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Research Article

Effect of Uniformly and Nonuniformly Coated Al_2O_3 Nanoparticles over Glass Tube Heater on Pool Boiling

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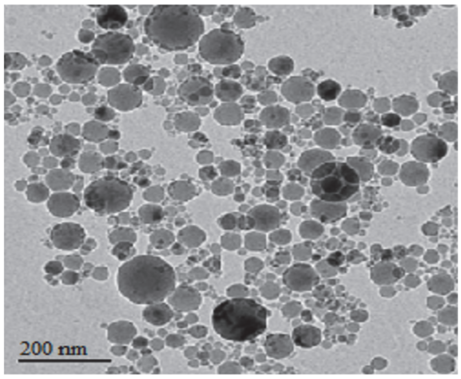
Effect of uniformly and nonuniformly coated Al_2O_3 nanoparticles over plain glass tube heater on pool boiling heat transfer was studied experimentally. A borosilicate glass tube coated with Al_2O_3 nanoparticle was used as test heater. The boiling behaviour was studied by using high speed camera. Result obtained for pool boiling shows enhancement in heat transfer for nanoparticle coated surface heater and compared with plain glass tube heater. Also heat transfer coefficient for nonuniformly coated nanoparticles was studied and compared with uniformly coated and plain glass tube. Coating effect of nanoparticles over glass tube increases its surface roughness and thereby creates more nucleation sites.

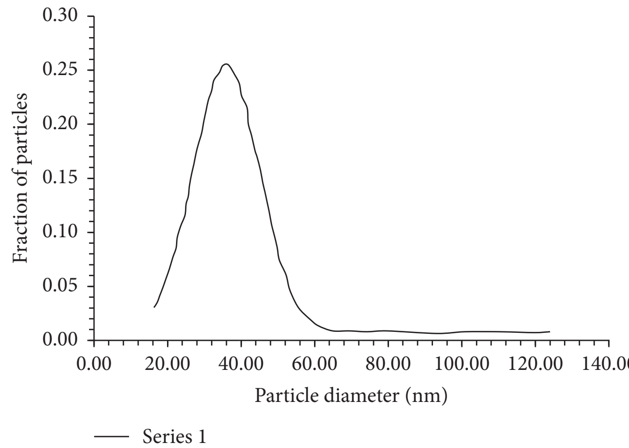
1. Introduction

Boiling occurs at solid-liquid interface when a liquid is brought into contact with a surface maintained at a temperature sufficiently above saturation temperature of liquid. The boiling process is characterised by the rapid formation of vapour bubbles at solid-liquid interface that detach from the surface when reaching at certain size and attempt to rise to the free surface of liquid. Over the past decades, a great amount of research has been carried out to enhance heat transfer during pool boiling and flow boiling, and it is still going on. Boiling has been found in a wide range of applications such as power generation, refrigeration, air-conditioning, chemical and thermal processes, cooling of electronic components, microfluidic system, thermal control of aerospace station, and material processing. Accordingly various techniques for augmentation of boiling heat transfer have been proposed and studied. Typical approaches that have been considered to enhance "Pool" boiling heat transfer in particular include treated surfaces, rough surfaces, mechanical aids, surface vibrations, electrostatic field, additives for fluids (surfactants), and so forth.

Among the different enhancement techniques studied, the use of surfactant additives and nanofluid technology has been found to be very effective. Surfactant additive changes the boiling phenomenon drastically. The addition of very small amounts of surfactant additive in water can enhance nucleate boiling heat transfer remarkably with nichrome wire as plain heater [1–5]. Das et al. [6] investigated pool boiling in water $-Al_2O_3$ Nanofluid on rectangular stainless steel vessel experimentally. It was observed that, with increasing particle concentration, the degradation in boiling performance took place. Bang and Chang [7] studied pool boiling heat transfer performance using Al_2O_3 Nanofluid on horizontal and vertical plane surface. CHF was found to be enhanced in both cases. Wang and Mujumdar [8] reviewed heat transfer characteristics of Nanofluid. H. Kim and M. Kim [9] reported pool boiling CHF enhancement using TiO_2, Al_2O_3, and SiO_2 Nanofluid. They observed nanoparticle coating on heating surface after experiment. Trisaksri and Wongwises [10] mixed TiO_2 nanoparticles at different concentrations with refrigerant R141b. They conducted pool boiling experiments of Nanofluid and compared them to that of the base refrigerant.



(a)



(b)

FIGURE 1: Characteristics of Al_2O_3 nanoparticles: (a) TEM photograph and (b) particle size distribution, data taken from Bang and Chang [7].

Gajghate et al. [11] studied the flow boiling heat transfer for plain heater surface inclined water tube with environmental friendly additives shows the improvement in heat transfer by the effect of tube angle of hollow glass tube plain heater surface. Kwark et al. [12] studied pool boiling behaviour of low concentration nanofluid over a flat heater surface experimentally. Kim [13] reviewed enhancement of CHF in nucleate boiling of nanofluids. He presented characteristics of CHF enhancement in nanofluids according to the effect of primary boiling parameters.

The objective of present investigation is to study pool boiling behaviour on plain glass tube, uniformly, and nonuniformly nanoparticles coated glass tube. Al_2O_3 nanomaterial was selected for study. Boiling behaviour over plain glass tube was compared with nanomaterial coated glass tubes.

2. Experimental Apparatus and Procedure

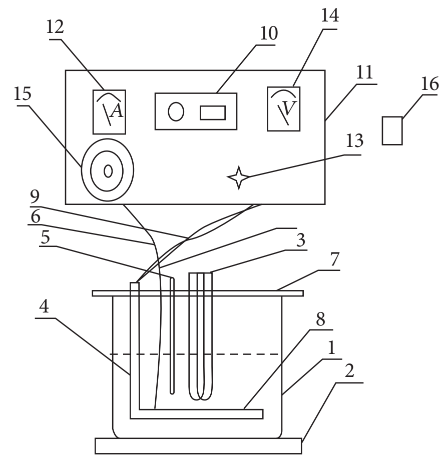
2.1. Preparation of Nanoparticle Coated Test Heaters. Alumina nanomaterial was selected for coating as they are widely used in this research area due to requirements such as stable, uniform, and continuous suspension without any outstanding chemical change of the base fluid. Figure 1(a) shows photo taken by transmission electron microscopy (TEM). The alumina nanoparticles have spherical image. The size has a normal distribution in a range (Figure 1(b)) from 10 nm to 120 nm (average diameter is 47 nm given from the manufacturer). The test heater was prepared by using a borosilicate glass tube (outer diameter = 19.80 mm, inner diameter = 12.6 mm, and length L = 100 mm). A cylindrical test heater (nichrome) of diameter 12.5 mm was inserted into glass tube. The glass tube was cleaned to remove dust and other impurities. Epoxy resin paste of thickness 0.3 mm was coated on the glass surface by general craftsman's technique. Immediately after sticking of epoxy resin, we use the fluidized powder coating method to coat the Al_2O_3 nanoparticles uniformly (coating all over the surface) on the glass coated epoxy surface. After coating of nanoparticles powder heat the coated surface for 5 to 10 minutes, for drying of epoxy resin. For preparing nonuniformly (exposing some surface without nanoparticles) distributed surfaces, apply the Al_2O_3 nanoparticles powder on the surface randomly or manually spray the powder. Figures 2(a) and 2(b) show glass tube coated with nonuniformly and uniformly nanoparticle coated test heaters, respectively.

2.2. Apparatus. The schematic of the apparatus used to study pool boiling is shown in Figure 3. The apparatus consists of a cylindrical glass container 5 liters capacity, housing the test heater, and a heater coil to maintain the temperature of the liquid pool at saturation temperature. This heater coil was directly connected to the mains and the test heater. Test heater was connected also to mains via a Dimmerstat. An ammeter was connected in series with a voltmeter across it to read the current and voltage, respectively. There was provision of illuminating test heater with the help of a lamp projecting light from behind the container. The heater could be viewed through lens of a high speed camera to study bubble nucleation, growth, and its departure. K-type thermocouple was calibrated by putting into ice and correspondingly checked for the effect of electric power on thermocouple where it is mounted on hollow glass tube test heater to clarify the system resistance or not. The pool temperature and temperature of test heater were measured by calibrated K-type thermocouple. The thermocouple was attached to the surface of test heater using transparent epoxy adhesive.

2.3. Procedure. Initially, glass container was filled with pure water, and it was heated to saturation temperature at atmospheric pressure using auxiliary heater. The auxiliary heater was switched OFF, and glass tube heater was switched ON as soon as pure water reaches saturation temperature. The electric power supply to the test heater was increased gradually using dimmer. The temperature of water and test heater were recorded at each step. At each value of heat input,

(a) (b)

Figure 2: Nanoparticle coated test heaters: (a) nonuniformly coated and (b) uniformly nanoparticle coated.



(1) Glass container
(2) Supporting stand
(3) Auxiliary heater
(4) Test heater
(5) Thermometer
(6) Thermocouple
(7) Clay lid
(8) Test heater
(9) Heater connecting cable
(10) Digital temperature indicator
(11) Control panel
(12) Ammeter
(13) Selector switch
(14) Voltmeter
(15) Dimmerstat
(16) Electric power switch

Figure 3: Schematic of experimental apparatus.

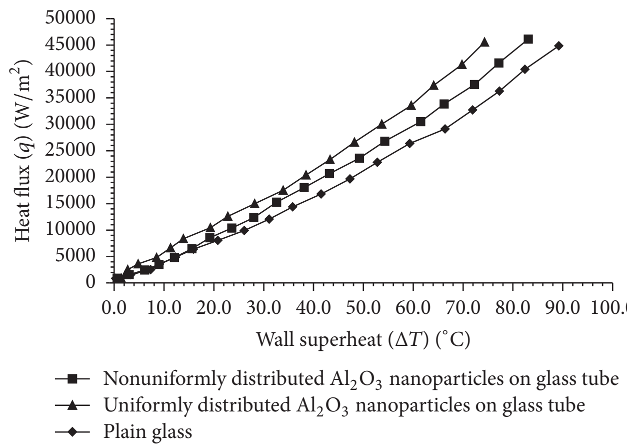


Figure 4: Heat flux v/s wall superheat for plain glass tube and nanoparticles coated glass tube.

wall heat flux, q was calculated from the measured voltage V, current I, and heater surface area A as

$$q = \frac{V \times I}{A}. \tag{1}$$

Boiling behaviour was recorded on high speed camera for additional analysis. The experiments were carried out until reproducibility of the boiling curves became satisfactory. The procedure was repeated. Glass vessel was emptied and filled with pure water and glass tube heater was replaced nanoparticle coated test heater. Thermocouple was reconnected. As the temperature distribution on boiling surface was nonuniform and transient, the following time space average temperature was used:

$$T = \frac{1}{At}\int_A^0 \int_t^0 T\, dA\, dt. \tag{2}$$

The heat diffusion equation was adopted to determine boiling surface temperature.

$$T_w = T(x) - \frac{ql}{2K}\left(1 - \frac{x^2}{l^2}\right). \tag{3}$$

The average heat transfer coefficient was calculated as follows:

$$h = \frac{q}{\Delta T_w}, \qquad \Delta T_w = T_w - T_{\text{sat}}. \tag{4}$$

2.4. Uncertainty Analysis. Uncertainty analysis was done as per method described by Holman [14]. The voltmeter and ammeter were within ±1 V and ±0.001 A accuracy level, respectively. The uncertainty in the measurement of heat flux was ±2%. The temperature test heater was measured by calibrated K-type thermocouple with the precision of ±0.1°C at 95% confidence level. The accuracy in the measurement of temperature of liquid pool was ±1°C.

3. Results and Discussion

We conducted 7 trials of the pool boiling experiment to obtain reliable estimates of average values. The average values were plotted to study boiling behaviour. The results of experimentation show enhancement in heat transfer. Figure 4. Shows the boiling curves, that is, the dependence of dissipated heat flux on wall superheat during present investigation. The coating of nanoparticle on plain glass heater shifted boiling curve to the left which indicates augmentation in boiling heat transfer. For the same value of heat flux, wall superheat was observed to be reduced. The reduction of wall

Table 1: Surface roughness values of different test heaters.

Sample number	Description of test heater	Surface roughness parameters R_a	R_q
1	Plain glass tube	36.23	51.32
2		37.19	51.73
3		36.84	52.79
4		36.59	52.26
5		37.18	51.57
1	Nonuniformly Al_2O_3 nanoparticles coated glass tube	113.73	150.25
2		114.69	151.06
3		114.87	150.56
4		113.91	151.46
5		113.12	151.39
1	Uniformly Al_2O_3 nanoparticles coated glass tube	231.63	293.14
2		231.89	293.61
3		232.04	293.23
4		231.19	294.09
5		232.07	294.12

superheat was 5.56% and 17.78% for nonuniform nanoparticles coated glass tube and uniformly nanoparticles coated glass tube, respectively. The reason behind this is related to surface roughness characteristics. The surface roughness of nanoparticle coated glass tube heaters was found to be increased as compared to plain glass tube. Surface roughness measurement was performed by using a Contact profilometer as used by Sarafraz and Peyghambarzadeh [15]. Five samples of each test heater were used to measure surface roughness. Typical measured values of surface roughness for different heaters are given in Table 1. In present study, plain glass tube heater has surface roughness smaller than nanoparticle size. The coating of nanoparticle on glass surface increases its surface roughness, thereby creating more nucleation sites. The higher the number of nucleation sites, the more bubbles generated on heater surface. The obtained results of present study are consistent with Bang and Chang [7]. The bubbles serve as "energy movers" from hot surface into liquid body by absorbing heat from hot surface and releasing it into the liquid as they condense and collapse. So the more bubbles form, the more the heat transfers from heated surface, which enhances boiling heat transfer coefficient [16].

The effect of heat flux on heat transfer coefficient of nanoparticle coated surfaces is more evident if the experimental data have expressed as a plot of heat transfer coefficient versus heat flux, as shown in Figure 5. It was observed that heat transfer coefficient increases with heat flux. Also, heat transfer coefficient for nonuniformly coated glass tube lies in between uniformly coated glass tube and plain glass tube. The increment in heat transfer coefficient was 14.39% and 31.06% for nonuniform nanoparticles coated glass tube and uniformly nanoparticles coated glass tube, respectively. Figure 6 shows different photographs of boiling behaviour with increasing heat flux (q = 5000, 10000, and 15000 W/m^2) for plain glass tube and nanoparticles coated heaters. The

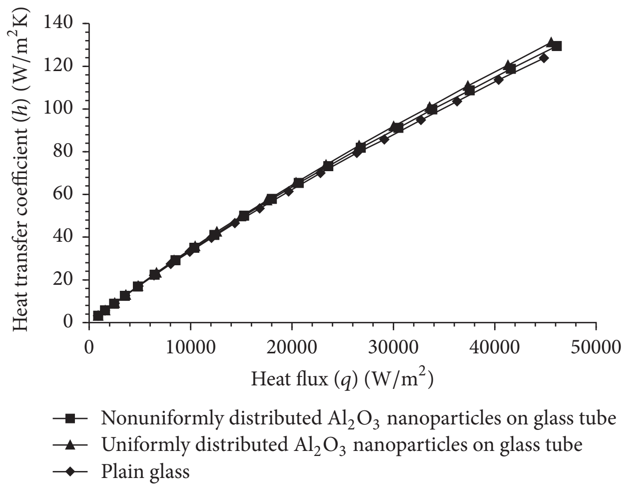


Figure 5: Heat transfer coefficient v/s heat flux for plain glass tube and nanoparticles coated glass tube.

Table 2: Values of critical heat flux.

Heater surface	CHF (MW/m^2)
Plain glass tube	0.412
Nonuniformly nanoparticle coated glass tube	0.428
Uniformly nanoparticle coated glass tube	0.455

boiling behaviour was observed to be different for different heaters in pure water. The coating of nanoparticle over glass tube creates irregularities on heater surface which encourages heterogeneous nucleation, and thereby promotes activation of nucleation sites. The boiling pool became significantly cloudier with nanoparticles coating. It was more vigorous and characterised by smaller shaped bubbles. The bubbles appear in a cluster mode. There is an early evolution of bubbles with the faster covering of heating surface, and higher bubble departure frequency which is essentially the outcome of nanoparticles coating. With uniform coating, boiling pool became considerably cloudier; bubbles tend to coalesce forming slugs and columns. So, it was very difficult to get clear photograph of uniformly nanoparticles coated heater. Hence, photographs at higher heat flux were not presented.

CHF characteristics were also investigated for nanoparticle coated heaters and plain glass tube heater. CHF condition was defined as sudden rise in temperature (~50°C) of the heater surface. Here, power supply to the test section was immediately switched OFF to avoid damage to heater surface. CHF was found to be increased by ~18% and ~39% for nonuniformly and uniformly coated glass tube heaters, respectively, compared to plain glass tube. Table 2 shows the results of CHF data.

4. Conclusion

The pool boiling experiment was carried out over a plain glass tube and nanoparticles coated glass tube for various heat fluxes. Water was used as working fluid and high speed

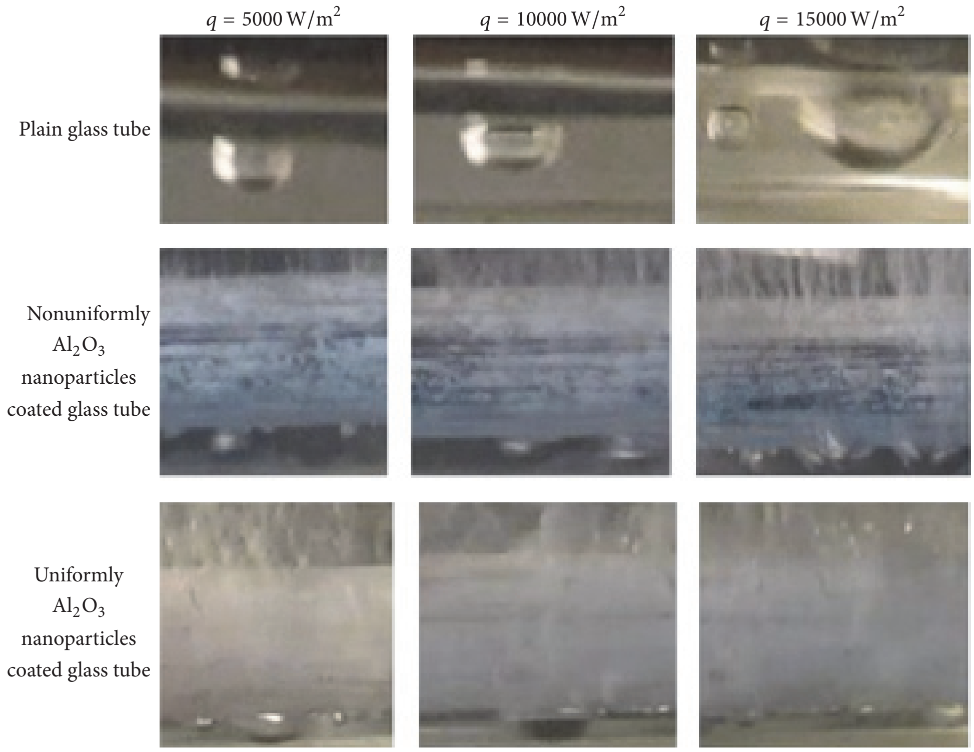


Figure 6: Boiling behaviour at different heat fluxes.

video technique was used to study pool boiling phenomenon. The reduction of wall superheat was 5.56% and 17.78% for nonuniformly nanoparticles coated glass tube and uniformly nanoparticles coated glass tube, respectively. Boiling curves were shifted to the left because of coating of nanoparticle over glass tube which indicates enhancement in boiling heat transfer.

Heat transfer coefficients were determined for plain glass tube and compared with nanoparticles coated glass tube. Heat transfer coefficient was found to be more for uniformly Al_2O_3 nanoparticle coated glass tube. The increment in heat transfer coefficient was 14.39% and 31.06% for nonuniformly nanoparticles coated glass tube and uniformly nanoparticles coated glass tube, respectively.

The boiling pool became significantly cloudier with nanoparticles coating. It was more vigorous and characterised by smaller shaped bubbles.

The coating of nanoparticles over a surface results in increased surface roughness if and only if its surface roughness is less than nanoparticle size before coating.

Nomenclature

A: Heater surface area (m^2)
d: Outer diameter of glass tube (mm)
h: Heat transfer coefficient (W/m^{2}K)
k: Thermal conductivity of liquid (W/m° K)
L: Length of test heater (m)
l: Wall thickness of heater (m)
h: Heat transfer coefficient (W/m^{2}K)
I: Electric current (A)
q: Wall heat flux (W/m^2)
R_a: Roughness parameter, $R_a = (1/\mathrm{L}) \int_0^L |f(x)| dx$
R_q: Roughness parameter, $R_q = \sqrt{(1/\mathrm{L}) \int_0^L f(x)^2 dx}$
T: Temperature (K)
T_w: Temperature of heating surface (K)
T_s: Saturation temperature of liquid (K)
$(T_w - T_s)$: Wall superheat (K)
t: Time (sec)
V: Voltage (Volts)
x: Wall thickness position (m).

Competing Interests

The authors declare that they have no competing interests.

Acknowledgments

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