Correlation for Prediction of Heat Transfer Coefficient for Pool Boiling Using TiO_2-Nanofluid

Sudev Das[1], Sagnik Pal[2], Harinder Singh[3] and Swapan Bhaumik[1*]
[1] *Mechanical Engineering Department, NIT Agartala, Tripura,India*
[2] *Department of Mechanical Engineering, IIIT, Banipur, WB,India*
[3] *Department of Chemical Engineering, Noida Institute of Engg. & Tech. (NIET), Greater Noida*
[1*] *Mechanical Engineering Department, NIT Agartala,Tripura,India*
E-mail address: sbhaumik6519@gmail.com,chemicdev@gmail.com

***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 heat transfer coefficient. The theoretical heat flux compared with the experimental heat flux which is within ±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 (given below) used knowing different thermal properties of nanofluid and heating surface for prediction of heat transfer coefficient:

$$h=\left\{(1+2.5\varphi)\mu_f\right\}h_{fg}\left[\frac{g\{(1-\varphi)\rho_f+\varphi\rho_p-\rho_v\}}{\sigma}\right]^{\frac{1}{2}}$$
$$\left[\frac{\{(1-\varphi)\rho_f c_f+\varphi\rho_p c_p\}(T_s-T_{sQt})\,{k_{nf}}^n}{\{(1-\varphi)\rho_f+\varphi\rho_p\}c_{sf}h_{fg}{\mu_{nf}}^n{c_{nf}}^n}\right]^3(T_s-T_{sQt})$$

I. 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-sized particles that can overcome these problems. Innovative heat transfer fluids-suspended by nanometer-sized solid particles are called 'Nanofluids'.

II. MODEL / CORRELATION DEVELOPMENT

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 are 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 to 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 ultrasonication 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.

$$T_W = T_m - \frac{q}{(K_W)} \tag{2}$$

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 pose 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 is expressed as

$$q = \mu_1 h_{fg} \left[\frac{g(\rho_1 - \rho_v)}{\sigma}\right]^{1/2} \left[\frac{c_1(T_W - T_S)}{c_{sf} h_{fg} \mathrm{Pr}_1{}^n}\right]^3 \tag{4}$$

In the above correlation '*Pl* ' (density of the liquid), 'μ_1' (viscosity of the liquid), Pr_1^n (Pranndtl no. of the liquid) are formulated for a simple based liquid or conventional heat transfer fluids. *Csf* (experimental constant) that depends on surface fluid combination, has great affects 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 is dispersed in the base fluid. The changes occur in the properties which are then formulated in the above correlation and are discussed in 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 on 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

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

2.1.2. Specific heat of the nanofluid [2]

The specific heat of nanofluid is written as

$$C_{nf} = \frac{(1-\varphi)\rho_f C_f + \varphi\rho_p C_p}{(1-\varphi)\rho_f + \varphi\rho_p} \tag{6}$$

2.1.3. Viscosity of the nanofluid [2]

The viscosity of nanofluid is written as

$$\mu_{nf} = (1+2.5\varphi)\mu_f \tag{7}$$

2.1.4. Thermal conductivity of the nanofluid [2]

The thermal conductivity of nanofluid is written as

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

2.1.5. Volume fraction of the nanoparticles [2]

The volume fraction of nanoparticles is written as

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

2.1.6. Prandtl number of the nanofluid [2]

The Prandtl number of nanofluid is written as

$$\mathrm{Pr}_{nf} = \frac{\mu_{nf} C_{nf}}{k_{nf}} \tag{10}$$

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

$$h = \left\{(1+2.5\varphi)\mu_f\right\} h_{fg} \left[\frac{g\{(1-\varphi)\rho_f + \varphi\rho_p - \rho_v\}}{\sigma}\right]^{\frac{1}{2}} \left[\frac{\{(1-\varphi)\rho_f c_f + \varphi\rho_p c_p\}(T_W - T_s)\, k_{nf}{}^n}{\{(1-\varphi)\rho_f + \varphi\rho_p\} c_{sf} h_{fg} \mu_{nf}{}^n c_{nf}{}^n}\right]^2 (T_W - T_s) \tag{11}$$

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

III. RESULTS AND DISCUSSIONS

The variation of 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 obtained for theoretical correlation is compared with experimental data for validation of the predicted model. The following section describes in detail.

The predicted heat flux results are then compared with experimental results [3], the prediction gives good agreement with the experimental results [3].The result regarding the comparison of heat flux at 0.32 wt. % nanoparticle concentrations is shown in Fig.1.

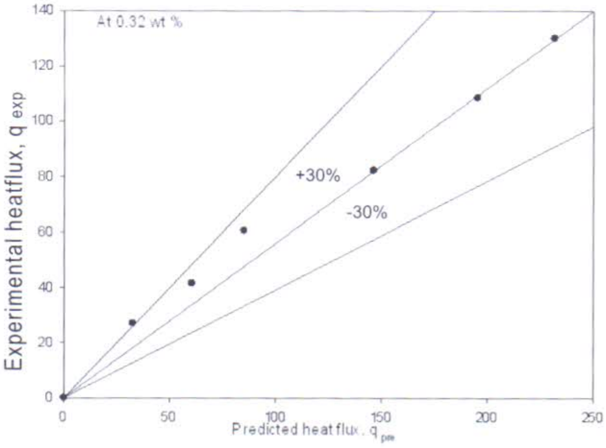

Fig.1 Comparison of predicted heat flux with experimental results [3] at 0.32 wt.% of Ti02 –nanofluid

Effect of varying nanoparticle concentration on heat transfer coefficient on varying nanoparticle concentrations. The heat transfer coefficient of TiO_2-water nanofluid compared with that obtained from Rohsenow correlation for water shown in Fig.2. The results show 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.

IV. CONCLUSIONS AND FUTURE SCOPE OF STUDY

The present study represents the development of theoretical correlation for pool boiling of nanofluid having TiO_2 as nanoparticle and water as base fluid on a mechanically polished stainless steel flat plate which is 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 coefficient.

Based on the study, it is summarized that

1. The theoretical correlation for prediction of heat transfer coefficient is developed.
2. The surface – liquid temperature difference decreases with increasing nanoparticle concentration.
3. The theoretical heat flux compared with the experimental heat flux is within ±30% error band agreement.
4. 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.

NOMENCLATURE

C	Specific heat, J/Kg K
C_{sf}	Experimental constant that depends on surface-fluid combination
D	Diameter
g	Gravitational acceleration, m/s^2
h	Heat transfer coefficient
h_{fg}	Enthalpy of vaporization, J/Kg
k	Thermal conductivity, W/mk

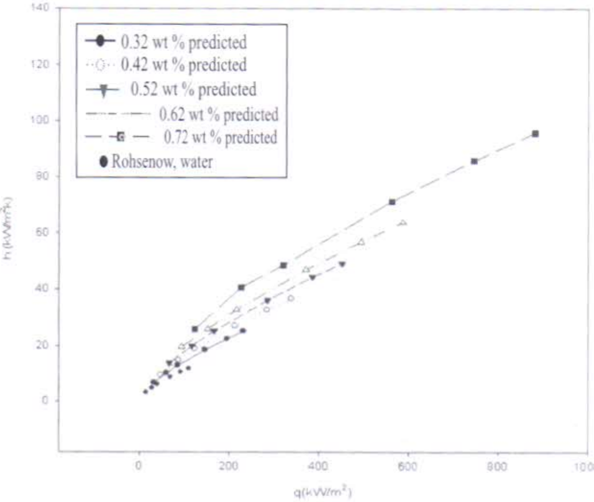

Fig. 2 Comparison of heat transfer coefficient with heat flux with different nanoparticle concentration

m	Mass, Kg
n	Shape factor
Pr	Prandtl number
Q	Heat, J
q	Heat flux, W/m^2
R	Heater resistance
T	Temperature, K
U	Voltage
V	Volume, m^3
α	Ratio of thermal conductivities
μ	Viscosity, Kg/ms
ρ	Density, Kg/m^3
φ	Volume fraction
φm	Mass fraction
σ	Surface tension of liquid-vapor interface, N/m
Ψ	Sphericity
f	base fluid
l	liquid
nf	nanofluid
p	particle
v	vapour

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