Int. J. Heat Mass Transfer. Vol. 24, pp. 99–107
Pergamon Press Ltd. 1981. Printed in Great Britain

0017-9310/81/0101-0099 $02.00/0

CORRELATIONS FOR NUCLEATE BOILING HEAT TRANSFER IN FORCED CONVECTION

KARL STEPHAN and HEIN AURACHER
Universität Stuttgart, 7000 Stuttgart 80, F. R. Germany

(*Received* 26 *February* 1979)

Abstract—As shown in a recent paper [9] the many existing data for natural convection nucleate boiling are well represented by using a different set of dimensionless numbers for different groups of substances. Furthermore a general equation valid for all substances could be built up. The influence of forced convection is now considered. It may be taken into account by an additional term. Existing experimental data could be fairly well correlated by introducing the new pool boiling equation into an equation by Chawla.

NOMENCLATURE

b,	$\sqrt{\left(\frac{\sigma}{g(\rho_l - \rho_g)}\right)}$, Laplace constant [m];
c_p,	specific heat capacity [J $\mathrm{kg^{-1}\,K^{-1}}$];
D,	tube diameter [m];
d,	break-off diameter [m];
g,	acceleration of gravity [$\mathrm{m\,s^{-2}}$];
Δh_v,	specific latent heat of vaporization [J $\mathrm{kg^{-1}}$];
$\dot{m}$,	mass velocity [$\mathrm{kg\,m^{-2}\,s^{-1}}$];
p,	pressure [$\mathrm{N\,m^{-2}}$];
p_k,	critical pressure [$\mathrm{N\,m^{-2}}$];
$\dot{q}$,	heat flux density [$\mathrm{W\,m^{-2}}$];
R_p,	mean roughness according to DIN (Deut. Ind. Norm) 4762;
T,	thermodynamic temperature [K];
x,	quality.

Greek symbols

α,	heat-transfer coefficient [$\mathrm{W\,m^{-2}\,K^{-1}}$];
β,	contact angle (water $\beta = 45°$, refrigerants and hydrocarbons $\beta = 35°$, cryogenic fluids $\beta = 1°$);
κ,	thermal diffusivity [$\mathrm{m^2\,s^{-1}}$];
λ,	thermal conductivity [$\mathrm{W\,m^{-1}\,K^{-1}}$];
ν,	kinematic viscosity [$\mathrm{m^2\,s^{-1}}$];
ρ,	mass density [$\mathrm{kg\,m^{-3}}$];
σ,	surface tension [$\mathrm{N\,m^{-1}}$].

Subscripts

B,	boiling in natural convection;
c,	cover on the surface of the heater;
g,	gas (vapour);
h,	heater-surface;
K,	forced convection;
l,	liquid;
s,	saturation.

INTRODUCTION

NUCLEATE boiling heat transfer in forced convection is mainly governed by the mechanism of nucleation as it is observed in natural convection boiling heat transfer as well. An additional effect of minor importance is due to the influence of forced convection. Empirical correlations and models, therefore, are based on experiments in natural convection nucleate boiling and often consider the influence of forced convection either by a factor or by an additional term. This procedure is based on the idea that bubble growth is scarcely influenced by the flow pattern as long as bubbles are smaller than the super-heated boundary layer. Though it is now possible to study formation of a single bubble in forced convection boiling from a solution of the partial differential equations (1)–(4) neither the temperature profile near a heated wall nor the flow pattern can be predicted since no safe predictions are possible of the number and distribution of active cavities and of their dependence on superheat and thermal properties. The link, still missing, in a general theory of boiling heat transfer concerns the relationship between the processes around a single bubble and the interactions of a great number of the single phenomena.

In order to escape from this unsatisfactory situation and to obtain at least empirical correlations some authors start from the fact that the process of heat transfer in forced convection nucleate boiling is similar to that in natural convection boiling as long as the heater is covered by the boiling liquid. Different procedures are employed in the technical literature. Part of them are based on the fact that in the range of forced convection nucleate boiling vapour contents are comparatively low. Equations neglect therefore the vapour content. They usually contain two terms, one for the heat transfer in natural convection nucleate boiling and a further term for forced convection heat transfer without boiling. As an example equations by Kutateladze [5] should be mentioned or those recommended by Rohsenow [6]. As a matter of fact equations of this kind may serve as a rough approximation. They do not include, however, the vapour content, which according to experiments is often not completely negligible. Better approximations therefore may be expected, when establishing equations taking into account the influence of the vapour content. An equation of this kind was proposed by Chawla [7]. He based his equation on heat transfer in natural convection boiling according to an equation by Stephan [8] and corrected it by a factor taking into account also the vapour content.

However, at present the application of the above mentioned equations is limited to a few fluids and thermal conditions only. One of the reasons for this situation is the fact that most of the equations for natural convection heat transfer in nucleate boiling are only valid for specific systems of heater and boiling liquid and for a limited pressure range. Furthermore they include factors and exponents to be fitted to the experimental data of the given system. Another reason is the lack of experiments in forced convection nucleate boiling.

In order to establish equations with a wider application in a recent paper [9] the existing experimental data in natural convection boiling were critically reviewed and correlated. In the present paper these equations served as a basis for correlating heat transfer data in forced convection nucleate boiling.

EQUATIONS FOR HEAT TRANSFER IN NATURAL CONVECTION BOILING

At first the procedure for obtaining correlations in natural convection boiling according to [9] shall be described. Starting from the fact that certain groups of thermal properties are decisive for natural convection boiling heat transfer the corresponding dimensionless numbers may be built up. As already stated in other papers (e.g. [8, 9]) an appropriate set of the dimensionless numbers X_i is given by

$$X_1 = (\dot{q}d)/(\lambda_l T_s); \qquad X_2 = (\kappa_l^2 \cdot \rho_l)/(\sigma d);$$

$$X_3 = (c_{pl} T_s d^2)/\kappa_l^2; \qquad X_4 = (\Delta h_v d^2)/\kappa_l^2;$$

$$X_5 = \rho_g/\rho_l; \qquad X_6 = \nu_l/\kappa_l;$$

$$X_7 = \kappa_l^2/(d^3 g); \qquad X_8 = Rp/d;$$

$$X_9 = (\rho c_p \lambda)_c/(\rho c_p \lambda)_l; \qquad X_{10} = (\rho c_p \lambda)_h/(\rho c_p \lambda)_l;$$

$$X_{11} = \kappa_h/\kappa_l; \qquad X_{12} = \kappa_c/\kappa_l.$$

The Nusselt number $Nu_B = Y = (\alpha_B d)/\lambda_l$ and these dimensionless numbers are correlated by

$$Y = f(X_1, X_2 \ldots X_{12}). \tag{1}$$

In the following analysis we do not assume that the above set of dimensionless numbers is complete. It must only include the essential dimensionless numbers, a condition which is undoubtedly all the more fulfilled since all thermal properties influencing heat transfer in natural convection boiling are included in the values X_i.

THE REGRESSION ANALYSIS

A very powerful tool to find a correlation between the Nusselt number and the values X_i is given by the regression analysis, which proved to be very useful in statistical economics [10, 11]. Recently Wagner [12, 13] applied this method to obtain a vapour pressure equation from experimental data. The regression analysis represents a method for deriving a correlation between a dependent and several independent variables. It is based on two assumptions

(i) A sufficient large number of experimental data must be available describing the influence of the essential variables in a wide range. The quality of the correlation depends decisively on the number and accuracy of the experimental data.

(ii) A general form of equation (1) must be known including all essential variables.

In fact there exist a great number of experimental data on heat transfer in natural convection boiling for many substances especially for water, hydrocarbons, cryogenic fluids and refrigerants, substances which are often used in technical applications. An appropriate form of equation (1) is a power law which proved to be very efficient in many heat transfer problems. It is, however, disadvantageous that the pressure dependency of heat-transfer coefficients then is mainly represented by a power of $X_5 = \rho_g/\rho_l$ which does not fit with the experiments over a wider pressure range. The pressure dependency may be much better described, as confirmed by the following results, when introducing an additional term $X_{13} = (\rho_l - \rho_g)/\rho_l$ in the power law. Instead of the general equation (1) we use therefore a power law

$$\hat{Y} = e^{\beta_0} X_1^{\beta_1} X_2^{\beta_2} \ldots X_{13}^{\beta_{13}}. \tag{2}$$

Herein $\hat{Y}$ is the dependent variable, which according to the approximative character of equation (2) may be slightly different from the Nusselt number $Nu_B = Y$. The exponents β_i are still unknown. The regression analysis does not aim at estimating all exponents β_i. This could be done by a mere adjustment to the experiments. The regression analysis rather allows to select those values X_i, which exert the most remarkable influence on the dependent variable $\hat{Y}$. This selection may be achieved in different steps according to the following scheme:

In a first step for each of the independent variables an equation of the form

$$\hat{Y} = e^{\mu_0} X_1^{\mu_1} \tag{3}$$

is assumed, where X_1 now stands for each of the 13 variables. For each of them the exponents μ_0 and μ_1 are evaluated according to the method of least error.† From all the different equations employed in the analysis that one contains the most essential dimensionless number X_1^*, which yields the smallest square error sum

---

† The values are determined by the methods of linear and non-linear regression analysis as well [11]; the results from the linear analysis represented experimental data better than those from the non-linear analysis.

$$Q_1 = \sum_{i=1}^{n} (Y_i - \hat{Y}_i)^2. \tag{4}$$

In a second step for the remaining 12 independent variables an equation of the form

$$\hat{Y} = e^{\mu_0} \cdot X_1^{*\mu_1} X_2^{\mu_2} \tag{5}$$

is introduced, where X_1^* is the most essential variable from the first step and X_2 stands for the other remaining variables. For each of these variables the square error sum Q_2 is calculated and yields the next essential variable X_2^*. The procedure is continued until the experimental accuracy is well represented by the power law. This is usually achieved when using only a limited number of the above mentioned variables. Introduction of further dimensionless numbers then does not improve the result.

SELECTION OF SUBSTANCES AND DATA

In their paper [9] Stephen and Abdelsalam applied the above described method of regression analysis on experimental data of natural convection heat transfer. They selected and critically reviewed the data under the following aspects:

(a) Only pool boiling data concerning boiling on horizontal surfaces were considered.
(b) Boiling should take place in a gravity field and in the range of fully established pool boiling.
(c) Reports should inform on the material of the heater used in the experiments.

These conditions were fulfilled by about 5000 data taken from 72 papers. Many of the authors represented their experimental data by fitting curves and did not publish the original data. Others also communicated the original data. In these cases the measuring points were fitted by curves $\alpha_B(\dot{q})$ and each of these represented by a certain number (usually four) of characteristic points, which were used then for the analysis. Thus the total of 5000 original measuring points were replaced by 1553 characteristic points. Due to the different range of values of some of the dimensionless numbers X_i for different substances some of these numbers important for certain substances turned out to be unimportant for others. It seemed to be reasonable therefore to subdivide the substances in four groups, namely water, hydrocarbons, cryogenic fluids and refrigerants and establish in a first step a seperate correlation for each of these groups. This procedure seemed to be justified all the more as each of the groups were represented by the same number of about 400 characteristic points. Eventually an overall-correlation valid for all substances of the four groups was established, its accuracy being below that of the correlation for the single groups.

In a first course of the analysis all the 1553 characteristic points were used in order to establish the correlation (2). When comparing then the results from the correlation with the characteristic points it turned out that a certain number of characteristic points deviated considerably from the results of the correlation and also from results of other authors. These characteristic points were then eliminated from a further analysis. There remained thus 983 characteristic points, representing 2806 original data in a wide pressure range between $0.0001 \le p/p_K \le 0.97$. From a second analysis with these characteristic points the final correlations were established.

RESULTS

As a result the following equations were obtained:

For *water* in a pressure range between $0.0001 \le p/p_k \le 0.8865$

$$\frac{\alpha_B \cdot d}{\lambda_l} = 0.246 \times 10^7 \left(\frac{\kappa_l^2}{\Delta h_v d^2}\right)^{1.58} \left(\frac{\dot{q} d}{\lambda_l T_s}\right)^{0.673} \left(\frac{c_{p_l} T_s d^2}{\kappa_l^2}\right)^{1.26} \left(\frac{\rho_l - \rho_g}{\rho_l}\right)^{5.22}, \tag{6}$$

mean deviation from the characteristic points $\pm$ 11.3%. For reasons of simplicity the equation

$$\alpha_B = C_1 \dot{q}^{0.673} \tag{6a}$$

is recommended, where C_1 depends on the pressure according to Fig. 1.

For *hydrocarbons* in a pressure range between $0.0057 \le p/p_k \le 0.9$

$$\frac{\alpha_B d}{\lambda_l} = 0.0546 \left(\left[\frac{\rho_g}{\rho_l}\right]^{0.5} \left[\frac{\dot{q} d}{\lambda_l T_s}\right]\right)^{0.67} \left(\frac{\rho_l}{\rho_l - \rho_g}\right)^{4.33} \left(\frac{\Delta h_v d^2}{\kappa_l^2}\right)^{0.248}, \tag{7}$$

mean deviation from the characteristic points $\pm$ 12.2%.

For *cryogenic fluids* in a pressure range between $0.004 \le p/p_k \le 0.97$

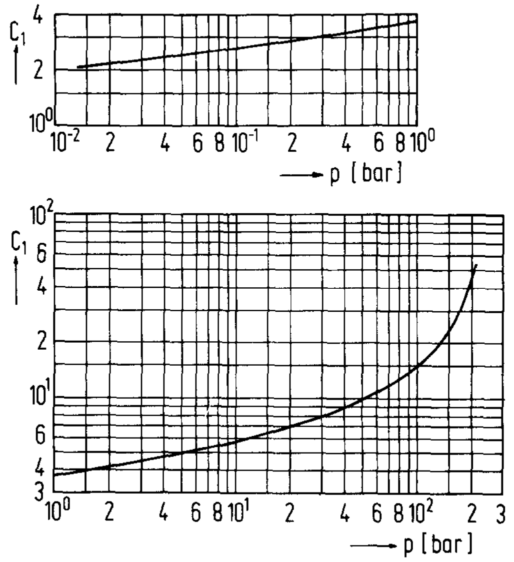

FIG. 1. Pressure dependence of constant C_1 in equation (6a).

$$\frac{\alpha_B d}{\lambda_l} = 4.82\left(\frac{c_{p_l} T_s d^2}{\kappa_l^2}\right)^{0.374}\left(\frac{\dot{q} d}{\lambda_l T_s}\right)^{0.624}$$

$$\times\left(\frac{\rho_g}{\rho_l}\right)^{0.257}\cdot\left(\frac{(\rho c_p \lambda)_c}{\rho_l c_{p_l} \lambda_l}\right)^{0.117}\left(\frac{\kappa_l^2}{\Delta h_v d^2}\right)^{0.329}, \quad (8)$$

mean deviation from the characteristic points ± 14.3%.

For *refrigerants* in a pressure range between $0.003 \leq p/p_k \leq 0.78$

$$\frac{\alpha_B d}{\lambda_l} = 207\left(\frac{\dot{q} d}{\lambda_l T_s}\right)^{0.745}\left(\frac{\rho_g}{\rho_l}\right)^{0.581}\left(\frac{\nu_l}{\kappa_l}\right)^{0.533}, \quad (9)$$

mean deviation from the characteristic points ± 10.6%.

For *all substances* in a pressure range between $0.0001 \leq p/p_k \leq 0.97$

$$\frac{\alpha_B d}{\lambda_l} = 0.230\left(\frac{\dot{q} d}{\lambda_l T_s}\right)^{0.674}\left(\frac{\rho_g}{\rho_l}\right)^{0.297}$$

$$\times\left(\frac{\Delta h_v d^2}{\kappa_l^2}\right)^{0.371}\left(\frac{\rho_l}{\rho_l - \rho_g}\right)^{1.73}\left(\frac{\kappa_l^2 \rho_l}{\sigma d}\right)^{0.350}, \quad (10)$$

mean deviation from the characteristic points ± 22.3%.

EQUATIONS FOR HEAT TRANSFER IN FORCED CONVECTION BOILING

As already mentioned the mostly employed equations contain as an essential term the heat transfer coefficient for natural convection boiling. When replacing these terms by the new equations (6)–(10) one obtains modified correlations, which are expected to apply to more substances with reasonable accuracy. As a prerequisite for this at first the main procedures for evaluating heat-transfer coefficients in forced convection boiling shall be briefly summarized.

Rohsenow's [6] equation is based on the assumption that the total heat flux density $\dot{q}$ is made up of two parts. The main part $\dot{q}_B$ is due to the mechanism of bubble formation and microconvection around the bubbles as it is observed in natural convection boiling, an additional part $\dot{q}_K$ comes from the influence of forced convection

$$\dot{q} = \dot{q}_B + \dot{q}_K. \quad (11)$$

The first term in this equation is calculated from Rohsenow's equation on natural convection boiling heat transfer

$$Nu_B = (\alpha_B b)/\lambda_l = C_f\, Re_B^{0.667}\, Pr^{-0.7}, \quad (12)$$

where the heat-transfer coefficient α_B is defined through $\alpha_B = q_B/(T_w - T_s)$, b is the Laplace constant and the Reynolds number Re_B and Prandtl number Pr are given by $Re_B = (\dot{q}_B b)/(\nu_l \cdot \Delta h_v \rho_l)$ and $Pr = \nu_l/\kappa_l$.

The factor C_f in equation (12) considers the thermal properties of the heater and the interaction between wall and boiling liquid. Values of C_f for different systems of heater and boiling liquid were given elsewhere [6]. The convective term $\dot{q}_K$ in equation (11) may be evaluated from the Colburn equation

$$Nu_K = (\alpha_K \cdot D)/\lambda_l = 0.023\, Re_K^{0.7} \cdot Pr^{0.33}, \quad (13)$$

with the Reynolds number $Re_K = (\dot{m}D)/(\nu_l \rho_l)$ and the Prandtl number $Pr = \nu_l/\kappa_l$.

A similar procedure for calculating heat transfer coefficients has been proposed by Kutateladze [5]. His equation also includes a heat transfer coefficient α_α for boiling without any influence of forced convection and is given by

$$\alpha/\alpha_K = [1 + (\alpha_\alpha/\alpha_K)^2]^{1/2}. \quad (14)$$

According to Borishansky *et al.* [14, 15] α_α is related to the heat-transfer coeffiicient α_B in natural convection boiling

$$\alpha_\alpha = 0.7\,\alpha_B \quad (14a)$$

with

$$\alpha_B = 3(0.18 \cdot p^{0.14} + 1.60 \times 10^{-14} p^2)\dot{q}^{0.7} \quad (14b)$$

for boiling water; p is the pressure in N m^{-2} and $\dot{q}$ the heat flux in W m^{-2}. For the convective term α_K in equation (14) the Dittus–Boelter equation $Nu_K = (\alpha_K D)/\lambda_l = 0.023\, Re_K^{0.8}\, Pr^{0.4}$ is recommended.

From experiments with boiling water flowing in tubes and other ducts Borishansky *et al.* [16] found that equation (14) yields fairly accurate results if the dimensionless number

$$(w_m\, \Delta h_v \rho_l)/\dot{q} < 5 \times 10^4, \quad (15)$$

where

$$w_m = \dot{m}[(1 - x)/\rho_l + x/\rho_g]. \quad (16)$$

Criterion (15) was experimentally verified for water in the pressure range 2 bar $\leq p \leq$ 170 bar and furthermore 0.8×10^5 W m^{-2} $\leq \dot{q} \leq 6 \times 10^6$ W m^{-2}, 1 m s^{-1} $\leq w_m \leq$ 300 m s^{-1} and 4 mm $\leq D \leq$ 32 mm.

Contrary to the above equations Chawla [7] developed a procedure taking into account also the influence of vapour content. From his experiments he derived the equation

$$\alpha/\alpha_B = 29\, Re_l^{-0.3}\, Fr_l^{0.2} \quad (17)$$

with $Re_l = [\dot{m}D(1 - x)]/\rho_l \nu_l$ and $Fr_l = [\dot{m}^2(1 - x)^2]/(\rho_l^2 g D)$. For α_B he recommended an equation by Stephan [8]

$$Nu_B = (\alpha_B d)/\lambda_l = 0.071\, K_1^{0.7}\, K_2^{0.3}\, K_3^{0.133}, \quad (18)$$

where $d = 0.0204\, b\, \beta$ is the break-off diameter of vapour bubbles with the Laplace constant b and the contact angle β. The dimensionless numbers are defined as $K_1 = (\dot{q}d)/(\lambda_l T_s)$, $K_2 = (d T_s \lambda_l)/(\nu_l \sigma)$ and $K_3 = (R_p \rho_g \Delta h_v)/(fd)^2\, d\, \rho_l$. Herein f stands for the bubble frequency, which according to McFadden and Grassmann [17] is given by $f^2 d = 3.06$ m s^{-2}.

For sufficient high fluid velocities and vapour contents the dependence of heat flux becomes smaller and equation (17) is no longer applicable; instead of equation (17) another correlation should be used, also derived e.g. by Chawla. According to him and also to

Table 1. Range of conditions for data used in testing correlations.

No.	Ref.	Fluid	Geometry	Diam./mm	Material, Surface	Flow
1	Chawla [7]	R11	tube, horiz.	25	copper	—
2	Chawla [7]	R11	tube, horiz.	14	copper	—
3	Chawla [7]	R11	tube, horiz.	6	copper	—
4	Bandel [22]	R12	tube, horiz.	14	copper	—
5	Kaufmann [24]	R12	tube, vert.	20, 5	stainl. st.	up
6	Haffner [23]	R12	tube, vert.	15	stainl. st., sandblast	up
7	Bandel [22]	R22	tube, horiz.	14	copper	—
8	Jallouk [20]	R114	tube, horiz.	20	copper	—
9	Morozov [21]	water	tube, vert.	32	stainl. st., honed	up
10	Steiner [25]	N_2	tube, horiz.	14	copper, $Rp = 0.09$ μm	—
11	Klein [26]	N_2	tube, horiz.	12	copper	—
12	Mohr [27]	neon	tube, horiz.	4	copper	—

No.	Number of data	Criterion of Select.	Press. bar	Heat flux density W m^{-2}	Mass velocity kg m^{-2} s^{-1}	Quality
1	65	Chawla	0.61	4652–13 956	14–54.4	0.10–0.90
2	56	Chawla	0.61	9304–23 260	7.9–49.2	0.10–0.80
3	48	Chawla	0.61	13 956–93 040	2.3–14.5	0.10–0.80
4	142	Observ. by [22]	3.09	2141–70 520	91.8–726.1	0.09–0.91
5	52	Observ. by [24]	11.2–29.7	9610–111 320	658.0–4850	0.02–0.20
6	35	Chawla	6.9–29.5	14 900–200 000	543.3–928.1	0.04–0.33
7	131	Observ. by [22]	3.56	3223–71 470	86.4–749.9	0.10–0.81
8	237	Chawla	3.21; 6.75; 12.28	8739–82 066	162.7–1256.9	0.01–0.84
9	85	Equation (15)	31.4; 41.3	116 300–515 209	772.7–1621.3	0.01–0.34
10	355	Observ. by [25]	6.0–16	300–40 000	40–450	0.02–1.0
11	23	Crit. by [26]	3.0	10 000–50 000	154.5–257.4	0.10–0.90
12	38	Crit. by [27]	1.44	10 430–45 780	74–128	0.16–0.76

Kutateladze and Borishansky [18] it is recommended to use that relation which gives the higher transfer coefficient. Therefrom a criterion for the range of validity of equation (17) has been derived by Chawla [7], which was also applied in this paper.

In the following the heat transfer coefficient α_B for natural convection boiling in equations (12), (14) resp. (14a) and (17) shall be replaced by those of equations (6)–(10) and these results for α compared with experimental data.

SELECTION OF DATA

Compared to natural convection boiling heat transfer data there exist a much smaller number of experiments for fully developed boiling in forced convection. Furthermore in order to test equation (17) the vapour content x must be known which unfortunately was specified only by a few authors.

Table 1 gives a survey of all experimental data disposable for the intended comparison. As the survey reveals, most experiments were done with refrigerants, whereas only a few data are available for water and cryogenic substances and no data at all exist for hydrocarbons. Table 1 also specifies the criteria for the selection of data. For refrigerants the Chawla criterion was used unless the author himself indicated what kind of flow pattern or kind of heat-transfer mechanism he observed in his experiments. The experimental data for water were selected according to the criterion of Borishansky, equation (15). Furthermore only those data were selected that fulfil the conditions for equation (6)–(10), which are only valid if the characteristic length of the heater, e.g. its diameter, is large compared to the break-off diameter of vapour bubbles. For this reason the well known data by Schrock and Grossmann [19] for boiling water inside tubes of 3 mm dia. were not used for a comparison with the correlation, because it seems useless to compare them with the results from an equation which is based on the assumption that tube diameters are of an order of magnitude larger than bubble diameters. In fact such experiments could not be fitted by the correlation.

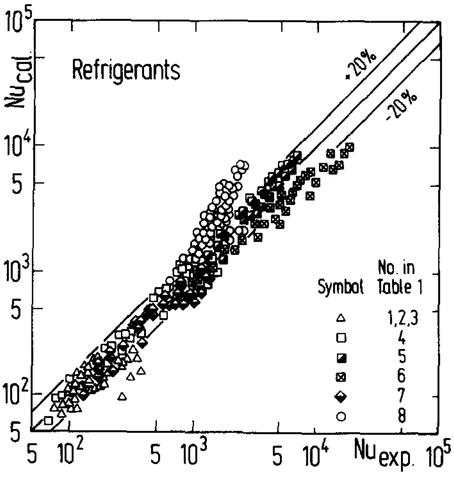

FIG. 2. Modified Chawla procedure, α_β calculated by equation (9).

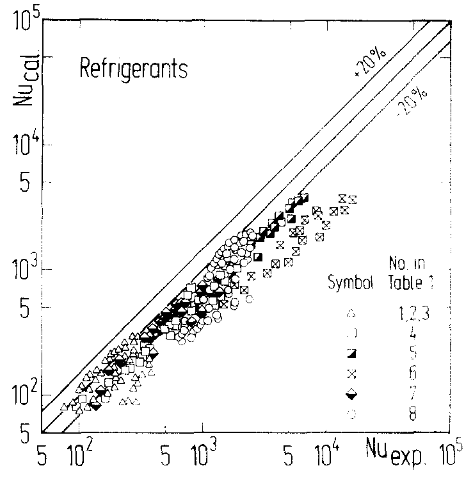

FIG. 3. Chawla procedure.

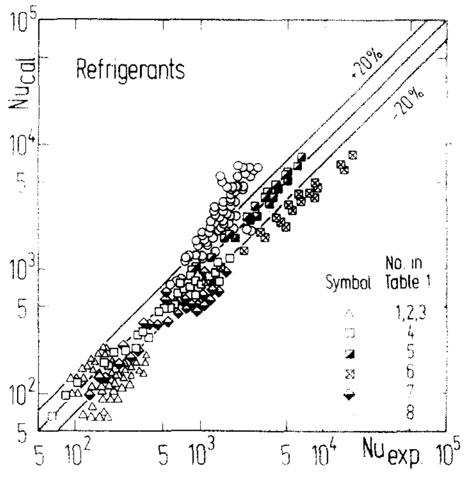

FIG. 6. Modified Rohsenow procedure, α_B calculated by equation (9).

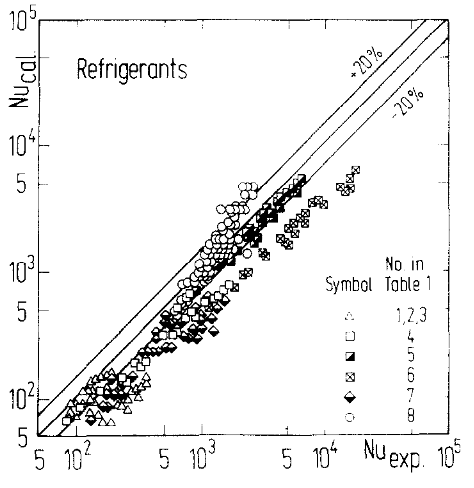

FIG. 4. Modified Kutateladze procedure, α_B calculated by equation (9).

RESULTS

As a result in Figs. 2–10 the calculated Nusselt numbers are plotted over those from experiments. All Nusselt numbers contain the tube diameter as a characteristic length. An attempt to compare with the results from Rohsenow's procedure, equations (11)–(13) failed, because the necessary constants C_f for the combinations heater and boiling liquid were not available.

Figures 2–6 compare the results for refrigerants. Obviously the introduction of equation (9) for the natural convection boiling heat transfer coefficient leads to a better representation of the experimental data. The good representation of the data by the modified Chawla equation seems to be noteworthy. Only the experiments by Jallouk [20] deviate considerably not only from the results of the correlation but also from the data of the other authors.

Experiments with water reported by Morozov [21]

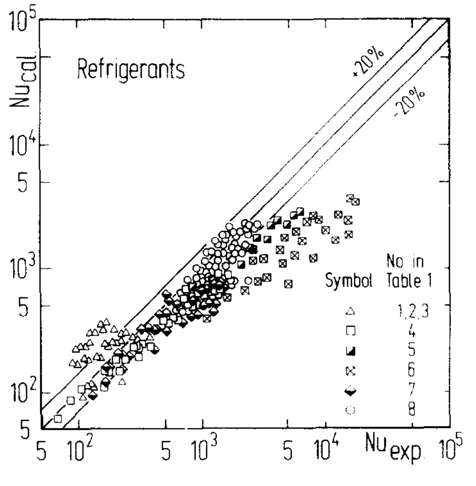

FIG. 5. Kutateladze procedure.

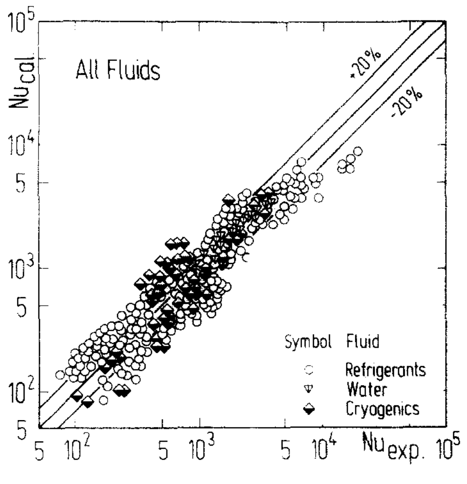

FIG. 7. Modified Chawla procedure, α_B calculated by general equation (10).

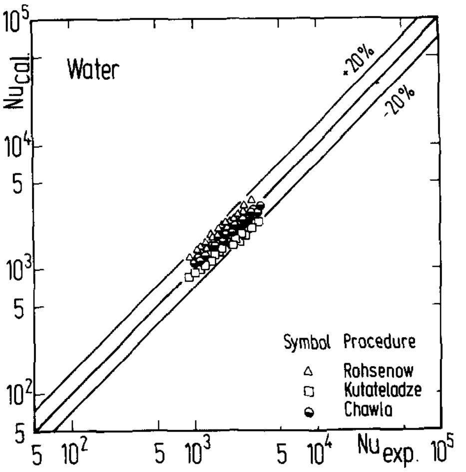

FIG. 8. Modified procedures by Rohsenow, Kutateladze and Chawla, α_B calculated by equation (6).

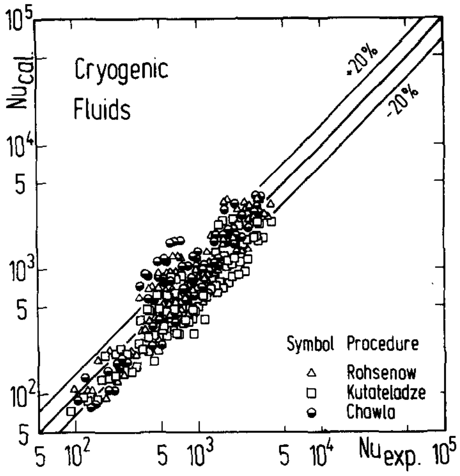

FIG. 10. Modified procedures by Rohsenow, Kutateladze and Chawla, α_B calculated by equation (10).

are better represented (Fig. 8) by the correlation modified by equation (6) than by former procedures (Fig. 9). As Fig. 8 shows the modified Chawla equation yields fairly accurate results. Figure 7 compares all experiments cited in Table 1 with the results from the modified Chawla equation. The heat transfer coefficients α_B now were calculated from equation (10) valid for all substances. Taking into account the great number of properties entering the equations the result seems to be satisfying. The accuracy is lower when employing the procedure by Kutateladze and Rohsenow. Figure 10 gives the results for cryogenics, where α_B also was calculated from the general equation (10) since no values for $(\rho c_p \lambda)_c$ in the individual equation (8) were reported in forced convection boiling.

SUMMARY AND CONCLUSIONS

Nucleate boiling heat transfer in forced convection is mainly governed by the mechanism of nucleation as it is observed in natural convection boiling heat transfer as well. An additional effect of minor importance is due to the influence of forced convection. By means of the regression analysis equations correlating the experiments data for nucleate boiling in natural convection were derived.

In order to calculate heat transfer coefficients in forced convection nucleate boiling the analysis was based on equations by Rohsenow, Kutateladze and Chawla, where the influence of forced convection is included in an additional term that corrects the heat transfer coefficient for nucleate boiling in natural convection. When replacing this coefficient by the new equations modified correlations are obtained. They allow a better representation of the experimental data than the original procedure. Especially good agreement is achieved by using the modified Chawla equations. Heat transfer for at least the often used liquids can thus be evaluated. In order to improve the accuracy of the equations, however, much more experiments on nucleate boiling in forced convection are required.

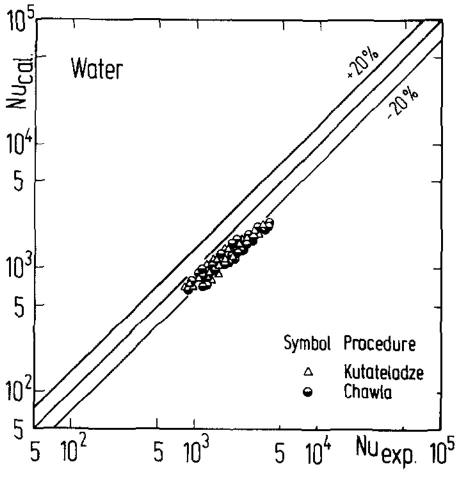

FIG. 9. Procedures by Kutateladze and Chawla.

REFERENCES

1. K. Stephan, in *Heat Transfer in Boiling*, pp. 3–20, edited by E. Hahne and U. Grigull. Academic Press, Washington (1977).
2. S. Levy, USAEC Report GEAP 5157.
3. H. Beer, Beitrag zur Wärmeübertragung beim Sieden, *Prog. Heat Mass Transfer* **2**, 311–370 (1969).
4. H. Beer, Das dynamische Blasenwachstum beim Sieden von Flüssigkeiten an Heizflächen, *Forsch. Geb. Ingwes*, **37**, 85–90 (1971).
5. S. S. Kutateladze, in *Fundamentals of Heat Transfer*, Arnold, London (1962).
6. W. M. Rohsenow, *Modern Develops in Heat Transfer*, p. 85, Academic Press, New York (1963).
7. J. M. Chawla, Wärmeübergang und Druckabfall in waagerechten Rohren bei der Strömung von verdampfenden Kältemitteln, *Forsch Hft. Ver. Dt. Ing.* **523** (1967).

8. K. Stephan, Beitrag zur Thermodynamik des Wärmeübergangs beim Sieden, *Abhandl. Deut. Kältetechn. Verein*, No. 18, C. F. Müller, Karlsruhe (1964).
9. K. Stephan and M. Abdelsalam, Heat-transfer correlations for natural convection boiling, *Int. J. Heat Mass Transfer* **23**, 73–87 (1980).
10. C. Craver and H. Boren, Multivariate logarithmic and exponential regression models, The Rand Corp., Memorandum RM-4879-PR (1967).
11. T. Yamane, in *Statistics. An Introductory Analysis*, 3rd ed. Happer (1973).
12. W. Wagner, *Fortschritts-Bericht Ver. Deut. Ing. Zeitschrift*, Reihe 3, Nr. 39 (1974).
13. W. Wagner, *IUPAC Thermodynamic Tables*. Proj. Center, Imperial College, London (1977).
14. V. M. Borishansky and I. I. Paleev, in *Convective Heat Transfer in Two- and One-Phase Flows, Collected Articles*. Energia Moscow (1964).
15. V. M. Borishansky and A. P. Kozyrev, Generalization of experimental data on nucleate boiling heat transfer based on the thermodynamic similarity theory, *Inzh. Fiz. Zh.*, No. 12 (1962).
16. V. M. Borishansky, I. I. Paleev, F. A. Agafonova, A. A. Andreevsky, B. S. Fokin, M. E. Lavzentiev, K. P. Malyus-Malitsky, V. N. Fromzel and G. P. Danilova, Some problems of heat transfer and hydraulics in two-phase flows, *Int. J. Heat Mass Transfer* **16**, 1073–1085 (1973).
17. P. W. McFadden and P. Grassmann, The relation between bubble frequency and diameter during nucleate pool boiling, *Int. J. Heat Mass Transfer* **5**, 169–173 (1962).
18. S. S. Kutateladze and V. M. Borishansky, in *A Concise Encyclopedia of Heat Transfer*, p. 207, Pergamon Press, Oxford (1966).
19. V. E. Schrock and L. M. Grossman, Local heat transfer coefficients and pressure drop in forced convection boiling, Lawrence Radiation Lab., Rep. No. UCRL-13062 (1957).
20. P. A. Jallouk, Two-phase flow pressure drop and heat transfer characteristics of refrigerants in vertical tubes, Diss. University of Tennessee (1974).
21. V. G. Morozov, Heat transfer during the boiling of water in tubes, in *Convective Heat Transfer in Two-Phase and One-Phase Flows*, pp. 106–114, edited by V. M. Borishansky and I. I. Paleev. Israel Progr. for Scient. Trans., Jerusalem (1969).
22. J. Bandel, Druckverlust und Wärmeübergang bei der Verdampfung siedender Kältemittel im durchströmten waagerechten Rohr, Diss. Universität Karlsruhe (1973).
23. H. Haffner, Wärmeübergang an Kältemittel bei Blasenverdampfung, Filmverdampfung und überkritischem Zustand des Fluids, Forschungsbericht K 70-24, Bundesministerium für Bildung und Wissen, Bonn (1970).
24. W. D. Kaufmann, Untersuchung des Wärmeübergangs und des Druckverlustes bei der Zweiphasenströmung von R 12 im senkrechten Rohr, Diss. No. 5196 ETH, Zürich (1974).
25. D. Steiner, Wärmeübergang und Druckverlust von siedendem Stickstoff bei verschiedenen Drücken im waagerecht durchströmten Rohr, Diss. Universität Karlsruhe (1975).
26. G. Klein, Wärmeübergang und Druckverlust bei Strömung von verdampfendem Stickstoff im waagerechten Rohr, *Chemie-Ingr.-Techn.* **49**, 757 (1977).
27. V. Mohr, Verdampfung von Neon in horizontalen Rohren, Diss. Universität Stuttgart (1975).

FORMULES POUR LE TRANSFERT THERMIQUE EN EBULLITION NUCLEEE AVEC CONVECTION FORCEE

Résumé—On présente des équations relatives au coefficient de transfert thermique par ébullition nucléée avec convection naturelle ou forcée. La plupart des données sur l'ébullition nucléée avec convection naturelle est bien représentée en utilisant un groupe différent de nombres sans dimension pour chaque groupe de substances. Néanmoins on peut construire une équation générale valide pour toutes les substances. L'influence de la convection forcée peut être considérée par un terme additionnel. Les données expérimentales existantes peuvent être correctement représentées en introduisant la nouvelle équation d'ébullition en réservoir dans une équation de Chawla.

GLEICHUNGEN ZUR BERECHNUNG DES WÄRMEÜBERGANGS BEIM BLASENSIEDEN IN ERZWUNGENER STRÖMUNG

Zusammenfassung — Wie kürzliche gezeigt wurde [9], kann man die vielen Versuchswerte über den Wärmeübergang beim Blasensieden in natürlicher Strömung gut wiedergeben, wenn man für verschiedene Stoffgruppen unterschiedliche Sätze von dimensionslosen Größen benutzt. Außerdem konnte eine für alle Stoffe gültige Gleichung ermittelt werden. Es wird nun der Einfluß der erzwungenen Strömung untersucht. Dieser läßt sich durch einen Zusatzterm in den bisherigen Gleichungen erfassen. Vorhandene Versuchswerte ließen sich mit guter Genauigkeit wiedergeben, indem man die neue Beziehung über den Wärmeübergang bei Blasenverdampfung in natürlicher Strömung in eine Gleichung von Chawla einführte.

ОБОБЩЕННЫЕ ЗАВИСИМОСТИ ДЛЯ ТЕПЛОПЕРЕНОСА ПРИ ПУЗЫРЬКОВОМ КИПЕНИИ И ВЫНУЖДЕННОЙ КОНВЕКЦИИ

Аннотация — Предложены корреляции для теплопереноса при пузырьковом кипении в условиях естественной и вынужденной конвекции. Большинство имеющихся данных по пузырьковому кипению при естественной конвекции хорошо описываются различными сочетаниями безразмерных критериев для различных групп веществ. Помимо этого, можно вывести общее уравнение, справедливое для всех веществ. Вводом дополнительного члена уравнения можно учесть влияние вынужденной конвекции. Имеющиеся экспериментальные данные довольно хорошо обобщаются с помощью нового соотношения для кипения в открытом объеме путем подстановки его в уравнение Чоулы.