2012 International Conference on Environment, Energy and Biotechnology
IPCBEE vol.33 (2012) © (2012) IACSIT Press, Singapore

Development of Theoretical Correlation for Prediction of Boiling Heat Transfer Using TiO_2-Water Nanofluid

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Abstract. The present study represents the development of theoretical correlation for pool boiling of nanofluid having TiO_2 as nanoparticle and water as base fluid in a mechanically polished stainless steel flat plate as a boiling surface, where the concentration of the TiO_2 particles in water increases from 0.32 wt.% to 0.72 wt.% to observe the effects on boiling heat transfer characteristics. The prediction of pool boiling heat flux using nanofluid at different surface – liquid temperatures by increasing nanoparticle concentration from 0.32 wt. % to 0.72 wt. % shows that with the increase of only 4.78°C surface – liquid temperature difference at 0.32 wt. % of the particle concentration, the heat flux increases up to 32.62 kW/m^2, approximately. The surface temperature decreases with increasing nanoparticle concentration. The theoretical heat flux compared with the experimental heat flux which is with in ±30% error band agreement. Heat transfer coefficient of nucleate pool boiling using nanofluid increases with nanoparticle concentration at high heat fluxes. Approximately 22% increase in heat transfer coefficient is observed for 0.72 wt. % nanoparticle concentration.
Thus, newly developed generalized correlation is given below used knowing different thermal properties of nanofluid and heating surface for prediction of heat flux and subsequently boiling heat transfer coefficient.

Keywords: Theoretical Correlation, Boiling Heat Transfer, Nanofluid

$$q = \mu h_{fg}\left[\frac{g\left\{(1-\varphi)\rho_f + \varphi\rho_p - \rho_v\right\}}{\sigma}\right]^{1/2}\left[\frac{\left\{(1-\varphi)\rho_f c_f + \varphi\rho_p c_p\right\}(T_s - T_{sat})}{\left\{(1-\varphi)\rho_f + \varphi\rho_p\right\} c_{sf} h_{fg} \Pr^n}\right]^3$$

1. Introduction

Conventional fluids, such as water, engine oil and ethylene glycol are normally used as heat transfer fluids. Although various techniques are applied to enhance the heat transfer. The low heat transfer performance of these conventional fluids obstructs the performance enhancement and the compactness of heat exchangers. The use of solid particles as an additive suspended into the base fluid is a technique for the heat transfer enhancement. Improving the thermal conductivity is the key idea to improve the heat transfer characteristics of conventional fluids. Since a solid metal has a larger thermal conductivity than a base fluid, suspending metallic solid fine particles into the base fluid is expected to improve the thermal conductivity of that fluid. The enhancement of thermal conductivity of conventional fluids by the suspension of solid particles, such as millimeter- or micrometer-sized particles, has been well known for more than 100 years. However, they have not been of interest for practical applications due to problems such as sedimentation, erosion, fouling and increased pressure drop of the flow channel. The recent advancement in materials technology has made it possible to produce nanometer-sizes particles that can overcome these problems. Innovative heat transfer fluids-suspended by nanometer-sized solid particles are called 'Nanofluids'.

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Research works have been carried out by different researchers to find the effect of nano-fluid in nucleate pool boiling heat transfer.

2. Model / Correalation Developement

This analysis is concerned about pool boiling heat transfer using nanofluids, a subject of several investigations over the past few years. The work is motivated by the controversial results reported in the literature and the potential impact of nanofluids on heat transfer intensification. Systematic calculation are carried out to formulate stable aqueous based nanofluids containing TiO_2 nanoparticles and to investigate their heat transfer behavior under nucleate pool boiling conditions. The details elaborated in the following paragraphs.

In this analysis, TiO_2 nanoparticles are used in water as a base fluid for the formulation of nanofluid. As it is well known, nanoparticles have a strong tendency to agglomerate due relatively strong Vander Waals attraction between particles in both dry and wet environments. Dry nanoparticles frequency occur in the form of agglomerates, particularly formed due to sintering, and are difficult to break even by using prolonged ultasonification and magnetic stirring [1].

In order to prevent formation of agglomerates, surfactants and/or dispersants are often used but surfactants may experience changes in their properties and even fail at elevated temperatures. The electrostatic stabilization method is adopted in the above case. Such a method makes use of repulsion due to electric double layers surrounding around individual nanoparticles.

In analytical experiment, nanofluid, of a preset concentration was prepared and filled into the boiling vessel. The fluid was then preheated to the saturated temperature, followed by the measurements in the nucleate boiling regime under the steady state. Temperature data can be recorded at each heat flux, q calculated by

$$q = \frac{Q}{R} \tag{1}$$

The steady state heat diffusion equation was adopted to obtain the boiling surface temperature.

$$T_w = T_m - \frac{qd}{(K_w)} \tag{2}$$

The heat transfer coefficient, is calculated by

$$h = \frac{q}{(T_w - T_s)} \tag{3}$$

In the nucleate boiling regime, the rate of heat transfer strongly depends on the nature of nucleation (the number of active nucleation sites on the surface, rate of bubble formation at each site, etc.), which is difficult to predict. The type and condition of the heated surface also affect the heat transfer. These complications made in difficult to develop theoretical relations for heat transfer in the nucleate boiling regime, and we had to rely on relation based on experimental data.The most widely used correlation for the rate of heat transfer in the nucleate boiling is Rohsenow correlation [4], and expressed as

$$q = \mu h_{fg} \left(\frac{g(\rho_l - \rho_v)}{\sigma} \right)^{1/2} \left(\frac{c_{\rho f}(T_s - T_{sat})}{c_{sf} h_{fg} \Pr^n} \right)^3 \tag{4}$$

In the above correlation ‘ ρ_l ’ (density of the liquid), ‘ μ_l ’ (viscosity of the liquid),’ $\Pr_l$ ’ (Pranndtl no. of the liquid) are formulated for a simple based liquid or conventional heat transfer fluids. ‘ c_{sf} ’ (experimental constant-surface-liquid combination factor) 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 heating surface, the volume fraction of the nanoparticles and the base fluid used. In general, the correlation changes its form when nanoparticle dispersed in the base fluid. The changes occurs in the properties which are then formulated in the above correlation are discussed on the next section.

2.1. Prediction of the Pool Boiling Heat Transfer Properties

The present study is aimed at developing a correlation to predict the heat flux of nucleate pool boiling of TiO_2-water nanofluid at different particle volume fractions with respect to the temperature in a mechanically polished flat stainless steel plate. The following section describes the expressions of different nanofluid properties.

2.1.1. Density of the Nanofluid [2]

The density of nanofluid is written as

$$\rho_{n,f} = (1-\varphi)\rho_f + \varphi\rho_p \tag{5}$$

2.1.2. Pecific Heat of the Nanofluid [2]

The specific heat of nanofluid is written as

$$c_{n,f} = \frac{(1-\varphi)\rho_f c_f + \varphi\rho_p c_p}{(1-\varphi)\rho_f + \varphi\rho_p} \tag{6}$$

2.1.3. Viscosity of the Nanofluid [2]

The viscosity of nanofluid is written as

$$\mu_{n,f} = (1+2.5\varphi)\mu_f \tag{7}$$

2.1.4. Thermal Conductivity of the Nanofluid [2]

The thermal conductivity of nanofluid is written as

$$\frac{K_{n,f}}{K_f} = 1 + \frac{3(\alpha-1)\varphi}{(\alpha+2)-(\alpha-1)\varphi} \tag{8}$$

2.1.5. Volume Fraction of the Nanoparticles [2]

The volume fraction of nanoparticles is written as

$$\varphi = \frac{1}{\left(\frac{1-\varphi_m}{\varphi_m}\right)\frac{p_p}{p_f}+1} \tag{9}$$

2.1.6. Prandtl Number of the Nanofluid [2]

The Prandtl number of nanofluid is written as

$$p_{n,f} = \frac{\mu_{n,f} c_{n,f}}{k_{n,f}} \tag{10}$$

Putting equation (5) (6) (7) (8) (9) (10) in equation (4) the following new equation is obtained.

$$q = \mu h_{fg}\left[\frac{g\{(1-\varphi)\rho_f + \varphi\rho_p - \rho_v\}}{\sigma}\right]^{1/2}\left[\frac{\{(1-\varphi)\rho_f c_f + \varphi\rho_p c_p\}(T_s - T_{sat})}{\{(1-\varphi)\rho_f + \varphi\rho_p\}c_{sf} h_{fg} Pr^n}\right]^3 \tag{11}$$

Thus newly developed generalized correlation may be used knowing different thermal properties of nanofluid and heating surface properties for prediction of heat flux and subsequently boiling heat transfer coefficient.

3. Results and Discussions

The variation of heat flux, surface temperature and heat transfer coefficient, at different nanoparticle concentration for TiO_2/water nanofluid have been studied in detail. The nanoparticle volume concentration, fluid temperature and surface temperature have been varied to observe their effects.the results of heat flux/heat transfer coefficient is obtained for theoretical correlation is compared with experimental data for validitation of the predicted model. The following section describes in details.

3.1. Effects of Heat Flux on Varying Nanoparticle Concentrations

The heat flux of the pool boiling of TiO_2-water nanofluid has been found out for different surface temperatures. With the addition of nanoparticles, the heat flux increases with increasing surface temperatures.

The heat flux has been formulated for five 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 4.78°C surface – liquid temperature difference at 0.32 wt.% of the particle, the heat flux increases up to 32.62 kW/m^2 approximately. The prediction gives reasonable results with increasing particle concentration of TiO_2 also. The concentration of the TiO_2 particles increases from 0.32 wt. % to 0.72 wt. %.

The traditional plot of heat flux against surface temperature together with the prediction of classical correlation of Rohsenow [4] for pool boiling of water is shown in the Fig.2. The Rohsenow correlation for water has been compared with the predicted results with different particle concentration at different surface temperature. 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 TiO_2-water nanofluid.

The predicted heat flux has been compared with experimental results [3], which ishaving good agreement with the experimental results [3].The result regarding the comparison of heat flux.at 0.32 wt. % nanoparticle concentrations is shown at Fig.3.

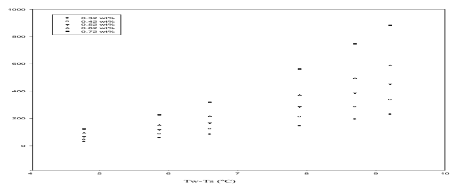
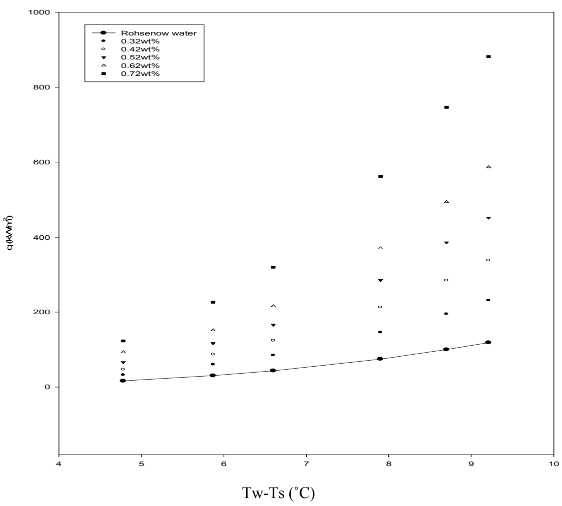


Fig. 1: Variation of predicted heat flux of the pool boiling of TiO_2-water nanofluid with surface – liquid temperature.



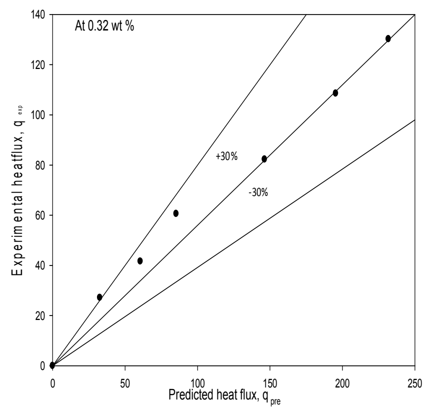


Fig.2. Comparison of predicted heat flux with Rohsenow correlation

Fig.3. Comparison of predicted heat flux with experimental results [3] at 0.32 wt. % of TiO2-water nanofluid

3.2. Effects on surface temperature on varying nanoparticle concentrations

Surface temperature as a function of heat flux as well as particle concentration is shown in Fig.4. This figure shows that presence of nanoparticles reduces the surface temperature significantly, and the reduction increases with heat flux. The surface temperature also decreases with nanoparticle concentration. The decreases of surface temperature with increasing nanoparticle concentration are 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.

3.3. Effect on Heat Transfer Coefficient on Varying Nanoparticle Concentrations

The heat transfer coefficient of TiO_2-water nanofluid is compared with the Rohsenow correlation for water shown in Fig.5. The results 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 0.72 wt. %, approximately 22% increase in heat transfer coefficient is achieved.

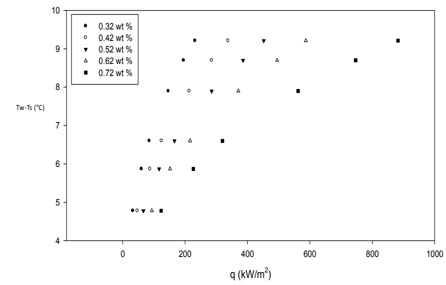


Fig.4. Surface temperature as a function of heat flux well as particle concentration

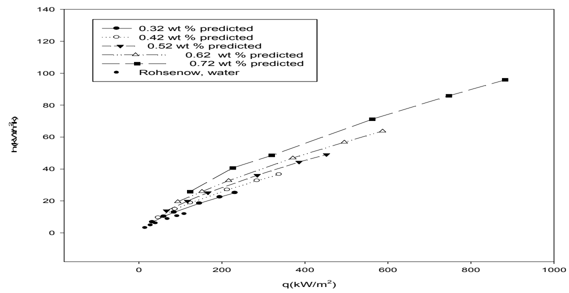


Fig.5. Comparison of heat transfer co-efficient with heat flux with different nano particle concentration

4. Conclusions

The present study represents the development of theoretical correlation for pool boiling of nanofluid having TiO_2 as nanoparticle and water as base fluid in a mechanically polished stainless steel flat plate is a boiling surface, where the concentration of the TiO_2 particles in water increases from 0.32 wt. % to 0.72 wt. % to observed the effects on boiling heat transfer charactertics.

Based on the study, it is summerised that

1. The theoretical correlation for prediction of heat flux, heat transfer coefficient is developed.
2. The prediction of pool boiling heat flux using nanofluid at different surface - liquid temperatures by increasing nanoparticle concentration from 0.32 wt. % to 0.72 wt. %. shows that with the increase of only 4.78°C surface – liquid temperature difference at 0.32 wt. % of the particle concentration, the heat flux increases up to 32.62 kW/m^2, approximately.
3. The surface – liquid temperature difference decreases with increasing nanoparticle concentration.
4. The theoretical heat flux compared with the experimental heat flux which is with in ±30% error band agreement.
5. Heat transfer coefficient of nucleate pool boiling using nanofluid increases with nanoparticle concentration at high heat fluxes. Approximately 22% increase in heat transfer coefficient is observed for 0.72 wt. % nanoparticle concentration.

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