NUCLEATE POOL BOILING ON PREPARED SURFACE

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ABSTRACT

This paper reports results from an investigation on the performance of the Rohsenow's type of correlation when applied to the nucleate boiling of water and nanofluids (SiO_2) over prepared cylindrical surface (pure stainless, copper embedded stainless steel and brass embedded stainless steel) under open conditions.Various indoor experiments were conducted for different heat inputs varying from 800 to 1600 W and at atmospheric pressure. Experimental data were analyzed by using Rohsenow pool boiling correlation with the help of simple linear regression analysis. The heat transfer flux were estimated in the range of 31.5 to 62.56 kW/m^2 °C . The nucleate boiling heat flux was observed to increase exponentially with the increase in excess temperature. The average values of constant 'Csf' for Rohsenow correlation for the prepared surface and nanofluids were in range of were found to be 0.0117 and 0.013 respectively.

ABSTRAK

Kertas kerja ini melaporkan hasil dari penyiasatan prestasi jenis korelasi Rohsenow , korelasi apabila di aplikasikan pada eksperimen pendidihan nucleus menggunakan air dan cecair nano partikel (SiO2) atas permukaan silinder yang di sediakan (kelului tahan karat, tembaga terbenam keluli tahan karat dan loyang terbenam keluli tahan karat) dengan berkondusifkan terbuka. Pelbagai eksperimen-eksperimen terbuka telah di jalankan untuk yang berbeza memberi input berbeza-beza dari 800 untuk 1600 W dan di bawah tekanan atmosfera. Data percubaan telah dianalisis dengan menggunakan korelasi didihan tenang Rohsenow dengan bantuan analisis regresi linear mudah. Fluks pemindahan haba dianggarkan dalam lingkungan 31.5 ke 62.56 kW/m^2 °C. Fluks haba pendidihan nukleus diperhatikan meningkatkan kepesatan dengan kenaikan suhu permukaan pemanasan. Nilai-nilai purata malar 'Csf' untuk korelasi Rohsenow untuk permukaan bersedia dan ceacair nanopartikel merupakan dalam julat telah didapati 0.0117 dan 0.013 masing-masing.

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LIST OF ABBREVIATIONS

Nomenclature

Csf = surface/liquid parameter of the Rohsenow correlation

cpl = specific heat of the liquid [J/Kg.K]

g = gravitational acceleration [m/s2]

h = heat transfer coefficient [W/m2.K]

hcorr = correlation heat transfer coefficient [W/m2.K]

hexp. = experimental heat transfer coefficient [W/m2.K]

hlg = latent heat of evaporation [J/kg]

kl = thermal conductivity of liquid [W/m.K]

m,n = exponents of Rohsenow correlation

Prl = Prandtl number of the liquid

q" = specific heat flux [W/m2]

Tsat = saturation temperature [K]

Tw = wall temperature [K]

Greek Symbols

r l = liquid density [kg/m3]

s = surface tension [N/m]

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Boiling is classified as a convective heat transfer process since fluid motion occurs and consequently is a driving factor for heat transfer. However, boiling is unique as compared to other convective heat transfer processes because a phase change occurs during the process. The phase change allows heat to be transferred to and from the surface without significantly affecting the fluid temperature, which can lead to large heat transfer rates that correspond to small temperature differences. The latter also leads to large heat transfer coefficients as compared to typical single phase convection processes. Partially due to large heat transfer coefficients, which allow for greater heat transfer, boiling is a highly desirable heat transfer process to engineers. For example, boiling is critical to thermodynamic systems. In a power cycle, the working fluid is usually heated, until phase change occurs and the resulting vapor is used to drive a turbine or cylinder. In refrigeration cycles, evaporators absorb the heat until a phase change, due to boiling, occurs. The resulting vapor, flows into the condenser, and condenses back into the working fluid and the process begins again.

Boiling also plays a key role in the thermal management industry. Thermal management devices are critical to further development in the electronics industry, particularly microelectronics. As technology continues to increase, faster and smaller devices are being manufactured. These smaller devices produce significantly higher heat fluxes, are required to operate for longer periods in hazardous thermal environments, and are more sensitive to temperature in general. In order to increase operating temperatures, reduce burnout, and increase product life cycle it is essential that thermal management devices evolve and become more efficient. Boiling heat transfer is already used in the thermal management industry in heat sinks, through heat pipes, to effectively cool central processing units (CPUs) and graphical processing units (GPUs).

Boiling heat transfer is a very complex process; successful characterization depends upon numerous parameters such as latent heat, nucleation sites, bubble formation, growth, size and detachment, buoyancy driven fluid forces, vapor formation, dynamics of liquid-bubble interactions, density variation between phases, fluid velocities, apparatus orientation, surface roughness and in some cases gravitational fields. Boiling heat transfer is also dependent on thermo-physical properties such as thermal conductivity and surface tension.

1.2 PROBLEM STATEMENT

A variety of investigations have been made to understand the physics behind boiling heat transfer, despite all the many experimental and numerical studies, there is still lack of experimental data concerning the influence of thermo physical properties such as surface material and types of liquid on nucleate pool boiling heat transfer. This project presents results of an experimental investigation carried out determine the effects of combination using fabricated prepared surface material on nucleate pool boiling heat transfer of a specific liquid at atmospheric pressure.

As for nanofluids, the study of nanofluids is still at its infancy, comprising primarily in heat transfer researches. To utilize the nanofluids usefully in heat transfer applications, research is necessary to understand and determine the deposition of nano-particles on heat transfer surfaces at different concentrations and temperatures. Once this understanding is achieved, it should enable the use of nanofluids at appropriate concentrations in heat transfer applications.

1.3 OBJECTIVES

The objectives of this project are to:

(i) Experimental investigation to determine the nucleate boiling heat transfer on prepared surface with water atmospheric pressure

(ii) Experimental investigation to determine the nucleate boiling heat transfer performance on prepared surfaces and with titanium dioxide nano fluid at atmospheric pressure.

1.4 SCOPE OF THE PROJECT

The scopes of the project are:

(i) Identify a suitable manufacturing process to develop new surfaces.
(ii) Fabricate a test facility for the conduct of experiments.
(iii) Conduct experiments with different surface – liquid combinations.

1.5 EXPECTED OUTCOME

The expected outcome of the project is to fabricate enhanced surface with better heat transfer properties and to develop a proper model which is applicable to obtain the boiling heat transfer characteristics in nanofluids is significant.

1.6 SIGNIFICANT OF THE STUDY

An experiment set up was designed and fabricated to confidently measure heat transfer characteristics on enhanced surface prepared and nanofluids.

CHAPTER 2

LITERATURE REVIEW

This chapter will review and summarize the data and information that has been collected from past journals, books and other reference s that are related to this project.

2.1 INTRODUCTION

During the last seven decades, many theoretical and empirical correlations have been proposed to estimate the heat transfer coefficients as well as critical heat fluxes, under boiling in different conditions decades, many theoretical and empirical correlations have been proposed to estimate the nucleate heat transfer coefficients as well as critical heat fluxes, under boiling in different conditions using dimensional analysis and the postulations of different investigators. Numerous studies on nucleate boiling have been conducted and correlations developed to predict heat transfer coefficients. The pioneering works of (Rohsenow, 1952) and (Mikic and Rohsenow,1969) reported in textbooks and handbooks of heat transfer are widely used. It is well known that the correlation developed by (Rohsenow, 1952) for estimating nucleate boiling heat flux depends on surface fluid combination. Certain other correlations offering computational ease and covering a wide range of system parameters have a large deviation when compared with the experimental data. Hence the problem is readdressed to tackle this issue.

2.2 POOL BOILING

The classical pool boiling curve is a plot of heat flux, q'', versus excess temperature, $\Delta T = T_w - T_{sat}$. As the value of the excess temperature increases, the curve traverses four different regimes: (1) natural or free convection, (2) nucleate boiling, (3) transition boiling, and (4) film boiling. Different experimental methods may be used to define the pool boiling curve; constant temperature control and constant heat flux control are the two most commonly cited.

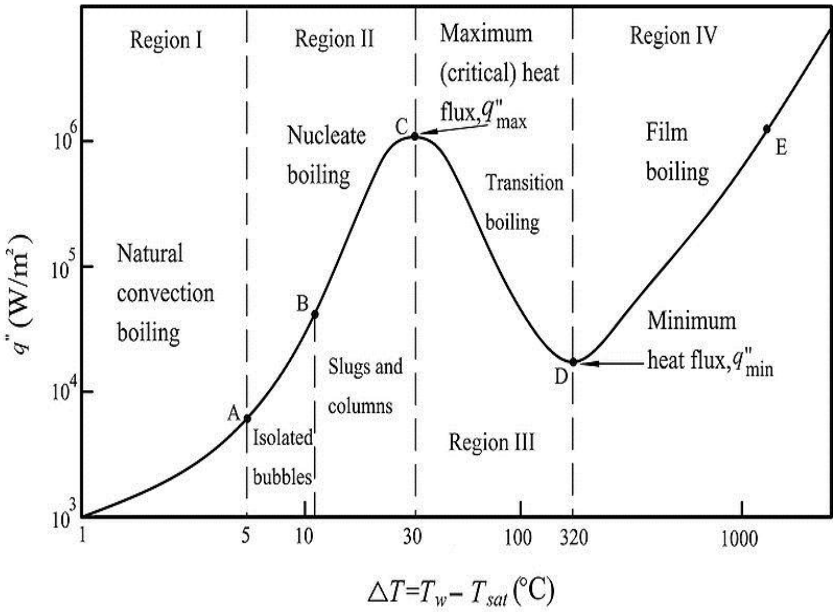

Figure 2.1: Boiling curve

source: http://encyclopedia2.thefreedictionary.com/Boiling

A typical boiling curve for saturated pool boiling of water at atmospheric pressure for a temperature-controlled environment is shown in Figure 2. 1. When the excess temperature ΔT is less than 5 °C, no bubbles form. Instead, heat is transferred from the solid surface to the bulk liquid via natural convection. Heat transfer coefficients in this regime can be calculated using the semi-empirical correlations for natural convection. When the excess temperature increases beyond 5 °C, the system enters the nucleate boiling regime – point A on Figure 2. 1. Vapor bubbles are generated at certain preferred locations on the heater surface called nucleation sites; these are often microscopic cavities or cracks on the solid surface. Nucleation occurs repeatedly from the same sites, indicating a causal link between bubble formation and some surface feature as well as the cyclical nature of the bubble-forming process. Small cavities and surface cracks act as sites for bubble generation because: (1) The contact area between the liquid and heating surface increases relative to a perfectly-smooth surface, so liquid trapped in these areas vaporizes first; and (2) The presence of trapped gases in such cracks creates liquid-vapor interfaces, which serve as sites where transfer of energy in the form of latent heat from the liquid to the vapor phase takes place. Once a vapor bubble has been initiated at a nucleation site, under the right conditions the bubble grows to a certain required diameter, detaches from the heating surface, and rises to the liquid free surface.

If the excess temperature remains at the low end of the nucleate boiling regime, shown between points A and B of Fig. 1, each bubble generated can grow and detach from the surface independently – that is, without interaction between bubbles. As the bubble-generating process occurs at the active nucleation sites, the surface area between these sites retains the liquid-solid contact that characterizes the natural convection regime. Convection remains the primary mechanism of heat transfer in this so-called “isolated bubble” regime. As we shall see, however, the character of this convection is markedly different from that of the natural convection encountered at lower excess temperatures ($\Delta T < 5$ °C for water).

As the excess temperature increases beyond point B in Figure 2.1, additional nucleation sites become active and more bubbles are generated. The higher density of bubbles leads to their interaction with each other. Bubbles from separate sites now merge to form columns and slugs of vapor, thus decreasing the overall contact area between the heating surface and the saturated liquid. Consequently, the slope of the boiling curve begins to decrease and the heat flux eventually reaches a maximum value, q''_{max}, referred to as the critical heat flux. The critical heat flux, which marks the upper limit of the nucleate boiling regime, reaches a value of approximately 10^6 W/m^2 for water at an excess temperature of about $\Delta T_c = 30$ °C. The nucleate boiling regime is most desirable for many industrial applications because of its high heat flux at relatively low levels of excess temperature (5 °C $\leq \Delta T \leq$30 °C for water). However, certain circumstances are required to avoid nucleate boiling, such as wicked heat pipes (Faghri, 1995).

As the temperature increases beyond the critical heat flux point, the rate of bubble generation exceeds the rate of bubble detachment from the heater surface. Bubbles from an increasing number of sites merge to form continuous vapor films over portions of the surface, further decreasing the contact area between the heating surface and the saturated liquid. These vapor films are not stable, however: they can detach from the surface, leading to restoration of contact with the liquid and resumption of nucleate boiling. Under these unstable conditions, the surface temperature may fluctuate rapidly, so the excess temperature shown on the ΔT-axis of Fig 1 between points C and D should be regarded as an average value. Since the boiling in this regime combines unstable film with partial-nucleate boiling types, it is referred to as the region of transition boiling. When the excess temperature becomes high enough to sustain a stable vapor film, the heat flux reaches its minimum value, q''_{min}.

This point, known as the Leidenfrost temperature, marks the upper temperature limit of the transition boiling regime. At temperatures above the Leidenfrost temperature, the bulk liquid and the heating surface are completely separated by a stable vapor film, so boiling in this regime is known as film boiling. The phase change in film boiling occurs at a liquid-vapor interface, instead of directly on the surface, as in the case of nucleate boiling. Thermal energy from the heating surface reaches the liquid-vapor interface by convection in the vapor film as well as by direct radiation to the interface. In the film boiling regime, the surface heat flux becomes a monotonically increasing function of the excess temperature, because radiation heat transfer from the solid surface to the liquid plays a significant role at high surface temperature. Pool boiling continues in this regime until the surface temperature reaches the maximum allowable temperature of the heating surface (2042 K for platinum, for example). Beyond that point, the heating surface can melt in a potentially catastrophic failure. If protective insulation is provided, however, as in the case of refractory metals, for example, it is possible for film boiling heat flux to exceed the critical heat flux, $q''_{\max}$.

The boiling curve presented in Figure2. 1 and described above assumes that the surface temperature is independently controlled and that the heat flux is the dependent variable. However, direct control over the surface temperature is not always possible. For example, when electric heating provides thermal energy to the solid, the controllable parameter is heat flux. Surface temperature then becomes the dependent variable, and heat flux becomes the independent variable. If the experiment of gradually increasing the added thermal energy is repeated using constant heat flux instead of constant temperature control, the resulting boiling curve matches that of controlled-temperature up to the critical heat flux, $q''_{\max}$. When the surface heat flux is increased slightly above the critical heat flux, however, portion C-D-E of the boiling curve is bypassed and the surface temperature increases abruptly to point E of the stable film boiling regime (Nukiyama, 1934). This abrupt increase in surface temperature is undesirable because T_E usually exceeds the melting point of the solid material. The critical heat flux can thus serve as the warning point above which burnout can occur; consequently, the critical point is sometimes referred to as the burnout point.

If the pool boiling curve is defined by decreasing the controlled heat flux from an initial point in the film boiling regime (point E, for example), a characteristic identical to Figure2.1 appears down to the point of minimum heat flux. After that point, a continued decrease of q'' yields a second hysteresis path that leads immediately to the nucleate boiling regime between points A and B. In this case, the transition boiling regime and a portion of the nucleate boiling regime are bypassed. Therefore, the transition regime that is observed when temperature control is used to define the pool boiling curve is unavailable in the controlled-heat-flux case.

2.3 PARAMETERS AFFECTING NUCLEATE POOL BOILING

Many investigators studied the effect of various parameters on nucleate pool boiling. These parameters are used to correlate the pool nucleate boiling data. An analysis of these earlier works shows that the major parameters affecting the HTC under nucleate pool-boiling conditions are heat flux, saturation pressure, and thermophysical properties of a working fluid; therefore, the effects of these parameters on the HTC under nucleate pool-boiling conditions have been the most investigated and are quite well established. On the other hand, the effects of surface characteristics such as thermophysical properties of the material, dimensions, thickness, surface finish, microstructure, etc., still require further investigation (I.L. Pioro,1999)

An analysis of the literature shows that based on their experimental findings, some researchers (Tolubinskiy,1980) concluded that for many practical applications the effects of solid surface/liquid/vapor interaction on the HTC under nucleate pool-boiling conditions are insignificant and can be neglected (except for the boiling of cryogenic fluids). However, others (Bonila, 1965) concluded that these effects were significant and proposed different methods to estimate them. Therefore, several studies were focused on the effects of contact angle, thermophysical properties, dimensions, shape, thickness, orientation in space, roughness (surface finish), and microstructure (including shapes, dimensions, and density of pores that are considered to be vapor bubble generating centers) of the boiling surfaces.

2.3.1 Effects of surface characteristics on pool-boiling heat transfer

In general, the effect of surface characteristics on the boiling process depends on thermophysical properties of the surface material (thermal conductivity and thermal absorption), interactions between the solid surface, liquid and vapor (wettability, adhesion, adsorption), surface microgeometry (dimensions and shape of cracks and pores), etc. All these parameters affect the HTC simultaneously and are interlinked. However, there are still not enough data available to solve this complex problem. For this reason, only separate effects are usually considered. The least known effect is the effect of boiling surface characteristics on the HTC. Some of these characteristics are difficult to assess quantitatively, and are dependent on the presence of surface contamination and oxide films, method of surface treatment, manufacturing process, etc. Therefore, a quantitative estimation of the effect of boiling surface characteristics on the HTC under pool-boiling conditions has not yet been determined. The most affecting parameters that influences the nucleate boiling are listed below are listed below

i. Effect of surface microgeometry
ii Effect of boiling surface material thermophysical properties
iii Effect of heated wall thickness
iv Effect of contact angle
v Orientation effect on HTC

An exhaustive literature survey showed that nucleate pool-boiling is a very complicated process and is affected by various parameters. The effect of these parameters on the HTC is usually a compound effect and varies with changing boiling conditions. In many cases, an accurate quantitative description of the parameters that affect nucleate pool boiling is impossible. Therefore, for a proper evaluation of the boiling heat transfer correlations, the number of relevant parameters should be minimized. This would ensure that the considered boiling conditions are more common for various applications.

The current review showed that, in general, the effect of surface characteristics on the boiling process depends on thermophysical properties of the surface material (thermal conductivity and thermal absorption), interaction between the solid surface, liquid and vapor, surface microgeometry (dimensions and shape of cracks and pores), etc. All these parameters affect the HTC simultaneously and are interlinked. However, there are still not enough data available to solve this complex problem; as a result, only separate effects are usually considered

2.4 CORRELATIONS OF NUCLEATE BOILING HEAT TRANSFER

Numerous studies on nucleate boiling have been conducted and correlations developed to predict heat transfer coefficients. The pioneering works of (Rohsenow,1952) and (Mikic and Rohsenow, 1969) reported in textbooks and handbooks of heat transfer are widely used. It is well known that the correlation developed by (Rohsenow, 1952) for estimating nucleate boiling heat flux depends on surface fluid combination. Certain other correlations offering computational ease and covering a wide range of system parameters have a large deviation when compared with the experimental data. Hence the problem is readdressed to tackle this issue.

The models employed by investigators on pool nucleate boiling are discussed in the review of literature. One of the important modeling approaches to nucleate boiling is through dimensional analysis. There are many correlations existing in the literature which are obtained through dimensional analysis. For example, the correlation of (Borishansky,1969), (Kutateladge,1966), (Kruzhilin,1949) and Stephan and (AbdelSalem, 1980) are often referred to in the boiling literature and are frequently used in thermal design. Hence these correlations are considered for comparison in the present analysis.

2.5 AVAILABLE EXPERIMENTAL DATA SET

The correlations related to nucleate boiling are taken from literature. Besides, a search is conducted to find out the availability of documented experimental data. In this regard the data of (Borishansky et al.,1966) covers wide range of system parameters. The material of the test surface is 18-8 Cr-Ni cold drawn stainless steel tubes of diameter varying from 4.96 to 6.94mm. The lengths of the test section varied in the range of 260 to 300 mm. The orientation of the test section is horizontal. The roughness factor of the surface is not considered as a parameter in the data regression done by (Borishansky, 1969).

The heating of the test surface is accomplished by low voltage - alternating current and the wall heat flux is evaluated from $q=\frac{I^2R}{\pi DL}$ where I is current in amps, R electrical resistance of the test section in ohms and D external diameter of the test surface. The measurement of temperature of test surface is recorded with the aid of chrome-alumel thermocouples preened to the surface at the upper and lower stagnations point of the cylindrical test section. An average of the two thermocouples is considered as the wall temperatures.

The bulk temperature is ascertained with the help of thermocouple located in the boiling medium midway from the heating surface and the free surface. The average convective heat transfer coefficient is estimated from equation $h=\frac{q}{\Delta T}$, where $\Delta T=(T_W-T_B)$, T_W is the external temperature of the surface of the tube wall and T_B is the bulk temperature of the boiling liquid.

The system is pressurized and controlled with the help of the condenser located in the free volume above the free surface of the fluid in the vessel. The vapors generated due to the boiling are re-condensed back by a condenser positioned above the free surface of the liquid bulk in the container. The system pressure is regulated by the rate of condensation of the vapors in the free volume. On every test section employed in the study, prolonged nucleate boiling is allowed before actual tests are commenced. Thus (Borishansky et al., 1966) experimentation covered a wide range of system parameters with pressures varying from atmospheric conditions up to values close to critical pressures for ethyl alcohol (1 bar < P< 60 bar, P_{cr}=64 bar) and water(1 bar <P< 200 bar , P_{cr}=221 bar).

2.6 AVAILABLE CORRELATION EQUATIONS

Various correlations available in the literature are compared with the experimental data of (Borishansky, 1966)

1) Rohsenow ’s correlation:

$$\frac{q}{\mu_l h_{fg}}\left[\frac{\sigma}{g(\rho_l - \rho_v)}\right]^{1/2} = \left(\frac{1}{C_{sf}}\right)^{1/r} Pr^{-s/r} \left\{\frac{C_{pl}\left[T_W - T_S\right]}{h_{fg}}\right\}^{1/r}$$

The correlation of (Rohsenow, 1969) is shown plotted in Rohsenow correlation contains a variable coefficient depending on the choice of material and medium

2) Correlation of Pioro et al.:

$$\frac{h}{k_l}\left(\frac{\sigma}{\rho_l - \rho_v}\right)^{0.5} = C_{sf}^{*}\left(\frac{q}{h_{fg}\rho_v^2\left[\sigma g\left(\rho_l - \rho_v\right)\right]^{0.25}}\right)^{\frac{1}{3}} Pr^{m}$$

(Pioro et al. 2004) conducted exhaustive survey and concluded in their analysis that Rohsenow’s correlation is the best among the correlations. However certain corrections in the coefficients for the surface-medium combination were incorporated by them. (Pioro et al.,2004) under predicts the experimental values as can be seen. Thus the corrections introduced into the correlation of Rohsenow do not seem to justify the claim of (Pioro et al.,2004) especially with regard to the data under consideration.

3) Foster-Zuber correlation:

$$q=0.00122\left[\frac{k_l^{0.79} c_{pl}^{0.45} \rho_l^{0.49}}{\sigma^{0.5} \mu_l^{0.29} h_{fg}^{0.24} \rho_v^{0.24}}\right]\left[T_W - T_S\right]^{1.24} \Delta P_{sat}^{0.75}$$

A plot is drawn between the predictions from (Foster-Zuber, 1955) and the experimental data both for water and ethyl alcohol. There is a systematic deviation with very wide scatter in the data predictions and does not predict closely for water and ethyl alcohol

.

4) Borishansky correlation:

The correlation of (Borishansky, 1969) is as follows:

$$q=(A^{*})^{3.33}\left[T_{W}-T_{S}\right]^{3.33}\left[F(P_{r})\right]^{3.33}$$

where $A^{*}=0.1011P_{cr}^{0.69}$;

$F(P_{r})=1.8P_{r}^{0.17}+4P_{r}^{1.2}+10P_{r}^{10}$ where $P_r=P/\ P_{cr}$

The correlation of (Borishansky, 1969) makes use of parameter ($P/\ P_{cr}$) as one of the dominant criteria in the regression of the data. It can be seen from Fig. 2.5 that the correlation of (Borishansky, 1969) under predicts the heat flux for all ranges of system parameters for ethyl alcohol. However it can be seen that the data of water fairly agrees with the predictions. The correlation has been developed based on dimensional analysis applied to the law of corresponding thermodynamic states

5) Correlation of Kichigin and Tobilevich:

$$Nu=\frac{hl^{*}}{k}=\frac{h\sqrt{\dfrac{\sigma}{g(\rho_l-\rho_v)}}}{k}=3.25*10^{-4}Re^{0.6}Pr^{0.6}\left(\frac{gl^{*}}{\upsilon^{2}}\right)^{0.125}\left(\frac{P_s}{\sqrt{\sigma(\rho_l-\rho_v)g}}\right)^{0.7}$$

where $Re=\dfrac{ql^{*}}{h_{fg}\upsilon_l\rho_v}$ and $l^{*}=\sqrt{\dfrac{\sigma}{(\rho_l-\rho_v)g}}$

Amongst the correlations tested, equation of (Kichigin et al.,1966) is found to give reasonably good agreement. However, the deviation seems to be on the high side with magnitudes of accuracy varying more than ±30%.

6) Labuntsov’s Correlation:

$$h=b\left(\frac{k_l^{2}}{\nu_l\,\sigma\,T_S}\right)^{\frac{1}{3}}q^{\frac{2}{3}}\quad\text{where}\quad b=0.075\left(1+10\left(\frac{\rho_v}{(\rho_l-\rho_v)}\right)^{\frac{2}{3}}\right)$$