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A general correlation for saturated and subcooled flow boiling in tubes and annuli, based on a nucleate pool boiling equation

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Abstract—Recent accurate correlations for predicting the heat transfer coefficient in saturated flow boiling all contain an empirical boiling number correction. The original idea behind the boiling number correction was to allow for the enhancement of the forced convective heat transfer mechanisms arising from the generation of vapour in the boundary layer next to the wall. However, the presence of the boiling number term appears to prevent application to subcooled boiling, throwing doubt on the physical basis of the correlation. This paper shows that the convective term in the correlation should have a Prandtl number dependence. In this way an accurate predictive method covering a very wide range of parameters is constructed with an explicit nucleate boiling term and without boiling number dependence.

INTRODUCTION

Over the last few years a large data bank for saturated and subcooled flow boiling in tubes and annuli has been built at Birmingham and various attempts have been made to fit correlations that cover all of the data. From fairly early on the aim has been to reduce the number of physical properties required in the correlations and to extend the range of applicability, to different types of fluid and to both saturated and subcooled boiling. In terms of generality the most successful correlation to date is the one previously reported in this journal [1]. That correlation gave the closest fit to the saturated boiling data of all the correlations tested and also was reasonably accurate for subcooled boiling.

Since then more data have been acquired, mainly for cryogenic fluids. The correlation in ref. [1] has both a nucleate boiling term and a boiling number correction to the forced convection term. The original idea behind the boiling number correction was to allow for the enhancement of the forced convective heat transfer mechanisms arising from the generation of vapour in the boundary layer next to the wall. However, it has become clear in the course of the work that correlations for saturated boiling without an explicit nucleate term, that rely only on the boiling number correction, do not work for subcooled boiling (e.g. ref. [1]). However, it is widely considered that the boiling contribution in subcooled boiling is independent of subcooling, so a saturated boiling correlation at zero quality should extend easily to subcooled boiling. For the pure boiling number correlations this does not happen, throwing some doubt on the correctness of the use of the boiling number (though for saturated boiling the boiling number based correlations are simple to use and give accurate results for water and refrigerants [2, 3]). Consequently one aim of the present investigation was to remove the boiling number term completely.

The new equation, fitted to the saturated, non-cryogenic data, is a distinct improvement. Tested against the subcooled boiling and cryogenic data it gives better results than any other correlation. The physical basis of the equations has been strengthened by the use of an explicit nucleate boiling term and no empirical boiling number correction. In addition a Prandtl number dependence is introduced for the forced convection term. With a correlation that clearly distinguishes between the effects of nucleate boiling and of forced convection, it becomes easier to understand the mode of action of devices for enhancing the heat transfer coefficient.

The first general correlation for saturated flow boiling with an explicit nucleate boiling term perhaps was that of Chen [4]. He assumed that in flow boiling heat transfer the convective and nucleate boiling heat transfer mechanisms both play a role and they are additive

$$h_{\mathrm{TP}} = fh_{\mathrm{l}} + sh_{\mathrm{pool}}. \tag{1}$$

The first term on the right-hand side, fh_{l}, is the forced convective contribution where h_{l} is the liquid-only heat transfer coefficient calculated from the Dittus–Boelter equation with the liquid phase flowing in the same channel. f is the forced convective heat transfer enhancement factor. The value of f is always greater than unity, because in two-phase flow, the fluid velocities are much higher than those in single-phase liquid-only flow. Chen assumed that f is strictly a

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NOMENCLATURE

a	constant, equation (9) [dimensionless]
A_{bp}, A_{qp}	dimensionless parameters defined by equation (28)
A_p	parameter defined by equation (18)
b	dimensionless constant in equation (10)
C	dimensionless parameter defined by equation (21)
d	diameter [m]
d_H	heated equivalent diameter [m]
E	lumped two-phase heat transfer enhancement factor, equation (1) [dimensionless]
e_f, e_s	Froude number correction factors [dimensionless]
f	forced convective heat transfer enhancement factor used by Chen [dimensionless]
F	forced convective heat transfer enhancement factor used in this paper [dimensionless]
Fr	Froude number, $G^2/(\rho_L^2 g d)$ [dimensionless]
g	gravitational acceleration [m s^{-2}]
G	mass flux [kg m^{-2} s^{-1}]
h	heat transfer coefficient [W m^{-2} K^{-1}]
K_l	liquid thermal conductivity [W m^{-1} K^{-1}]
M	molecular weight
p_r	reduced pressure (absolute pressure/critical pressure) [dimensionless]
Pr_l	liquid Prandtl number [dimensionless]
q	heat flux [W m^{-2}]
Re_l	liquid Reynolds number, Gd/μ_l [dimensionless]
s	suppression factor used by Chen [dimensionless]
S	suppression factor used in this paper [dimensionless]
T	temperature [K]
x	quality.

Greek symbols

μ	dynamic viscosity [N s m^{-2}]
ρ	density [kg m^{-3}].

Subscripts

b	bulk
cal	calculated
exp	experimental
l	liquid; liquid phase
L	all the mass flow rate taken as liquid
pool	pool boiling
s	saturation
TP	two phase
v	vapour
w	wall.

flow parameter and is a function of the Martinelli parameter. The second term, sh_{pool}, is the nucleate boiling contribution. h_{pool} is the pool boiling transfer coefficient which is calculated from the Forster and Zuber pool boiling equation. The suppression factor s (<1.0) reflects the fact that lower effective superheat is available in flow boiling than that in pool boiling, due to the thinner boundary layer. s was assumed to be a function of the two-phase Reynolds number Re_{TP}. Originally both f and s were presented as graphs, but later equations were developed to fit the graphs [5].

The Chen correlation was developed on the basis of 665 data points from six different data sources. The overall deviation for the data was 12%. But more recently, many comprehensive comparisons showed that this correlation gives a rather poor fit to the data, at least for refrigerants. The correlation is complicated, and requires many physical properties.

DEVELOPMENT OF THE CORRELATION

As discussed in the introduction, the physical basis of the Chen correlation is clearer than that of other correlations, though it does not fit the experimental data very well compared with the boiling number based correlations. Therefore, Chen's basic postulate that both convective and nucleate boiling heat transfer mechanisms play a role in flow boiling was used in this paper. But whether these two mechanisms are simply additive is questionable. The detailed comparison of the correlation shows in ref. [3] that the heat transfer coefficient is considerably overpredicted in the high quality region and underpredicted in the low quality region. This indicates that the combination of the two heat transfer mechanisms by a simple addition method is not very suitable, since in the high quality region, even with a relatively small mass flow rate, the actual velocities of the phases must be very high and a great convective heat transfer intensity must be expected, hence the nucleate boiling mechanism must have been more greatly suppressed than that predicted by the Chen correlation.

The method of combining the two contributions suggested by Kutateladze [6] is used in this paper

$$h_{TP}^2 = (Fh_L)^2 + (Sh_{pool})^2. \qquad (2)$$

This method has the advantage over the simple addition method that nucleate boiling is further suppressed once Fh_L is appreciably larger than Sh_{pool}.

In the above equation Fh_L is the contribution of the forced convection mechanism; F the forced convection heat transfer enhancement factor, and h_L is calculated from the Dittus–Boelter equation with the entire mass flow rate flowing as liquid in the same channel

$$h_L = 0.023(k_l/d)Re_L^{0.8}\ Pr_l^{0.4}. \tag{3}$$

Sh_{pool} is the contribution of the nucleate boiling mechanism; h_{pool} is calculated from Cooper's pool boiling correlation [7]

$$h_{pool} = 55p_r^{0.12}q^{2/3}(-\log_{10} p_r)^{-0.55}M^{-0.5} \tag{4}$$

in which the wall roughness has been arbitrarily set to 1×10^{-6} m; S is the suppression factor.

Chen, by applying the Reynolds analogy to both the single phase liquid flow and the two-phase flow, was able to show that the effect of the two-phase flow is to increase the heat transfer compared to equation (3) by a factor

$$F = \left[\frac{(dp/dz)_{TP}}{(dp/dz)_L}\right]^{0.444}. \tag{5}$$

Many accurate equations have been recommended for calculating the two-phase multiplier [8, 9], but these more accurate equations are usually very complex and involve the Martinelli parameter which introduces the vapour viscosity. Therefore, in order to obtain a simple presentation of the present correlation, the homogeneous model was used to estimate the two-phase multiplier, which gives

$$\frac{(dp/dz)_{TP}}{(dp/dz)_L} = 1 + x\left[\frac{\rho_l}{\rho_v} - 1\right]. \tag{6}$$

The above expressions contain no Prandtl number. However, more recently Bennett and Chen detected a Prandtl number effect on the forced convection enhancement factor [10]. They corrected this effect by multiplying F directly with a Prandtl number correction factor

$$F = Pr_L^{0.296}\left[\frac{(dp/dz)_{TP}}{(dp/dz)_L}\right]^{0.444} \tag{7}$$

or

$$F = \left[\frac{Pr_L + 1}{2}\right]^{0.444}\left[\frac{(dp/dz)_{TP}}{(dp/dz)_L}\right]^{0.444}. \tag{8}$$

This was at least partly verified by the recent work of Ross *et al.* for pure fluid data [11].

The reason for a Prandtl number dependence, though not necessarily in the precise form of equation (7) or (8), may be understood as follows. Considering first the simpler case of turbulent single phase flow, a simple model of the heat transfer [12], in which initially it is assumed that the velocity and temperature profiles in the flow are similar (i.e. $Pr = 1$), gives a Nusselt number independent of Prandtl number. With $Pr > 1$ the diffusivity of momentum near the wall is greater than that of heat and the velocity profile becomes flatter than the temperature one. An extension of the model predicts that the steeper temperature gradient (relative to the velocity gradient) will give an increased Nusselt number. So the $Pr^{0.4}$ term in equation (3) is a result of the steeper temperature gradient near the wall.

In a two-phase convective flow the temperature and velocity profiles are very different to their single phase counterparts. For saturated boiling the bulk of the flow is at, or very close to, saturation temperature. Temperature differences are confined to a 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 has become even more important and it is reasonable to expect an enhancement of the Prandtl number effect. So we write, following the form of equation (6)

$$F = (1 + ax\,Pr_l^{m_0}(\rho_l/\rho_v - 1))_l^{m_1} \tag{9}$$

where a, m_0 and m_1 are constants to be determined from the experimental data.

Note that this mathematical form gives the correct trends for F as x tends to zero or ρ_l tends to ρ_v (unlike equations (7) and (8)).

The suppression factor S in equation (2) is always less than unity, which takes account of the fact that the boundary layer of superheated liquid in which the vapour bubbles grow is thinner in forced flow boiling than that in pool boiling. The extent of this suppression is controlled by the intensity of the forced convection heat transfer mechanism. The exact behaviour of the suppression factor is difficult to predict, but it should approach unity at zero flow rate (pure pool boiling conditions) and zero at infinite flow rate (nucleate boiling fully suppressed conditions). Therefore, it is postulated that in all ranges of flow S can be represented as a function of the convective heat transfer enhancement factor F and the liquid Reynolds number Re_L. The function for S was chosen to be in the form of

$$S = \frac{1}{1 + bF^{n_0}\,Re_L^{n_1}} \tag{10}$$

which would automatically satisfy the required behaviour at both low and high flow rate. b, n_0 and n_1 are constants to be determined from the experimental data, as will now be explained.

As has been observed in ref. [6], the dominant term in equation (2) is the forced convection term Fh_L, under most conditions. So even an approximate estimate of the suppression factor S might give acceptable results in calculating F from the experimental data

$$F = \sqrt{\left(\left[\frac{h_{exp}}{h_L}\right]^2 - \left[\frac{Sh_{pool}}{h_L}\right]^2\right)}. \tag{11}$$

Accordingly, at the very beginning a constant value of S was used to calculate F from equation (11) where h_{exp} is the experimental heat transfer coefficient; then using these values of F, the first approximate values of the constants a, m_0 and m_1 were obtained by the least square method. These constants were used to estimate S from

$$S = \sqrt{\left(\left[\frac{h_{\text{exp}}}{h_{\text{pool}}}\right]^2 - \left[\frac{Fh_L}{h_{\text{pool}}}\right]^2\right)}. \tag{12}$$

This time F was calculated from equation (9). These values of S were then used to find the constants b, n_0 and n_1, in equation (10). After the first approximate values of b, n_0 and n_1 were obtained, they were used to calculate values of F and hence the second approximate values of the constants a, m_0 and m_1. This procedure was repeated until no significant improvement could be observed in the fit to the experimental data.

As the present correlation stands, it has considerable empirical input. Therefore, the data used to determine these constants should be as extensive as possible so that the correlation obtained can be used over a wide range of the parameters involved.

The data used in developing the present correlation are the same as those described in ref. [3]. All the saturated boiling data in the data bank were used. The data bank contains 4202 data points for saturated boiling and 991 data points for subcooled boiling. These data were collected from 30 different literature sources involving nine different fluids. The detailed information on the data bank and the calculations of the physical properties of the fluids were described in refs. [1, 3]. The ranges of the important parameters are as follows:

mass flux	12.4–8179.3 kg m^{-2} s^{-1}
heat flux	348.9–2.62 × 10^6 W m^{-2}
quality	0.0–94.8%
superheat	0.2–62.3 K
subcooling	0.1–173.7 K
diameter	2.95–32.0 mm
Froude number	2.66 × 10^{-4}–2240
reduced pressure	0.0023–0.895
Reynolds number Re_L	568.9–8.75 × 10^5
liquid Prandtl number	0.83–9.1.

THE FINAL EQUATIONS

Using all of the saturated boiling data available at that time, the expressions for F and S are

$$F = \left[1 + x\,Pr_l\left(\frac{\rho_l}{\rho_v} - 1\right)\right]^{0.35} \tag{13}$$

$$S = (1 + 0.055F^{0.1}\,Re_L^{0.16})^{-1}. \tag{14}$$

Therefore, the heat transfer coefficient in saturated flow boiling may be calculated using these two equations together with equations (2)–(4). All properties are calculated at the saturation temperature for saturated flow boiling.

If the tube is horizontal and the Froude number is less than 0.05, then Fh_L and Sh_{pool} should be multiplied by

$$e_F = Fr^{(0.1-2Fr)} \tag{15}$$

and

$$e_s = \sqrt{Fr} \tag{16}$$

respectively. These Froude number correction factors were first used in ref. [1].

If the heat flux is known then the present correlation can be used directly to calculate the heat transfer coefficient and hence the wall temperature. If the wall temperature rather than heat flux is known then multiplying equation (2) by $\Delta T_s = T_w - T_s$ squared and substituting equation (4) into it, gives

$$q^2 = (Fh_L\Delta T_S)^2 + (A_p S\Delta T_S)^2 q^{4/3} \tag{17}$$

where

$$A_p = 55p_r^{0.12}(-\log_{10} p_r)^{-0.55}M^{-0.5} \tag{18}$$

defining

$$q_L = Fh_L\Delta T_S \tag{19}$$

$$q_*^3 = \left[\frac{q}{Fh_L\Delta T_S}\right]^2 = \left[\frac{q}{q_L}\right]^2 \tag{20}$$

and

$$C = (A_p S/Fh_L)^2 q_L^{4/3} \tag{21}$$

then equation (17) can be rearranged as

$$q_*^3 - Cq_*^2 - 1 = 0 \tag{22}$$

which is a standard cubic equation which can be solved for q^* directly. The equation has a single (real) root which is always greater than unity. The value of h_{TP} can be calculated from

$$h_{TP} = Fh_L q_*^{3/2}. \tag{23}$$

For flow boiling in annuli, the heated equivalent diameter is used

$$d_H \doteq \frac{4 \times \text{flow area}}{\text{heated perimeter}}. \tag{24}$$

Subcooled boiling

In subcooled boiling, the driving temperature differences for nucleate boiling and for forced convection are different, therefore equation (2) is replaced by

$$q = \sqrt{((Fh_L\Delta T_b)^2 + (Sh_{\text{pool}}\Delta T_S)^2)} \tag{25}$$

where $\Delta T_b = T_w - T_b$ and $\Delta T_S = T_w - T_S$. All the other equations remain the same as for saturated boiling but the quality x is set to zero and hence $F = 1.0$ (equation (14) is still used for S, i.e. $S < 1$).

If the temperature difference is known then h_{TP} can be computed from equations (18) to (23) with q_L defined by

$$q_L = Fh_L\Delta T_b \tag{26}$$

and the term A_pS/Fh_L, which appears in equation (21), replaced by $A_pS\Delta T_S/Fh_L\Delta T_B$.

Except those related to the liquid Prandtl number and the liquid Reynolds number which are calculated at the bulk temperature T_b, all the other thermophysical properties are determined at the saturation temperature T_S.

If the temperature difference is unknown, then rearranging equation (25) gives

$$\Delta T_b = \frac{T_S - T_b}{1 + A_{bp}^2}[1 + \sqrt{(1 + (1 + A_{bp}^2)(A_{qp}^2 - 1))}] \quad (27)$$

where

$$A_{bp} = \frac{Fh_L}{Sh_{pool}}, \quad A_{qp} = \frac{q}{Sh_{pool}(T_S - T_b)} \quad (28)$$

and the two-phase heat transfer coefficient h_{TP} is

$$h_{TP} = \frac{q}{\Delta T_b}. \quad (29)$$

COMPARISON AGAINST THE DATA

In addition to the correlation proposed in this paper, several other more recent and successful general correlations were tested against the data. These include the Shah [2], the Gungor–Winterton (1987) [3], the Chen [4] and the Gungor–Winterton (1986) [1] correlations. All the comparisons made in this paper were based on the assumption that the experimental heat flux is correct.

Comparisons for saturated boiling data, non-cryogenic fluids

This part of the data is exactly the same as used in ref. [3] and in developing the present correlation. There are 19 data points with a quality bigger than 95% and these points are predicted with a very large error by all the correlations. This may be because dryout might have occurred at such a high quality, so these data points were excluded in the comparisons. The results of the comparisons are shown in Table 1.

Figure 1 shows the comparisons of the proposed correlation with the data. For the purpose of drawing this figure, only every twentieth point for water, all the data points for R12, every tenth point for the other refrigerants and ethylene glycol and every fifth point for ethanol were used.

The Chen correlation gives the poorest fit to the data with a mean deviation of 37.2%. It works even worse for refrigerants (53.1% for 1682 data points) and organics (47.5% for 289 data points). This is partly because some of the data are for horizontal tubes, and the Chen correlation was developed originally only using vertical tube data.

Both the Gungor–Winterton correlation (1986) and that of Shah give a similar result (23% for the Shah and 24% for the Gungor–Winterton correlation

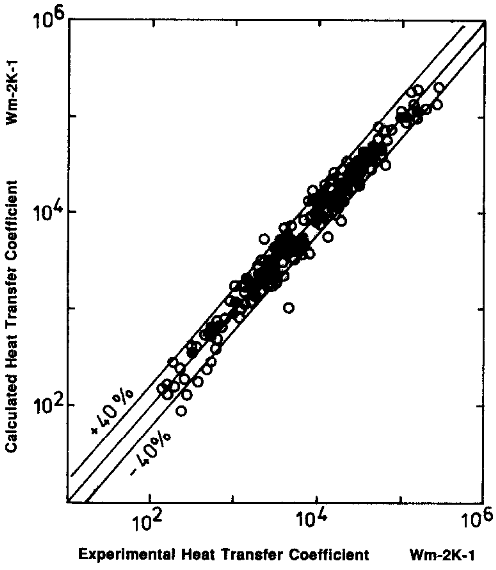

FIG. 1. Comparison between the calculated heat transfer coefficients using the present equations and the experimental values in the data bank.

Table 1. Comparison of the correlations with the non-cryogenic fluids (saturated)†

Correlation	Gungor–Winterton (1987)		Gungor–Winterton (1986)		Shah		Chen		Present		Number of data points
Deviation Fluid	Mean	Average	Mean	Average	Mean	Average	Mean	Average	Mean	Average	
Water	18.8	0.5	24.0	5.3	21.4	0.2	23.8	−14.0	18.1	0.9	2212
R12	29.3	−18.9	31.1	−16.1	34.1	−24.1	36.5	−15.9	30.0	−13.9	526
R22	15.0	−6.9	28.9	12.9	14.4	−5.4	27.2	19.6	18.3	4.9	32
R11	15.6	−7.8	16.8	−4.8	14.4	5.8	81.7	72.3	19.9	−3.1	751
R113	18.6	−14.1	19.6	−16.0	23.2	−21.3	20.8	3.1	20.3	−15.2	250
R114	27.4	2.5	20.0	4.5	25.8	−9.5	21.7	−18.2	23.8	12.9	123
Ethylene glycol	23.4	2.0	31.1	6.2	21.4	−7.4	39.2	−37.5	21.9	12.1	101
n-Butanol	37.8	−37.8	42.5	−42.5	43.5	−43.5	55.6	−55.6	21.9	−21.5	127
Ethanol	50.0	−50.0	42.4	−40.8	53.3	−53.3	44.4	−44.4	23.1	−22.8	61
Total	20.9	−6.2	24.3	−2.1	23.1	−5.8	37.2	0.2	20.5	−2.3	4183

Mean deviation = $1/N\,\Sigma_{i=1}^{N}\,|[h_{cal} - h_{exp}]/h_{exp}| \times 100\%$.
Average deviation = $1/N\,\Sigma_{i=1}^{N}\,[h_{cal} - h_{exp}]/h_{exp} \times 100\%$.
† All comparisons are based on the assumption that the experimental heat flux is correct.

(1986)). The Gungor–Winterton correlation (1987) and the present correlation give the best fit to the data bank (20.9% for the Gungor–Winterton correlation (1987) and 20.5% for the present correlation). But except for the present correlation, all the others work rather unevenly for the different fluids. For example, the best of them, the Gungor–Winterton correlation (1987) gives a deviation of 19% for water, 21% for refrigerants and 36% for organics. The present correlation works much more evenly with all the fluids involved than the other correlations. This can be seen clearly from Table 1.

More detailed comparisons were also made by dividing the data into small ranges according to different dimensionless numbers (i.e. Re_L, Fr, Pr_l, x). Unlike the other correlations, there does not exist any range of dimensionless parameters over which the correlation proposed in this paper works particularly well or badly. The present correlation works more evenly over all the dimensionless parameters than the other correlations do. Over the different ranges of x and Fr, the present correlation gives similar results to the Gungor–Winterton (1987) correlation but much better than any other correlation. For the large Reynolds number region ($Re_L > 5.0\times10^5$), all the correlations apart from the present one give a very bad fit to the data (the mean deviation being greater than 40%); for small Prandtl numbers ($Pr_l < 1.0$) all the correlations give an acceptable result (around 23%) but the present correlation works a little bit better (18%); for large Prandtl numbers ($Pr_l > 6.0$) only the present correlation gives an acceptable result (22%), all the others are poor (greater than 42% error).

Cryogenic fluid data

The present correlation was developed without using the data for cryogenic fluids. There are 1366 data points in the data bank for argon and nitrogen. They were collected from three different literature sources [13–15]. In preparing this part of the data, some of the data obtained from the literature had a very small heat flux and hence a very small temperature difference (for some of these the temperature difference is less than 0.3 K). We thought these data might involve large errors. Therefore, these very small heat-flux data were not put into the data bank.

The thermophysical properties of argon and nitrogen were taken from a variety of sources [16–20]. Since for these fluids the property data were less established than for ordinary fluids, whenever possible, the most recent values were used.

The results of this comparison are shown in Table 2. Although the present correlation does not give a particularly good fit to the data, it does give the best result among the correlations compared.

Besides the original Shah correlation, his slightly-changed correlation for cryogenic fluids [21] was also programmed. But it gives a very similar result to that of his original correlation. The results of the Shah correlation in Table 2 are for his original correlation.

Comparisons for subcooled boiling

There are 991 subcooled boiling data points for five different fluids from nine different literature sources. The details of the data were given in ref. [3]. For the comparison with the subcooled data, the Moles–Shaw correlation [22] which was specially developed for subcooled boiling (and was proved to be the best of those specially developed for subcooled boiling [1]) was programmed in addition. The original Shah correlation is not applicable for subcooled boiling, hence his subcooled boiling correlation [23] was computed. The Gungor–Winterton (1987) correlation is not applicable to subcooled boiling and is not included in this comparison.

The results of the comparison are shown in Table 3. Note this comparison is again based on the assumption that the experimental heat flux is correct. Except for the correlation proposed in this paper and that of Moles and Shaw, all the other correlations need a degree of iteration. For the Chen correlation some of the data did not converge; oscillating values appeared. For these data points the maximum and minimum values were averaged; the deviations for these unconverged data were similar to those of the converged data. The Moles–Shaw correlation was modified slightly to improve the prediction. The equation for calculating h_l which was originally the ESDU-recommended equation [24] was replaced by the Dittus–Boelter equation, and the temperature used to evaluate the liquid Prandtl number changed from the film temperature to the bulk temperature. The original Moles–Shaw correlation gives slightly worse results than those in Table 3.

Table 2. Comparison of the correlations with cryogenic fluid data†

Fluid	Argon		Nitrogen		Total	
Deviation	Mean	Average	Mean	Average	Mean	Average
Correlation						
Gungor–Winterton (1987)	31.4	10.5	34.4	−21.1	33.5	−10.9
Gungor–Winterton (1986)	49.0	35.3	35.7	−8.2	40.0	5.8
Shah	28.5	1.6	41.0	−28.6	36.9	−18.8
Chen	76.2	72.5	39.4	3.2	51.2	25.5
Present	25.3	9.4	31.7	−4.1	29.6	0.3

† A total of 1349 data points were used for the comparison. Seventeen points with quality greater than 0.95 were excluded.

Table 3. Comparison of the correlation with the subcooled boiling data

Correlation	Moles–Shaw		Shah†		Gungor–Winterton (1986)		Chen		Present		Number of data points
Deviation Fluid	Mean	Average	Mean	Average	Mean	Average	Mean	Average	Mean	Average	
Water	17.4	−9.6	19.3	15.7	21.4	6.4	14.2	−11.8	12.9	6.4	546
R12	27.4	15.1	29.5	22.1	19.6	−5.9	14.4	−5.8	14.4	−1.2	6
R11	38.5	21.6	15.5	−0.1	26.1	−24.8	23.4	−22.9	16.7	−15.0	68
R113	27.1	−27.1	6.6	0.5	40.0	−39.1	44.7	−44.7	7.1	−7.0	44
Ethanol	16.1	−4.8	21.4	−20.3	20.9	−17.5	16.1	−14.4	11.8	−10.8	327
Total	18.9	−6.5	19.1	2.1	22.4	−19.0	16.9	−14.8	12.6	−1.4	991

† The original Shah correlation is not applicable for subcooled boiling, the results shown are those of his modified correlation [23].

Though all the correlations compared seem to give a reasonable fit to the data, the present correlation gives the best results. Since the present correlation was developed without using the subcooled data, this proves it has a wide applicable range and a great reliability.

CONCLUSIONS

A flow boiling correlation for vertical and horizontal flow in tubes and annuli has been successfully developed. It is based on an explicit nucleate boiling term rather than an empirical boiling number dependence. Compared with the saturated boiling data used in developing the equations the new correlation is more reliable than any of the other correlations tested.

Tested against data for saturated cryogenic fluids and against data for subcooled boiling, none of which was used in developing the equations, the new correlation is again more accurate than the others.

Since the correlation accurately predicts plain surface behaviour, and distinguishes clearly between nucleate boiling and forced convection effects, it can be used as a starting point in understanding the performance of surfaces designed to enhance heat transfer.

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UNE FORMULE GENERALE POUR L'EBULLITION SATUREE OU SOUSREFROIDIE D'UN ECOULEMENT DANS DES TUBES ET DES ESPACES ANNULAIRES, BASEE SUR UNE EQUATION D'EBULLITION NUCLEEE EN RESERVOIR

Résumé—Des formules précises récentes pour prédire le coefficient de transfert thermique dans l'ébullition saturée d'un écoulement contiennent toutes une correction empirique de nombre d'ébullition. L'idée derrière cette correction de nombre d'ébullition est de tenir compte de l'accroissement des mécanismes de convection thermique forcée provenant de la création de vapeur dans la couche limite près de la paroi. Néanmoins, la présence du terme de nombre d'ébullition paraît interdire l'application à l'ébullition sous-refroidie, ce qui jette un doute sur la base physique de la formule. On montre que le terme convectif dans la formule doit avoir une dépendance vis-à-vis du nombre de Prandtl. Dans cette voie, une méthode prédictive précise est construite pour couvrir un très large domaine de paramètres avec un terme explicite d'ébullition nucléée et sans dépendance vis-à-vis du nombre d'ébullition.

EINE ALLGEMEINGÜLTIGE KORRELATION FÜR GESÄTTIGTES UND UNTERKÜHLTES STRÖMUNGSSIEDEN IN ROHREN UND RINGSPALTEN, AUFBAUEND AUF EINER BEZIEHUNG FÜR DAS BEHÄLTERSIEDEN

Zusammenfassung—Die üblichen genauen Korrelationen für die Berechnung des Wärmeübergangskoeffizienten für das gesättigte Strömungssieden enthalten stets eine empirische Korrektur für die Siedekennzahl. Der Korrektur liegt die Absicht zugrunde, eine Verbesserung des konvektiven Wärmeübergangs infolge der Dampferzeugung innerhalb der wandanliegenden Grenzschicht zu berücksichtigen. Allerdings scheint das Vorhandenseins des Korrekturterms die Anwendung solcher Korrelationen auf das unterkühlte Sieden zu verhindern, was Zweifel an der physikalisch korrekten Basis der Korrelation aufkommen läßt. In der vorliegenden Arbeit wird gezeigt, daß der konvektive Therm in der Korrelation von der Prandtl-Zahl abhängig sein sollte. Darauf aufbauend wird ein genaues Berechnungsverfahren entwickelt, das einen großen Parameterbereich abdeckt und einen expliziten Term für das Blasensieden ohne Abhängigkeit von der Siedezahl enthält.

ОБОБЩЕННОЕ СООТНОШЕНИЕ ДЛЯ КИПЕНИЯ ПРИ ТЕЧЕНИИ НАСЫЩЕННОЙ НЕДОГРЕТОЙ ЖИДКОСТИ В ТРУБАХ И КОЛЬЦЕВЫХ КАНАЛАХ, ОСНОВАННОЕ НА УРАВНЕНИИ ДЛЯ ПУЗЫРЬКОВОГО КИПЕНИЯ В ВОЛЬШОМ ОБЪЕМЕ

Аннотация—Недавно полученные точные соотношения для расчета коэффициента теплопереноса в условиях кипения при течении насыщенной жидкости содержат эмпирическую поправку. Идея ввода этой поправки заключалась в учете усиления вынужденноконвективного теплопереноса, вызванного парообразованием в прилегающем к стенке пограничном слое. Однако наличие этого слагаемого препятствует применению упомянутых соотношений к кипению при недогреве, т.к. в этом случае искажается их физический смысл. В настоящем исследовании показано, что конвективный член, входящий в такое соотношение должен зависеть от числа Прандтля. Таким образом, разработан метод точного определения коэффициента теплопереноса в широком диапазоне параметров, который содержит слагаемое, описывающее пузырьковое кипение.