A correlation for heat transfer during subcooled boiling on a single tube with forced crossflow

M. M. Shah*

Many heat exchangers, such as shell and tube heat exchangers and kettle reboilers, involve boiling with flow across tubes. For rational design of such heat exchangers, it is desirable to be able to predict heat transfer on a single tube. The dimensionless correlation presented here agrees well with available data for subcooled boiling during crossflow on a single tube. The correlating parameters are the same as those used for boiling inside tubes[16]. The data correlated include three fluids, four tube materials, tube diameters from 1.2 to 25.4 mm, subcooling from 0 to 80 °C, and velocities from 0.02 to 7.8 m/s. The mean deviation of 334 data points is 9.5%. Hence the new correlation appears to be usable over a wide range of parameters.

Key words: *heat transfer, boiling, two-phase flow*

For rational design of such heat exchangers as kettle reboilers and shell and tube evaporators which involve boiling with crossflow over tubes, it is desirable to be able to predict heat transfer to a single tube. Generally, the lower tubes of the bundles experience subcooled boiling while boiling at positive qualities occurs at the upper tubes. Hence predictive techniques for boiling under both conditions are needed. This paper is concerned only with prediction of heat transfer during subcooled boiling (zero to negative vapour quality) of single-component fluids with forced convection across single tubes.

Several studies on subcooled boiling with forced convection on single tubes have been reported[1–13,28] and attempts have been made to correlate the experimental data by the superpositions techniques of Rohsenow[14] and Kutateladze[15]. Yilmaz and Westwater[1,2] and Leppert *et al*[4] found the Rohsenow technique satisfactory while Fand *et al*[8] and Lemmert and Chawla[13] could not correlate their data using this method. Fand *et al* correlated their data by a modification of the Kutateladze method but Lemmert and Chawla found that this method was also unsatisfactory. Hence neither method can be considered satisfactory, even if the difficulties in accurately predicting pool boiling heat transfer are overlooked. The method proposed by Lemmert and Chawla has only been compared with their own data and, furthermore, it involves factors which are difficult to calculate.

Clearly, a reliable predictive technique which may be applied over a wide range of parameters is needed. A simple dimensionless correlation is presented in this paper which shows satisfactory agreement with virtually all available data. The data analyzed include three liquids (water, R-11, R-113), four tube materials, tube diameters from 1.2 to 25.4 mm, and heat flux from 1 to 1000 KW/m^2. The heat transfer coefficients are predicted with a mean deviation of only 9.5%, with over 98% of the data predicted within ±30% of the measured values.

The purpose of this paper is to present the new correlation and demonstrate its agreement with available experimental evidence. In order that this correlation may be viewed in the proper perspective, other predictive techniques are also briefly discussed.

The new correlation

The correlation uses three correlating parameters: $\Delta T_{SC}/\Delta T_{SAT}$, boiling number Bo, and Ψ where:

$$Bo = \frac{q}{G i_{fg}} \tag{1}$$

$$\Psi = \frac{q}{\Delta T_{SAT} h_L} \tag{2}$$

Ψ_0, the value of Ψ at zero subcooling, is given by:

$$Bo > 2.5 \times 10^{-4} \qquad \Psi_0 = 443\, Bo^{0.65} \tag{3}$$

$$Bo \leqslant 2.5 \times 10^{-4} \qquad \Psi_0 = 19\, Bo^{0.27} \tag{4}$$

If Eq (4) predicts $\Psi_0 < 1$, use $\Psi = 1$.

There are two regimes of subcooling, high and low subcooling. In the low subcooling regime:

$$\Psi = \Psi_0 \tag{5}$$

In the high subcooling regime:

$$\Psi = \Psi_0 + \Delta T_{SC}/\Delta T_{SAT} \tag{6}$$

---

* Consulting Engineer, 15 Rush Street, Port Jefferson Station, New York 11776, USA

Received 21 March 1983 and accepted for publication on 25 October 1983

The demarkation between the two regimes of subcooling is shown in Fig 1. It is seen that if $\Delta T_{SC}/\Delta T_{SAT} > 4$, the regime is that of high subcooling. The regime is also that of high subcooling when $Bo < 5.4 \times 10^{-4}$ and:

$$\Delta T_{SC}/\Delta T_{SAT} > 7.63 \times 10^{4}\, Bo^{1.31} \qquad (7)$$

For the calculation of single-phase heat transfer coefficient h_L, best results have been obtained with:

$$\frac{h_L D}{k_b} = 0.21\left(\frac{GD}{\mu_b}\right)^{0.62} Pr_b^{0.4} \qquad (8)$$

The mass velocity G is based on the narrowest flow area, ie the clearance between the tube and the walls of the enclosing test channel. It should be noted that the velocity used in defining Bo should be the same as used in Eq (8).

Development of the correlation

An earlier general correlation for subcooled boiling in tubes and annuli showed excellent agreement with a wide range of test data[16,17]. Since it was expected that the correlation for crossflow boiling would be similar, the data were analysed using the same parameters.

The first question that had to be addressed was the choice of a single-phase heat transfer correlation to calculate h_L. While several correlations have been presented, none of them has been thoroughly verified. Among the better known correlations are those of Michejew[18], Fand and Kheswani[19], and Perkins and Leppert[20]. These were applied to a few representative data points. It was found that, usually, the boiling data from a particular researcher could be best represented by using the single-phase heat transfer correlation he recommended. Considering data from all sources, it was found that best agreement is obtained by using Eq (8) which is a slightly modified form of the Michejew Equation. Use of Eq (8), however, resulted in gross overprediction of the data of Yilmaz[1].

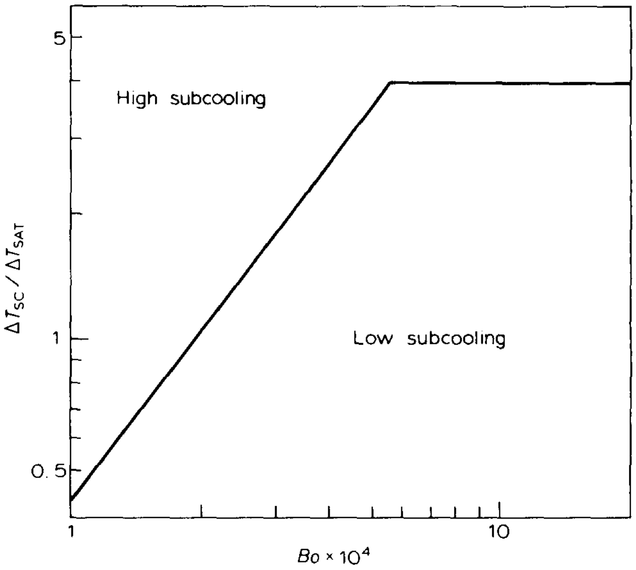

Fig 1 Demarkation between high and low subcooling regimes

These show adequate correlation if the equation, given by Fand and Keshwani[19], is used:

$$Nu_f = (0.255 + 0.699\, Re_f^{0.5})\, Pr_f^{0.29} \qquad (9)$$

The velocity used in Eq (9) is according to definition given by Vliet and Leppert[21]. Yilmaz[1] had indeed recommended this equation, even though he himself did not do any single-phase measurements. It was decided to analyse the Yilmaz data using Eq (9) while all other data were analysed using Eq (8).

The data for insignificant subcooling ($\Delta T_{SC} <$ 2 °C) were first analysed as shown in Fig 2. Preliminary correlations were thus obtained for the low subcooling regime. These were later modified slightly to obtain Eqs (3) and (4) which give the best fit when data at all values of subcooling are considered.

Notation

A	Total surface area of tube
A_{bn}	Part of the tube area on which bubble nucleation occurs
Bo	Boiling number (Eq (1))
C_p	Specific heat of liquid at constant pressure
D	Outside diameter of tube
G	Mass velocity
h_L	Single-phase heat transfer coefficient
h_{pb}	Heat transfer coefficient with pool boiling
h_{TP}	Heat transfer coefficient with forced convection boiling ($= q/(T_w - T_b)$)
i_{fg}	Latent heat of vaporization
k	Thermal conductivity of liquid
Nu	Nusselt number
p	Absolute pressure
p_r	Reduced pressure $= p/p_{critical}$
Pr	Prandtl number of liquid
q	Total heat flux
q_{pb}	Heat flux under pool boiling conditions
q_{SPC}	Heat flux due to single-phase convection
Re	Reynolds number ($= GD/\mu$)
T_b	Bulk temperature of liquid
T_f	Film temperature ($= (T_b + T_w)/2$)
T_{SAT}	Saturation temperature of liquid
T_w	Wall temperature
ΔT_b	$= (T_w - T_b)$
ΔT_{SAT}	$= (T_w - T_{SAT})$
ΔT_{SC}	$(T_{SAT} - T_b)$
Ψ	Parameter defined by Eq (2)
Ψ_0	Value of Ψ when $\Delta T_{SC} = 0$
μ	Dynamic viscosity of liquid

Subscripts

b	with properties taken at bulk liquid temperature
f	with properties taken at film temperature

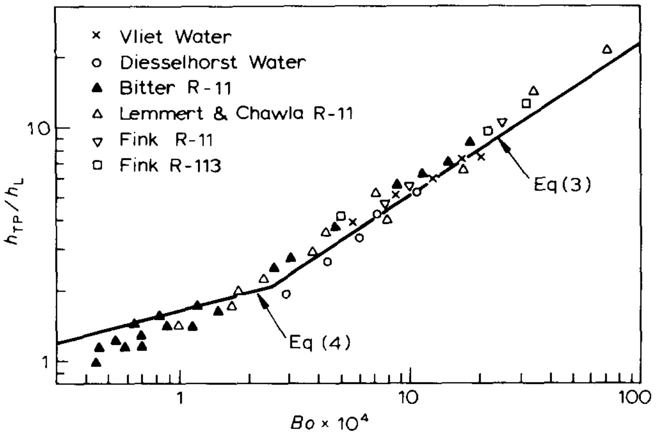

Fig 2 Analysis of data for boiling with negligible subcooling

In the high subcooling regime, it is postulated that the total heat flux is the sum of heat flux removed by nucleate boiling and the heat flux removed by single phase convection:

$$q = q_{nb} + q_{spc} \tag{10}$$

From the definition of Ψ_0 it is noted that at zero subcooling:

$$q = h_L(T_w - T_{SAT}) + h_L(\Psi_0 - 1)(T_w - T_{SAT}) \tag{11}$$

Comparing Eqs (10) and (11) it is noted that:

$$q_{nb} = h_L(\Psi_0 - 1)(T_w - T_{SAT}) \tag{12}$$

Hence for high subcooling regime:

$$q = h_L(\Psi_0 - 1)(T_w - T_{SAT}) + h_L(T_w - T_b) \tag{13}$$

By rearranging Eq (13), Eq (6) is obtained. It may also be put in the alternative form:

$$\Delta T_{SAT} = \frac{1}{\Psi_0}\left(\frac{q}{h_L} - \Delta T_{SC}\right) \tag{14}$$

Thus the equations for the two subcooling regimes were known. The demarkation between the two regimes was determined by trial and error, and is shown in Fig 1.

Discussion of the correlation

In the high subcooling regime, this correlation assumes that the total heat flux is the sum of heat flux removed by nucleate boiling and that removed by single-phase convection. It would therefore appear to be the same as the Rohsenow superposition method[14]. The difference is in the method of calculating the nucleate boiling heat transfer. Here it is calculated from flow boiling data for low subcooling while the Rohsenow method uses pool boiling correlations for this purpose. Another difference is that the Rohsenow superposition method is used at all values of subcooling, while here it is applied only at high subcooling.

It is interesting to study the parameteric trends predicted by the present correlation. At zero subcooling and using Eq (8), the correlation may be written for $Bo > 2.5 \times 10^{-4}$ as:

$$h_{TP} = \frac{93 q^{0.65}}{G^{0.03} D^{0.38}}\left[\frac{C_p^{0.4} k^{0.6}}{i_{fg}^{0.65} \mu^{0.22}}\right] \tag{15}$$

and for $Bo < 2.5 \times 10^{-4}$:

$$h_{TP} = \frac{4 q^{0.27} G^{0.35}}{D^{0.38}}\left[\frac{C_p^{0.4} k^{0.6}}{i_{fg}^{0.27} \mu^{0.22}}\right] \tag{16}$$

It is seen that at high boiling number (ie high heat flux, low velocity), mass velocity has essentially no effect. This is in agreement with the experiments of most researchers which show that as heat flux is increased, the boiling curves for different velocities merge. (See for example Refs (5) and (6)). It is also interesting to note that at higher boiling numbers, the exponent of q is 0.65 which is close to those generally reported for pool boiling. For example, the value of this exponent vary from 0.624 to 0.745 in the correlation of Stephan and Abdelsalam[22].

Comparison with the pool boiling correlation of Cornwell *et al*[29] is also interesting. This correlation is based on a large amount of varied data for tubes and may be written as:

$$h = C_{tb}\frac{q^{0.67} k}{i_{fg}^{0.67} \mu^{0.67} D^{0.33}} \tag{17}$$

C_{tb} is a constant which depends on pressure, type of fluid, and surface roughness. The resemblance between Eqs (15) and (17) is rather striking. This suggests that heat transfer during natural convection and forced convection are similar. It should be noted, however, that heat transfer during pool boiling is strongly affected by surface conditions while these have little or no effect on forced convection boiling.

At lower boiling numbers (low heat flux, high velocity), the correlation predicts significant increase in heat transfer with velocity. This predicted trend is in agreement with all experimental data.

According to Eq (15), $h_{TP} \to \infty$ as $G \to 0$. According to Eq (16), $h_{TP} \to 0$ as $G \to 0$. Both of these trends are incorrect as, in the absence of forced convection, heat transfer will occur through natural convection boiling and h_{TP} will have a non-zero and finite value. Thus there will be a minimum value of G below which the present correlations will be inapplicable.

It is appropriate at this point to discuss the various definitions of velocity used by researchers. Bitter[11] based the velocity on the minimum flow area. McKee and Bell[6] and Yilmaz[1] among others used the upstream velocity. The velocity used by Fand *et al*[8] also takes into account the restriction caused by the test section but it comes out slightly lower than the velocity based on minimum area. For all the data analysed here, the maximum spread in the velocities according to the three definitions does not exceed 20%. According to Eq (15), a 20% change in velocity will have virtually no effect on h_{TP}. Hence at high values of Bo, which velocity is used is unimportant. On the other hand, Eq (16) predicts about 7% change in h_{TP} for a 20% change in velocity. Hence for closely spaced tube bundles, the definition of velocity can significantly affect the predictions of this correlation. Which definition is best cannot be determined on the basis of data analysed here, as their range is too narrow. More research with smaller flow areas is needed to resolve this question. It should be remembered that the same definition of velocity should be used in calculating *Re* and *Bo*.

Analysis of experimental data

Vigorous efforts were made to collect as much varied experimental data as possible. Only ten experimental studies could be located[1-13,28]. Only a few data points have been deleted from the present analysis for reasons discussed below.

Beecher[3] experimented with two test sections. One was a platinum wire and the other was a stainless steel tube. Different measurement techniques were used for the two test sections. Beecher states that the measurement technique used for the platinum wire was not reliable. Hence these data were rejected. With the stainless steel section, he used untreated water. Surface deposits were found on the tube after most runs. Different runs at identical velocity and temperature generally gave different results, probably due to different extent of scaling. Because of this lack of reproducibility, rejection of all the data would have been justified. However, these data are of much interest because the tube diameter used was much smaller than that in any other study. Hence the data were selected on the following basis. Where repeat runs had been made under identical conditions, that run was accepted which gave the highest heat transfer coefficients as these were believed to be least affected by scale. Data were not accepted if there was no repeat run at identical conditions.

From the tests of Yilmaz[1], one data point at each velocity at the lowest heat flux was not considered. These three data points are well below the single-phase correlations of Eq (8) and Eq (9). All other data points below critical heat flux were considered. Critical heat flux was assumed to occur when heat transfer coefficient began to fall.

No data points were rejected from any other study. The data of Yilmaz, Beecher, and Fand *et al* have been taken from tabulations. All other data have been read from graphs.

Yilmaz has stated that subcooling varied from 4 to 5 °C. A constant value of 4.5 °C was used in analysing his data. Leppert *et al*,[4] have stated that subcooling in their tests varied from 10 to 23 °C. A value of 16 °C was used in analysing their data. The values of *Bo* and ΔT_{SAT} in their tests were such that this approximation has negligible effect on the accuracy of prediction.

For analysing the data of Yilmaz, h_L was calculated with Eq (9) with the definition of velocity according to that used by Fand and Keshwani[19]. For all other data h_L was calculated with Eq (8), using the velocity based on the minimum flow area. *Bo* was calculated using the same velocity as used in calculating h_L.

Deviation of correlation on the basis of ΔT_{SAT} was calculated as:

$$Deviation = \frac{Measured\ \Delta T_{SAT} - Predicted\ \Delta T_{SAT}}{Predicted\ \Delta T_{SAT}} \qquad (18)$$

Deviation of correlation on the basis of h_{TP} was calculated as:

$$Deviation = \frac{Predicted\ h_{TP} - Measured\ h_{TP}}{Measured\ h_{TP}} \qquad (19)$$

Mean deviation of a data set is calculated as the sum of the absolute values of the deviations of individual data points divided by the total number of data points.

Results of data analysis

Table 1 lists the deviations of ΔT_{SAT} and h_{TP} for each data set together with the range of important parameters. On the basis of ΔT_{SAT}, the mean deviation for all 334 data points is 16.7%. On the basis of h_{TP}, which is the more appropriate basis, the mean deviation is 9.5%. Only six of the data points showed deviations of h_{TP} greater than 30%. Three of these data points were from the tests of Beecher[3], two from the tests of McKee[5], and one from Bitter[12].

Figs 3 and 4 show the comparison of measured and predicted heat transfer coefficients for refrigerants and water respectively.

Discussion of results

The data analysed and satisfactorily correlated are from ten independent studies. These include three fluids, four tube materials, velocities from 0.02 to 7.8 m/s, Reynolds numbers from 700 to 150 000, subcooling from 0 to 80 °C, heat flux from 1 to 1000 KW/m^2, and boiling number from 0.6 to 98. Mean deviation for all 334 data points is only 9.5% with 99% of the data points predicted within 30% of measurements. Hence it appears that this correlation can be applied with confidence over a wide range of parameters.

Greater accuracy is certainly desirable, but may be difficult to achieve. Even for single-phase flow through tubes, which has been so thoroughly researched and which involves much simpler phenomena, the accuracy of correlations for heat transfer is about ±30%. Hence it will be unreasonable to except a better accuracy for a correlation for boiling heat transfer, which involves much more complex phenomena.

Tube diameter

Data correlated include tube diameters from 1.2 to 25.4 mm. Heat exchangers rarely use tubes outside this range and hence the correlation has been verified for most practical purposes.

In view of the resemblance between Eqs (15) and (17) some guidance on the effect of diameter may be obtained from the work of Cornwell *et al*[29] who found that heat transfer decreases as diameter increases from 6 to 32 mm as given by Eq (17). Heat transfer was found to increase with further increase in tube diameter. Data for a wire 0.24 mm diameter did not fit Eq (17). They concluded that much of the heat transfer to thin wires occurs due to convection while in larger diameter cylinders, the contribution of convection is negligible.

Table 1 Results of comparison of data with the new correlation

Source	D_t, mm	Tube material	Fluid	p_r	ΔT_{SC}, °C	$\frac{\Delta T_{SC}}{\Delta T_{SAT}}$	Velocity m/s	Re_L	q, $\frac{KW}{m^2}$	$Bo \times 10^4$	Deviations, %		Number of data points
											ΔT_{SAT}	h_{TP}	
Yilmaz[1]	6.4	Copper	R-113	0.029	4	0.09	2.8	53 500	60	0.6	13.9	10.8	36
					5	0.32	7.8	150 000	584	6.6			
Beecher[3]	1.2	Stainless steel	Water	0.005	0	0.0	0.9	1 940	13	4.8	26.1	13.1	14
					80	12.0	1.5	4 400	850	27.4			
Leppert *et al*[4]	2.8	Stainless steel	Water	0.005	10	0.5	0.17	1 480	86	23.3	11.0	5.9	10
					23	1.5			286	77.9			
McKee[5]	6.3	Stainless steel	Water	0.005	7	0.14	1.14	25 000	22	0.7	18.8	14.2	50
	17.9					1.10	2.17	135 300	286	8.0			
Vliet[7]	3.2	Stainless steel	Water	0.005	2	0.06	0.2	1 500	86	5.6	5.6	3.1	45
					55	1.72	3.3	26 000	714	98.1			
Fand *et al*[8]	11.4	Stainless steel	Water	0.014	32	1.12	0.02	970	166	6.6	42.3	16.8	13
						2.92	0.12	4 830	366	66.2			
	11.9	Titanium	Water	0.009	39	1.3	0.02	700	160	6.0	24.5	5.8	61
				0.018	52	173.0	0.12	4 710	323	64.0			
Dieselhorst[9]	3.0	Stainless steel	Water	0.005	0	0	0.24	2 500	150	2.9	8.2	8.2	15
							0.44	4 600	1000	10.4			
Bitter[11]	15.0	Porcelein, nickel coated	R-11	0.022	0	0	0.04	2 000	1	0.5	14.1	14.1	31
				0.025			0.92	50 000	32	17.9			
Lemmert & Chawla[13]	25.4	Copper	R-11	0.04	0	0	0.12	13 300	3	0.7	12.3	9.2	32
					10	2	1.2	133 000	225	70.0			
Fink *et al*[28]	25.4	Copper	R-11	0.040	1	0.05	0.13	13 300	57	2.6	13.6	10.8	15
					16	0.74	1.33	133 000	138	41.4			
Fink *et al*[23]	25.4	Copper	R-113	0.051	1	0.05	0.13	11 600	57	4.3	19.2	16.0	12
					16	0.87	1.33	116 000	138	51.7			
All data	1.2			0.005	0	0.0	0.02	700	1	0.6	16.7	9.5	334
	to 25.4			0.040	80	173.0	7.8	150 000	1000	98.1			

Use of this correlation should be confined to the verified range of $D = 1.2$ to 25.4 mm.

Pressure

The data analysed cover a range of 1 to 4 bar. In terms of reduced pressure, the range is 0.005 to 0.04. Verification over a wider range of pressures is highly desirable. However, most shell and tube heat exchangers operate with low pressure on the shell side because of structural considerations. Hence the verified pressure range covers most practical applications. Use of this correlation beyond the verified reduced pressure range is discouraged.

Type of fluid

The correlation has been verified for water, R-11, and R-113. The properties of these fluids differ considerably. Furthermore, this correlation is similar to Shah's

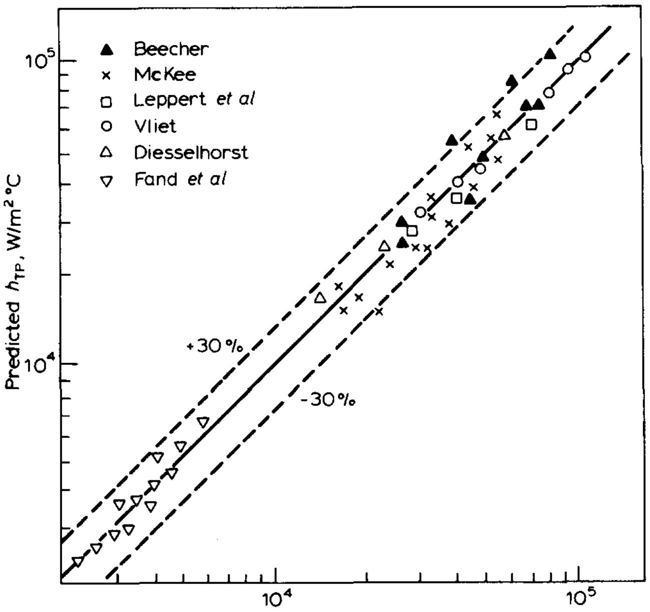

Fig 3 Comparison of the new correlation with boiling data for water

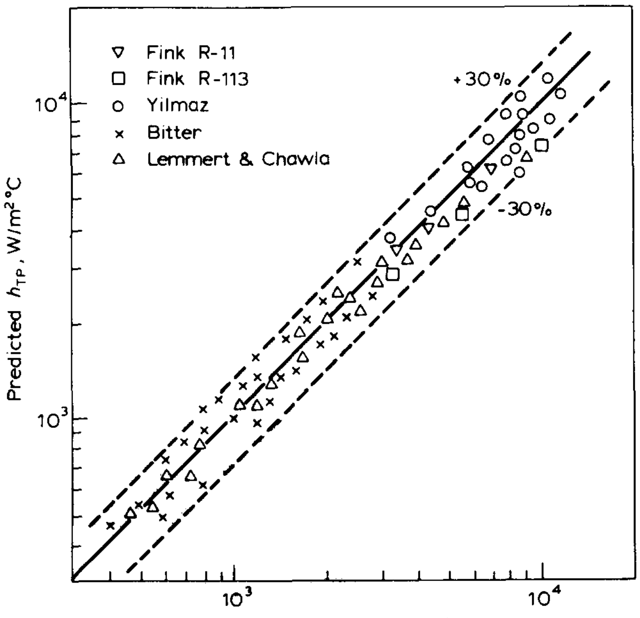

Fig 4 Comparison of correlation with boiling data for R-11 and R-113

correlation for boiling inside tubes and annuli which was verified with data for water, R-11, R-12, R-113, *n*-butyl alcohol, methanol, ammonia, and isopropyl alcohol[16,17]. Hence this correlation is expected to be generally applicable to water, refrigerants, and chemicals. Applicability to cryogenic fluids is uncertain as their behaviour is often different from common fluids. Comparison with data for cryogenic fluids is highly desirable.

Tube material and liquid-surface combination

The data analysed include four tube materials (copper, stainless steel, titanium, and nickel-coated porcelein) and five liquid-surface combinations. Yet all the data are satisfactorily correlated. The ΔT_{SAT} from the Fand *et al* data for water-stainless steel are overpredicted but their heat transfer coefficients are satisfactorily correlated. Besides, five other data sets for water-stainless steel are well correlated. Hence it appears that this correlation can be applied to plain tubes of any material. Indeed, most researchers have found that forced convection boiling is insensitive to tube material. The general correlations of Shah for subcooled boiling[16,17] and saturated boiling[23,24] in tubes and annuli were found to agree for a wide variety of tube materials. Palen *et al*[25] tested a number of kettle reboilers using a number of tube materials including carbon steel, cupro-nickel, and admiralty brass. They found no significant effect of tube material.

The available evidence strongly indicates that this correlation can be applied to plain tubes of any material. In view of the comparison of Eqs (15) and (17), however, surface properties may effect heat transfer at very low velocities in a way similar to that in pool boiling.

Single-phase heat transfer correlation

Several correlations for single-phase heat transfer are available and they often give significantly different predictions. Investigation of the reasons for this discrepancy and the development of a unified single-phase correlation was beyond the scope of this study. Effort here was confined to finding a correlation which will adequately represent the boiling data. For this purpose, several available correlations were tried. None was satisfactory for all the data sets. The Michejew equation:

$$Nu_b = 0.21\, Re_b^{0.62}\, Pr_b^{0.38} (Pr_b/Pr_w)^{0.25} \tag{20}$$

gave fairly good results but the data for refrigerants and water diverged at higher wall temperature differences. It was, therefore modified to the form of Eq (8) which made the refrigerant and water data converge.

Eq (8) resulted in good correlation of boiling data from all sources except those of Yilmaz. Fig 5 shows the comparison of Eq (8) with single-phase data from the test sections on which boiling tests were made. Yilmaz has not reported any single-phase data. The data points shown in Fig 5 are those at the lowest heat flux in his boiling runs. It is seen that Eq (8) agrees fairly well with all data except those of Yilmaz which are very low. The Yilmaz data show better agreement with Eq (9) and his boiling data are also better correlated with that equation.

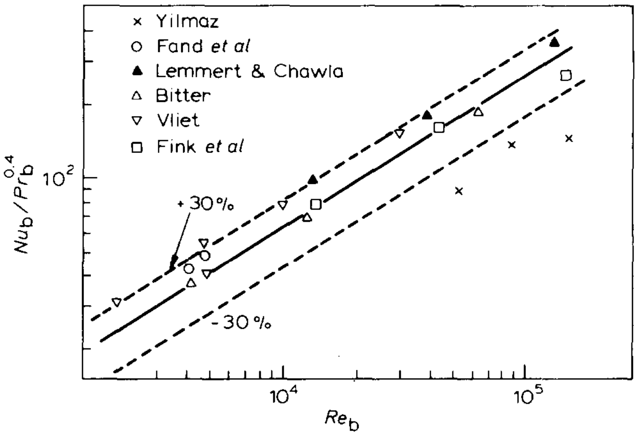

Fig 5 Comparison of single-phase heat transfer data with Eq (8)

As noted by Palen *et al*[25], most researchers have found the exponent of Reynolds number to be near 0.66 for boiling and non-boiling flow over tube bundles. Thus the exponent 0.62 in Eq (8) agrees with the work on tube bundles.

Hence this research as well as the research on tube bundles indicates that Eq (8) is a good choice for calculating single-phase heat transfer. The data of Yilmaz, of course, raise questions. The author's recommendation is that if single-phase heat transfer data are available from a particular test section, the constant in Eq (8) be modified to suit them. Thus Fig 5 shows that for the Yilmaz data, the constant in Eq (8) will change to 0.11 from 0.21. This change will result in satisfactory correlation of all the boiling data of Yilmaz. Where single-phase data are unavailable, Eq (8) is to be used unmodified.

Reynolds number

The data analysed here include Reynolds numbers from 700 to 150 000. As Eq (15) shows very little effect of velocity and as at low velocity *Bo* will be high, applicability to lower Reynolds number is probable but needs to be verified by data analysis. Data[26] for heat transfer to gases across cylinders show that at *Re* of the order of 10^6 and higher, the exponent of *Re* becomes close to 0.8. Hence applicability of Eq (8) becomes doubtful at higher Reynolds number. Analysis of boiling data beyond the range of 700 to 150 000 is needed to determine the applicability of the present correlation.

It is recommended that for the present, the use of this correlation be confined to Reynolds number between 700 to 150 000.

Hysterisis effects

Hysterisis is common in subcooled boiling. Among the data analysed here, only Lemmert and Chawla[13] have reported data showing hysterisis. Their data for both increasing and decreasing heat flux have been satisfactorily correlated, though those for decreasing heat flux are generally underpredicted to some extent.

Recommendations for use

The results of data analysis have been presented and discussed; the reader may reach his own conclusion regarding the limits of its applicability. The author's recommendations are:

1. The use of the correlation should be confined to the range of dimensional and non-dimensional parameters for which it has actually been verified.
2. The correlation is recommended for water, chemicals, and refrigerants.
3. The correlation may be used for plain tubes of any material.
4. This correlation should not be used at velocities lower than those covered by the data in Table 1 as it predicts the wrong trend for $G \rightarrow 0$.
5. Single-phase heat transfer coefficient h_L is to be calculated by Eq (8). However, if single-phase data are available for a particular test section, the constant in Eq (8) may be modified to suit those data.

Other predictive techniques

A thorough review of other predictive techniques is beyond the scope of this paper. Some of the proposed techniques are briefly discussed here in order that the new correlation may be viewed in the proper perspective.

Several researchers have attempted to correlate their data according to Rohsenow's superposition method[14] which may be written as:

$$q = q_{pb} + q_{SPC} \tag{21}$$

where q_{pb} is determined from pool boiling data or correlations. Yilmaz and Westwater[1,2] and Leppert *et al*[4] found satisfactory correlation by this method, using their own pool boiling data to calculate q_{pb}. McKee[5], using his own pool boiling data, found that some of his data were satisfactorily correlated while some were underpredicted. Fand *et al*[8], and Lemmert and Chawla[13], state that their data could not be correlated in terms of Eq (21). Hence the Rohsenow method has not been successful even when pool boiling data for the particular test section was available. The difficulties in accurately predicting pool boiling heat transfer are well-known. Perhaps the most verified pool boiling correlation available at the present is that of Stephan and Abdelsalam[22]. Even these authors were unable to correlate about half of the data examined by them and had to discard it. It is also worth noting that Bergles and Rohsenow[27] conducted experiments to evaluate Eq (21). They concluded that it is not valid. They recommended that heat flux due to nucleate boiling should be determined from flow boiling data, not from pool boiling data. The present correlation is in accordance with their recommendation.

Another superposition technique is that proposed by Kutateladze[15] and can be written as:

$$h_{TP} = h_L[1 + (h_{pb}/h_L)^n]^{1/n} \tag{22}$$

Kutateladze recommended $n = 2$. Lemmert and Chawla[13] found poor agreement of their data with Eq (22), using $n = 2$. Fand *et al*[8] also found poor agreement using $n = 2$. However, their data are well-correlated with $n = 5.5$. It will be noted that Eq (21) is the same as Eq (22) when $n = 1$ and three researchers have reported agreement of their data with Eq (21). Thus it is seen that n can vary from 1 to 5.5 and there is no way to predict its value.

McKee[5] attempted to improve the Rohsenow method by distinguishing between areas with bubble nucleation and those without bubble nucleation. His equation is:

$$qA = q_{pb}A_{bn} + q_{SPC}(A - A_{bn}) \tag{23}$$

He determined A_{bn}/A by a dimensional equation which fits his data. Whether it fits other data, is unknown.

Lemmert and Chawla[13] also used the approach of Eq (23) but developed different expressions for determining A_{bn}/A and heat flux due to bubble nucleation. While their expressions fit their own data well, they have not been compared with any other data.

On the basis of these discussions, it can be concluded that the predictive techniques which have been available till now have been either found to be unsatisfactory or have not been verified with more than one data set. On the other hand, the present correlation has been verified with data from ten independent studies covering a wide range of parameters. Hence the present correlation appears to be preferable to other predictive techniques.

Application to tube bundles

Cornwell and Schuller[30] carried out studies of heat transfer in the upper tubes of a tube bundle. They concluded that most of the heat transfer occurs due to the action of bubbles that slide up the sides of the tubes and grow at a rapid rate. Some of the bubbles originate from the nucleation sites at the base of the tubes while some impact on the tubes from the upstream and thus originate from the lower tubes.

The correlation given here is based on data for single tubes with single-phase flow upstream. Thus the effect of bubbles originating on the tube itself is included in the correlation but the effect of bubbles in the flow upstream is not included. Hence the new correlation can be considered applicable only to the lowest tubes of a bundle.

Concluding remarks

1. A simple dimensionless correlation has been presented which agrees with all available data for subcooled boiling with forced flow across a single tube. No well-verified predictive technique had been available till now. Availability of this correlation should be helpful in the design of shell and tube evaporators.
2. While this correlation agrees with all available data, the range of these data is rather narrow. Further experimentation over a wider range of parameters is highly desirable. Specially desirable are data at very low velocities to determine the limits of applicability of this correlation.
3. The correlation presented here applies only to subcooled boiling. Development of a correlation for

boiling at positive vapour qualities is also needed. For this purpose it is desirable that varied data from experiments on single tubes be available. At present, such data are scarce. Hence further experimentation with two-phase flow across single tubes is suggested.

Acknowledgement

The author thanks Drs E. Hahne and Dr R. C. Bitter for providing copies of Refs (9) and (11) respectively.

References

1. **Yilmaz S. B.** Effect of velocity on boiling Freon-113. *Doctorate Thesis, Chem. Eng. Dept. Univ. of Illinois, 1979*
2. **Yilmaz S. B. and Westwater J. W.** Effect of velocity on heat transfer to boiling Freon-113. *ASME Paper 79-WA/HT-35, 1979*
3. **Beecher N.** Heat transfer to water flowing normal to a single cylinder. *M.S. Thesis, Chem. Eng. Dept., Massachusetts Institute of Technology, 1948*
4. **Leppert G., Costello C. P. and Hoglund B. M.** Boiling heat transfer to water containing a volatile additive. *Trans. ASME, October 1958,* **80**, *1395–1403*
5. **McKee H. R.** Forced Convection Boiling From a Cylinder Normal to the Flow. *PhD Thesis, Chem. Eng. Dept., Oklahoma State University 1967*
6. **McKee H. R. and Bell K. J.** Forced convection boiling from a cylinder normal to the flow. *Chem. Eng. Progress Symp. Ser., 1969,* **65**, *No. 92, 222–230*
7. **Vliet G. C.** Local boiling peak heat flux for water flowing normal to cylinder. *PhD Thesis, Mech. Eng. Dept., Stanford Univ., 1962*
8. **Fand R. M., Keshwani K. K., Jotwani M. M. and Ho R. C. C.** Simultaneous boiling and forced convection heat transfer from a horizontal cylinder to water. *J. Heat Transfer, Trans. ASME, Series C, Aug. 1976,* **98**, *395–400*
9. **Disselhorst T.** Hydrodynamische und oberflächenspezifische Einflüsse auf die Siedekrisis beim Behältersieden. *Dr. Ing. Thesis, Techn. Univ. Munich, 1978*
10. **Diesselhorst T., Grigull U and Hahne E.** Hydrodynamic and surface effects on the peak heat flux in pool boiling. *In "Heat Transfer in Boiling". (Eds E. Hahne and U. Grigull) Hemisphere Publishing Corp., Washington, 1977*
11. **Bitter R. C.** Zum Wärmeübergang von einem querangeströmten Rohr an siedendes R-11 bei Ein-und Zweiphasenströmung. *Dr. Ing. Thesis, Tech. Univ. Clausthal, 1973*
12. **Bitter R. C.** Heat transfer from a horizontal tube with transverse flow of evaporating saturated R-11. *Int. Inst. of Refrigeration Commission B-1, B-2, and E-1, Freudenstadt, Fed. Rep. of Germany, Supplement to Int. Inst. Refrig. Bulletin, pp 97–107, 1972*
13. **Lemmert M. and Chawla J. M.** Influence of flow velocity on surface boiling heat transfer coefficients. *In "Heat Transfer in Boiling", (Eds E. Hahne and U. Grigull) Hemisphere Publishing Corp. Washington, 1977*
14. **Rohsenow W. M.** Heat transfer associated with nucleate boiling. *Proc. Heat Transfer and Fluid Flow Institute, Stanford Univ. Press, p. 123, 1953*
15. **Kutateladze S. C.** Boiling heat transfer. *Int. J. Heat & Mass Transfer, 1961,* **4**, *31–45. Quoted by Fand et al*[8].
16. **Shah M. M.** A general correlation for heat transfer during subcooled boiling in tubes and annuli. *ASHRAE Trans., 1977,* **83**, *Part 1*
17. **Shah M. M.** Generalized prediction of heat transfer during subcooled boiling in annuli. *Heat Transfer Engineering, 1982,* **4**, *No. 1*
18. **Michejew E.** Die Grundlegen der Wärmeübertragung. *VEB Verlag Technik, Berlin. Quoted by Bitter*[12]
19. **Fand R. M. and Keswani K. K.** The influence of property variation on forced convection heat transfer to liquids. *Int. J. Heat & Mass Transfer, 1972,* **15**, *1515–1536*
20. **Perkins H. C. and Leppert G.** Forced convection heat transfer from a uniformly heated cylinder. *Trans. ASME Ser. C, J. Heat Transfer, 1962,* **84**, *257–263. Quoted by McKee*[5]
21. **Vliet G. and Leppert G.** Forced convection heat transfer from an isothermal sphere to water. *Trans. ASME Ser. C, J. Heat Transfer, 1961,* **83**, *163–175. Quoted by Fand and Keswani*[19]
22. **Stephan K. and Abdelsalam M.** Heat transfer correlations for natural convection boiling. *Int. J. Heat & Mass Transfer, 1980,* **23**, *73–87*
23. **Shah M. M.** A new correlation for heat transfer during boiling flow through pipes. *ASHRAE Trans., 1976,* **82**, *Part 2, 66–86*
24. **Shah M. M.** Chart correlation for saturated boiling heat transfer: equations and further study. *ASHRAE Trans., 1982* **88**, *Part 1*
25. **Palen J. W., Yarden A. and Taborek J.** Characteristics of boiling outside large-scale horizontal multitube bundles. *AIChE Symp. Ser., 1972,* **68**, *No. 118, 50–61*
26. **Hilpert R.** Wärmeabgabe von geheizen Drahten und Rohren. *Forsch. Gebiete Ingenieurw., 1933, 4, 220. Quoted in J. P. Holman, "Heat Transfer", Second Edition, McGraw-Hill, New York, 1968*
27. **Bergles A. E. and Rohsenow W. M.** The determination of forced convection surface boiling heat transfer. *Trans. ASME—J. Heat Transfer, 1964, 305–311, Aug*
28. **Fink J., Gaddis E. S. and Vogelpohl A.** Forced convection boiling of a mixture of Freon-11 and Freon-113 flowing normal to a cylinder. *Proc. 7th Int. Heat Transfer Conf., Munich, paper FB5, pp 207–212, 1982*
29. **Cornwell K., Schüller R. B. and Einarsson J. G.** The influence of diameter on nucleate boiling outside tubes. *Proc. 7th Int. Heat Transfer Conf., Munich, paper PB8, pp 47–52, 1982*
30. **Cornwell K. and Schüller R. B.** A study of boiling outside a tube bundle using high speed photography. *Int. J. Heat & Mass Transfer, 1982,* **25**, *No. 5, 683–690*