 3–13.6%. For the vertical configuration, however, the effect is much lesser. The larger particles give 0.5–8% higher Nusselt numbers.

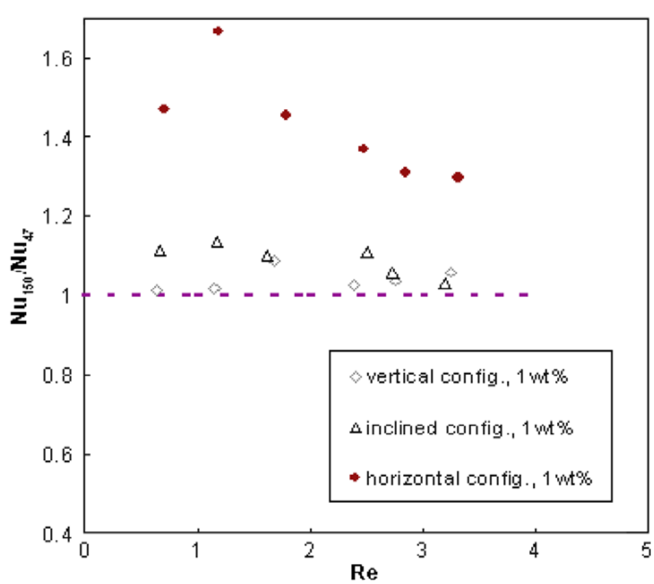

Fig. 9. Effect of particle size on the boiling heat transfer at various configurations for 1 wt% nanofluid.

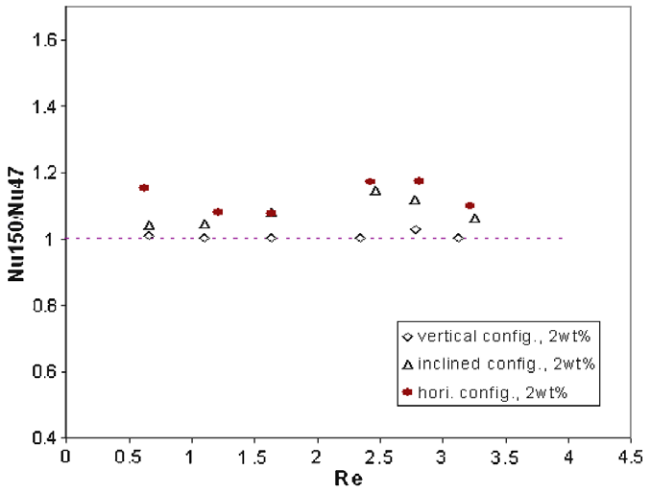

Fig. 10. Effect of particle size on the boiling heat transfer at various configurations for 2 wt% nanofluid.

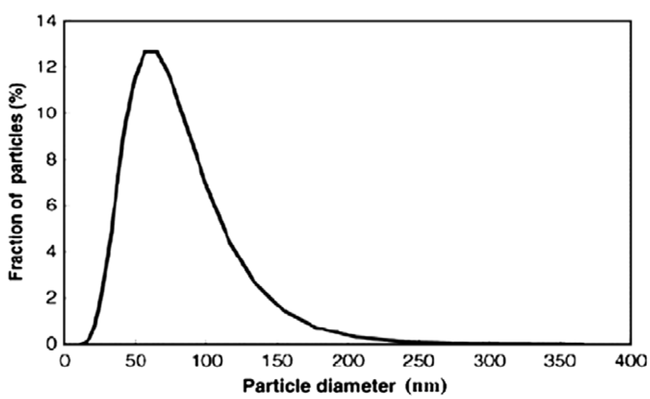

Fig. 11. Particle size variation for the 47 nm nanoparticles.

Fig. 10 shows the effect of particle size for 2 wt% nanofluids. The increase in heat transfer (*Nu*) for the larger particles is much lesser for this higher concentration. For the horizontal orientation, the increase in *Nu* for the larger particles compared to the smaller particles is from 7.8% to 17.2%. For the inclined arrangement it is from 6.1% to 14% and for the vertical tube it is from 0.3% to 2.8%.

Comparing Figs. 9 and 10, it can be observed that there is change in the effect of particle size on the pool boiling behavior with change in volume concentration. The reason for this can be, possibly, because of the variation in particle size in a sample itself as shown in Fig. 11. With increase in particle concentration of the smaller size particles (average size 47 nm), there are more particles of the size of the larger particle (average size 150 nm) and hence, the particle–surface interactions could be similar for both the particles.

4. Discussion

4.1. Effect of surface particle interactions

Based on a previous study the authors reported elsewhere (Prakash (2006)) have found that the deterioration/enhancement of pool boiling heat transfer by the nanoparticle suspensions on a vertical, tubular heating surface depends strongly on the surface–particle interaction parameter. This is the ratio of average surface roughness, *Ra*, to average primary diameter of the particle, d_p. If this parameter is close to one it was found that heat transfer got deteriorated because of reduction in number of nucleation sites. In the current study, a heater surface of average surface roughness 48 nm was used. So for the 47 nm APS alumina particle the surface–particle interaction parameter is 1.02, very close to one. Hence, the pool boiling performance (Fig. 7) deteriorates (especially at higher concentrations).

For the larger particles (150 nm), the surface–particle interaction parameter is 0.32. This is also closer to one. However, there is lesser number of particles in the range of the average roughness of the heating surface and hence the chances of nucleation sites getting deactivated by the particle will be less. This explains why the suspensions with larger particles (150 nm) provide higher heat transfer (Fig. 9) compared to suspensions with the smaller (47 nm) particles.

The higher the concentration, the greater the number of particles available for deactivating the nucleation sites. Hence, on a vertical heater, with increase in concentration the boiling performance worsens.

For boiling with nanoparticle suspensions, the heating surface in horizontal orientation gives maximum heat transfer (Fig. 6). In the case of a horizontal tube the nucleation occurs primarily at the bottom of the tube. The chances of particles sitting on the underside of the tube are much less than on the top by virtue of the forces involved in particle deposition. This has also been observed visually. After the experiments on the horizontal configuration, the heating surface was found to have a thin layer of particles on the topside. Hence, the number of deactivated nucleation sites will be less than that for other orientations.

It has also been observed that the effect of the particle size is more profound in the horizontal configuration. The reason for which, may be, the combination of two aforementioned reasons: First, lesser number of particles in the range of roughness and hence lesser nucleation sites get deactivated by the particles second, the chances of particles settling on the bottom of the tube are much lesser and hence fewer of nucleation sites is deactivated.

4.2. Bubble sliding

Fig. 12 shows the effect of nanoparticle suspensions on bubble sliding mechanism at 45° inclination. The difference in temperatures between top and bottom thermocouples is between 1.3 °C and 2.3 °C for the base fluid. This tangible temperature drop is caused by the sliding of the bubbles on the inclined tube after it incepts from the nucleation site. This is in agreement with the observations that Sateesh (2006) made in his doctoral dissertation. For the nanoparticle suspensions, this temperature drop is between −0.2 °C and 1.2 °C, which tells us that the bubble sliding mechanism is impeded by the presence of particles in the proximity of the heating surface. This would be the reason why minimum heat transfer is obtained for the inclined configuration (Fig. 6) compared to vertical and horizontal configurations.

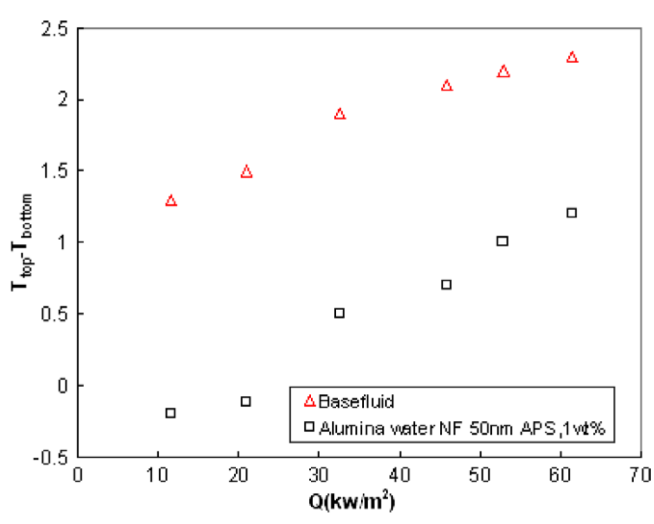

Fig. 12. Top and bottom wall superheats difference on 45° inclined tube.

5. Conclusions

Systematic experiments on pool boiling heat transfer of nanoparticle suspension at different orientations were conducted and the following conclusions were arrived at

(1) Pool boiling heat transfer is highest for the horizontal arrangement of the tube. The reason is that the bubbles primarily nucleate on the bottom of the tube and the particles have a lesser chance of deactivating nucleation sites on the bottom.
(2) The inclined orientation provides the lowest heat transfer. This is attributed to the fact that bubble sliding is impeded by particles in the proximity of the heating surface.
(3) The suspensions with larger particles (150 nm) provide higher heat transfer for all three configurations. This effect is highest for horizontal configurations. This might be explained by various surface particle interactions between the SS tube and the alumina nanoparticles.
(4) Pool boiling is found to deteriorate for the smooth heating tube used for the experiments (especially at higher concentrations). This is explained by the value of surface–particle interaction parameter (Prakash, 2006) being close to one.
(5) A wide range of heat transfer performances can be obtained by designing the nanoparticle suspension (its volume concentration and particle size) and the heating surface (its surface roughness and surface orientation) for the required result.

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