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A Correlation for the Prediction of Nucleate Pool Boiling Performance of Pure Liquids from Enhanced Tubes

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Abstract

This investigation is devoted to study the enhancement factor of single enhanced tubes boiling pure liquids. 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 based on the Buckingham (π) theorem for these tubes. The enhancement factor is a strong function of the fin shape of the enhanced surface structure and boiling liquids physical properties. Five liquids boiling at atmospheric pressure were considered, R-113, n-pentane, ethanol, water and R-11, for a heat flux in the range between (10) and (50) kW/m2. The total mean absolute errors of the enhancement factors were (6%) and (9%) for the low finned and Gewa-T surfaces respectively. The present correlation showed a good agreement with the available experimental data in the literatures for the nucleate pool boiling heat transfer coefficient. It correlated the available data with a corresponding total mean absolute errors were (9.5%) and (13.5 %) for the low finned and Gewa-T surfaces respectively.

Keywords: Nucleate Boiling; Performance; Enhancement Factor; Correlation; Machined Tube.

Nomenclature:

$C_{S,F}$: Liquid-Surface Contribution Factor ineq.(13.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. (13.c), (Dimensionless)
n : Constant in eq.(13.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.(5), (kW/m^2)
T : Temperature, (C°)
ΔT: Wall Superheat, (deg C)

Greeks

α:Nucleate Boiling Heat transfer Coefficient, (kW/m2 K)
η : Enhancement Factor of Boiling Heat Transfer Coefficient,(Dimensionless)
μ : Viscosity of Fluid, (Pa.s)
ρ : Density of Fluid, (kg/m3)
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

1. 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. The early work of Jakob and Fritz [1] showed that the rough surfaces exhibited a temporary improvement in the boiling heat transfer performance. Courty and Froust [2] found that the roughness has a strong influence on the performance of the heating element boiling liquid. 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.

At the present time there are quite a number of enhanced surfaces available commercially, some of them

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are shown in figure (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.

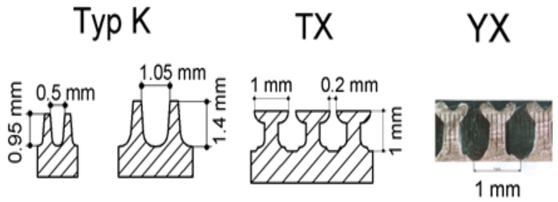

Figure (1.a): Typical Enhanced Gewa-T tube Structure

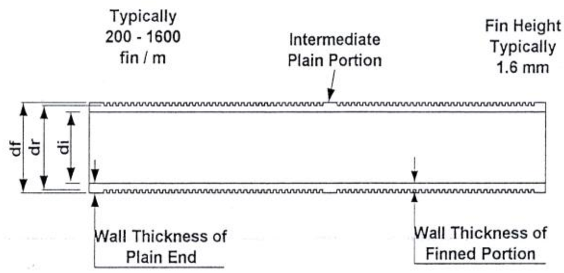

Figure (1.b): Typical Enhanced Low Finned Tube Structure

Marto and Lepere [8] 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. [9] found that the enhanced surfaces improved the boiling heat transfer coefficients of p-xylene and isopropyl alcohol by an order of magnitude approaching (10) times when compared with those of the smooth surface depending on the operating conditions and boiling liquid type. Yilmaz and Westwater [10] concluded that the enhancement in heat transfer performance depends on the enhanced surface structure and liquid properties.

Marto and Hernandez [11] reported an enhancement factor of about three times when boiling R-113 on the Gewa-T surface at atmospheric pressure. Hahne and Muller [12] have found an improvement in the boiling heat transfer coefficient of R-11 when compared the finned tubes with that of the smooth one. Tarrad [13] 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.

Kandikar and Howell [14] reported an increase in bubble activity on a micro fin surface when compared to a plain surface for flow boiling investigation. Yuming et al. [15] made a comparison between the smooth tube and enhanced tubes for bubble growth rate, departure diameter, frequency, active site density and rise velocity. The effects of physical properties on the bubble dynamics were clear especially the departure diameter and the nucleation site density.

The present work establishes a correlation for the prediction of the enhancement factor and the nucleate pool boiling heat transfer coefficient of pure liquids from two types of commercially available enhanced tubes, known as *low finned* and *Gewa-T* surfaces.

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 [16] 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.

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

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 [16] 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 correlated their experimental data in the form of:

$$\alpha = C1 \tag{2}$$

The constants (C_1) and (n) were given for each liquid surface combination. Hahne and Muller [12] presented the following experimental forms for R-11 nucleate boiling on a single low finned tube as:

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

$$\alpha = 8.53 q^{0.54} \quad \text{for } q > 20 \text{ kW/m}^2 \tag{3.b}$$

Palen and Yang [17] proposed a correlation for the prediction of the boiling heat transfer coefficient on low finned tube in the form:

$$\alpha_{L-F} = F_c F_e \eta \alpha_{pla.} + \alpha_{nc} \tag{4}$$

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 represented a formula for the surface factor (η) in the form:

$$\eta = C_1\left(\frac{q}{q_{ref}}\right)^{m_1}\left(\frac{p}{p_c}\right)^{m_2} F_c^{\,m_3} \tag{5}$$

The authors [17] 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. [18] proposed a model to predict the boiling heat transfer coefficients of R-11 from copper single and twin finned tube arrangements for the heat flux range (20) to (50) kW/m^2. Their correlation involved three empirical constants to be determined for each surface.

Tarrad [13] correlated his own results for boiling on the plain and enhanced surfaces in an expression having the form:

$$q = C_1 \Delta T^n \qquad \text{for } 5 \le q \le 60 \text{ kW/m}^2 \tag{6}$$

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:

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
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 through the plain tube prediction of the boiling heat transfer coefficient.

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

$$\eta = \eta\left(h_{fg}, \rho_l, k_l, cp_l, \sigma, q\right) \tag{7}$$

Where (η) refers to the enhancement factor defined by:

$$\eta = \frac{\alpha_{enh.}}{\alpha_{pla.}} = \frac{\Delta T_{pla.}}{\Delta T_{enh.}} \tag{8}$$

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

$$\alpha_{enh.} = \eta \alpha_{pla.} \tag{9.a}$$

Or in terms of the wall superheats in the form:

$$\Delta T_{enh.} = \frac{\Delta T_{pla.}}{\eta} \tag{9.b}$$

The plain nucleate pool boiling heat transfer coefficient, αpla., is predicted by the available correlations such as Mostinski [19] equation in the following expression:

$$\alpha_{pla.} = 0.1 p_c^{\,0.69} q^{0.7} F(p_r) \tag{10.a}$$

Where

$$F(p_r) = 1.8 p_r^{\,0.17} + 4 p_r^{\,1.2} + 10 p_r^{\,10} \tag{10.b}$$

Where (pc) in bar, (q) in W/m2 and (αpla.) in W/m2 K.

The equation which was proposed by McNelly [20] could also be used for the estimation of the plain nucleate pool boiling heat transfer coefficient in the form:

$$\frac{\alpha_{pla.} d}{k_l} = 0.225\left(\frac{qd}{h_{fg}\mu_l}\right)^{0.69}\left(\frac{\mu_l cp_l}{k_l}\right)^{0.69}\left(\frac{pd}{\sigma}\right)^{0.31}\left(\frac{\rho_l}{\rho_v}-1\right)^{0.33} \tag{11}$$

4. 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 seven variables, h_{fg}, ρ_l, k_l, cp_l, q, σ and η, expressed in terms of four fundamental dimensions. Therefore, the equation relating the variables will contain three independent dimensionless groups including the enhancement factor in the forms:

$$\pi_1 = \eta \tag{12.a}$$

$$\pi_2 = \frac{\rho_l h_{fg}^{\,3/2}}{q} \tag{12.b}$$

and

$$\pi_3 = \left(\frac{\sigma}{k_l}\right)\frac{cp_l}{h_{fg}^{\,0.5}} \tag{12.c}$$

Therefore, the suggested correlation has the following expression:

$$\pi_1 = \phi\left(\pi_2, \pi_3\right) \tag{13.a}$$

$$\eta = \phi\left\{\left(\frac{\rho_l h_{fg}^{\,3/2}}{q}\right), \left(\frac{cp_l \sigma}{k_l h_{fg}^{\,0.5}}\right)\right\} \tag{13.b}$$

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

$$\eta = C_{S,F}\left(\frac{\rho_l h_{fg}^{\,3/2}}{q}\right)^m \left(\frac{cp_l \sigma}{k_l h_{fg}^{\,0.5}}\right)^n \tag{13.c}$$

The liquid-surface combination factor, ($C_{S,F}$), and the exponents of the groups, (m) and (n), 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 experimental data bank presented by Tarrad [13], the data of Marto and Hernandez [11] and the experimental results of Hahne and Muller [12] will be used for verification of the present correlation. A total number of about (520) data points were used in the present correlation for the heat flux range between (10) and (50) kW/m^2 at atmospheric pressure. Table (1) shows the structure characteristics of the plain and enhanced surfaces used in the developing of the present correlation.

Table 1. The Structure Characteristics of the Surfaces Used in the Present Correlation.

Surface Type	Reference	Fins/ inch	Enhancement Thick. (mm)	d_o/d_r (mm)
Plain	Tarrad [13]	-----	--------	19/19
Low Finned	Tarrad [13] Hahne & Muller [12]	19 19	1.5 1.5	18.8/15.8 18.9/15.9
Gewa-T	Tarrad [13] Marto & Hernandez [11]	19 19	1.12 1.12	18.9/16.7 21.2/19

The thermal physical properties of the pure liquids tested by the present correlation are shown in table (2).

Table 2.The Physical Properties of the Liquids Used in the Present Correlation.

Liquid	ρ_l kg/m^3)	cp_l (kJ/kgK)	k_l(W/mK)	h_{fg} (kJ/kg)	$\mu_l\times10^3$ (Pa.s)	σ N/m)	P bar)
R-113	1507.42	0.98	0.07	147	0.5015	0.0159	34.15
n-Pentane	610.598	2.376	0.1096	356.3	0.1944	0.012	40.5
Ethanol	736.45	3.0202	0.15147	823.83	0.4376	0.0177	63.8
Water	958.4	4.219	0.681	2257	0.2817	0.0589	221.2
R-11	1479.4	0.8703	0.08898	180.33	0.405	0.018	44.1

These values are deduced from Tarrad [13], Incropera and Dewitt [21] and Sinnott [22]. Equation (13.c) showed a total mean absolute error of (7.5 %) when the exponents (m) and (n) were (0.1806) and (1.7) respectively. The liquid-surface combination factors, ($C_{S,F}$), were (0.389) and (0.48) for the *low finned* and *Gewa-T* surfaces respectively.

The numerical values of (*m*) and (*n*) conclude that the enhancement factor shows a decrease as the operating heat flux and liquid surface tension 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.

5. 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. (13.c), to the plain tube prediction equation either eq.(10) or eq.(11). The choice of the plain tube nucleate boiling heat transfer coefficient correlation depends on the accuracy and the limitation of use of the considered equation.

Mostinski [19] correlation has been used for all of the test liquids except that of the ethanol prediction. The selection of McNelly [20] equation was based on the excellent agreement between the experimental data and the predicted values of the plain tube. Therefore, the general form of the present correlation when incorporated with the Mostinski equation was obtained by combining eq.(10) and eq.(13.c) in the form:

$$\alpha_{enh.} = 0.1 C_{S,F}\, p_c^{\,0.69} q^{0.7} F(p_r) \left(\frac{\rho_l h_{fg}^{\,3/2}}{q} \right)^m \left(\frac{cp_l \sigma}{k_l h_{fg}^{\,0.5}} \right)^n \qquad (14)$$

When McNelly correlation for the plain tube heat transfer coefficient is used, the boiling heat transfer coefficient obtained from the plain surface, eq.(11), replaces that of eq.(10) to obtain:

$$\alpha_{enh.} = C_{S,F} \left(\frac{\rho_l h_{fg}^{\,3/2}}{q} \right)^m \left(\frac{cp_l \sigma}{k_l h_{fg}^{\,0.5}} \right)^n \times \alpha_{pla.} \qquad (15)$$

6. 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.(13.c), and the nucleate boiling heat transfer coefficient, eq.(14) or eq.(15), are defined by the following expressions:

$$(Err\%)_\eta = \frac{\eta_{pred.} - \eta_{meas.}}{\eta_{meas.}} \times 100 \qquad (16.a)$$

and

$$(Err\%)_\alpha = \frac{\alpha_{pred.} - \alpha_{meas.}}{\alpha_{meas.}} \times 100 \qquad (16.b)$$

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

$$\mathbf{(Err\%)_{abs.} = \Sigma|Err\%| / N} \qquad (17)$$

The above parameters were calculated for all of the tested liquids and presented in table (3).

Table 3. The Predicted Enhancement Factor and Boiling Heat Transfer Coefficient Error Percentages.

Surface Type	Liquid	Err% η	Err% $\alpha_{enh.}$	$\lvert Err\% \rvert_m$ η	$\lvert Err\% \rvert_m$ $\alpha_{enh.}$
Low Fin	R-113	2 — 13	-3 — 11	7	5.4
	n-Pentane	-12 — - 4	- 21 — -11	8	14
	Ethanol	-7 — 0	10 — 20	4	11
	Water	- 4 — 21	-1 — 13	7	5
	R-11	-3 — 22	9 — 30	5	12.5
Gewa-T	R-113	-17 — 5	-18 — - 5	12	12
	n-Pentane	0 — 32	- 4 — 9	7	3.4
	Ethanol	- 3 — 38	14 — 33	12	18.6
	Water	-9 — 31	-10 — 21	8	6.7

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 (4%) and (8%), whereas, the corresponding values for the *Gewa-T* surface were (8%) and (12%). The total mean absolute errors of the enhancement factor for both tubes were (6%) and (9.8%) 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 within (9.6%) and (10.2%) 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.

It is worthy to mention here that the high absolute error percentage range of the predicted enhancement factor for ethanol, n-pentane and water boiling on the Gewa-T tube occurred at the low heat fluxes ranged between (10 and 15) kW/m^2 only. The corresponding values for the rest range of heat flux (20 to 50) kW/m^2 were (-3 to 21)%, (0 to 9)% and (-9 to 3)% for these liquids respectively. Of course neglecting the effect at low heat fluxes of the above correlation will improve the mean accuracy and reduces the mean absolute error of the present formula.

Figure (2) shows the predicted and measured enhancement factors of the boiling liquids on the *low finned* and *Gewa-T* tube structures at the atmospheric pressure. It is obvious that the predicted values of (η) by the form of eq.(13.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 in this work. Noting that the predicted values of (η) for the *low finned* and *Gewa-T* tubes fell in the range ((±15%) and (±20%) respectively.

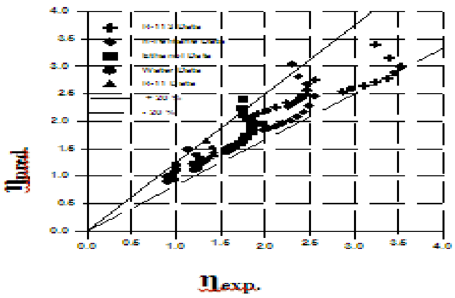

Figure 2. Comparison of the predicted enhancement factor with experimental data of the *low finned* and *Gewa-T* surfaces.

A comparison between the experimental data and the predicted values of ($\alpha_{enh.}$) either by eq.(14) or eq.(15) for the *low finned* and *Gewa-T* surfaces are shown in figures (3) and (4) respectively. The correlation of the present work predicted the boiling heat transfer coefficient for the *low finned* tube within (±25%) 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 (±25%) for more than (98%) of the boiling data of the heat transfer coefficient. The range of the error percentage of the predicted results with the present correlation revealed a qualitative agreement with the experimental data.

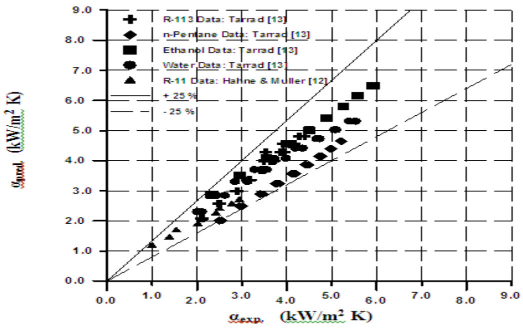

Figure 3. Comparison of the predicted nucleate pool boiling heat transfer coefficient with the experimental data of the ***low finned*** tube

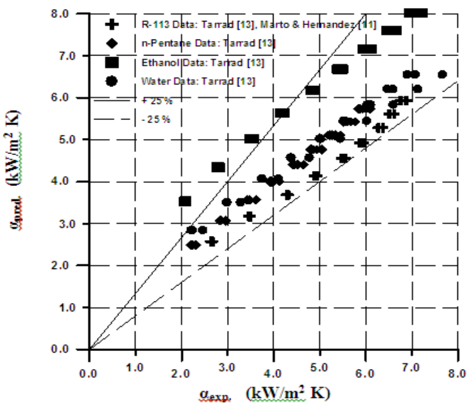

Figure 4. Comparison of the predicted nucleate pool boiling heat transfer coefficient with the experimental data of the *Gewa-T* tube

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 elements showed a good response to the surface and liquid combination type. 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.

7. 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.

The formula 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 (±25%) for the *low finned* and *Gewa-T* surface for the heat flux range (10 - 50) kW/m^2. The total mean absolute error of the correlation of the enhancement factor is within (7.5%) for the (520) 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. Further correlations are required for other liquid surface combination and enhanced surfaces.

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