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A general correlation for flow boiling in tubes and annuli

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Abstract—A new general correlation for forced convection boiling has been developed with the aid of a large data bank. This data bank consists of over 4300 data points for water, refrigerants and ethylene glycol, covering seven fluids and 28 authors, mostly for saturated boiling in vertical and horizontal tubes, but with significant information also for subcooled boiling and for annuli. The new correlation is simpler to apply and overall gives a closer fit to the data than existing correlations. The mean deviation between the calculated and measured boiling heat transfer coefficient is 21.4% for saturated boiling and 25.0% for subcooled boiling.

INTRODUCTION

A LARGE number of correlations have been proposed for flow boiling [1–16]; however, many of these are restricted to one fluid. General correlations have been proposed by refs. [1–4] for saturated boiling, and by refs. [12–16] for subcooled boiling. However, it is difficult to find any correlation or procedure for calculating the boiling heat transfer coefficient that covers the whole range from subcooled to saturated boiling.

An early general correlation for saturated boiling, still widely quoted, was that of Chen [1] who divided the heat transfer into two parts: a microconvective (nucleate boiling) contribution based on Foster and Zuber's pool boiling equation [17]; and a macroconvective (non-boiling forced convection) contribution based on the single-phase (liquid only) Dittus–Boelter equation [18]. These were combined to give an overall heat transfer coefficient:

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

The factor f (> 1) reflects the much higher velocities and hence forced convection heat transfer in the two-phase flow compared to the single-phase, liquid-only flow. The factor f was correlated against the Martinelli parameter. The factor s (suppression factor, < 1) reflects the lower effective superheat available in forced convection as opposed to pool boiling, due to the thinner boundary layer. The suppression factor was correlated against a two-phase Reynolds number. In the original papers f and s are presented as graphs, but ref. [19] has fitted equations to the graphs.

As might reasonably be expected in view of its age this correlation has to some extent been superseded by more recent ones.

A more recent correlation for saturated boiling, that gives a good fit to a large body of data, is that of Shah [2] (much the same correlation was earlier given in the form of graphs rather than equations [20]). Again two distinct mechanisms are considered to apply—nucleate boiling and forced convection—but instead of adding the two contributions together the larger of the two calculated heat transfer coefficients is chosen. A feature of the Shah correlation is that the boiling number, *Bo*, plays an important part. Use of the boiling number in correlations goes back at least as far as Mumm [6].

Since a few general correlations are already available, with one at least giving good results, some justification is required for proposing a new one. It would be desirable for any new correlation to be tested against a data bank at least as large as those used previously; for it to be simple to apply (simple equations, not requiring obscure property values); for it to extend to subcooled as well as saturated boiling; for it to apply to tubes and annuli for both vertical and horizontal flow; and for it to be a close fit to the data. The correlation proposed in this paper satisfies all these requirements.

THE DATA BANK

An attempt has been made to collect data from a wide range of sources taken under a wide range of conditions. The data points taken from the literature consist of the experimentally measured values of heat transfer coefficient and wall temperature as a function of pressure (or saturation temperature), mass flux, heat flux and quality. For subcooled boiling, the bulk temperature (or subcooling) is recorded in place of the quality. The inlet length has also been recorded, but has not been used in the present study.

In Table 1 a complete list has been given, including the number of data points and the range of each of the parameters covered. So far as possible all the data from a given source has been used, to avoid any subjectivity in choosing just a sample. A possible disadvantage of this procedure is that the data base becomes unduly weighted towards just one or two sources that happened to report a very large number of readings. In the present case the largest sources are refs. [6] (419 points for water) and [32] (593 points for R11). Since

NOMENCLATURE

Bo	boiling number
C_p	specific heat [J kg^{-1} K^{-1}]
d	tube diameter [m]
E	enchancement factor
f	Chen's empirical F function, $(Re_{tp}/Re_l)^{0.8}$
Fr	Froude number, $G^2/(\rho_l^2 g d)$
g	acceleration of gravity [m s^{-2}]
G	mass flux [kg m^{-2} s^{-1}]
h	heat transfer coefficient [W m^{-2} K^{-1}]
k	thermal conductivity [W m^{-1} K^{-1}]
M	molecular weight
P	pressure [N m^{-2}]
Pr	Prandtl number
q	heat flux [W m^{-2}]
Re	Reynolds number
Re_l	liquid Reynolds number, $G(1-x)d/\mu_l$
S	suppression factor
T	temperature [K]
x	quality
X_{tt}	Martinelli parameter.

Greek symbols

κ	thermal diffusivity [m^2 s^{-1}]
λ	latent heat [J kg^{-1}]
ρ	density [kg m^{-3}]
σ	surface tension [N m^{-1}]
μ	dynamic viscosity [N s m^{-2} (kg m^{-1} s^{-1})].

Subscripts

b	bulk
c	critical
cal	calculated
e	equivalent
exp	experimental
l	liquid
pool	pool boiling
r	reduced
S	saturation
tp	two-phase
v	vapour
w	wall.

each of these sources covered a reasonable range of the parameters, and in the context of 3693 saturated boiling data points in total, the influence of these two sources is not excessive.

CONSTRUCTION OF THE CORRELATION

The basic form of the correlation used is:

$$h_{tp} = Eh_l + Sh_{pool} \tag{2}$$

but the precise method of calculating the various terms has evolved through a number of stages. h_l, right from the beginning, has been given by the Dittus–Boelter equation for liquid only flowing in the duct, i.e.

$$h_l = 0.023\, Re_l^{0.8}\, Pr_l^{0.4} k_l/d. \tag{3}$$

However, in two-phase flow, even for quite modest vapour qualities, the velocities are higher, the void fraction is high and the boundary layer next to the heat transfer surface is thin. The heat transfer is consequently increased by an enhancement factor E well above the level for a single-phase liquid flow (of the same mass flux). This effect is clearly going to depend on the quality x and on the vapour to liquid density ratio ρ_v/ρ_l, and it has in fact been common practice for a long time to correlate both void fraction and heat transfer coefficients in two phase flows in terms of the Martinelli parameter:

$$X_{tt} = \left(\frac{1-x}{x}\right)^{0.9} \left(\frac{\rho_v}{\rho_l}\right)^{0.5} \left(\frac{\mu_l}{\mu_v}\right)^{0.1}. \tag{4}$$

There does not appear to be any good reason to change this aspect of the correlation.

It is not just the high axial velocities that are significant in disturbing the boundary layer next to the heat transfer surface and improving the heat transfer. The generation of vapour itself in the boiling process results in significant disturbance of the layer and improved heat transfer. A dimensionless measure of how important this effect may be is given by the boiling number:

$$Bo = \frac{q}{\lambda G} \tag{5}$$

being the ratio of mass flux perpendicular to the wall due to boiling to the total (axial) mass flux.

Consequently it should be possible to write the enhancement factor as:

$$E = f(X_{tt}, Bo). \tag{6}$$

The pool boiling term in equation (2) is multiplied by a suppression factor S. This takes account of the fact that the boundary layer of superheated liquid in which the vapour bubble grows is thinner in forced convection. The extent of this suppression will be controlled by the effectiveness of the forced convection heat transfer, that is by the two-phase Reynolds number $Re_{tp} = E^n\, Re_l$ (this form of expression for the two-phase Reynolds number is suggested in [1]).

Iteration to find the unknown E *and* S *factors*

It became clear at an early stage that the dominant term in equation (2) was the first one, so even an approximate method of finding S and h_{pool} might give acceptable results in calculating E from the experimental data. Accordingly, Chen's equations for S and h_{pool} were used to estimate E from:

$$E = (h_{exp} - Sh_{pool})/h_l \tag{7}$$

Table 1.

Data (ref.)	d (mm) Tube diameter	Fluid	Orientation of flow	Saturation temperature T_s(°C)		Mass velocity G(kg m^{-2} s^{-1})		Heat flux q × 10^{-3} (W m)		Saturation pressure P_s(bar)		Quality x*(%)		Temperature difference ΔT(°C)		No. of data points
				Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	
[23]	32.00	water	vertical up	271.2	237.3	1633.8	773.3	515.2	116.3	41.34	31.41	34.2	0.4	10.8	5.1	171
[6]	11.81	water	horizontal	194.3	134.6	1383.4	339.1	788.6	157.7	13.78	3.1	56.3	0.0	26.1	4.4	419
[24]	18.30	water	horizontal	114.4	102.3	1031.1	248.3	157.1	42.9	1.653	1.099	14.3	1.9	6.3	1.6	52
[25]	18.30	water	vertical down	135.8	101.2	3535.0	248.6	277.6	4.74	3.189	1.056	19.3	0.6	6.5	0.4	103
[26]	25.40	water	vertical	135.9	88.6	1390.0	59.2	624.6	8.20	3.20	0.66	43.5	0.1	18.6	0.7	60
[27]	5.00	water	vertical down	280.8	237.7	8179.3	1249.0	2280.0	540.0	64.23	31.97	69.9	9.8	17.5	4.5	41
[28]	12.20	water	vertical	126.1	99.4	1070.2	67.0	1995.0	44.0	2.39	0.99	57.0	0.5	29.3	2.8	71
[29]	5.00	water	vertical	286.0	286.0	1528.9	1528.9	1340.0	54.2	70.12	70.12	52.1	17.4	11.9	1.3	79
[42]	2.95	water	vertical	166.8	132.4	2939.3	1244.1	2085.0	306.3	7.30	2.89	49.4	5.2	10.2	3.3	18
[7]	18.60	R12	vertical up	32.6	26.2	3151.8	676.8	27.8	3.3	7.95	6.72	89.1	17.3	5.7	0.8	41
[30]	14.00	R12	horizontal	0.9	−0.7	736.7	91.0	70.8	1.1	3.18	3.02	52.0	9.0	12.2	0.3	168
[31]	11.68	R22	horizontal	11.5	11.5	474.5	113.0	21.0	1.99	7.00	7.00	67.6	20.3	7.6	0.3	23
[32]	25–14	R11	horizontal	20.0	0.0	173.2	12.4	23.3	0.35	0.88	0.39	98.0	10.0	23.0	0.5	593
[8]	15.77	R113	vertical up	86.1	49.8	1234.7	205.4	56.7	5.87	2.13	0.08	43.0	0.1	25.2	3.5	143
[8]	15.77	R113	vertical down	85.2	52.1	1246.5	205.4	56.7	2.98	2.05	0.16	70.2	1.1	11.1	4.7	107
[9]	19.05	R12	horizontal	42.7	29.3	1917.3	242.5	44.8	6.9	10.3	7.3	99.3	2.0	38.4	2.1	166
[33]	20.5	R12	vertical up	92.4	45.3	4850.0	658.0	111.3	9.5	29.1	10.9	20.9	1.7	7.6	1.1	99
[34]	15.0	R12	vertical up	93.0	27.5	928.5	510.0	200.0	14.8	29.5	6.9	33.0	3.8	5.4	0.8	46
[7]	18.6	R12	horizontal	29.8	24.0	2863.0	1326.0	38.5	7.1	7.4	6.3	82.1	26.4	4.3	0.7	18
[7]	18.6	R22	horizontal	23.4	22.2	1699.0	1166.0	34.6	9.9	10.0	9.7	62.9	43.7	3.4	1.0	9
[30]	14.0	R11	horizontal	10.1	9.4	726.3	106.5	70.1	0.97	0.61	0.59	82.0	9.0	15.6	0.2	165
[35]	16–22	water	annular	121.9	100.2	295.6	69.8	500.0	100.0	2.1	1.0	58.9	0.2	29.4	3.2	70
[36]	8.5–15	water	annular	364.9	329.5	5700.0	1360.0	1233.0	494.0	198.0	127.7	12.7	0.3	5.7	2.0	46
[37]	9.5–22	water	annular	145.7	100.8	1076.0	134.0	795.0	29.6	4.2	1.0	65.9	0.2	62.3	1.0	367
[38]	14.91	water	subcooled	194.7	102.2	3819.0	1870.0	4579.0	119.4	13.9	1.1	145.0	1.0	33.3	6.1	44
[36]	13–8.5	water	subcooled	364.1	329.3	3620.0	1350.0	2303.0	529.0	202.6	131.7	107.9	0.5	56.2	2.7	53
[39]	3.05	water	subcooled	213.4	150.0	61518.0	21970.0	91534.0	46848.0	20.4	4.8	173.7	1.0	106.7	8.7	24
[15]	7.90	water	subcooled	190.0	128.9	3314.0	1120.0	2616.0	1333.0	12.5	2.6	146.1	1.0	40.6	1.7	97
[40]	11.68	water	subcooled	248.7	170.0	7830.0	1693.0	2961.0	712.0	37.9	6.9	130.2	1.0	39.4	2.0	328
[41]	19–6.5	R11	subcooled	105.2	75.0	4792.0	1472.0	92.8	16.3	9.1	5.6	18.4	0.1	13.5	1.8	75
[41]	18.85	R12	subcooled	28.7	27.6	4361.0	1440.0	52177.0	25612.0	7.1	6.9	11.6	0.8	9.2	2.6	6
[10]	19.94	R114	saturated	94.2	35.9	4757.0	157.0	81.6	8.7	14.8	4.4	88.8	2.5	17.1	2.5	123
[21]	20.4	water	saturated	120.3	120.3	1591.0	184.0	181.2	136.1	2.0	2.0	34.2	0.4	24.6	3.9	255
[21]	20.4	ethylene glycol	saturated	220.4	220.4	1030.0	206.0	576.4	136.3	2.0	2.0	26.9	0.0	53.1	8.1	101

* In the case of subcooling x refers to the subcooling degree $(T_s - T_b)$ K.

where h_{exp} is the experimental boiling heat transfer coefficient.

Values of the fluid properties were obtained from a number of sources. For water and R22, equations supplied by the National Engineering Laboratory, Glasgow, were used. For other fluids in some cases equations for the properties were found in the literature [8, 10, 21], in other cases equations were fitted to literature property data as part of this project.

Based on these results a first estimate of the function $f(X_{tt}, Bo)$ in equation (6) was obtained. With this equation for E it was possible to go through the data again to obtain a better estimate of S. Also a number of literature expressions for h_{pool} were investigated, the best being that proposed by Cooper [22]:

$$h_{pool} = 55\, P_r^{0.12}(-\log_{10} P_r)^{-0.55}\, M^{-0.5}\, q^{0.67} \quad (8)$$

(assuming that the roughness of tube is 1 μm).

In this way an equation for the suppression factor as a function of the two-phase Reynolds number was obtained.

This procedure was repeated until there was no significant improvement in the fit.

Up to this point no account had been taken of the orientation of the tube. Further iterations showed that for horizontal tubes with less than a certain critical Froude number both E and S required modification.

THE FINAL EQUATIONS

Using all of the saturated boiling tube data available at that time, the expressions for E and S were:

$$E = 1 + 24\,000\, Bo^{1.16} + 1.37(1/X_{tt})^{0.86} \quad (9)$$

and

$$S = \frac{1}{1 + 1.15 \times 10^{-6} E^2\, Re_l^{1.17}}. \quad (10)$$

So the heat transfer coefficient in saturated boiling may be calculated using these two expressions and the following equations. All properties are calculated at the saturation temperature.

$$h_{tp} = Eh_l + Sh_{pool} \quad (2)$$

$$h_l = 0.023\, Re_l^{0.8}\, Pr_l^{0.4}\, k_l/d \quad (3)$$

$$h_{pool} = 55\, P_r^{0.12}(-\log_{10} P_r)^{-0.55}\, M^{-0.5}\, q^{0.67}. \quad (8)$$

If the tube is horizontal and the Froude number is less than 0.05 then E should be multiplied by:

$$E_2 = Fr^{(0.1 - 2Fr)} \quad (11)$$

and S should be multiplied by:

$$S_2 = \sqrt{Fr}. \quad (12)$$

As the equations stand it is assumed that heat flux q is known, in which case it is straightforward to calculate T_w. If T_w is known then, as with many other correlations, a degree of iteration is required.

Boiling in annuli

This is treated by means of an equivalent diameter d_e that depends on the width of the annular gap:

$$d_e = \frac{4 \times \text{flow area}}{\text{wetted perimeter}} \quad \text{for gap} > 4 \text{ mm}$$
$$d_e = \frac{4 \times \text{flow area}}{\text{heated perimeter}} \quad \text{for gap} < 4 \text{ mm}. \quad (13)$$

Note that in the data only one of the annulus walls was heated.

Subcooled boiling

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

$$q = h_l(T_w - T_b) + Sh_{pool}(T_w - T_s) \quad (14)$$

There is no enhancement factor since there is no net vapour generation, but the suppression factor remains effective [calculated according to equations (9) and (10)]. It could be argued that there should still be an enhancement factor since there is still local vapour generation, but this approach gave a worse fit to the data.

TESTS OF THE VARIOUS CORRELATIONS AGAINST THE DATA

In addition to the equations developed as part of this study, i.e. equations (2)–(5) and (8)–(14), and the Chen and Shah correlations described in the introduction, a number of other correlations were programmed. These were the modified Chen correlation [3], the modified versions of the Rohsenow, Chawla and Kutateladze correlations proposed by Stephan and Auracher (i.e. as the original correlations [4] but with Stephan's pool boiling term). Also two sets of equations that are really intended for water only were included out of interest because they did not appear to have been compared with many different sources of data.

The results of the comparison of the correlations with all of the saturated boiling data in the data bank, i.e. 3693 data points, is shown in Table 2. In addition, Fig. 1 shows a comparison of the data with the equations recommended in this paper. For the purpose of drawing this figure only every 20th point for water and every 10th point for the other liquids was used. The overall results in Table 2 conceal of course some individual examples of very good or very poor agreement with the data of individual authors. For example, presumably something of a fluke, Bjorge's equation (which is intended for water) correlates Lavin's R22 data with a mean deviation of only 7.5%. On the other hand, the original Chen correlation gives 189% mean deviation with Chawla's data for R11.

Stephan and Auracher found reasonable agreement between their data file and the modified versions of the Rohsenow, Kutateladze and especially Chawla equations that they proposed, though they do not

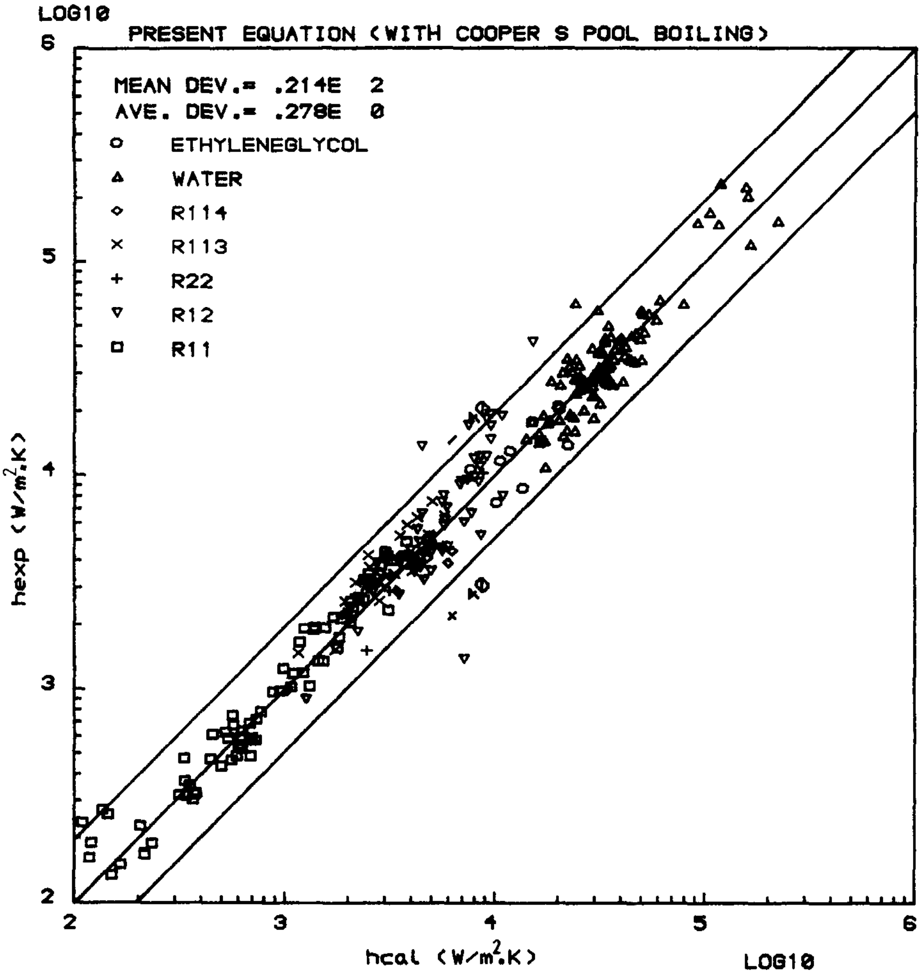

FIG. 1. Comparison of the equations proposed in this paper with the data.

quote any mean deviation values. In Table 2 the agreement is not very good. The reason for this discrepancy is not clear, though the data is not the same. Where the same data sources were used we have considerably more individual data points. In ref. [43] it is shown that large discrepancies are possible if only part of the data is used.

The two equations intended only for use with water give, not surprisingly, poor results with refrigerants or with data for annuli, but Mumm's equation gives accurate results for water in spite of its simplicity. This is presumably because it includes a boiling number term.

Both the original Chen correlation and the later modification [3] give poor results with refrigerants.

Only the equations developed in the present paper and those of Shah give reasonable agreement with all of the saturated boiling data. If a more detailed comparison is made with data of individual authors the disagreement (on mean deviation) does not exceed 58% (present study) or 65% (Shah). The other correlations give maximum errors, compared with data from individual authors, of from 67% to 253%. Presumably these large errors arise from the parameters of the data, such as pressure, mass flux, etc., being outside the range for which the correlation was developed. If these correlations are used for prediction it must be accepted that errors as large as 100% or more could occur.

In virtually all cases the predictions for annuli are closer using the equivalent diameter given by equation (13) instead of the usual hydraulic diameter.

For the comparison with subcooled boiling data, a number of other correlations, specifically for subcooled boiling, were programmed in addition. The results of the comparison are shown in Table 3. The two correlations that performed well with the saturated boiling data give mean deviations of 35.5% (Shah) and 25.0% (present study). Only the Moles and Shaw equation, which is specifically for subcooled boiling, with 22.6% mean deviation, is better than the equations of the present study.

DISCUSSION

At an earlier stage the Stephan and Auracher [4] pool boiling equation was used in place of equation (8). It gave nearly as good results, but since the Cooper equation is very much simpler it is the one that is

Table 2. Percentage deviation between the various correlations and the data for saturated boiling

Data	Number of data points	Modified Chawla [4]		Modified Rohsenow [4]		Modified Kutaeladze [4]		Mumm [6]		Shah [2]		Standard Chen [1]		Modified Chen [3]		Bjorge [5]		Present work	
		Mean	Ave.	Mean	Ave.	Mean	Ave.	Mean	Ave.	Mean	Ave.	Mean	Ave.	Mean	Ave.	Mean	Ave.	Mean	Ave.
Ethylene glycol	101	33.3	19.0	29.7	10.0	30.7	−24.3	49.6*	−49.6	21.4	−7.4	51.0	−50.1	19.1	−12.1	105.7*	79.4	28.3	5.7
Refrigerants	1701	36.1	0.8	41.9	0.6	42.9	−30.0	43.6*	−27.3	22.6	−4.3	91.7	55.9	114.1	94.2	62.2*	16.0	21.3	−3.9
Water (tube)	1269	46.5	22.8	30.7	−5.9	34.7	−33.7	22.7	1.7	17.4	−9.5	30.1	−25.8	27.6	−1.9	37.8	−31.0	17.1	−5.2
Annulus†	622	75.9	70.2	28.6	−16.9	43.4	−43.2	97.5	94.0	45.0	41.0	38.0	27.3	81.6	72.3	100.9	83.4	51.8	48.6
Annulus‡	622	39.7	18.1	29.1	−18.2	44.2	−44.0	75.6	69.7	29.1	21.8	22.5	5.6	55.9	44.9	88.8	68.9	29.4	22.2
All water‡	1891	44.3	21.2	30.2	−10.0	37.8	−37.1	40.1	24.1	21.3	0.8	27.6	−15.4	36.0	12.4	54.6	1.8	21.1	3.8
All saturated	3693	40.2	11.8	35.6	−4.6	40.0	33.5	42.0	−1.6	21.9	−1.8	57.7	16.5	71.5	49.4	59.5	10.5	21.4	0.3

* Not applicable to that data but if it is applied, it gives table result.

† If the diameter is replaced by the hydraulic diameter.

‡ If the diameter is replaced by the equivalent diameter [equation (15)].

$$\text{Mean deviation} = \frac{1}{n}\sum_{1}^{n}\left|\frac{(h_{\mathrm{cal}}-h_{\mathrm{exp}})\,100}{h_{\mathrm{exp}}}\right|$$

$$\text{Average deviation} = \frac{1}{n}\sum_{1}^{n}\frac{(h_{\mathrm{cal}}-h_{\mathrm{exp}})\,100}{h_{\mathrm{exp}}}.$$

Table 3. Percentage deviation between the various correlations and the data for subcooled boiling

Data source	Modified Chawla* [4]		Modified Rohsenow*		Modified Kutateladze*		Mumm* [6]		Shah* [2]		Chen [1]		Modified Chen [3]		Bjorge† [5]		Present		Jens–Lottes [13]†		Thom† [14]		Papell [15]		Badiuzzamman [12]		Moles [16]	
	Mean	Ave.	Mean	Ave.	Mean	Ave.	Mean	Ave.	Mean	Ave.	Mean	Ave.	Mean	Ave.	Mean	Ave.	Mean	Ave.	Mean	Ave.	Mean	Ave.	Mean	Ave.	Mean	Ave.	Mean	Ave.
[38]	35	20	26	−24	48	−48	32	−32	36	−35	26	−16	82	−82	28	−20	28	−18	90	89	130	130	7	7	14	14	25	−25
[36]	280	280	68	68	40	15	42	16	42	7	64	7	94	−37	453	393	41	−21	54	−54	20	−17	147	143	60	47	40	2
[39]	456	455	50	30	27	−9	127	118	95	82	18	14	68	−68	26	26	17	12	80	64	305	305	8	1	31	31	15	−15
[15]	102	89	37	−6	38	−36	33	−12	33	−20	27	27	70	−69	22	19	24	16	124	119	145	144	18	18	49	49	5	−4
[40]	123	121	41	33	20	−7	55	49	31	19	20	−5	58	−58	21	−1	22	−8	42	37	58	57	73	73	11	1	22	−22
[41] R11	41	13	34	−18	43	−43	47	−47	37	−27	37	−37	56	−55	51	−51	33	−30	128	128	47	−0	176	165	43	−31	37	11
[41] R12	57	47	38	17	38	−14	40	−14	40	−10	29	10	42	−33	26	−6	31	13	133	133	31	−3	163	163	44	44	27	6
All	130	123	41	20	29	−16	50	23	36	5	27	−2	65	−60	62	29	25	−8	71	58	82	72	76	73	26	3	23	−13

* This equation has not been recommended for subcooled boiling but if it is applied tabulated results are obtained.

† This equation is not applicable to the refrigerant data.

recommended. It does not require values of surface tension.

Only the correlation developed in this paper gives reasonable results for both saturated and subcooled boiling. For saturated boiling it is similar in accuracy to the Shah correlation (but requires slightly fewer equations). For subcooled boiling it is nearly as good as the best of the correlations developed specifically for this boiling regime.

The final equations [i.e. (9) and (10)] were not fitted to all of the data currently in the data bank. The data for subcooled boiling and boiling in annuli were not used, but subseuqently were found to be in good agreement with the equations. Also, as a final test of the equations, further data were found [10, 21] for water and two new fluids (R114 and ethylene glycol) which were in good agreement, giving mean deviations of 14.8–28.3%. The results in Table 2 refer to all the data currently in the data bank, i.e. including this further data.

CONCLUSIONS

Flow boiling heat transfer, for saturated and subcooled conditions, vertical and horizontal flow, tubes and annuli, can be predicted with reasonable accuracy by the equations given in this paper.

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UNE RELATION GENERALE POUR L'EBULLITION FORCEE DANS LES TUBES ET LES ESPACES ANNULAIRES

Résumé—Une nouvelle formule générale pour l'ébullition en convection forcée est développée à l'aide d'une grande banque de données. Celle-ci concerne 4300 points de mesures pour l'eau, les réfrigérants et l'éthylène glycol, couvrant sept fluides et 28 auteurs; la plupart des points pour l'ébullition saturée dans des tubes verticaux et horizontaux, mais avec une information significative aussi pour l'ébullition sous-refroidie et pour les espaces annulaires. La nouvelle relation est plus simple à appliquer et donne généralement une meilleure adaptation aux données que les formules existantes. La déviation moyenne entre les coefficients de transfert calculé et mesuré est de 21,4% pour l'ébullition saturée et de 25% pour l'ébullition sous-refroidie.

EINE ALLGEMEINGÜLTIGE GLEICHUNG FÜR STRÖMUNGSSIEDEN IN ROHREN UND RINGSPALTEN

Zusammenfassung—Unter Verwendung einer großen Datenbank wurde eine neue allgemeingültige Korrelation für das Sieden bei erzwungener Konvektion entwickelt. Die Datenbank enthält über 4300 Datenpunkte für Wasser, Kältemittel und Äthylenglykol. Sie beinhaltet sieben Stoffe und 28 Autoren, meist für gesättigtes Sieden und für Ringspalte. Die neue Korrelation ist einfacher in der Anwendung und zeigt eine bessere Anpassung an die Daten als bestehende Korrelationen. Die mittlere Abweichung zwischen den berechneten und gemessenen Wärmeübergangskoeffizienten beim Sieden beträgt 21,48% für gesättigtes Sieden und 25,0% für unterkühltes Sieden.

ОБОБЩЕННОЕ СООТНОШЕНИЕ ДЛЯ ТЕПЛООБМЕНА ПРИ КИПЕНИИ В ТРУБАХ И КОЛЬЦЕВЫХ КАНАЛАХ

Аннотация—С использованием большого банка данных получено новое обобщенное соотношение для коэффициента теплообмена при кипении в смысле вынужденной конвекции. Банк данных включает свыше 4300 данных для воды, хладагентов и этилен глюколя, охватывающих данные 28 авторов по 7 жидкостям в основном для кипения насыщенной жидкости в вертикальных и горизонтальных трубах, причем значительная часть информации относится к кипению недогретой жидкости и для кольцевых каналов. Новое соотношение более просто в применении и в общем дает более близкое совпадение с данными, чем существующие. Среднее отклонение между рассчитанным и измеренным коэффициентами теплообмена при кипении составляет 21,4% для кипения насыщенной жидкости и 25,0% для кипения недогретой жидкости.