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DEVELOPMENT OF EMPIRICAL RELATIONS FOR THE PREDICTION OF HEAT FLUX USING AL_2O_3 -WATER NANOFLUID

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ABSTRACT

Nanofluids are the new class of technology fluids developed by dispersing high thermal conductivity nano particles to the base fluids. Cooling techniques are one of the vital points in industries and using high heat transfer medium for the cooling of high energy equipments and machineries and the way to develop the traditional fluids to a high thermal heat transfer fluid is crucial. Development of high thermal fluid as a nanofluid is purely depends on the thermal and physical properties of base fluid and the particles dispersed on it and some other factors on which it depends like particle shape, particle size and the particle concentration. This paper explains the thermal properties of nanofluid viz., thermal conductivity, specific heat and other thermal properties. A theoretical correlation have been developed to predict the heat flux for nucleate pool boiling of Al_2O_3-Water nanofluids considering the effects of temperature, volume fraction and shape of the particle while neglecting Brownian motion of the nanoparticle, cluster/particle agglomeration and the development of the liquid layer over the plate surface. The predicted result has been compared with the Rohsenow equation and the experimental data of other investigators which shows a good agreement. Using this equation, heat transfer coefficient and heat transfer enhancement ratio of the nucleate pool boiling of Al_2O_3-Water nanofluids have been calculated. This enhanced thermo physical and heat transfer characteristics of developed fluid dispersed with nanoparticles can be used for the high heat transfer medium for future applications.

KEYWORDS: Empirical Relation, Nanofluids, Pool Boiling Heat Transfer, Thermo Physical Properties

INTRODUCTION

Boiling is a very effective mode of heat transfer and due to this reason it has wide applicability in various industries. Many researchers have conducted very systematic study of the basic mechanism of boiling worldwide but, its physical mechanism remains too complex to be completely understood even for a common fluid like water. It is known to depend mainly on surface heat flux, heater surface, and heater geometry. Also it is known that the inclusion of particles in a liquid alters the boiling characteristics. Various researchers investigate experimentally the pool boiling heat transfer in Nanofluids with various proportions of particle concentrations. Deterioration in heat transfer coefficient are mainly observed at higher particle concentrations (4-16% by weight) and enhancements mainly at lower particle concentrations (0.32-1.25% by weight).Moreover, the relative size of the particle with respect to the surface roughness of the heating surface seems to play an important role in understanding the boiling behaviour.

Nucleate pool boiling characteristics of Al_2O_3-H_2O nanofluids on a cylindrical stainless steel cartridge heaters of 20mm diameter and 420 Volt, 2.5 kW rating was investigated by "Das et al. (2003a)". They conducted experiments with high solid particle concentrations of 4-16% by weight. In this work the nanofluids were neither electro-statically stabilized nor was surfactant used to stabilize the nanofluid. The result shows the higher the concentration the more was the sedimentation and hence the boiling performance worsened. The reason is the nanoparticles were found to sediment on the

heater, thus making it smoother and deteriorating the boiling performance. This brings out the probable cause for the deteriorating in boiling characteristics. Due to the fact that the sizes of the nanoparticles (20-50nm) are one to two orders of magnitude smaller than the roughness (0.38-1.12 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.

Later on "Das et al. (2003b)". showed that pool boiling on nanofluids on narrow horizontal tubes (4 and 6.5mm diameter) is qualitatively different from the large diameter tubes due to difference in bubble sliding mechanism it was found that at this range of narrow tubes the deterioration in performance in boiling of nanofluids is less compared to large industrial tubes, which make it less susceptible to local overheating in convective applications. For boiling on tubes of 4mm and 6.5mm diameter there seems to be less importance of sliding mechanism for larger bubbles, which are comparable to the size of bubbles of boiling on 20mm tube. This is because of the relatively small size of the tube, which produces a large curvature of the surface, which does not allow the sliding of larger bubbles but induces direct departure. However, a large number of smaller bubbles are produced in a sustainable way here and they slide but to a relatively smaller distance by Das et al (2003a)".

"Bang and Chang, (2005ab)" studied pool-boiling heat transfer characteristics of Al_2O_3-Water nanofluids at higher heat fluxes and smoother heaters compared to "Das et al. (2003a)". Their experiments were also with 4-16wt% nanofluids, having surface roughness equivalent to370 nm. They had some important observations regarding the boiling characteristics of nanofluids. Firstly they also observed deterioration of boiling with nanofluids concentration in nanofluids similar to "Das et al. (2003a)" but the rate of heat transfer was somewhat different which they attributed to the difference in geometrical features of the heaters in the two studies. They could also identify a clear natural convection regime followed by nucleate boiling. They observed that the experimental data does not conform to the Rohsenow correlation just by changing the properties of the fluid with effective nanofluid properties. They tried different variations of the same correlation like using Rohsenow correlation with changing only the effective conductivity or changing the constant Csf (surface fluid combination factor) of the Rohsenow correlation. It was found that rather changing the properties of the fluid, the modification of the surface fluid combination factor, Csf gives closer approximation to the experimental boiling data of nanofluids. This definitively indicates that the modification of surface characteristics during the boiling of nanofluids might hold the key in explaining the deterioration of boiling of nanofluid.

"Zhou et al. (2004)" experimentally investigated the effects of acoustical parameters, nanofluid concentration and fluid subcooling on boiling heat transfer characteristics of a copper–acetone nanofluid. The results showed that the presence of the copper nanoparticles did not affect the dependence of the heat transfer on the acoustic cavities and fluid subcooling. Without an acoustic field, the boiling heat transfer of the nanofluid was reduced. In contrast with the experimental results of "Das et al. (2003 ab)", in this study the pool boiling heat transfer was not reduced with increasing nanofluid concentrations. With an acoustic field generated to the nanofluid, the boiling heat transfer was enhanced and the boiling hysteresis disappeared. The enhancement became obvious with increasing fluid subcooling, sound source intensity, and nanoparticle concentration. The pool boiling of nanofluids depends on many factors, among those the particle dispersion and its concentrations is one of the most important parameter for the heat transfer enhancement.

"Wen and Ding, (2005a)" gave a completely different picture of boiling of nanofluids. They observed an enhancement of boiling in the presence of nanoparticles. The particles used by them were same as those used by "Das et al. (2003a)" with particle sizes 10-50nm.they stabilized the suspension by adjusting the pH value near 7, which is away from the iso-electrical point (IEP) of Alumina (about 9.1). They also used a high-speed homogenizer (≈24000 rpm) for breaking

the agglomerates of Al_2O_3 powder. Even after these processes they found considerable agglomeration giving an average particle size of 167.54 nm but the nanofluid was stable. They used 2.4kw ring heater below stainless steel boiling surface.

"You et al. (2003)" performed experiments with alumina-water nanofluids of very small solid particle concentrations (0.0001-0.005% by weight) on a 10mm square heater in sub-atmospheric conditions. They found no significant change in nucleate pool boiling.

"Vasallo et al. (2004)" conducted experiments with silica-water nanofluids (2% by weight) of different particle sizes, ranging from 15nm to 3,000 nm on a NiCr wire heater and found no significant change in the boiling performance at low and medium heat fluxes. But at heat fluxes near to CHF of water, they observed there is boiling deterioration for the 50nm nanofluid.

"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 heat transfer coefficient also increased.

"Prakash et al. (2007 ab)" experiments have been carried out by using stable water based nanofluids containing alumina nanoparticles of various sizes with vertical tubular heaters of various surface roughnesses. He has found that when the average particle size is of the order of the surface roughness, the number of nucleation sites is greatly decreased. It was also found that when average particle size is much smaller than the heater surface roughness the number of nucleation sites is greatly increased. Here they define a new term called surface-particle interaction parameter. This is the ratio of average surface roughness Ra to average primary diameter of the particle d_p .Physically, it signifies that if it is less than 1 particle size is more than the roughness value and vice versa.

THERMAL PROPERTIES OF NANOFLUID

A nanofluid can be defined as a mixture consisting of a continuous base fluid component and a discontinuous solid component called particles. The properties like the thermal conductivity and viscosity, of nanofluids depend on their microstructures such as the component particles, component volume fractions or volume concentrations, particle size, particle shape, particle distribution and base fluid – particle interfacial effects. It is impossible to formulate the effective properties of nanofluids unless all the details of their microstructures are completely known. To avoid this problem, the effective properties are estimated in the literature based on some reasonable assumptions on the microstructures of mixtures. In this section, the effective properties are shown for mixtures and new improvements in nanofluids are presented.

Density

The calculation of the density of a nanofluid is straightforward. It can be estimated based on the physical principle of the mixture rule as

$$\rho_{nf} = \frac{m}{v} = \frac{m_f + m_p}{V_f + V_p} = \frac{\rho_f V_f + \rho_p V_p}{V_f + V_p} = (1 - \varphi)\,\rho_f + \varphi\rho_p \quad (1)$$

For a typical nanofluid with nanoparticles at a value of volume fraction less than 1%, a change of less than 5% in the fluid density is expected.

Specific Heat

The specific heat of a nanofluid can be calculated as

$$(\rho C)_{nf} = \rho_{nf}\left(\frac{Q}{m\Delta T}\right)_{nf} = \rho_{nf}\frac{Q_f + Q_p}{(m_f + m_p)\Delta T} = \rho_{nf}\frac{(mC)_f\Delta T + (mC)_p\Delta T}{(m_f + m_p)\Delta T} = \rho_{nf}\frac{(\rho C)_f V_f + (\rho C)_p V_p}{\rho_f V_f + \rho_p V_p}$$

$$= (1-\varphi)(\rho C)_f + \varphi(\rho C)_p \quad (2)$$

This can be re written as

$$C_{nf} = \frac{(1-\varphi)\rho_f C_f + \varphi\rho_p C_p}{(1-\varphi)\rho_f + \varphi\rho_p} \quad (3)$$

By using these equations, it can be easily predict that small decreases in specific heat will typically result when solid particles are dispersed in liquids. For example, adding 3% Al_2O_3 by volume to water leads to decrease the specific heat by approximately 7-8% compared with that of water alone. The simple equations obtained by using energy balance as stated above may need to be modified if nanoparticles are found to exhibit a size-dependent specific heat.

Viscosity

The viscosity of water-based nanofluids containing Al_2O_3 nanoparticles dispersed by different dispersion techniques was experimentally measured by "Wang et al. (2002)." and showed that nanofluids have lower viscosities when the particles are better dispersed. They also showed an increase of about 30% in viscosity at 3 vol. % Al_2O_3, compared with that of water alone. However, the viscosity of the Al_2O_3 - water nanofluids prepared by "Pak and Cho (1998)." was three times higher than that of water. For metallic nanofluids containing a low volume fraction of nanoparticles (usually <0.01), Einstein proposed a model that would predict the viscosity as

$$\mu_{nf} = (1 + 2.5\varphi)\mu_f \quad (4)$$

"Brinkman (1952)." has modified equation (4) into more generalized form as

$$\mu_{nf} = \frac{\mu_f}{(1-\varphi)^{2.5}} \quad (5)$$

"Wang et al. (1999)." gave a correlation for water–Al_2O_3 nanofluid, as follows

$$\mu_{nf} = 123\varphi^2 + 7.3\varphi + 1 \quad (6)$$

"Pak and Cho (1998)." gave correlation for the viscosity of nanofluids, as follows

For Water–Al_2O_3

$$\mu_{nf} = \mu_f(1 + 39.11\varphi + 533.9\varphi^2) \quad (7)$$

Thermal Conductivity

Maxwell was one of the first to analytically investigate conduction through suspended particles. Maxwell considered a very dilute suspension of spherical particles by ignoring the interactions among the particles. Many theoretical and empirical models have been proposed to predict the effective thermal conductivity of nanofluids. Using potential theory, "Maxwell (1881)" obtained a simple relationship for the conductivity of randomly distributed and non-interacting homogeneous spheres in a homogeneous medium as

$$\frac{k_{nf}}{k_f} = 1 + \frac{3(\alpha-1)\varphi}{(\alpha+2) - (\alpha-1)\varphi} \quad (8)$$

Where $\alpha = \frac{k_p}{k_f}$

The Maxwell equation is only a first-order approximation and applies only to mixtures with low particle volume concentrations. "Hamilton & Crosser, (1962)" modified the Maxwell correlation as

$$\frac{k_{nf}}{k_f} = \frac{[k_p + (n-1)k_f - (n-1)\varphi(k_f - k_p)]}{[k_p + (n-1)k_f + \varphi(k_f - k_p)]} \quad (9)$$

Where the parameter n is the 'shape factor' and defined as $n = \frac{3}{\Psi}$, and is called as the 'sphericity'. Sphericity is defined as the ratio of the surface area of the sphere to that of the particle for the same volume. For spherical particles Ψ = 1, and for the cylinders Ψ = 0.5.

"Jang and Choi (2004)." found that the Brownian motion of nanoparticles at the molecular and nanoscale level is a key mechanism governing the thermal behavior of nanofluids. They derived a model, which considers the concentration, temperature and, size. They proposed four modes of energy transport, viz., (1) collision between base fluid molecules; (2) thermal diffusion in nanoparticles suspended in fluids, (3) collision between nanoparticles and (4) thermal interactions of dynamic or dancing nanoparticles with base fluid molecules and derived the thermal conductivity of nanofluid k_{nf} by neglecting the third mode.

Volume Fraction

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

$$\varphi = \frac{1}{\left(\frac{1-\varphi_m}{\varphi_m}\right)\frac{\rho_p}{\rho_f} + 1} \quad (10)$$

The heat transfer coefficient, h, is calculated by

$$h = \frac{q}{(T_w - T_s)} \quad (11)$$

In the nucleate boiling régime, the rate of heat transfer strongly depends on the nature of nucleation (the number of active nucleation sites on the surface, the rate of bubble formation at each site, etc.), which is difficult to predict. The type and the condition of the heated surface also affect the heat transfer. These complications made it difficult to develop theoretical relations for heat transfer in the nucleate boiling regime, and we had to rely on relations based on experimental data.

The most widely used correlation for the rate of heat transfer in the nucleate boiling regime by "Rohsenow, (1952)" and expressed as

$$q = \mu_l h_{fg}\left[\frac{g(\rho_l - \rho_v)}{\sigma}\right]^{1/2}\left[\frac{c_l(T_w - T_s)}{c_{sf}h_{fg}Pr_l^{\,n}}\right]^3 \quad (12)$$

In the above correlation 'ρ_l' (density of the liquid), 'μ_l' (viscosity of the liquid), 'C_l' (specific heat of the liquid), 'Pr_l' (Prandtl no. of the liquid) are formulated for a simple base fluid or conventional heat transfer fluids. 'C_{sf}' (experimental constant) and 'n' (experimental constant) that depends on surface-fluid combination has great effects on the formulation of the heat flux. These properties are creating a huge change in the above correlation when it is subjected to pool boiling of nanofluids depending on the heater surface, the volume fractions of the nanoparticles, type of the nanoparticles and the base fluid used. In general the correlation changes its form when nanoparticles dispersed in the base fluid. The changes occurs in the properties which are then formulated in the above correlation are discussed in the next section.

THEORETICAL ANALYSIS

The present study is aimed at developing a correlation to predict the heat flux of nucleate pool boiling of Al_2O_3–water nanofluid at different particle volume fractions with respect to the temperature in a mechanically polished flat stainless steel plate. As it is evident from literature survey, that there exists no direct formulated correlation for nucleate pool boiling of nanofluids. In general, most nanofluids used in practical applications contain oxide particles and can be easily fluidized. Consequently, it can be treated as single-phase fluid which possesses thermo physical properties as explained earlier. Thus a direct extension of conventional fluid to nanofluid is feasible and classical theory developed for single-phase fluid is also applicable to nanofluid. The conservation of mass, momentum, energy is also applicable. Applicability of the above assumptions is difficult to assess due to lack of data. However, under negligible slip condition, assuming thermal equilibrium between the phases and assuming the particle spatial distribution as uniform the single-phase assumption is valid. From the practical point of view, mixtures with relatively low particle concentration ensure a perfect mixing of particles inside the liquid phase. The stability of particle suspension is also crucial for experimental verification and also for the formulation of correlation.

In the equation (14), the Prandtl number has been taken for base fluid only, while this non-dimensional number has a crucial effect on the boiling and can be predicted from the following relation for the Al_2O_3-water nanofluid

$$Pr_{nf} = \frac{\mu_{nf} C_{nf}}{k_{nf}} \tag{13}$$

The specific heat of the Al_2O_3-water nanofluid can be formulated by putting the values of density of water (ρ_f) and density of Al_2O_3 (ρ_p) in the equation (2) and can be written as

$$C_{nf} = \frac{4039464.3 - 1000429.3\varphi}{\rho_{nf}} \tag{14}$$

Where values of ρ_f for water and ρ_p for Al_2O_3 has been taken which is suitable to nanofluid experimental data.

The density of Al_2O_3 –water nanofluid can be calculated by putting the values of ρ_f for water and ρ_p for Al_2O_3 in equation (1) and can be written as

$$\rho_{nf} = (1 - \varphi)957.9 + 3970\varphi \tag{15}$$

The viscosity of the Al_2O_3 –water nanofluid can be calculated by putting μ_f for water in equation (4) and can be written as

$$\mu_{nf} = 0.282 \times 10^{-3}(1 + 2.5\varphi) \tag{16}$$

The thermal conductivity of Al_2O_3–water can be calculated by putting the values of k_f for water and kp for Al_2O_3 in equation (8) and can be written as

$$k_{nf} = 0.679\left[1 + \frac{173.7\varphi}{(60.9 - 57.9\varphi)}\right] \quad (17)$$

The heat flux of the nucleate pool boiling of Al_2O_3-water nanofluid can be calculated from Rohsenow correlation using the properties of the nanofluid from equations (13-17), where the constants 'C_{sf}' and 'n' represent the coefficients suitable to boiling of Al_2O_3-water nanofluid in the stainless steel polished surface. The analysis of all the properties and constants with respect to experimental data provides a mathematical prediction of heat flux for Al_2O_3-water nanofluid proportional to temperature difference and particle volume fraction.

Thus the predicted heat flux of the nucleate pool boiling of Al_2O_3-water nanofluid is as follows

$$\left[\frac{(T_w - T_s)(A - B\varphi)}{0.013 Pr_{nf}^{n} \times h_{fg} \times \rho_{nf}}\right]^3 = \left[\frac{q \times 2.5 \times 10^{-3}}{\mu_{nf} \times h_{fg}}\right] \quad (18)$$

Where **A= 4039464.3 and B= 1000429.3**.These constants are applicable only for Al_2O_3-water nanofluid considering spherical shape particle while neglecting Brownian motion of the nanoparticle, cluster/particle agglomeration and the development of the liquid layer over the plate surface.

RESULTS AND DISCUSSIONS

The heat flux, heat transfer coefficient and heat transfer enhancement ratio for Al_2O_3-water nanofluid have been studied in detail. The nanoparticle volume fraction, fluid temperature and surface temperature have been varied to observe their effects.

Effects on Heat Flux of Varying Nanoparticle Concentrations

The heat flux of the pool boiling of Al_2O_3-water nanofluid has been found out at different surface temperatures. With the addition of nanoparticles, the heat flux increases with increasing surface temperatures. The heat flux has been formulated for four different particle concentrations. The prediction of heat flux at different surface temperatures by increasing the nanoparticle concentration are shown in fig. 1. The results shows that with the increase of only 2.87 °C surface temperature at 0.32 wt % of the particle, the heat flux increases up to 68.74 kW/m2 approximately. The prediction gives reasonable results with increasing particle concentration of Al_2O_3 also. The concentration of the Al_2O_3 particles increases from 0.32 wt % to 1.25 wt %. The results show that with the increase of 0.93 wt % of particle concentration, the average heat flux increases up to 80%. The traditional plot of heat flux against surface temperature together with the prediction by the classical correlation of "Rohsenow, (1952)" for pool boiling of water is shown in the figure 2. The Rohsenow correlation for water has been compared with the predicted results with different particle concentration at different surface temperatures. The constants in the Rohsenow correlation, C_{sf} and n are taken as 0.013 and 1 for pure water, respectively. The Rohsenow correlation has been compared only to measure the deviation of heat flux in case of pool boiling of Al_2O_3-water nanofluid. The predicted heat flux results are then compared with experimental results "Wen and Ding, (2005)", the prediction give good agreement with the experimental results. The result regarding the comparison of heat flux at 0.32 wt % nanoparticle concentration is shown at figure 3. The figure (4-6) shows the comparison of predicted heat flux with experimental results "Wen and Ding, (2005)" at 0.71 wt %, 0.95 wt % and at 1.25 wt % mass fraction of Al_2O_3 nanoparticles.In the figure 3, at low surface temperatures the predicted results have less difference with experimental but some differences are there at high surface temperatures.In the figure 4 ,the results shows that predicted

heat flux increases with increasing surface temperature and have a good agreement with the experimental results also at high surface temperature.The average difference with the experimental results are very less.At high particle concentration,the heat flux increases significantly. When the predicted heat flux at 0.95 wt % particle concentration get compared with 0.38 wt % mass fraction of Al_2O_3 nanoparticles, the increase of heat flux comes as approximately 21%,which is a good achievement of boiling in nanofluid as compared with the other conventional heat transfer fluids.The pool boiling of nanofluids are a new advanced heat transfer methodology as compared to the boiling of conventional heat transfer fluids are clear with this predicted results. The results gives a clear idea on high heat flux with increasing surface temperature and increasing nanoparticle concentrations in the conventional fluids.

Effect on Heat Transfer Coefficient

The heat transfer coefficient of Al_2O_3-water nanofluid is compared with the Rohsenow correlation for water shown in figure 8.The result shows significant improvement on the heat transfer coefficient of nucleate pool boiling due to the presence of nanoparticles. The improvement increases with nanoparticle concentration at high heat fluxes. At the nanoparticle concentration of 1.25 wt %, approximately 22% increase in heat transfer coefficient is achieved.

Effects on Surface Temperature

The average surface temperature at different nanoparticle concentrations is shown in Figure 7. The figure shows that the presence of nanoparticles reduces the surface temperature significantly, and the reduction increases with increasing heat flux. The surface temperature also decreases with increasing nanoparticle concentration. The decrease of surface temperature with increasing nanoparticle concentration is due to the formation of a layer above the boiling surface due to the dispersion of nanoparticle. This layer of nanoparticle decreases the surface temperature with increasing its concentration and heat flux.

Heat Transfer Enhancement

The heat transfer enhancement ratio is compared with pure water and shown in figure 9.The heat transfer enhancement ratio of Al_2O_3-water is measured at different particle concentration at different surface temperature. The enhancement shows near about same result at different temperatures but it shows significant improvement at different particle concentration and is more considerable at high heat fluxes. At high nanoparticle concentration it shows good results and marked a good ratio of enhancement

CONCLUSIONS

The present study represents the development of theoretical correlation for pool boiling of nanofluid having Al_2O_3 as nanoparticle and water as base fluid in a mechanically polished stainless steel flat plate as a boiling surface, where the concentration of the Al_2O_3 particles in water increases from 0.32 wt % to 1.25 wt % to observe the effects on boiling heat transfer characteristics. The summary of the study is presented below:

- The theoretical correlation for prediction of heat flux, heat transfer coefficient and heat transfer enhancement ratio is developed.
- The predictions of pool boiling nanofluid heat flux at different surface temperatures by increasing the nanoparticle concentration from 0.32 wt % to 1.25 wt % shows that with the increase of only 2.87 °C surface temperature at 0.32 wt % of the particle concentration, the heat flux increases up to 68.74 kW/m^2 approximately.

- The presence of nanoparticles reduces the surface temperature significantly, and the reduction increases with increasing heat flux. The surface temperature also decreases with increasing nanoparticle concentration.
- Heat transfer coefficient of nucleate pool boiling using nanofluid increases with nanoparticle concentration at high heat fluxes such as at nanoparticle concentration of 1.25 wt %, approximately 22% increase in heat transfer coefficient is observed.

The predicted heat transfer enhancement ratio is having a good agreement with the experimental results

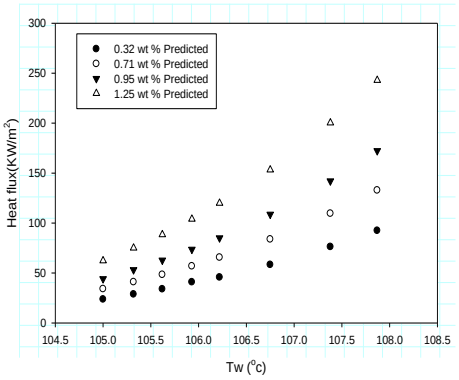

Figure 1: Predicted Heat Flux of the Pool Boiling of Al_2O_3 -Water Nanofluid

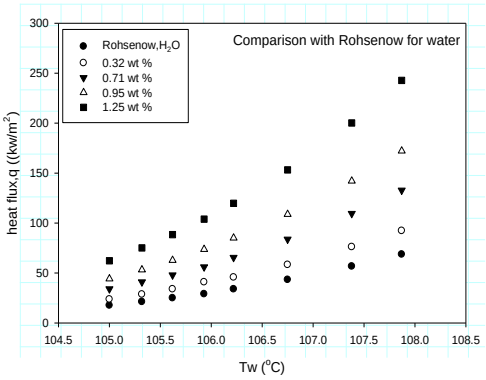

Figure 2: Comparison of Predicted Heat Flux with Rohsenow Correlation

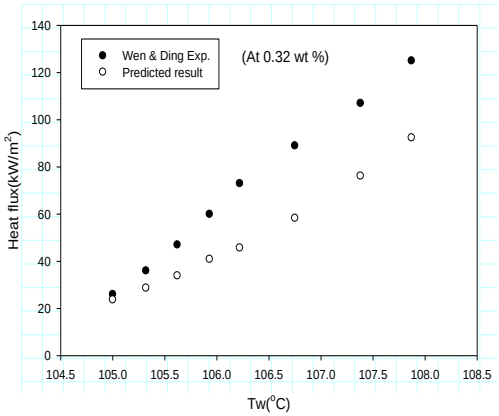

Figure 3: Comparison of Predicted Heat Flux with Experimental Results "Wen and Ding, (2005)" at 0.32 wt % of Al_2O_3

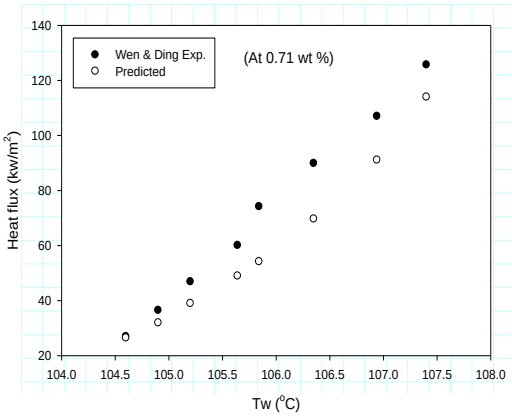

Figure 4: Comparison of Predicted Heat Flux with Experimental Results "Wen and Ding, (2005)" at 0.71 wt % of Al_2O_3

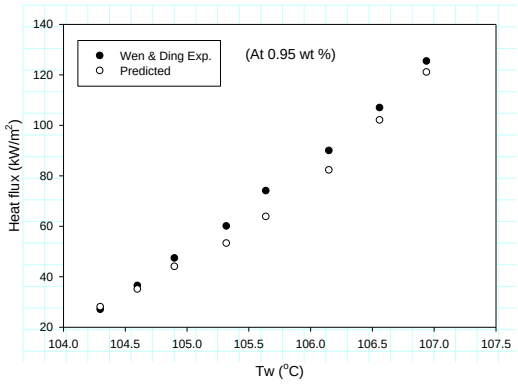

Figure 5: Comparison of Predicted Heat Flux with Experimental Results "Wen and Ding, (2005)" at 0.95 wt % of Al_2O_3

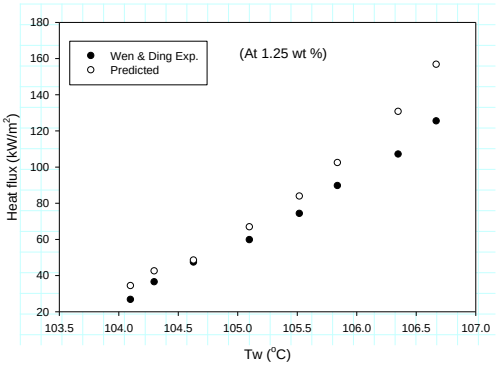

Figure 6: Comparison of Predicted Heat Flux with Experimental Results "Wen and Ding, (2005)" at 1.25 wt % of Al_2O_3

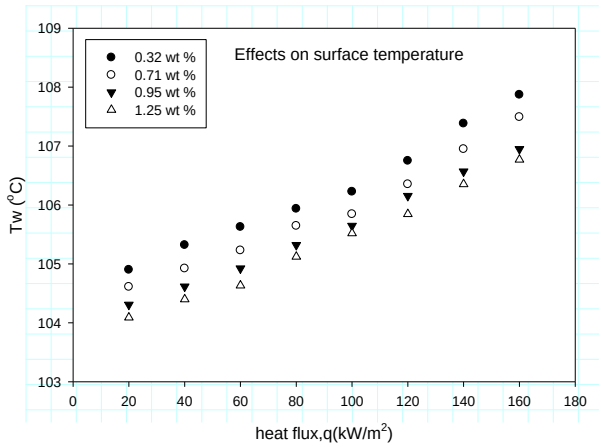

Figure 7: Surface Temperature as a Function of Heat Flux

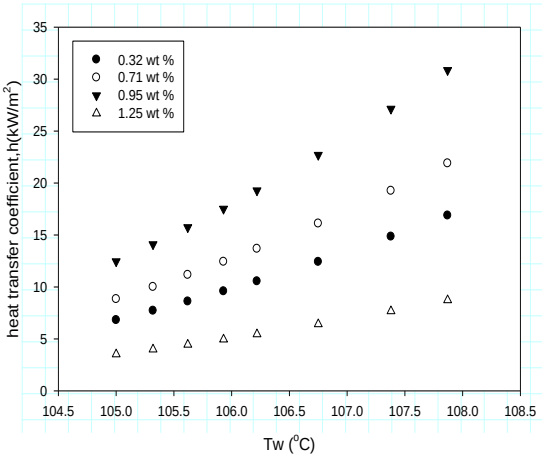

Figure 8: Heat Transfer Coefficient

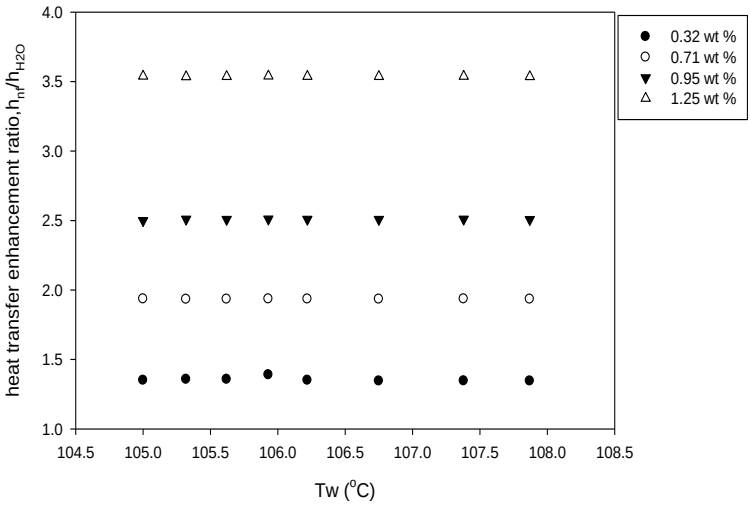

Figure 9: Heat Transfer Enhancement Ratio

Nomenclature

A	Surface area of the heater, m^2	Q	Heat, J
C	Specific heat, J/Kg K	q	Heat flux, W/m^2
C_{sf}	Experimental constant that depends on surface-fluid combination	R	Heater resistance
D	Diameter	T	Temperature, K
f	base fluid	U	Voltage conductivities
g	Gravitational acceleration, m/s^2	V	Volume, m^3
h	Heat transfer coefficient	v	vapour
h_{fg}	Enthalpy of vaporization, J/Kg	α	Ratio of thermal
k	Thermal conductivity, W/mk	μ	Viscosity, Kg/ms
m	Mass, Kg	ρ	Density, Kg/m^3
l	liquid	φ	Volume fraction
N	Shape factor	$φ_m$	Mass fraction
nf	nanofluid	σ	Surface tension of liquid-vapor interface, N/m
p	particle	Ψ	Sphericity
Pr	Prandtl number		

Table 1: For Values of Various Parameter Used in Equations (18)

Parameter Name	Value	Unit
Nanofluid	**Al_2O_3**	
Base fluid density	957.9	Kg/m^3
Base fluid thermal conductivity	0.679	W/mK
Base fluid viscosity	0.282×10^{-3}	Ns/m^2
Base fluid heat capacity	4217	J/KgK
Nanoparticle density	3970	Kg/ m^3
Nanoparticle thermal conductivity	40	W/mK
Nanoparticle heat capacity	4217	J/KgK

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