A New Heat Transfer Correlation for Saturated Flow Boiling of Water with Prandtl Number Improvement

Doymuş Suyun Zorlanmış Taşınımda Kaynamasına İlişkin Prandtl Sayısı İyileştirmesi İçeren Yeni Bir Isı Transfer Korelasyonu

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Abstract

A new correlation predicting the heat transfer coefficient (HTC) for the saturated flow boiling of water is presented in this study. The correlation is valid for tubes and annuli having both vertical and horizontal orientations. The fundamental aim of the study is to investigate the likely effect of the Prandtl number on the HTC for saturated flow boiling by adding the Colburn analogy into the derivation. The derivation ended up with a new dimensionless number, hereafter called as A, and it has been thought that A may be sensitive to the flow regime. Thanks to the comparison carried out with the flow mapping procedure of the RELAP5/Mod3.3 system analysis thermal-hydraulic code, the prudent inference was made that A is dependent on the two-phase flow regimes. Rigorously evaluation of the proposed correlation makes clear that new correlation possesses admissible accuracy and that predicts the experimental HTC data with 16.6% mean deviation for saturated flow boiling. In addition,1.5% improvement in the mean deviation as per the closest correlation in which the Prandtl number effect is not considered is attributed to the positive effect of the Prandtl number improvement on HTC.

Keywords: Correlation, Flow boiling, Flow mapping, Prandtl number improvement

Öz

Bu çalışmada; suyun, doymuş zorlanmış taşınımda kaynamasına ilişkin ısı transfer katsayısını (ITK) öngören yeni bir korelasyon sunulmuştur. Korelasyon hem dikey hem de yatay konuma sahip tüpler ve eş-merkezli iç içe geçmiş tüpler için geçerlidir. Çalışmanın temel amacı, Colburn andırımını derivasyona ekleyerek, doymuş zorlanmış taşınımda kaynama için Prandtl sayısının ITK üzerindeki olası etkisini araştırmaktır. Derivasyon, akış rejimine duyarlı olabileceği düşünülen ve bu noktadan sonra A olarak adlandırılan yeni bir boyutsuz sayı ile son bulmuştur. RELAP5/Mod3.3 ısıl-hidrolik sistem analiz kodunun akış haritalama prosedürüyle yapılan karşılaştırma sayesinde, A'nın iki fazlı akış rejimlerine bağlı olduğu konusunda ihtiyatlı bir çıkarım yapılmıştır. Önerilen korelasyonun titizlikle değerlendirilmesi, yeni korelasyonun kabul edilebilir bir doğruluğa sahip olduğunu ve deneysel ITK verilerini, doymuş zorlanmış taşınımda kaynama için 16.6%'lık ortalama sapma ile tahmin ettiğini açıkça ortaya koymaktadır. Ek olarak, Prandtl sayısı etkisinin göz önünde bulundurulmadığı en yakın korelasyona göre ortalama sapmadaki 1.5%'lik iyileşme, Prandtl sayısı iyileştirmesinin ITK üzerindeki olumlu etkisine bağlanmıştır.

Anahtar Kelimeler: Korelasyon, Zorlanmış taşınımda kaynama, Akış haritalaması, Prandtl sayısı iyileştirmesi

1. Introduction

Reliable prediction of the boiling heat transfer coefficient (HTC) is one of the important factors for the successful design of components used particularly in the energy industry. Generally, the prediction of heat transfer remains essentially empirical, due to the complex hydrodynamics and heat transfer processes involved (Cheng and Chen 2000). Though many well-known flow boiling correlations for horizontal and vertical tubes have been introduced in the last decades, the multitude studies digging the various sides of the flow-boiling phenomenon still continue. On one hand, some technological breakthroughs set the stage for either flow boiling or pool boiling of the nanofluids (Yun et al. 2018, Hassanpour et al. 2018, Prakash and Prasanth 2018) and mini/micro structures (Lu et al. 2017, Ferrari et al. 2018). On the other hand, boiling phenomenon of the

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conventional channels and fluids (Chen et al. 2018, Kim et al. 2018) emerge as still widely studied areas. This is mainly because the hydrodynamics and transport phenomena in the boiling heat transfer are not thoroughly understood. Essentially because of this, the far-reaching studies are underway to get a deep insight in the various sides of flow-boiling such as flow pattern (or flow mapping) and determination of the pressure drop (de Oliveira et al. 2018, Jige et al. 2017). The complexity of the subject compels researchers to scrutinize even the most basic topics such as the bubble growth rate, bubble departure and departure from nucleate boiling (DNB) (Raj et al. 2017, Giustini et al. 2018). Another pillar of the flow boiling related studies is the development of the correlations based on the empirical or semi-empirical models as well as the validation of these with well-known correlations and the experimental data.

In a nutshell, different aspects of flow boiling and the use of the development of various correlations in this area or the validation of previously developed correlations are extremely intriguing topics. In the following section, a brief explanation of the Chen correlation (Chen 1966) will be given to understand the Reynolds number factor (or the enhancement factor) and to follow how this factor would be linked to the present study. It is also within the scope of the next section that why the Güngör-Winterton enhancement formula (Güngör and Winterton 1987) is taken as the underlying point of the present study.

2. Material and Methods

2.1. Chen correlation (Chen 1966)

Chen presented one of the most successful and well-known correlations for heat transfer in flow boiling. This correlation is essentially based on the simple addition of two postulated heat transfer mechanisms as seen in Eqn. (1): The heat transfer associated with the bulk movement of the vapor and liquid or macroscopic heat transfer (h_{mac}) and the heat transfer related to the turbulence induced by the conception, growth and departure of vapor bubbles or shortly microscopic heat transfer (h_{mic}).

$$h_{TP} = h_{mac} + h_{mic} \qquad (1)$$

where h is the HTC (W/m²K) and subscript TP stands for the two-phase flow boiling. Eqn. (2) shows how the microscopic or micro convective contribution is consolidated by Chen in terms of the suppression factor, S, and the pool boiling HTC (h_{pool} in W/m²K), which is calculated from Forster and Zuber equation (Foster and Zuber 1955). The

suppression factor or nucleate boiling suppression factor, which was correlated against the two-phase Reynolds number, reflects the fact that in flow boiling, due to thinner thermal boundary layer, the mean effective superheat is lower than that encountered in pool boiling.

$$h_{mic} = Sh_{pool} \qquad (2)$$

Chen postulation with regard to the two-phase region, in which both liquid and vapor are present, is that the macroscopic or macro convective heat transfer could be described by a modified form of the Dittus-Boelter equation. That is,

$$h_{mac} = 0.023 \, Re_{TP}^{0.8} \, Pr_{TP}^{0.4} (k_{TP/D}) \qquad (3)$$

In Eqn. (3), the Prandtl number (Pr_{TP}), the Reynolds number (Re_{TP}) and the thermal conductivity (k_{TP} in W/mK) represent effective values associated with two-phase fluid and D (m) is the tube diameter. Chen stated that in the case of ordinary fluids, (i.e., not liquid metals) the Prandtl numbers of the liquid and vapor are normally the same magnitude. The Prandtl number of the two-phase fluid should therefore also be of the same magnitude. Furthermore, since heat is transferred through an annular film of liquid adhering to the wall, it is expected that the liquid properties would have a dominant effect. Accordingly, it is reasonable to assume that both Pr_{TP} and k_{TP} could be replaced by those of liquid counterparts or β and γ given in Eqn. (4) can be conceded as unity (Chen 1966).

$$\beta = \frac{Pr_{TP}}{Pr_L}; \gamma = \frac{k_{TP}}{k_L}; F = \left(\frac{Re_{TP}}{Re_L} \right)_{0.8} \qquad (4)$$

After this postulation, Eqn. (3) was rearranged by Chen as:

$$h_{mac} = 0.023 \, Re_L^{0.8} \, Pr_L^{0.4} (k_L/D) F \qquad (5)$$

or

$$h_{mac} = h_L F \qquad (6)$$

where h_L is the Dittus-Boelter equation to calculate the liquid-only HTC (W/m²K) and F is called as the Reynolds number factor or forced convective enhancement factor (Barbosa et al. 2002).

2.2. Development of the Enhancement Factor for the Present Correlation

The microscopic heat transfer term (h_{mic}) in Eqn. (1) can be neglected pursuant to some analysis carried out on experimental data (Güngör and Winterton 1987) and the HTC for flow boiling can be described solely by the macroscopic heat transfer contribution (h_{mac}), which is a function of F and the liquid-only HTC. Correlations of this

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type, known as the enhancement type of correlations, have been shown to be simpler and more accurate as a result of comparing the Güngör-Winterton correlations (Güngör and Winterton 1986, 1987). Because of these reasons and even due to the same experimental data shared with Güngör-Winterton (Güngör and Winterton 1987), the use of the enhancement model was deemed suitable for this study. In other words, while the h_{mic} term seen in Eqn. (1) has been neglected, h_{TP} is expressed only as a function of h_{mac} term in this study. Under these circumstances, the HTC for flow boiling could be written in accordance with the Chen postulation as follows:

$$h_{TP} = h_{mac} = 0.023 \, \mathrm{Re}_{TP}^{0.8} \mathrm{Pr}_{TP}^{0.4}(k_{TP}/D) \qquad (7)$$

In two-phase convective flow, the temperature and velocity profiles are very different from their single-phase counterparts. For saturated flow boiling, the bulk of the flow is at or very close to the saturation temperature and temperature differences are confined to the small region close to the wall. Velocity differences, on the other hand, still extend right across the flow. So, relative to the single-phase case the temperature gradient near the wall become even more important and it is reasonable to expect an enhancement of the Prandtl number effect (Liu and Winterton 1991). In other words, to take cognizance of the Prandtl number effect, Pr_{TP} term is left in Eqn. (7) whereas k_{TP} is substituted by k_L pursuant to the Chen postulation. After applying these postulations and if Eqn. (7) is then divided by Dittus-Boelter equation for liquid-only flow, the HTC for flow boiling is obtained in terms of the liquid-only HTC and the Reynolds and Prandtl numbers associated with both two-phase and liquid-only flows:

$$\frac{h_{TP}}{h_L} = \frac{0.023 \, \mathrm{Re}_{TP}^{0.8} \mathrm{Pr}_{Tp}^{0.4}(k_L/D)}{0.023 \, \mathrm{Re}_{L}^{0.8} \mathrm{Pr}_{L}^{0.4}(k_L/D)} \Leftrightarrow h_{TP} = \Big(\frac{\mathrm{Re}_{TP}}{\mathrm{Re}_L}\Big)^{0.8} \Big(\frac{\mathrm{Pr}_{TP}}{\mathrm{Pr}_L}\Big)^{0.4} h_L \qquad (8)$$

If Eqn. (8) is compared with Eqn. (6), the enhancement factor of the present study (E_{PS}) may be represented as:

$$E_{PS} = \Big(\frac{\mathrm{Re}_{TP}}{\mathrm{Re}_L}\Big)^{0.8} \Big(\frac{\mathrm{Pr}_{TP}}{\mathrm{Pr}_L}\Big)^{0.4} \qquad (9)$$

By recalling the Eqn. (4), it is obvious that the Reynolds number ratio on the right-hand side of the Eqn. (9) is the Reynolds number factor (or the enhancement factor) that

does not use the Prandtl number improvement. Therefore, the relationship between the enhancement factor introduced for the present study and that of others becomes as follows:

$$E_{PS} = F\Big(\frac{\mathrm{Pr}_{TP}}{\mathrm{Pr}_L}\Big)^{0.4} \qquad (10)$$

In the majority of the prominent studies, the Reynolds number factor is defined as a function of the Boiling number (Bo)[1], the Martinelli parameter (X_{tt})[2], the Convection number (Co)[3] or of the combination of them. It should be remembered that if the horizontal flow is in question, the Froude number (Fr)[4] is also reckoned jointly by the dimensionless numbers mentioned in the previous sentence. However, Shah (Shah 1982) concluded that the viscosity ratio, which is one of the constituents of the Martinelli parameter, has no significant effect in determining the two-phase HTC and he proposed replacement of the Martinelli parameter with the convective number (Kandlilar 1990). Güngör-Winterton (1987) also adopted this approach and expressed the enhancement factor as a function of only the quality ratio (x/1-x) and the density ratio (ρ_L/ρ_v). Comparisons with expanding experimental data showed that the enhancement factor is also strongly affected by the Boiling number (Güngör and Winterton 1987). In light of this explanation, the Reynolds number ratio on the right-hand side of the Eqn. (9) may be expressed as:

$$F = \Big(\frac{\mathrm{Re}_{TP}}{\mathrm{Re}_L}\Big)^{0.8} = \Big[1 + C_1 B_0^m + C_2 \Big(\frac{x}{1-x}\Big)^n \Big(\frac{\rho_L}{\rho_V}\Big)^z\Big] \qquad (11)$$

It should be noted that Eqn. (11) is the enhancement factor formulation proposed by Güngör-Winterton (Güngör and Winterton 1987).

Colburn defined the j-factor using the experimental data collected in laminar and turbulent flow regimes for both mass transfer and heat transfer. This analogy is the improvement of the Reynolds analogy and would not be restricted with the Prandtl and Schmidt numbers, which must be equal to one. The analogous j-factor for heat transfer is:

$$\frac{h}{C_p G} \mathrm{Pr}^{2/3} = j_H = \frac{f}{2} \qquad (12)$$

where j is the factor in Colburn analogy and f is the friction factor. While G stands for mass flux (kg/m²s), C_p is the specific heat (J/kgK). Ağlar (1993) assumed that the obvious

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[1] Bo=q"/Gh$_{fg}$ where q": Heat Flux (W/m²), h$_{fg}$: Latent Heat (J/kg), G: Mass Flux (kg/m²s)
[2] X$_{tt}$= (1-x/x)$^{0.9}$(ρ_v/ρ_L)$^{0.5}$(μ_L/μ_V)$^{0.1}$ where x: quality, ρ: Density (kg/m³), µ: Viscosity (kg/ms), v and L denote vapor and liquid.
[3] Co= (1-x/x)$^{0.8}$(ρ_v/ρ_L)$^{0.5}$
[4] Fr = G²/(ρ_L^2 gD) where g: Acceleration of Gravity (m/s²), D: Diameter (m)

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relationship between j and the friction factor (f) for single-phase flow should also be available for two-phase flows. i.e., similar to Colburn analogy. Thus, Eqn. (12) is redefined for the homogeneous flow model as:

$$j_{TP} = \frac{f_{TP}}{2} \qquad (13)$$

where f_{TP} is the two-phase friction coefficient. The validity of Eqn. (13) was studied in reference (Sarma et al. 2000) and the agreement was found to be satisfactory. Hence, by taking Eqns. (12 and 13) into account, the Prandtl number ratio in Eqn. (10) can be written as:

$$\left(\frac{Pr_{TP}}{Pr_L}\right)^{0.4} = \left[\frac{f_{TP} Cp_{TP} h_L}{f_L Cp_L (1-x) h_{TP}}\right]^{0.6} \qquad (14)$$

where x is the quality. Finally, if Eqns. (11 and 14) are substituted into Eqn. (10) and after some mathematical arrangements, the HTC for flow boiling of the present study can be represented as:

$$h_{TP} = h_L \left[1 + C_1 B_0^m + C_2 \left(\frac{x}{1-x}\right)^n \left(\frac{\rho_L}{\rho_V}\right)^z\right]^{\left(\frac{1}{1.6}\right)} [A]^{\left(\frac{0.6}{1.6}\right)} \qquad (15)$$

where A is the dimensionless number and can be denoted as:

$$A = \left[\frac{f_{TP}}{f_L}\left(1 + \frac{Cp_V}{Cp_L}\frac{x}{1-x}\right)\right] \qquad (16)$$

C1, C2, m, n, and z are the unknowns to be determined by non-linear regression computer code developed as a part of this study and it is based on the Levenberg-Marquardt method. However, by taking the non-linear character of the Eqn. (15) into consideration, the constants (1/1.6) and (0.6/1.6) appearing in Eqn. (15) are also treated as a variable (p and r) in addition to C_1, C_2, m, n, and z for the sake of high accuracy. So, this arrangement gives rise to the final form of the present study as follows:

$$E_{PS} = \left[1 + C_1 Bo^m + C_2 \left(\frac{x}{1-x}\right)^n \left(\frac{\rho_L}{\rho_V}\right)^z\right]^p A^r \qquad (17)$$

2.3. Experimental Data and Final Equations

The experimental data (Güngör 1992) consists of 2211 data points for saturated flow boiling of water for both tubes and annuli. Details of the data sources could be found in Güngör-Winterton (1986, 1987) and range of the variables that are directly relevant to the interval at which the proposed correlation is valid could be specified as follows:

Saturation temperature	88.6-364.9 °C
Heat flux	4.7-2616.0 kW/m²

Quality	0.0-78.1%
Diameter	2.95-32.0 mm
Mass flux	59.30-8197.0 kg/m²s
Prandtl number	0.84-3.60

The two-phase HTC for saturated flow boiling for water is expressed by Eqn. (18).

$$h_{TP} = E_{PS} h_L \qquad (18)$$

where E_{PS} is estimated from Eqn. (17). h_L is the Dittus-Boelter equation for liquid-only flow. By using all of the saturated water data available, the unknown parameters of Eqn. (17) have been found via the non-linear regression code and results are provided in Table 1.

Table 1. Parameters of present correlation (Eqn. 17).

Parameters	Vertical Flow	Horizontal Flow
C_1	3650.0	532.3
C_2	0.31	0.30
m	0.83	0.64
n	0.80	0.88
z	0.68	0.63
p	1.01	1.06
r	0.82	0.11

The friction factors appeared in dimensionless number. A for two-phase and liquid phase may be defined as (McCabe et al. 1986):

$Re_{TP} \leq 3000 \rightarrow$ $Re_L \leq 3000 \rightarrow$	$f_{TP} = 16/Re_{TP}$ $f_L = 16/Re_L$	
$Re_{TP} > 3000 \rightarrow$ $Re_L > 3000 \rightarrow$	$f_{TP} = 0.014 + (0.125/Re_{TP}^{0.32})$ $f_L = 0.014 + (0.125/Re_L^{0.32})$	(19)
where	$Re_L = \dfrac{DG(1-x)}{\mu_L}$	

The boiling in annuli is treated by means of equivalent diameter that depends on the heated perimeter.

$$D_e = \frac{4 Flow\ Area}{Heated\ Perimeter} \qquad (20)$$

3. Results and Discussion

The comparison of the present correlation with mostly-referenced correlations and experimental data is presented in Table 2 and Figure 1, respectively. In order to be able to see the effect of the Prandtl number on two-phase HTC more clearly, the Güngör-Winterton correlation (Güngör

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and Winterton 1987) was rearranged for water-data as a part of the present study and henceforth it will be named as the revised Güngör-Winterton correlation. There are two reasons for this approach. Firstly, the present study is basically based on the Güngör-Winterton correlation (Güngör and Winterton 1987). Secondly, this approach provides a way of understanding the effect of the Prandtl number on HTC by offering better comparison opportunity.

The correlations lined up in Table 2 gave the systematically better prediction for annuli data when the equivalent diameter based on the heated-perimeter seen in Eqn. (20) was used. This is also the case for Shah correlation (Shah 1982) unless the clearance (ro-ri) is less than 4 mm; otherwise, Shah suggests using the wetted perimeter instead of the heated perimeter seen in Eqn. (20).
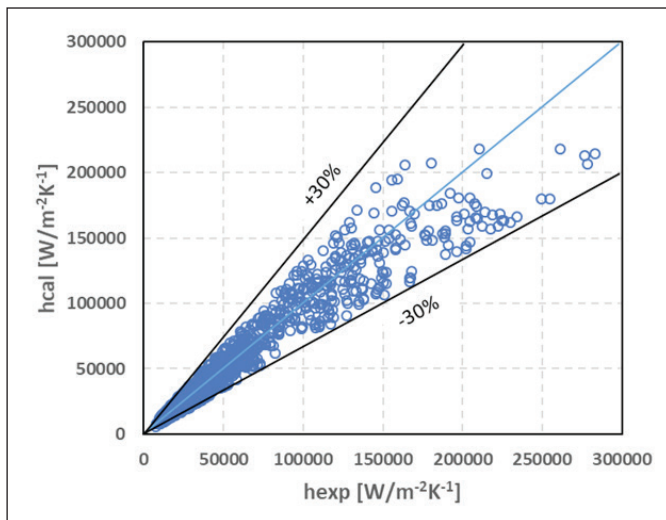
Figure 1. Comparison of the present correlation with experimental data.

Inspection of Table 2 reveals that the Chen correlation gives the poorest fit to the data with a mean deviation of 27.9%. If the general correlations are regarded, except for the Chen correlation, the mean deviations of the others are nearly the same and are around 20%. Examination of Table 2 also reveals that among the general correlations, the Güngör-Winterton correlation (Güngör and Winterton 1987) with a mean deviation of 18.9% yields the nearest results to the present correlation that predicts the experimental data with 16.6% deviation. If the comparison is extended to the revised Güngör-Winterton, it could be seen that the present correlation provides 1.5% lower deviation which is not to be underestimated for two-phase flow. This difference between two correlations developed by using the same experimental data and non-linear regression code could be attributed to the effect of the Prandtl number on the HTC. Bennett and Chen (Bennett and Chen 1980) stated that an additional Prandtl number effect is evident for fluids with high Prandtl number. Hence, if the present correlation is turned into the general correlation with a suitable experimental data, it is thought that further improvement in the mean deviation especially for high Prandtl number fluids might be obtained. If the average deviations are compared, the present correlation with -1.3% is in the third rank after the Shah and the Güngör-Winterton correlations. It should be remembered that the negative average deviation is the sole indicator of the underprediction capability of the correlations. Figure 1 clearly depicts this feature of the present correlation. The dimensionless numbers such as the Boiling number, the Convection number etc., used in the present correlation and the correlations given in Table 2 were divided into small ranges in order to investigate any likely relationship between

Table 2. Comparison of the correlations with the saturated flow boiling data.

	Number of data points	Chen (1966) Mn[a]/Av[b]	Shah (1982) Mn/Av	Güngör-Winterton (1987) Mn/Av	Liu-Winterton (1991) Mn/Av	Kandlikar (1990) Mn/Av	Revised Güngör and Winterton Mn/Av	Present Mn/Av
Vertical	982	28.1/–21.0	20.8/–8.0	21.1/–2.1	20.2/–3.4	22.2/–12.8	21.1/–6.2	19.4/–4.7
Horizontal	471	30.6/–13.3	11.7/–3.8	9.9/–1.3	13.6/–5.3	12.9/–11.1	10.1/–4.0	7.7/–0.2
Annuli (I)[c]	622	25.2/2.3	27.0/17.4	21.1/9.4	22.8/–2.6	23.8/14.0	18.2/5.4	17.7/4.0
Annuli (B)[c]	136	30.6/–21.2	24.8/–19.1	23.8/–6.8	21.0/–14.7	27.2/–23.2	23.7/–12.2	21.3/–5.9
All Water Data	2211	27.9/–12.7	21.2/–0.5	18.9/1.0	19.6/–4.3	21.3/–5.3	18.1/–2.8	16.6/–1.3

[a]*Mean deviation=$\frac{1}{n}\sum_1^n\left|\frac{(h_{cal}-h_{exp})100}{h_{exp}}\right|$*, [b]*Average deviation=$\frac{1}{n}\sum_1^n\frac{(h_{cal}-h_{exp})100}{h_{exp}}$*, [c] *I: inner tube heated, **B:** both tubes heated.*

the aforementioned dimensionless numbers and the mean deviation. The same was also performed for the quality. The numerical results of this detailed comparison are tabulated in Table 3 and noteworthy disclosures related to this table are presented in the subsequent paragraphs.

The nucleate boiling and the forced convective boiling are two governed mechanisms for saturated flow boiling. In forced convection dominant region, bubble nucleation is more and more suppressed and heat is transferred mainly by single-phase convection through the thin annular liquid film. The heat transfer coefficient (HTC) in this region is dependent upon mass velocity but fairly independent of heat flux (Qu and Mudawar 2003). The prevailing parameter for the phenomenon given above is the quality and can be related to the Convection number. To be brief, increasing quality leads to decreasing values of the Convection number. If the comparison is carried out from this point of view, only the Liu-Winterton correlation gives decreasing deviation varying from 32% to ~11% with increasing the Convection number located within the range of 0.017 and 37. In the region where the Convection number changes from 0.017 to 1.2, the present correlation is much more accurate than others and the mean deviation of it increases from 14.2% to 15.4%. The poorest fitting is observed for the Chen correlation with 55% especially at low-quality region corresponding to high Convection number.

Yen et. al. (Yen et al. 2003) proclaim comparatively simple criterion which basically states that the forced convective boiling effect dominates when the vapor quality exceeds 0.5 and otherwise the nucleate boiling effects become important. In nucleate boiling, liquid near the wall is superheated to a sufficient degree to sustain the nucleation and growth of vapor bubbles. In comparison to the convective boiling, the HTC is dependent upon the heat flux, but generally far less sensitive to mass velocity and vapor quality. If the comparison is performed according to this criterion, in nucleate boiling region where the vapor quality is less than 0.5, the Chen correlation gives the poorest fitting with a 26.8% mean deviation. The present, the revised Güngör-Winterton, and the Güngör-Winterton correlations (Güngör and Winterton 1987) predict the data with 16.7%, 18.1%, and 18.9% respectively. However, in the convective boiling region, except for the present correlation having 22.4% deviations, others give rather poor predictions. In this region, the second is the Shah correlation (Shah 1982) with a mean deviation of 27.3%, followed subsequently by the Güngör-Winterton (Güngör and Winterton 1987) with

27.4%, the revised Güngör-Winterton and the Kandlikar (Kandlikar 1990) with 27.7% and the Chen (Chen 1966) with the 31.2%.

Upon inspection of Table 3, it is seen that increasing Boiling numbers gives generally decreasing deviation. If all Boiling number ranges are considered, the present correlation gives lower deviations than those observed in other correlations. At high Boiling numbers region where the nucleate boiling effects are dominant, i.e., at low qualities (Shah 1976), smaller deviations have been observed compatible with the conclusion drawn in the previous paragraph. It is remarkable that only the Kandlikar, the revised Güngör-Winterton, and the present correlations provide the decreasing deviation with increasing Boiling numbers in all ranges.

Careful study of the Table 3 also indicates that the mean deviation observed in the Liu-Winterton correlation is inversely proportional to the Re_L. Particularly at high Re_L values this correlation gives the best prediction with 13.1% mean deviation. The present correlation ensures the minimum deviation, which is around 13.8% in the range where Re_L changes between 27.8×10^3 and 39.3×10^3.

In this paragraph, consideration will be given to the dimensionless number A. This number alters between 0.391 and 2.069 and designates the effect of the Prandtl number on two-phase HTC. In other words, it sometimes acts as further enhancement factor while sometimes it behaves as a suppression factor by moving in the opposite direction.

In two-phase flow, to know the flow regime is the *sine qua non* to determine the HTC for a given geometry. The notable change of A according to the data points required the investigation of the relationship between A and the flow regime. In this way, the likely relationship between A and the flow regime was scrutinized by comparing A and the flow mapping methodology of the RELAP5/Mod3.3 (Information Systems Lab. Inc. 2001) which is one of the well-known and intensely validated system analysis thermal-hydraulic codes. Thus, it is aimed to understand what the possible relationship between A and the flow regime might be.

It is vigorously deduced that the region, which is classified as annular-mist flow by RELAP5/Mod3.3, possesses A values either greater than 1 or equal to 1. The region where A changes from 0.390 to 0.439 is definitely a slug flow regime. The region in which A values change between 0.44 and 0.549 is the most problematic region and it is inferred that the featured parameters detecting flow pattern are the quality

Table 3. Detailed comparisons of the correlations in terms of percent mean deviation.

	Chen (1966)	Shah (1982)	Güngör and Winterton (1987)	Liu and Winterton (1991)	Kandlikar (1990)	Revised Güngör and Winterton	Present
Co≤0.06	17.5	20.5	13.6	32.0	18.6	13.0	14.2
0.06<Co≤0.2	23.2	24.7	20.6	21.7	22.5	19.2	17.3
0.2<Co≤0.4	27.7	20.8	20.7	19.6	20.8	20.4	17.6
0.4<Co≤0.8	26.5	18.0	17.6	17.4	21.5	17.1	15.7
0.8<Co≤1.2	28.8	19.2	17.2	15.0	18.9	16.4	15.4
1.2<Co≤3.0	36.1	21.0	20.0	16.0	20.8	19.6	18.3
Co>3.0	55.0	26.4	25.3	11.4	28.8	23.4	22.9
x≤0.5	26.8	21.0	18.9	19.3	21.1	18.1	16.7
x>0.5	31.2	27.3	27.4	37.5	27.7	27.7	22.4
x≤0.032	32.3	19.6	18.0	17.7	22.0	18.1	16.5
0.032<x≤0.073	30.2	19.9	18.1	18.4	20.0	19.0	16.5
0.073<x≤0.143	27.2	19.9	19.5	16.2	20.0	18.7	16.3
0.143<x≤0.241	23.6	21.9	20.0	16.9	21.0	17.4	16.5
0.241<x≤0.37	21.6	25.0	19.6	22.8	23.7	18.0	17.9
x>0.37	24.6	22.5	19.0	33.1	22.0	19.3	17.9
Box10⁴≤12	28.2	26.3	23.9	24.0	26.0	24.0	21.5
12<Box10⁴≤22.5	29.4	23.2	18.1	15.2	23.3	17.2	16.7
22.5<Box10⁴≤36.5	26.6	19.9	17.1	18.5	20.4	17.2	16.1
36.5<Box10⁴≤67.6	24.7	17.8	18.0	20.9	18.7	16.8	15.3
Box10⁴>67.6	26.2	18.5	18.5	20.5	16.7	16.2	13.3
Re_L≤12896	20.3	23.0	18.6	27.9	21.4	17.4	15.8
12896<Re_L≤27832	26.6	25.9	22.3	23.8	22.9	20.3	19.2
27832<Re_L≤39307	21.9	15.6	16.9	14.5	17.0	16.0	13.8
39307<Re_L≤68082	28.7	21.4	19.8	20.5	23.5	20.8	18.8
68082<Re_L≤138337	32.1	18.8	15.7	15.7	20.6	16.0	14.5
Re_L>138337	37.0	21.8	21.0	13.1	22.5	19.2	18.8

and the slip ratio (SR[5]). If A and SR vary between 0.44-0.5 and 5.35-6, respectively, the slug and annular-mist flows could be dissociated with 66% success and this ratio is found out as 65% in the region where A and quality are changing between 0.501-0.549 and 0.135-0.618, respectively. The proposed methodology can make more successful estimates in the region where A is changed between 0.391-0.439 and 0.55-0.99. It is found that the lowest decomposition rate is 80%, also the quality is major parameter to assign flow regime in the mentioned regions.

It was observed that all A values were smaller than 1.0 in the horizontal flow for which the decomposition rate is 100%. The parameters used to decompose the slug, transition slug/annular and annular flow regimes are the slip ratio (SR) and the Convection number (Co). According to the developed

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[5]The ratio of the velocity of the vapor phase to that of the liquid phase.

methodology, if Co is in the closed interval of 0.037-0.6, the flow is decisively annular and if Co is greater than 0.96, the flow regime is found as slug flow. Between these two regions, the SR appears to be a determinative parameter. According to the extremely strict conclusions, if SR varies between 2.68-3.11, the flow regime is assigned to be slug-flow and between 3.12-3.86, slug/annular transition flow is observed. Findings also show that flow regime could be admitted as annular flow in the region in which the SR ranges from 3.87 to 5.34. The results of the flow mapping methodology briefly given above are provided in Table 4.

4. Conclusion

The main conclusions arising from this study are as follows:

1. The new correlation shows a rather good agreement with experimental data. The deviation between the calculated

and the experimental HTCs for flow boiling is estimated to be 16.6%.

2. The Prandtl number improvement on the enhancement factor provides 1.5% reduction in mean deviation for water compared to the revised version of the Güngör-Winterton correlation. It is expected that further improvement could be made if the correlation is rehabilitated for high Prandtl number fluids.

3. The analysis carried out by considering the quality and Boiling number states that all correlations in Table 2 get high accuracy at the region where nucleate boiling effects are relatively dominant.

4. It is observed that the flow mapping is performed more precisely with increasing A values. However, it should be noted that the correlation does not predict well when A is within 0.44 and 0.549.

Table 4. Relationship between A number and flow regime findings of RELAP5/Mod3.3.

Vertical Flow					
Criterion-1 (A Number)	Criterion-2 (Quality, x)	Criterion-3 (Slip ratio, SR)	Criterion-4 (Convection Number, Co)	Flow Regime (RELAP5/ Mod3.3)	Decomposition Rate (%)
1.0≤A≤2.07	-	-	-	Annular-Mist	100
0.39≤A≤0.439	-	-	-	Slug	100
0.44≤A≤0.5	-	5.35≤SR≤6.0	-	Annular-Mist	66
	-	6.0≤SR≤6.25	-	Slug	91
0.501≤A≤0.549	0.004≤x≤0.13	-	-	Slug	92
	0.135≤x≤0.62	-	-	Annular-Mist	65
0.55≤A≤0.60	0.0036≤x≤0.125	-	-	Slug	84
	0.129≤x≤0.64	-	-	Annular-Mist	96
0.6<A≤0.70	0.0016≤x≤0.055	-	-	Slug	88
	0.056≤x≤0.092	1.202≤SR≤5.27	-	Annular-Mist	100
		5.35≤SR≤6.15	-	Slug	100
	0.096≤x≤0.66	-	-	Annular-Mist	90
0.701<A≤0.799	0.003≤x≤0.025	-	-	Slug	90
	0.026≤x≤0.435	-	-	Annular-Mist	80
0.80<A≤0.99	0.001≤x≤0.04	-	-	Slug	100
	0.044≤x≤0.59	-	-	Annular-Mist	100
Horizontal Flow					
A<1.0	-	-	0.037≤Co≤0.6	Annular	100
	-	2.68≤SR≤3.11	0.601≤Co<0.96	Slug	100
	-	3.12≤SR≤3.86		Transition Annular/Slug	100
	-	3.87≤SR≤5.34		Annular	100
	-	-	Co≥0.96	Slug	100

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5. Researchers should be prudent about the flow mapping methodology proposed in this study. Frankly, further work is needed to verify and improve the methodology.

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6. References

Ağlar, F. 1993. Determination of heat transfer coefficient for saturated flow boiling of water. M. Sc. thesis, Middle East Technical University, Ankara.

Barbosa, JR., Hewitt, GF., Richardson, SM. 2002. Forced convective boiling of steam-water in a vertical annulus at high qualities. *Exp. Therm. Fluid Sci.,* 26: 65-75.

Bennett, DL., Chen, CJ. 1980. Forced convective boiling in vertical tubes for saturated pure components and binary mixtures. *AICHE J.,* 26: 454-461.

Chen, CJ. 1966. Correlation for boiling heat transfer to saturated fluids in convective flow. *Ind. Eng. Chem. Process Des. Dev.,* 5: 322-329.

Chen, L., Zhou, P., Huang, R., Han, X., Hua, S., Li, Z., Gao, L. 2018. Experimental investigation on the suppression factor in subcooled boiling flow. *Appl. Therm. Eng.,* 135: 549-558.

Cheng, L., Chen, T. 2000. Comparison of six typical correlations for upward flow boiling heat transfer with kerosene in a vertical smooth tube. *Heat Transfer Eng.,* 21: 27-34.

de Olivera, JD., Passos, JS., Copetti, JB., Geld, CWM. 2018. Flow boiling heat transfer of propane in 1.0 mm tube. *Exp. Therm. Fluid Sci.,* 96: 243-256.

Ferrari, A., Magnini, M., Thome, JR. 2018. Numerical analysis of slug flow boiling in square microchannels. *Int. J. Heat Mass Tran.,* 123: 928-944.

Foster, HK., Zuber, N. 1955. Dynamics of vapor bubbles and boiling heat transfer. *AIChE J.,* 1: 531-535.

Giustini, G., Ardron, KH., Walker, SP. 2018. Modelling of bubble departure in flow boiling using equilibrium thermodynamics. *Int. J. Heat Mass Tran.,* 122: 1085-1092.

Güngör, KE. 1992. Personal Communication.

Güngör, KE., Winterton, RSH. 1986. A general correlation for flow boiling in tubes and annuli. *Int. J. Heat Mass Tran.,* 29: 351-358.

Güngör, KE., Winterton, RSH. 1987. Simplified general correlation for saturated flow boiling and comparisons of correlations with data. *Chem. Eng. Res. Des.,* 65: 148-156.

Hassanpour, M., Vaferi, B., Masoumi, ME. 2018. Estimation of pool boiling heat transfer coefficient of alumina water-based nanofluids by various artificial intelligence (AI) approach. *Appl. Therm. Eng.,* 128: 1208-1222.

Information Systems Laboratories Inc. 2001. RELAP5/Mod3.3 Code Manual, Vol:4 Models and Correlations, Idoha Falls, ID.

Jige, D., Sagawa, K., Inoue, N. 2017. Effect of tube diameter on boiling heat transfer and flow characteristics of refrigerants R32 in horizontal small-diameter tubes. *Int. J. Refrig.,* 76: 206-218.

Kandlikar, S. 1990. A general correlation for saturated two-phase flow boiling heat transfer inside horizontal and vertical tubes. *J. Heat Transf.,* 112: 219-228.

Kim, SH., Chu, IC., Choi, MH., Euh, DJ. 2018. Mechanism study of departure of nucleate boiling on forced convective channel flow boiling. *Int. J. Heat Mass Tran.,* 126: 1049-1058.

Lu, Q., Chen, D., Li, C., He, X. 2017. Experimental investigation on flow boiling heat transfer in conventional and mini vertical channels, Int. J. Heat Mass Tran., 107: 225-243.

Liu, Z., Winterton, RSH. 1991. A general correlation for saturated and subcooled flow boiling in tubes and annuli, based on a nucleate pool boiling equations. *Int. J. Heat Mass Tran.,* 34: 2759-2766.

McCabe, WL, Smith, CJ, Harriott, P. 1986. Unit Operations of Chemical Engineering, McGraw-Hill Book Co., New York.

Mohanta, L., Sohag, FA., Cheung, FB., Bajorek, SM., Kelly, JM., Tien, K., Hoxie, CL. 2017. Heat transfer correlation for film boiling in vertical upward flow. *Int. J. Heat Mass Tran.,* 107: 112-122.

Prakash, CGJ., Prasanth, R. 2018. Enhanced boiling heat transfer by nano structured surfaces and nanofluids, Renew. *Sust. Energy Rev.,* 82: 4028-4043.

Qu, W., Mudawar, I. 2003. Flow boiling heat transfer in two-phase micro-channel heat sinks-I. Experimental investigation and assessment of correlation methods. *Int. J. Heat Mass Tran.,* 46: 2755-2771.

Raj, S., Pathak, M., Khan, MK. 2017. An analytical model for predicting growth rate and departure diameter of a bubble in subcooled flow boiling. *Int. J. Heat Mass Tran.,* 109: 470-481.

Sarma, PK., Rao, VD., Subrahmanyam, T., Kakac, S., Liu, HT. 2000. A method to predict two-phase pressure drop using condensation heat transfer data. *Int. J. Therm. Sci.,* 39: A17:Y29 184-190.

Shah, MM. 1976. A new correlation for heat transfer during boiling flow through pipes. *ASHRAE Tran.,* 82: 66-86.

Shah, MM. 1982. Chart correlation for saturated boiling heat transfer: equations and further study. *ASHRAE Tran.,* 88: 185-196.

Yen, TH., Kasagi, N., Suzuki, Y. 2003. Forced convective boiling heat transfer in microtubes at low mass and heat fluxes. *Int. J. Multiphase. Flow,* 29: 1771-1792.

Yun, W., Kuanghan, D., Junmei, Wu., Guanghui, S., Suizheng, Q. 2018. The characteristics and correlation of nanofluid flow boiling critical heat flux. *Int. J. Heat Mass Tran.,* 122: 212-221.

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