Journal of Engineering and Development, Vol. 11, No. 3, December (2007) **ISSN 1813-7822**

A Simplified Correlation for the Prediction of Nucleate Pool Boiling Performance of Single Integral Enhanced Tubes Boiling Pure Liquids at Atmospheric Pressure

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Abstract

This investigation is concerned with the prediction art of the nucleate boiling heat transfer coefficient obtained from boiling on enhanced surfaces. It is devoted to study the enhancement factor of single enhanced tubes boiling pure liquids at atmospheric pressure which in turn reflects the boiling performance of the heating element during the process. Two surfaces of the integral machined structure; Gewa-T and Low Finned, tubes were considered.

A new correlation for the estimation of the heat transfer coefficient in the nucleate region was developed for these tubes. This equation was formulated by a dimensional analysis based on the Buckingham (π) theorem to handle the various variables considered to describe the mutual effect of the surface and liquid on the enhancement factor of a given surface structure. It is obvious that the enhancement factor is a strong function of the fin shape of the enhanced surface structure and boiling liquids physical properties. Six liquids boiling at atmospheric pressure were used, R-113, n-pentane, ethanol, water, p-xylene and R-11, for a heat flux in the range between (10) and (50) kW/m²^{2}***.***

The present correlation showed a good agreement with the available experimental data of the nucleate pool boiling heat transfer coefficient from the literature with a total absolute mean errors of (8%) and (9%) for the low finned and Gewa-T surfaces respectively.

الخــلاصـــــــة

يتعلق البحث بالتنبؤ بمعامل انتقال الحرارة أثناء الغليان على السطوح المحسنة. يهتم البحث بدراسة معامل التحسين أثناء الغليان للسوائل النقية على أنبوب منفرد تحت الضغط الجوي والذي يعكس أداء سطح التسخين خلال العملية. تم استخدام نوعين من السطوح المحسنة والمشغلة ميكانيكياً والمعروفة باسم (Low Finned & Gewa-T). تم بناء علاقة جديدة للتنبؤ بمعامل انتقال الحرارة خلال منطقة الغليان النووي لتلك الأنابيب.

تم بناء المعادلة المقترحة بتطبيق تحليل بعدي يعتمد على نظرية Buckingham للمجاميع اللابعدية لاحتواء المتغيرات المختلفة التي تم اعتمادها لتمثل التأثير المتبادل للسطح والسائل على معامل التحسين للسطح المحسن. من الواضح إن معامل التحسين يعتمد بصورة كبيرة على شكل الزعانف للسطح الخارجي للأنبوب والمواصفات الفيزياوية للسوائل خلال عملية الغليان. لاستنتاج العلاقة المقترحة تم استخدام ستة سوائل تغلي تحت الضغط الجوي وهي فريون-١١٣ ، البنتان، الأيثانول، الماء، باراسايلين، وفريون-١١ ولمدى فيض حراري يتراوح بين (١٠) و (٥٠) (kW/m^2).

لقد بينت العلاقة الحالية تطابق جيد مع القراءات العملية المتوفرة بالأدبيات المنشورة لمعامل انتقال الحرارة أثناء الغليان الحوضي وبمتوسط خطأ مطلق كلي يتراوح بين (٨%) و(٩%) لكل من الأنابيب (Low Finned) و (Gewa-T) على التوالي.

Introduction

It is well known that the surface structure affects the pool boiling heat transfer from a heater surface. The number and size distribution of cavities present on a heater surface affect the nucleation characteristics. This fact is utilized in developing structured and porous surfaces for enhanced boiling performance. The nucleate boiling component in flow boiling is also expected to exhibit a somewhat similar dependence. A quantitative and qualitative amount of investigations have been reported to establish the effect of surface finish and structure on the pool boiling performance.

1-1 Rough Surface Finishing

Jakob and Fritz [1] investigated the effect of the sandblasted surface and a surface with machined grooves on the boiling process. Both of these surfaces showed an improvement in the boiling heat transfer performance. However, the enhancement of the heat transfer was temporary. Courty and Froust [2] found that the roughness has a strong influence on the performance of the heating element boiling liquid at a given heat flux. An increase in the surface roughness shifted the boiling curve to lower wall superheat.

The above argument has been proved either experimentally or theoretically by Berenson [3], Kurihara and Myers [4], Griffith and Wallis [5] and many other investigators.

1-2 Enhanced Surfaces

At the present time there are quite a number of enhanced surfaces available commercially, some of them are shown in **Fig.(1)**. They are either integrally machined or a porous coating surfaces.

Gottzmann et. al. [6] reported that a tenfold enhancement in the boiling heat transfer coefficient was obtained when the High Flux surface was compared with those of the smooth plain tube. Later Gottzmann [7] proved that the High Flux surface has a remarkable resistance to fouling in a long term operation. Fujii et. al. [8] showed that the porous surfaces improved the boiling heat transfer coefficient over the smooth tube several times when boiling R-113 and R-11 at 1 and 2 bar. Marto and Lepere [9] showed that the pool boiling heat transfer coefficient when boiling R-113 and FC-72 was strongly related to the liquid-surface combination factor, the past history of the surface and the operating liquid properties.

Yilmaz et. al. [10] found that the enhanced surfaces improved the boiling heat transfer coefficients of p-xylene and isopropyl alcohol by an order of magnitude when compared with those of the smooth surface. Yilmaz and westwater [11] concluded that the enhancement in heat transfer performance depends on the enhanced surface structure and liquid properties.

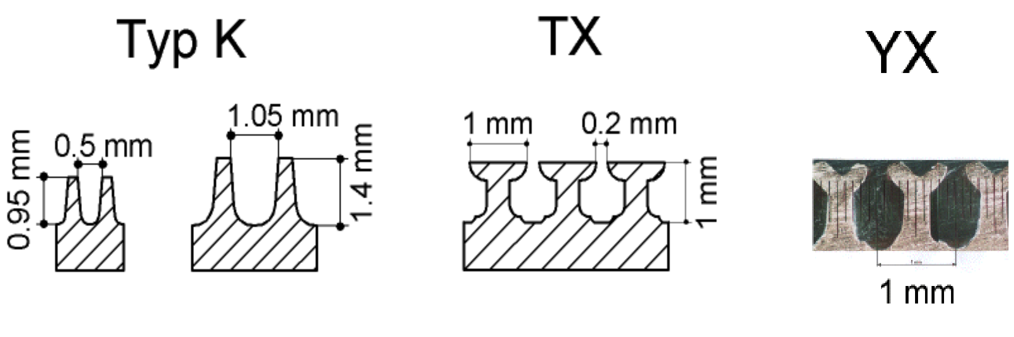

Figure (1.a) Typical enhanced Gewa-T tube structure

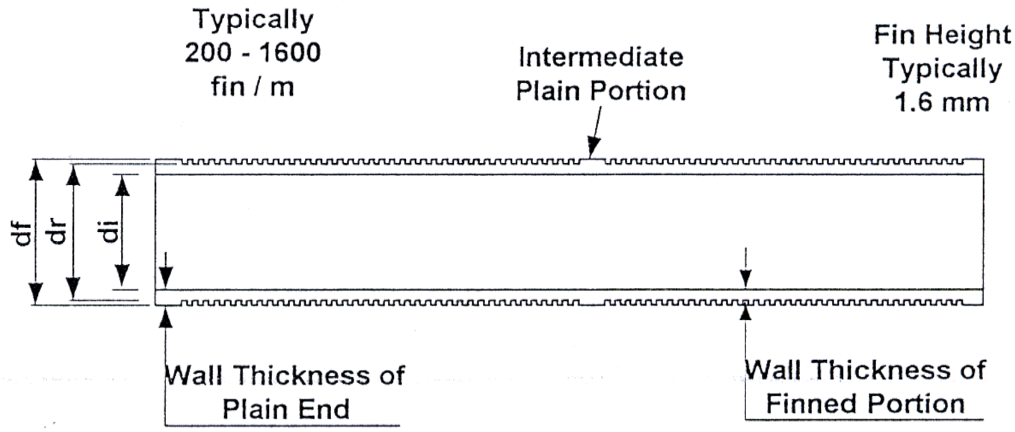

Figure (1.b) Typical enhanced low finned tube structure

Marto and Hernandez [12] reported an enhancement factor of about three times when boiling R-113 on the Gewa-T surface at atmospheric pressure. Hahne and Muller [13] carried out an experimental investigation boiling R-11 on horizontal electrically heated copper single and bundle finned tubes at atmospheric pressure. They have found an improvement in the boiling heat transfer coefficient when compared the enhanced surface with that of the smooth one. Tarrad [14] has concluded that the enhancement factor of the enhanced tubes is a function of the liquid thermal properties, binary mixtures or pure liquids, and the enhanced tube structure. That is the enhancement percentage depends on the surface-liquid contribution.

Kandikar and Howell [15] reported an increase in bubble activity on a micro fin surface when compared to a plain surface for flow boiling investigation. Rao and Balakrishnan [16] presented an expression for the total heat flux in terms of wall superheat, pore geometry and the physical properties of the liquid boiling over porous surfaces. The model correlated the experimental data within an accuracy of (± 30) %. Although the value of the predicted error percentage is quite high but it is an acceptable range when the difficult boiling phenomenon is considered. Yuming et. al. [17] made a comparison between the smooth tube and enhanced tubes for bubble growth rate, departure diameter, frequency, active site density, rise velocity and latent heat transfer. The effects of physical properties on the bubble dynamics were clear especially the departure diameter and the nucleation site density.

2. Available Correlations

The formulation of the nucleate pool boiling in terms of simple geometry parameters and operating liquid conditions is quite difficult art to be handled. Therefore, the available correlations in the open literature are either semi-empirical or they require a large quantity of parameters to be determined prior to the application of such correlations. This of course will exhibit an additional difficulty of handling the enhanced surface effect on the boiling heat transfer performance prediction.

Myers and Katz [18] tried to correlate the experimental data measured boiling different pure liquids on copper and finned tubes. They were successful in producing a correlation for the plain tubes in the form:

$$\frac{\alpha}{k_l}\sqrt{\frac{\sigma}{\rho_l}} = m\left(\frac{k_l \Delta T}{\mu_l h_{fg}}\right)^n \quad \text{.......... (1)}$$

where, the constants of the above equation were given according to the boiling liquid considered. In an attempt to apply Eq.(1) to the boiling data of the finned tube, the authors [18] found that there were individual curves for each liquid. They were unable to obtain a general correlation for the prediction of the boiling data.

Many investigators were correlated their experimental data in the form of:

$$\alpha = C_1\, q^n \quad \text{.......... (2)}$$

The constants (C_1) and (n) were given for each liquid surface combination. Hahne and Muller [13] presented the following experimental forms for R-11 boiling on a single low finned tube:

1. Transition region between convection and incipience of boiling:

$$\alpha = 2.27 q^{0.64} \quad \text{for } 0.7 < q < 3 \text{ kW/m}^2 \quad \text{.......... (3)}$$

2. Moderate nucleate boiling:

$$\alpha = 0.697 q^{0.79} \quad \text{for } 3 < q < 20 \text{ kW/m}^2 \quad \text{.......... (4)}$$

3. Fully developed nucleate boiling:

$$\alpha = 8.53 q^{0.54} \quad \text{for } q > 20 \text{ kW/m}^2 \quad \text{.......... (5)}$$

Palen and Yang [19] proposed a correlation for the prediction of the boiling heat transfer coefficient on low finned tube in the form:

$$\alpha_{L-F} = F_c F_e \eta \alpha_{pla.} + \alpha_{nc} \quad \text{.......... (6)}$$

where:

($\alpha_{pla.}$): is the boiling heat transfer coefficient achieved by a plain tube and

(α_{nc}): is the natural convection part of the heating surface which is usually small; of the order of (250) $W/m^2.K$ for hydrocarbons. The mixture correction factor (F_c), equal to (1.0) for pure fluids and azeotropes and less than (1.0) for mixtures. The fin efficiency (F_e), equal to (1.0) for plain tube and close to unity for finned tube.

Palen and Yang [19] represented a formula for the surface factor (η) in the form:

$$\eta = C_1 \left(\frac{q}{q_{ref}} \right)^{m_1} \left(\frac{p}{p_c} \right)^{m_2} F_c^{m_3} \quad \text{...} \quad \textbf{(7)}$$

The authors [19] postulated that this expression has been found by the (HTRI) organization and did not give numerical values for the exponents and the empirical constant.

Chen et. al. [20] proposed a model to predict the boiling heat transfer coefficients of copper single and twin finned tube arrangements when boiling R-11 at atmospheric pressure for the heat flux range (20) to (50) kW/m^2. They started from the bubble departure diameter, frequency and bubble nucleation site density including a series of assumptions and empirical constants to obtain their correlation which involved three empirical constants to be determined for each surface.

Tarrad [14] correlated his own results for boiling on the plain and enhanced surfaces in an expression having the form:

$$q = C_1 \Delta T^n \quad \text{for } 5 \le q \le 60 \text{ kW/m}^2 \quad \text{..} \quad \textbf{(8)}$$

where, the empirical constant (C_1) and the wall superheat index (n) were given for each liquid-surface combination.

These values showed a great dependence on the liquid properties and surface structure considered.

3. The Present Correlation

3-1 Theoretical Background

The present correlation is based on the Buckingham (*pi*) theorem technique to formulate the independent variables chosen to represent the dependent parameter. It has been proved previously that the enhancement factor produced by an enhanced surface is directly proportional to the operating liquid-surface combination and the boiling liquid physical properties. This argument may be presented as:

1. The boiling liquid physical properties include the, latent heat of Vaporization, liquid density and thermal conductivity, liquid specific heat and surface tension.

2. The operating conditions of the boiling process including the heat flux and pressure. And finally,
3. The liquid-surface combination factor which includes the effect of the enhancement structure and its interaction with the boiling liquid at the vicinity of the heating surface.

The dependency of the enhancement factor on the working pressure of the boiling process will be introduced by the use of the reduced pressure parameter, p_r. This is defined by the ratio of the operating system pressure to the critical pressure of the boiling liquid during the process.

The above highlight points can be expressed by the following mathematical presentation:

$$\eta = \eta\left(h_{fg}, \rho_l, k_l, cp_l, \sigma, q, p_r\right) \quad \text{(9)}$$

where, (η): refers to the enhancement factor defined by:

$$\eta = \frac{\alpha_{enh.}}{\alpha_{pla.}} = \frac{\Delta T_{pla.}}{\Delta T_{enh.}} \quad \text{(10)}$$

The enhanced surface nucleate boiling heat transfer coefficient is therefore has the form:

$$\alpha_{enh.} = \eta \alpha_{pla.} \quad \text{(11.a)}$$

Or in terms of the wall superheats in the form:

$$\Delta T_{enh.} = \frac{\Delta T_{pla.}}{\eta} \quad \text{(11.b)}$$

The plain nucleate pool boiling heat transfer coefficient, $\alpha_{pla.}$, is predicted by the available correlations such as Mostinski [21] equation in the following expression:

$$\alpha_{pla.} = 0.1 p_c^{0.69} q^{0.7} F(p_r) \quad \text{(12.a)}$$

where,

$$F(p_r) = 1.8 p_r^{0.17} + 4 p_r^{1.2} + 10 p_r^{10} \quad \text{(12.b)}$$

where:

(p_c): in bar,
(q): in W/m^2 and
($\alpha_{pla.}$): in W/m^2 K.

The equation which was proposed by McNelly [22] could also be used for the estimation of the plain nucleate pool boiling heat transfer coefficient in the form:

$$\frac{\alpha_{pla.} d}{k_l} = 0.225\left(\frac{qd}{h_{fg}\mu_l}\right)^{0.69}\left(\frac{\mu_l cp_l}{k_l}\right)^{0.69}\left(\frac{pd}{\sigma}\right)^{0.31}\left(\frac{\rho_l}{\rho_v}-1\right)^{0.33} \quad \text{(13)}$$

3-2 Correlation Formulation

In performing a dimensionless groups from the independent variables, the four dimensions will be considered for these variables (M, L, T, θ) together with four selected repeating variables (h_{fg} , ρ_l , k_l and cp_l). There are eight variables expressed in terms of four fundamental dimensions. Therefore, the equation relating the variables will contain four independent dimensionless groups including the reduced pressure group in the forms:

$$\pi_1 = \eta \quad \text{(14.a)}$$

$$\pi_2 = \frac{\rho_l h_{fg}^{3/2}}{q} \quad \text{(14.b)}$$

$$\pi_3 = \left(\frac{\sigma}{k_l}\right)\frac{cp_l}{h_{fg}^{0.5}} \quad \text{(14.c)}$$

and,

$$\pi_4 = {p}/{p_c} \quad \text{(14.d)}$$

Therefore, the suggested correlation has the following expression:

$$\pi_1 = \phi(\pi_2, \pi_3, \pi_4) \quad \text{(15.a)}$$

$$\eta = \phi\left\{\left(\frac{\rho_l h_{fg}^{3/2}}{q}\right), \left(\frac{cp_l \sigma}{k_l h_{fg}^{0.5}}\right), \left(\frac{p}{p_c}\right)\right\} \quad \text{(15.b)}$$

This function may be represented in an equation with the form:

$$\eta = C_{S,F}\left(\frac{\rho_l h_{fg}^{3/2}}{q}\right)^m\left(\frac{cp_l \sigma}{k_l h_{fg}^{0.5}}\right)^n\left(\frac{p}{p_c}\right)^j \quad \text{(15.c)}$$

The liquid-surface combination factor, ($C_{S,F}$), and the exponents of the groups, (m), (n) and (j), should be determined from experimental data to establish the correlation suggested in the present work at its final form.

The independent groups (π_2) and (π_3) are reflecting the effect of the enhancement structure on the ability of bubble nucleation activity and departure parameters, the bubble size and frequency. The first group, (π_2), represents the rate of vaporization of the boiling liquid at the vicinity of the heating element. In fact it represents the intensity of bubble generation in the liquid layer penetrating through the tunnels of the surface structure. The second group, (π_3), corresponds to the effect of the surface tension force during the bubble detachment for the heating surface and the force implemented by the vapor generation and its movement in the structure tunnels at the heating surface. The last dimensionless group, (π_4), represents the effect of the operating pressure on the enhancement factor and the predicted nucleate boiling heat transfer coefficient.

The above equation reveals the strong dependency of the enhancement factor (η) on the numerical values of the constants incorporated in the general form of the correlation. The experimental data bank presented by Tarrad [14], the experimental results obtained by Yilmaz et. al. [10], the data of Marto and Hernandez [12] and the experimental results of Hahne and Muller [13] will be used for verification of the present correlation. **Table (1)** shows the range of data points considered in this work for the heat flux range between (10) and (50) kW/m^2 at atmospheric pressure. A total number of (279) data points were used in the present correlation distributing among the six liquids tested with both of the surface structures.

Table (1.a) The boiling characteristics of the low-finned enhanced surface with different working fluids at atmospheric pressure

Boiling Liquid	**Reference**	**No. of Data Points (----------)**
R-113	Tarrad [14]	45
n-pentane	Tarrad [14]	36
Ethanol	Tarrad [14]	18
Water	Tarrad [14]	18
R-11	Hahne & Muller [13]	9

Table (1.b) The boiling characteristics of the gewa-t enhanced surface with different working fluids at atmospheric pressure

Boiling Liquid	**Reference**	**No. of Data Points (----------)**
R-113	Tarrad [14] Marto and Hernandez [12]	45
n-pentane	Tarrad [14]	45
Ethanol	Tarrad [14]	27
Water	Tarrad [14]	27
p-xylene	Yilmaz et. al. [10]	9

Table (1.c) The boiling experimental data of the plain surface with different working fluids at atmospheric pressure

Boiling Liquid	Reference	No. of Data Points (---------)
R-113	Tarrad [14] Marto and Hernandez [12]	33
n-pentane	Tarrad [14]	18
Ethanol	Tarrad [14]	18
Water	Tarrad [14]	24
R-11 & p-xylene	Hahne & Muller [13] Yilmaz et. al. [10]	18

The experimental data of the enhancement factor was used in a power fitting formula in terms of (π_2), (π_3) and (π_4) which reveals the best fit to the data of the test liquids and surfaces. Hence the best predictions of the enhancement factor and the boiling heat transfer coefficient for the whole range of the experimental data were obtained with the values of (m), (n) and (j) as (0.1856), (0.3) and (-0.2) respectively. Further, the liquid-surface combination factor, $C_{S,F}$, was determined from the fitting for each liquid boiling on the specified enhanced surface.

The numerical values of (m) and (j) conclude that the enhancement factor shows a decrease as the operating heat flux and system pressure increase. This behavior is perfectly corresponds to the experimental data tested in the present work from the point of view of the effect of the heat flux on the predicted enhancement factor. Palen and Yang [19] concluded that the reduced pressure exponent, m_2, has a negative value in an enhancement correlation presented in the form of Eq.(7). However, no numerical values for all of the coefficients in the above equation were given in the open literature.

Table (2) shows the structure characteristics of the plain and enhanced surfaces used in the developing of the present correlation. The thermal physical properties of the pure liquids tested by the present correlation are shown in **Table (3)**. These values are deduced from Tarrad [14], Incropera and Dewitt [23] and Sinnott [24]. These liquids cover a good range of the physical properties concerning the mutual effect between the liquid and heating surface.

Table (2) The structure characteristics of the enhanced surfaces used in the present correlation

Surface Type	Reference	Fins/inch	Enhancement Thick. (mm)	d_o/d_r (mm)
Plain	Tarrad [14] Yilmaz et. al. [10]	----- -----	-------- --------	19/19 12.7/12.7
Low Finned	Tarrad [14] Hahne & Muller [13]	19 19	1.5 1.5	18.8/15.8 18.9/15.9
Gewa-T	Tarrad [14] Yilmaz et. al. [10] Marto & Hernandez [12]	19 19 19	1.12 1.12 1.12	18.9/16.7 18.9/16.7 21.2/19

Table (3) The physical properties of the liquids used in the present correlation

Liquid	ρ_l (kg/m^3)	cp_l (kJ/kgK)	k_l (W/m K)	h_{fg} (kJ/kg)	$\mu_l\times 10^3$ (Pa. s)	σ (N/m)
R-113	1507.42	0.98	0.07	147	0.5015	0.0159
n-Pentane	610.598	2.376	0.1096	356.3	0.1944	0.012
Ethanol	736.45	3.0202	0.15147	823.83	0.4376	0.0177
Water	958.4	4.219	0.681	2257	0.2817	0.0589
R-11	1479.4	0.8703	0.08898	180.33	0.405	0.018
P-Xylene	752	1.759	0.11	337.195	0.5154	0.00476

3-3 General Formula

The final form of the suggested correlation of the present work is obtained by applying the above formula of the enhancement factor correlation, Eq.(15.c), to the plain tube prediction equation either Eq.(12) or Eq.(13). The choice of the plain tube nucleate boiling heat transfer coefficient correlation depends on the accuracy limit and the limitation of use of the considered equation.

It has been found that the correlation presented by Mostinski [21] has a wide application range of heat flux and boiling liquid physical properties. In the present work, this equation was used for all of the test liquids except of that of the ethanol prediction. The McNelly [22] equation was applied for this liquid for the prediction of the boiling heat transfer coefficient. The selection of the above equations was based on the comparison between the experimental data and the predicted values of the plain tube by the above correlations. Therefore, the general form of the present correlation when incorporated with the Mostinski equation was obtained by combining Eq.(11.a), Eq.(12.a) and Eq.(15.c) in the form:

$$\alpha_{enh.} = 0.1C_{S,F}p_c^{\ 0.69}q^{0.7}F(p_r)\left(\frac{\rho_l h_{fg}^{\ 3/2}}{q}\right)^{0.1856}\left(\frac{cp_l\sigma}{k_l h_{fg}^{\ 0.5}}\right)^{0.3}\left(\frac{p}{p_c}\right)^{-0.2} \quad \ldots\ldots\ldots\ldots\ldots\ldots (16)$$

When McNelly correlation for the plain tube heat transfer coefficient is used, the boiling heat transfer coefficient obtained from the plain surface, Eq.(13), replaces that of Eq.(12.a) to obtain:

$$\alpha_{enh.} = C_{S,F}\left(\frac{\rho_l h_{fg}^{\ 3/2}}{q}\right)^{0.1856}\left(\frac{cp_l\sigma}{k_l h_{fg}^{\ 0.5}}\right)^{0.3}\left(\frac{p}{p_c}\right)^{-0.2}\times\alpha_{pla.} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (17.a)$$

where:

$$\alpha_{pla.} = 0.225\frac{k_l}{d}\left(\frac{qd}{h_{fg}\mu_l}\right)^{0.69}\left(\frac{\mu_l cp_l}{k_l}\right)^{0.69}\left(\frac{pd}{\sigma}\right)^{0.31}\left(\frac{\rho_l}{\rho_v}-1\right)^{0.33} \quad \text{..................... (17.b)}$$

The liquid-surface contribution factor, ($C_{S,F}$), is defined for each liquid boiling at specified heating surface structure. This factor is shown in **Table (4)** for each liquid-surface combination considered in the present work.

Table (4) The predicted liquid/surface contribution factor and error percentage of the enhancement factor and boiling heat transfer coefficient

Surface Type	Liquid	$C_{S,F} \times 10^2$ (--------)	Err% η	Err% $\alpha_{enh.}$	$\lvert Err\% \rvert_m$ η	$\lvert Err\% \rvert_m$ $\alpha_{enh.}$
Low Fin	R-113	7.877	-4 --- 6	-8 --- 12	3	3
	n-Pentane	9.040	14 --- 21	4 --- 15	15	11
	Ethanol	4.267	-5 --- 3	11 --- 21	3	14
	Water	1.642	-6 --- 17	-6 --- 12	6	5
	R-11	4.142	-24 --- 3	-9 --- 15	17	7
Gewa-T	R-113	11.796	-6 --- 18	-7 --- 11	4	4
	n-Pentane	7.9160	-7 --- 19	-14 --- 5	7	8
	Ethanol	4.6380	-14--- 20	0 --- 24	9	16
	Water	1.9940	-14 --- 23	-21 --- 20	8	9
	P-xylene	28.392	-13 --- 17	12 --- 24	6	7

4. Results and Discussion

The present formula was tested against different liquids boiling on the plain, low finned, and the Gewa-T surfaces at atmospheric pressure. The errors percentage of the predicted enhancement factor, Eq.(15.c), and the nucleate boiling heat transfer coefficient, Eq.(16) or Eq.(17), are defined by the following expressions:

$$(Err\%)_\eta = \frac{\eta_{pred.} - \eta_{meas.}}{\eta_{pred.}} \times 100 \quad \text{.. (18)}$$

and,

$$(Err\%)_\alpha = \frac{\alpha_{pred.} - \alpha_{meas.}}{\alpha_{pred.}} \times 100 \quad \text{.. (19)}$$

The mean absolute errors of the above expressions are also calculated by the following forms:

$$(Err\%)_{abs.} = \Sigma|Err\%| \, / \, N \quad \text{.. (20)}$$

The above parameters were calculated for all of the tested liquids and presented in **Table (4)**. The correlation showed a quite high accuracy for the enhancement factor of both surfaces. The mean absolute error of the enhancement factor for the low finned tube is ranged between (3%) and (17%), whereas, the corresponding values for the Gewa-T surface were (4%) and (9%). The total mean absolute errors of the enhancement factor for both tubes are (9%) and (7%) for the low finned and Gewa-T surfaces respectively. The corresponding values of the mean absolute error of the predicted boiling heat transfer coefficients were in the range (3% to 14%) and (4% to 16%) for the low finned and Gewa-T tubes respectively. It is obvious that with these values of absolute errors, the correlation prediction fall within acceptable limits of the mathematical expectation. The total mean absolute errors of the predicted boiling heat transfer coefficients were (8%) and (9%) for the low finned and Gewa-T tube surfaces respectively.

Figure (2.a) shows the predicted and measured enhancement factors of the boiling liquids on the low finned tube structure at the atmospheric pressure. It is obvious that the predicted values of (η) by Eq.(15.c) showed a good agreement with those of the measured values and bounded within the limit of (±20) for whole number of the data points considered for this surface. The comparison between the predicted and measured values of (η) for the Gewa-T is presented in **Fig.(2.b)**. Here, the predicted values fall within a limit of (±15) for the whole range of data points considered.

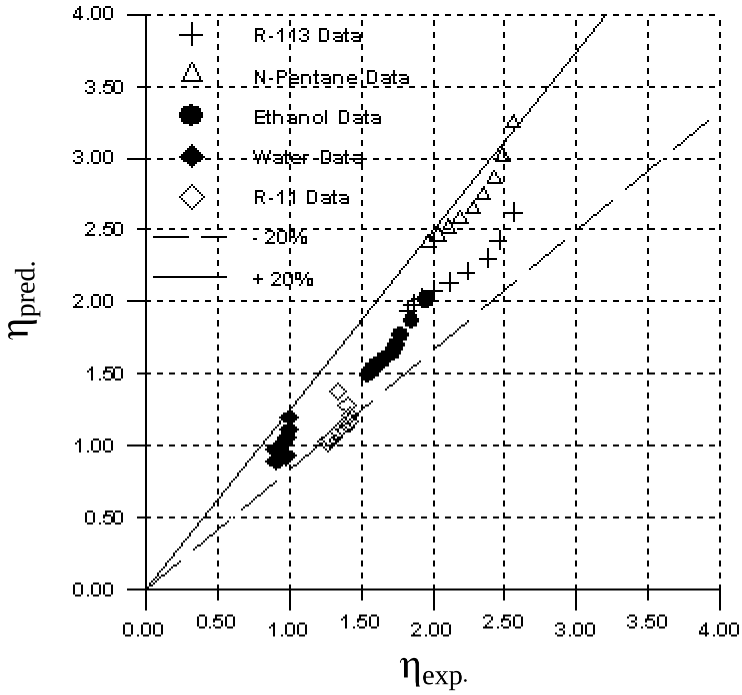

Figure (2.a) Comparison of the enhancement factor predicted by the present correlation with experimental data of the Low Finned tube

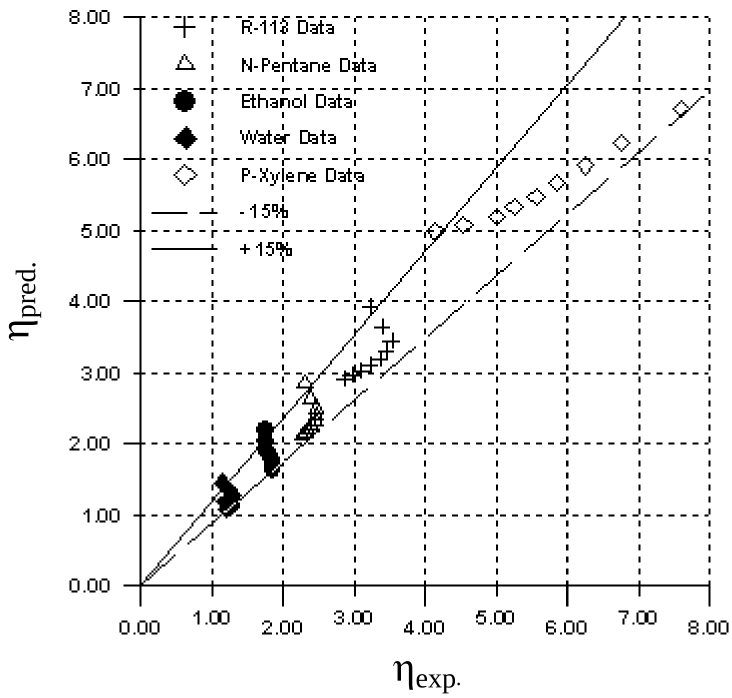

Figure (2.b) Comparison of the enhancement factor predicted by the present correlation with experimental data of the Gewa-T tube

A comparison between the experimental data and the predicted values of ($\alpha_{enh.}$) by Eq.(16) or Eq.(17) is shown in **Fig.(3)**. The correlation of the present work predicted the boiling heat transfer coefficient for the low finned tube within (±20) for the whole range of the data points considered for this surface. In fact, the predicted values of the boiling heat transfer coefficient fell within an error percentage ranged between (-10%) and as high as (+15%) for more than (98%) of the data points. The corresponding prediction accuracy for the Gewa-T surface was within (±20) for more than (99%) of the boiling data of the heat transfer coefficient. The range of the error percentage of the predicted results with the present correlation reviled a qualitative agreement with the experimental data.

It is worthwhile to point out that the accuracy and limitation error margin of the present correlation of the nucleate boiling heat transfer coefficient is directly related to the plain tube prediction values. Therefore, it is recommended to select the most appropriate correlation for this object. However, the present work showed that the use of Mostinski equation is acceptable for the majority of the liquids considered in this investigation.

The present correlation for the prediction of the nucleate boiling heat transfer coefficient of the integral machined heating element showed a good response to the surface and liquid combination type. Its accuracy when using the low finned tube surface was better than that of the Gewa-T tube. This concludes that the shape of enhancement has a great interaction effect on the behavior of the bubble nucleation in the machined tunnels where the flow of the boiling liquid is very high there. Further, the boiling liquid properties account for the higher part of the influence on the enhancement expected from a specified surface. For example, the enhancement factor produced by boiling n-pentane on the low finned tube was ranged between (2) and (2.6) for the whole range of heat fluxes. The corresponding values of ethanol were (1.6) and (2). Whereas, boiling of water on this surface didn't show any augmentation for the boiling heat transfer coefficient. When boiling R-113 on the Gewa-T produces better enhancement than that obtained during boiling on the low finned tube. It was ranged between (1.8 to 2.6) and (2.9 to 3.5) for the entire range of the heat flux for the low finned and Gewa-T respectively. This behavior of the variation was also exhibited by the present formula for the prediction of the enhancement factor and the nucleate boiling heat transfer coefficient of the enhanced surfaces.

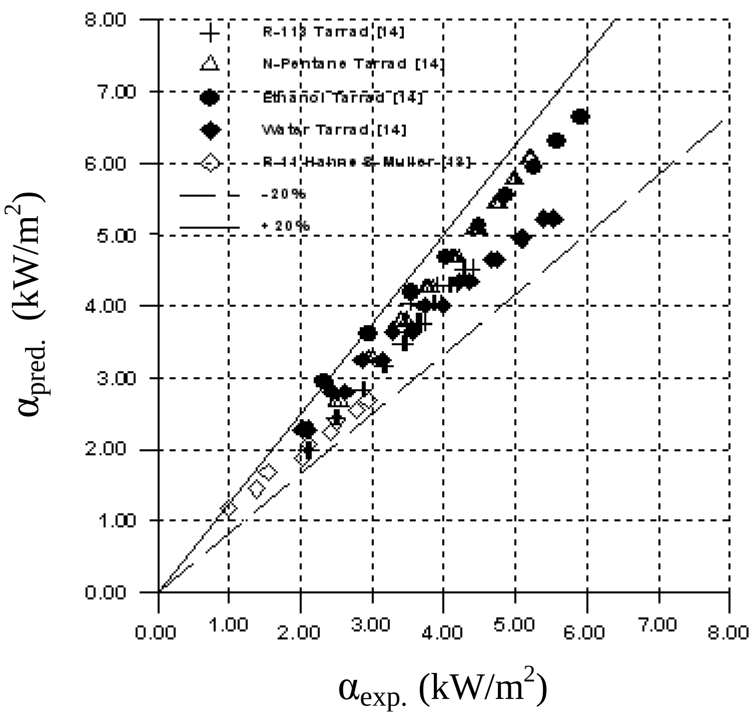

Figure (3.a) Comparison of the nucleate pool boiling heat transfer coefficient predicted by the present correlation with the experimental data of the Low Finned tube

Journal of Engineering and Development, Vol. 11, No. 3, December (2007) **ISSN 1813-7822**

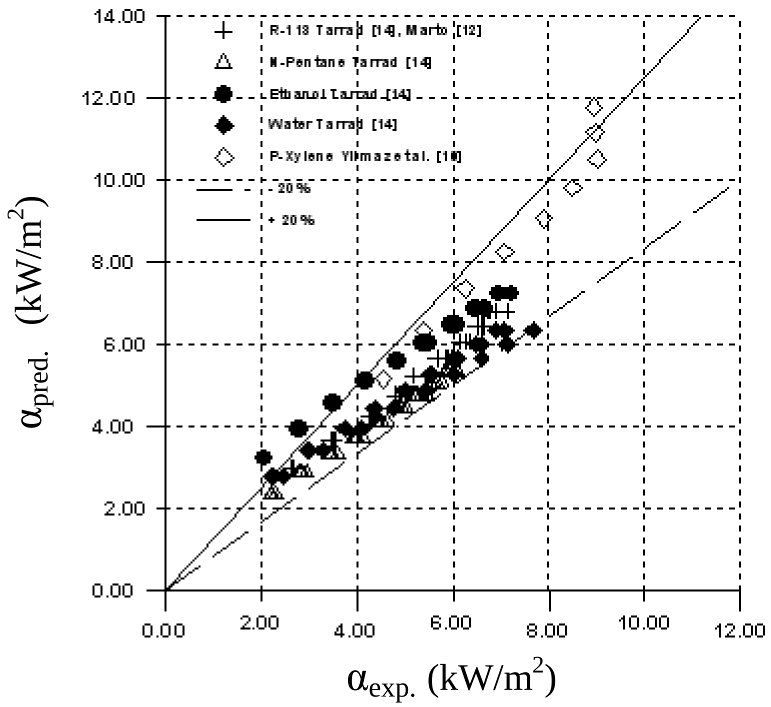

Figure (3.b) Comparison of the nucleate pool boiling heat transfer coefficient predicted by the present correlation with the experimental data of the Gewa-T tube

5. Conclusions

General forms of correlations for the enhancement factor and boiling heat transfer coefficient exhibited by the enhanced surfaces were developed in the present investigation. A list of the liquid-surface contribution factor is given for the various liquids boiling on the enhanced surfaces considered.

The formulae showed a good response to the variation of both of parameters, (η) and ($\alpha_{enh.}$) when compared with the experimental data during boiling on the integral machined heating surfaces. The suggested equation of the enhanced boiling heat transfer coefficient prediction exhibited an acceptable range of accuracy to be within (±20%) for the low finned and Gewa-T surface for the heat flux range (10 - 50) kW/m^2. The total mean absolute error of this correlation is within (9%) for the (279) data points used in the present work for both of the enhanced surfaces.

The present form of the correlation for the enhanced boiling heat transfer coefficient prediction can be incorporated with models used for the design of the kettle reboilers and pool boiling evaporators used in a variety of industrial applications. However, further correlations are required for other liquid surface combination and enhanced surfaces.

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Nomenclature

$C_{S,F}$: Liquid-Surface Contribution Factor in Eq.(15.c), (Dimensionless)
C_1: Empirical Constant in Equations
cp: Specific Heat of Fluid, (kJ/kg K)
d: Tube Diameter, (m)
h_{fg}: Heat of Vaporization, (kJ/kg)
k: Thermal Conductivity of Fluid, (W/m.K)
m: Constant in Eq. (15.c), (Dimensionless)
n: Constant in Eq.(15.c), (Dimensionless)
N: Number of Data Points, (Dimensionless)
p: Process Operating Pressure, (kPa)
q: Heat Flux Density, (kW/m^2)
q_{ref}: Reference Heat Flux in Eq.(7), (kW/m^2)
T: Temperature, (C^o)
ΔT: Wall Superheat, (deg C)

Greek Symbols

α: Nucleate Boiling Heat transfer Coefficient, (kW/m^2 K)
η: Enhancement Factor of Boiling Heat Transfer Coefficient, (Dimensionless)
μ: Viscosity of Fluid, (Pa.s)
ρ: Density of Fluid, (kg/m^3)
σ: Surface Tension, (N/m)

Subscripts

c: Critical Value
enh.: Enhanced surface Value
exp.: Experimental Value
l: Liquid
L-F: Low Finned Surface
o: Outside
pla.: Plain Tube Value
pred.: Predicted Value
r: Reduced or Measured at Fin Root