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Fully developed nucleate boiling in upflow and downflow

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Abstract—Heat transfer coefficients from experiments on flow boiling with R12 are obtained for a wide range of pressure, mass flux, heat flux and flow quality. The experimental results are compared with seven different correlations given in the literature. Good agreement is found only for some correlations. Best agreement is found for the modified Chen correlation using the pool boiling equation by Gorenflo and the suppression factor by Bennett *et al.* In the correlation proposed by Bjorge *et al.* a numerical value for the constant B_M for R12 is recommended. With a minimum liquid velocity of 0.25 m s^{-1}, a clear effect of flow direction—upwards or downwards—cannot be observed.

1. INTRODUCTION

THERE ARE numerous investigations on forced convection boiling heat transfer, most of them are experimental. Because of the great variety of effective parameters and the complexity of the phenomena, theoretical analysis cannot provide a general equation for the boiling heat transfer coefficients for different substances and different conditions. All correlations given in the literature have a relatively large uncertainty and can be used only in restricted cases. For this reason measurements on heat transfer coefficients for different substances and different conditions still appear necessary.

According to heat transfer mechanisms, saturated flow boiling heat transfer can be divided into the following regions:

(1) partial nucleate boiling;
(2) fully developed nucleate boiling;
(3) convective evaporation; and
(4) film boiling.

Here, fully developed nucleate boiling is investigated and heat transfer coefficients of saturated R12 are measured in both upflow and downflow.

2. LITERATURE SURVEY

Seven flow boiling correlations from the literature have been checked for their applicability to our case. They are listed in Table 1, and their theoretical results are compared with our experimental data. For the calculation of heat transfer coefficients from these correlations the following parameters have to be given:

for the operating conditions $\dot{q}$, $\dot{m}$, $\dot{x}$ and T_s;
for the fluid properties Δh, η_l, λ_l, c_{pl}, ρ_l and ρ_g;
and for the geometry D.

Some correlations need other parameters. Although the parameters are the same in many cases, the structures of the correlations are quite different.

Chen [1] suggested to calculate the heat transfer coefficient of flow boiling as the sum of the heat transfer coefficients of forced convection and pool boiling (Table 1, equation (1)). While the forced convection heat transfer is intensified by the factor F ($F \geqslant 1$), which is a function of the Martinelli parameter X_{tt}, the boiling heat transfer is suppressed by the factor S ($S < 1$). For the calculation of α_B, the surface tension σ, the saturation pressure p_s, the tube wall temperature T_w and the saturation pressure corresponding to the tube wall temperature $p_s(T_w)$ are needed as additional parameters. In order to obtain the tube wall temperature an iteration is necessary.

The correlations by Shah [2] (equation (2)) and by Gungor and Winterton [3] (equation (3)) consist of only one term as compared with the Chen correlation, namely the term for forced convection. The boiling effect is included in the enhancement factors ψ or E. These factors are functions of the boiling number Bo and of $[\dot{x}/(1-\dot{x})]^n(\rho_l/\rho_g)^m$. The advantage of these correlations is their simplicity in form and the need for only the 11 parameters listed above. Because the Shah equations are correlated from a chart, they are somewhat more complicated than the correlation by Gungor and Winterton.

Steiner [4] used the cubic mean value to combine the two heat transfer mechanisms—convective evaporation and nucleate boiling (equation (4)). If the heat flux is below a certain value $\dot{q}_{ib}$, the term for nucleate boiling α_b is not included. The Steiner correlation needs many constants, which can be found in ref. [4] for many substances.

The correlation recommended by Stephan and Auracher [5] consists of a pool boiling correlation and a factor considering the effect of forced convection (equation (5)). Five pool boiling correlations are pre-

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NOMENCLATURE

- a thermal diffusivity [$m^2 s^{-1}$]
- b Laplace constant, $\sqrt{(\sigma/g(\rho_l-\rho_g))}$ [m]
- B_M constant in the correlation of Bjorge et al. [$s^{9/4} m^{-9/8}$]
- Bo boiling number, $\dot{q}/\dot{m}\Delta h$
- c_p specific heat capacity [$J kg^{-1} K^{-1}$]
- D tube diameter [m]
- d break-off bubble diameter [m]
- g gravitational acceleration [$m s^{-2}$]
- Δh specific latent heat of evaporation [$J kg^{-1}$]
- $\dot{m}$ mass flux [$kg m^{-2} s^{-1}$]
- p pressure [Pa]
- Pr Prandtl number
- $\dot{q}$ heat flux [$W m^{-2}$]
- R_p roughness defined by DIN 4762 [m]
- T thermodynamic temperature [K]
- $\dot{x}$ flow quality, $\dot{m}_g/(\dot{m}_g+\dot{m}_l)$.

Greek symbols
- α heat transfer coefficient [$W m^{-2} K^{-1}$]
- β contact angle [deg.]
- η dynamic viscosity [$kg m^{-1} s^{-1}$]
- λ thermal conductivity [$W m^{-1} K^{-1}$]
- ρ density [$kg m^{-3}$]
- σ surface tension [$N m^{-1}$].

Subscripts
- c critical
- cal calculated
- exp experimental
- g gas (vapour)
- ib incipient boiling
- l liquid
- s saturation
- w wall.

sented in ref. [5]. One is applicable to all substances and the other four to water, hydrocarbons, cryogenic fluids and refrigerants, respectively. In these correlations the characteristic length is the break-off bubble diameter. It follows that the surface tension and the contact angle of the fluid must be known.

The Styushin [6] correlation (equation (6)) consists of five dimensionless numbers. It is valid only in the fully developed nucleate boiling region. In this correlation the mixture velocity w_m and the factor $(\sigma/g\rho_g)^{1/2}$ will cancel, which means that the mass flux $\dot{m}$, the flow quality $\dot{x}$ and the density of vapour ρ_g

Table 1. Heat transfer correlations for flow boiling

Correlations		Annotations
Chen [1]		
$\alpha = \alpha_{FC}F+\alpha_B S$	(1)	$\alpha_{FC} = \frac{\lambda}{D}0.023Re_l^{0.8}Pr_l^{0.4}$
$\alpha_B = 0.00122\left(\frac{\lambda_l^{0.79}c_{pl}^{0.45}\rho_l^{0.49}}{\sigma^{0.5}\eta_l^{0.29}\Delta h^{0.24}\rho_g^{0.24}}\right)\Delta T_s^{0.24}\Delta p_s^{0.75}$		$\Delta T_s = T_w - T_s$
$F = 1 \quad (1/X_{tt} \leqslant 0.1)$		$\Delta p_s = p_s(T_w) - p_s(T_s)$
$F = 2.35(1/X_{tt}+0.213)^{0.736} \quad (1/X_{tt} > 0.1)$		$X_{tt} = \left(\frac{\rho_g}{\rho_l}\right)^{0.5}\left(\frac{\eta_l}{\eta_g}\right)^{0.1}\left(\frac{1-\dot{x}}{\dot{x}}\right)^{0.9}$
$S = \frac{1}{1+2.53\times10^{-6}Re_l^{1.17}}$		$Re_l = \frac{\dot{m}(1-\dot{x})D}{\eta_l}$
Shah [2]		
$\alpha = \psi\alpha_{FC}$	(2)	
$\psi = \max\{\psi_{cb}, \psi_{nb}\}$		
$\psi_{cb} = 1.8/C_0^{0.8}$		$C_0 = \left(\frac{1-\dot{x}}{\dot{x}}\right)^{0.8}\left(\frac{\rho_g}{\rho_l}\right)^{0.5}$
If $C_0 > 1.0$:		
$\psi_{nb} = 230Bo^{0.5} \quad (Bo > 0.3\times10^{-4})$		
$\psi_{nb} = 1+46Bo^{0.5} \quad (Bo < 0.3\times10^{-4})$		
If $0.1 < C_0 \leqslant 1.0$:		
$\psi_{nb} = F\,Bo^{0.5}\exp(2.74C_0^{-0.1})$		
If $C_0 \leqslant 0.1$:		
$\psi_{nb} = F\,Bo^{0.5}\exp(2.47C_0^{-0.15})$		
$F = 14.7 \quad (Bo \geqslant 11\times10^{-4})$		
$F = 15.3 \quad (Bo < 11\times10^{-4})$		

Table 1. *Cont.*

Correlations	Annotations
Gungor and Winterton [3]	
$\alpha = E\alpha_{\mathrm{FC}}$ (3)	
$E = 1+3000Bo^{0.86}+1.12\left(\frac{\dot{x}}{1-\dot{x}}\right)^{0.75}\left(\frac{\rho_l}{\rho_g}\right)^{0.41}$	
Steiner [4]	
$\alpha = (\alpha_k^3+\alpha_b^3)^{1/3}$ (4)	α_{Lo} and α_{Go} should be calculated according to Gnielinski [18] with
If $\dot{q} < \dot{q}_{\mathrm{ib}} = \frac{2\sigma T_s \alpha_{\mathrm{Lo}}}{r_{\mathrm{kr}}\rho_g \Delta h}$, $\alpha_b = 0$	$Re_{\mathrm{Lo}} = \frac{\dot{m}D}{\eta_l}$; $Re_{\mathrm{Go}} = \frac{\dot{m}D}{\eta_g}$
otherwise	$r_{\mathrm{kr}} = 0.3\times10^{-6}$ m
$\alpha_b = \alpha_{0.3}C_F\left(\frac{\dot{q}}{\dot{q}_0}\right)^n\left[1.66\left(\frac{p}{p_c}\right)^{0.45}+\left(2+\frac{1}{1-(p/p_c)^7}\right)\left(\frac{p}{p_c}\right)^{3.7}\right]\left(\frac{D_0}{D}\right)^{0.4}\left(\frac{R_p}{R_{p0}}\right)^{0.133}$	$\dot{q}_0 = 20\,000$ W m^{-2}
$\alpha_k = \alpha_{\mathrm{Lo}}\left\{\left[(1-\dot{x})^{1.5}+1.9\dot{x}^{0.6}\left(\frac{\rho_l}{\rho_g}\right)^{0.35}\right]^{-2.2}+\left[\frac{\alpha_{\mathrm{Go}}}{\alpha_{\mathrm{Lo}}}\left(1+8(1+\dot{x})^{0.7}\left(\frac{\rho_l}{\rho_g}\right)^{0.67}\right)\right]^{-2}\right\}^{-0.5}$	$D_0 = 1\times10^{-2}$ m $R_{p0} = 1\times10^{-6}$ m for refrigerants $n = 0.8–0.1\times10^{(0.76p/p_c)}$ for R12 $\alpha_{0.3} = 6960$ W m^{-2} K^{-1} $C_F = 0.97$
Stephan and Auracher [5]	$Re_l = \frac{\dot{m}(1-\dot{x})D}{\eta_l}$
$\alpha = (29Re_l^{-0.3}Fr_l^{0.2})\alpha_B$ (5a)	
For refrigerants:	$Fr_l = \frac{\dot{m}^2(1-\dot{x})^2}{\rho_l^2 gD}$
$\frac{\alpha_B d}{\lambda_l} = 207\left(\frac{\dot{q}d}{\lambda_l T_s}\right)^{0.745}\left(\frac{\rho_l}{\rho_g}\right)^{0.581}Pr^{0.533}$ (5b)	$d = 0.0204\beta b$ for refrigerants $\beta = 35$
Styushin [6]	
$St(K_p')^{-1/3} = 1.25Bo'(Pe')^{-1/3}K_s^{0.5}$ (6)	$K_s = \frac{\Delta h}{c_{pl}T_s}$
$St = \frac{\alpha}{c_{pl}\rho_l w_m}$; $K_p' = \frac{\dot{q}}{\sigma}\left(\frac{\sigma}{g\rho_g}\right)^{1/2}$	$w_m = \frac{\dot{m}}{\rho_l}\left[1+\dot{x}\left(\frac{\rho_l}{\rho_g}-1\right)\right]$
$Bo' = \frac{\dot{q}}{\Delta h\rho_l w_m}$; $Pe' = \frac{\dot{q}}{\Delta h\rho_l a_l}\left(\frac{\sigma}{g\rho_g}\right)^{1/2}$	
Bjorge *et al.* [7]	
$\dot{q} = \dot{q}_{\mathrm{FC}}+\dot{q}_B\left[1-\left(\frac{\Delta T_{s,\mathrm{ib}}}{\Delta T_s}\right)^3\right]$, $(\Delta T_s \geqslant \Delta T_{s,\mathrm{ib}})$ (7)	$X_{tt} = \left(\frac{\rho_g}{\rho_l}\right)^{0.5}\left(\frac{\eta_l}{\eta_g}\right)^{0.1}\left(\frac{1-\dot{x}}{\dot{x}}\right)^{0.9}$
$\dot{q}_{\mathrm{FC}} = \frac{Re_l^{0.9}Pr_l F(X_{tt})\lambda_l}{F_2 D}\Delta T_s$	$Re_l = \frac{\dot{m}(1-\dot{x})D}{\eta_l}$
$F(X_{tt}) = 0.15\left[\frac{1}{X_{tt}}+2.0\left(\frac{1}{X_{tt}}\right)^{0.32}\right]$	$\alpha_{\mathrm{FC}} = \frac{\lambda}{D}0.023Re_l^{0.8}Pr_l^{0.4}$
$F_2 = 5Pr_l+5\ln(1+5Pr_l)+2.5\ln(0.0031Re_l^{0.812})$ $(Re_l > 1125)$	
$F_2 = 5Pr_l+5\ln[1+Pr_l(0.0964Re_l^{0.585}-1)]$ $(50 < Re_l < 1125)$	
$F_2 = 0.0707Pr_l\,Re_l^{0.5}$ $(Re_l < 50)$	
$\frac{\dot{q}_B}{\eta_l\Delta h}\left(\frac{\sigma}{g(\rho_l-\rho_g)}\right)^{1/2} = B_M\frac{\lambda_l^{1/2}\rho_l^{17/8}c_{pl}^{19/8}\rho_g^{1/8}}{\eta_l\Delta h^{7/8}(\rho_l-\rho_g)^{9/8}\sigma^{5/8}T_s^{1/8}}\Delta T_s^3$	
$\Delta T_{s,\mathrm{ib}} = \frac{8\sigma T_s(1/\rho_g-1/\rho_l)\alpha_{\mathrm{FC}}}{\lambda_l\Delta h}$	

have no effect on the heat transfer coefficient in the nucleate boiling regime.

Bjorge *et al.* [7] suggested a heat flux superposition equation (equation (7)). In the equation for $\dot{q}_B$ there is a dimensional constant B_M, which should have a specific value for a given fluid. Only the value for water is cited in ref. [7]. In most cases the heat flux $\dot{q}$ is given, while the temperature difference ΔT_s is to be calculated. Thus an iteration method has to be applied here.

In most of these correlations the effect of flow direction is not considered, as only a few authors have reported on it. Steiner [4] and Stephan [8] suggest, according to measurements by Pujol [9], that for downflow the following modification of their correlations should be taken:

$$\alpha_{\mathrm{downflow}} = 0.75\,\alpha_{\mathrm{upflow}}. \tag{8}$$

Thorsen *et al.* [10] found that the boiling heat transfer coefficient for upflow is higher than that for downflow. Under saturated flow conditions, however, the difference is small.

Bartolini *et al.* [11] reported that for fully developed nucleate boiling with flow velocities of 0.2 and 0.8 m s^{-1} the flow direction has a negligible effect on the heat transfer coefficient.

3. EXPERIMENTAL APPARATUS

A schematic flow diagram including the main components of the experimental apparatus is shown in Fig. 1. Subcooled R12 is pumped by a canned motor pump P. The total volumetric flow rate is measured by the turbine flowmeter F1. A part of the liquid R12, measured by the turbine flowmeter F2, is evaporated in the evaporator E. The other part of the liquid R12 is preheated to saturation temperature in the preheater PH. Liquid and vapour are mixed in the mixing chamber M1 or M2, depending on the flow direction. The two-phase mixture then flows through an inlet section 2 m long before entering the test section.

The 550 mm long test section is a copper tube with an inner diameter of 20 mm (Fig. 2). The thermal conductivity of the tube is 372 W m^{-1} K^{-1}. The roughness of the tube inner surface R_p, defined according to DIN 4762, is 0.385 μm. The heated length is 500 mm. Four heating wires (Philips Thermocoax) are wound in four spiral grooves around the tube. The diameter of the heating wires is 1 mm. The maximum heating power is 4×1000 W.

In order to measure the inner surface temperature of the test section, 12 thermocouples (NiCr–Ni, ϕ 0.5 mm) are inserted into holes in the tube wall at six levels. These holes, shown in Fig. 2, were bored by a spark erosion machine. The distance between the thermocouple tip and the inner tube surface is 0.3 mm. In order to obtain the temperature of the heat transfer surface, the measured wall temperatures are corrected for the radial temperature drop in the tube wall. Because of heat losses in the axial direction, the temperatures at the end levels are lower than

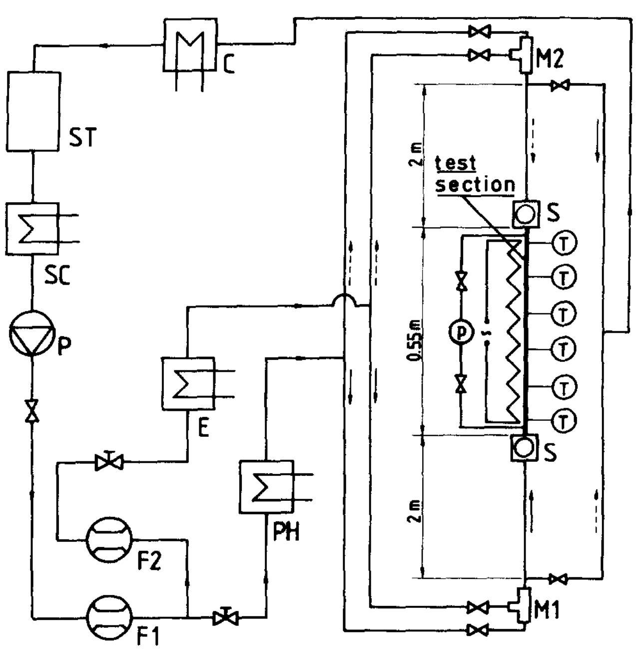

FIG. 1. Schematic diagram of the experimental apparatus: P, pump; F1, flowmeter for the total flow; F2, flowmeter for the vapour flow; PH, preheater; E, evaporator; M1, mixing chamber for upflow; M2, mixing chamber for downflow; S, sight glass; C, condenser; ST, storage tank; SC, subcooler; ——→, upflow; – – →, downflow; Ⓟ, pressure gauge; Ⓣ, thermocouple.

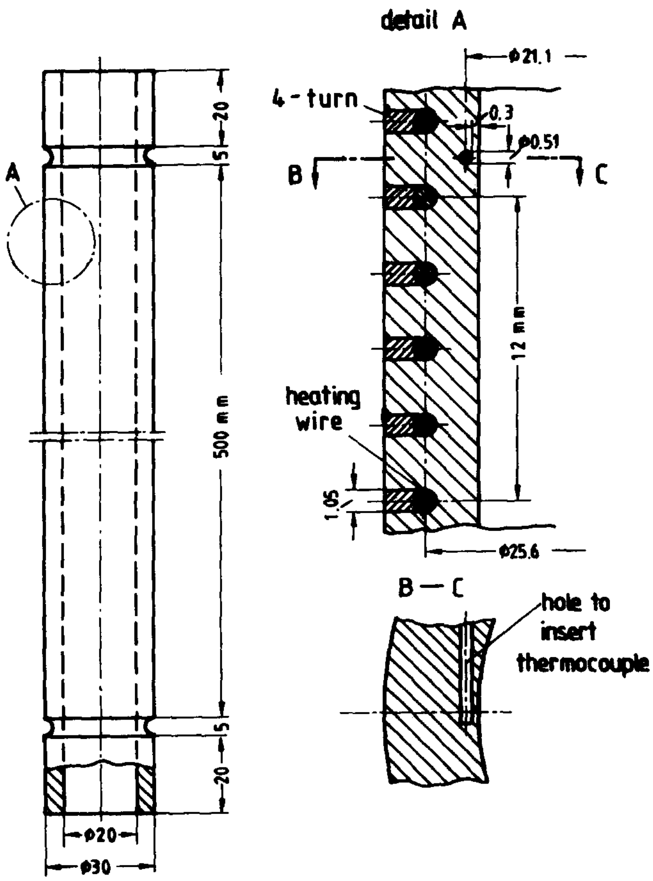

FIG. 2. Test section.

the temperatures at the other levels. Thus, only eight thermocouples are used for the calculation of the mean temperature of the inner tube surface.

At the inlet and outlet of the test section, small holes are provided to measure the pressure and the pressure drop in the test section. The saturation temperature of the fluid is calculated from this pressure using the vapour-pressure equation.

Sight glasses made of Macrolon are mounted on both ends of the test section to observe flow phenomena in the tube.

The refrigerant R12 was obtained from Kali-Chemie AG. The purity of the refrigerant is of industrial standard. Before filling, the system was evacuated to 0.1 bar and flushed.

The measuring instruments and their accuracies are listed in Table 2. The electrical signals from the instruments are processed by a computer-controlled system which consists of a HP 9816S computer, a HP 3497A scanner and a HP 3456A voltmeter.

Table 2. Measuring instruments

Parameter	Instrument	Accuracy
pressure	Bourdon pressure gauge	± 4 kPa
flow rate	turbine flowmeter	$\pm 0.15\ \mathrm{l\ min^{-1}}$
heating power	wattmeter	± 0.3 W
wall temperature	NiCr–Ni thermocouple	± 0.1 K

The overall accuracy of a measured heat transfer coefficient is $\pm 12\%$ on the average and better than $\pm 17\%$ in the worst case.

4. RESULTS AND DISCUSSION

For the experiments, the following parameters had to be regulated: flow direction, system pressure, mass flux, flow quality at the entrance of the test section and heat flux. Measurements were performed with both stepwise increasing and stepwise decreasing heat flux. The results for both conditions exhibit good agreement in the fully developed boiling region.

Altogether, 102 heat transfer coefficients were obtained in the fully developed boiling region—75 in upflow and 27 in downflow. The parameter ranges were

$$p = 640\text{–}1100\ \mathrm{kPa}$$

$$\dot{m} = 311\text{–}1535\ \mathrm{kg\,m^{-2}\,s^{-1}}$$

$$\dot{q} = 10\text{–}103\ \mathrm{kW\,m^{-2}}$$

$$\dot{x} = 0\text{–}0.174.$$

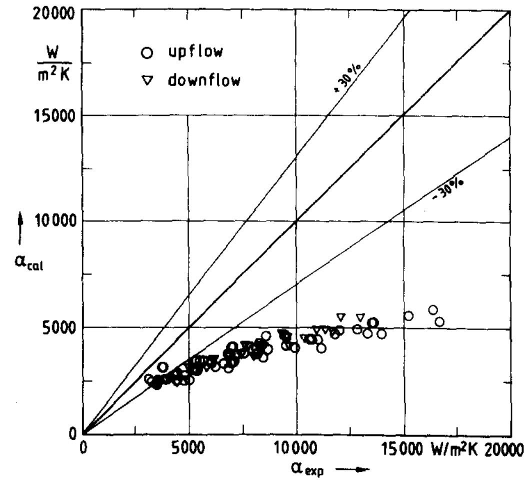

FIG. 3. The Chen correlation compared with our data.

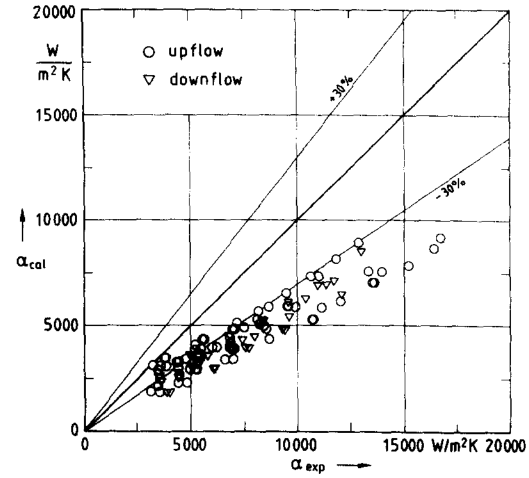

FIG. 5. The correlation by Gungor and Winterton compared with our data.

In Figs. 3–9 the measured heat transfer coefficients α_{exp} are compared with the heat transfer coefficients α_{cal} calculated from the seven correlations given in Table 1. The mean and average deviations of these correlations to the measured values are defined as

$$\text{mean deviation (\%)} = \frac{1}{n}\sum_{1}^{n}\left|\frac{(\alpha_{cal}-\alpha_{exp})\times 100}{\alpha_{exp}}\right| \quad (9)$$

$$\text{average deviation (\%)} = \frac{1}{n}\sum_{1}^{n}\frac{(\alpha_{cal}-\alpha_{exp})\times 100}{\alpha_{exp}} \quad (10)$$

and listed in Table 3.

The Chen correlation (equation (1)) underpredicts the heat transfer coefficients by an average of 47.8%. But, as shown in Fig. 3, the points do not exhibit a large scatter. If in such a case the constant in the equation for α_B was varied, the results may yield good agreement.

The Shah correlation (equation (2)) underpredicts the measured values by an average of 41.6%. The scatter of data points in Fig. 4 is quite large.

Comparison with the correlation by Gungor and Winterton (equation (3)) is made in Fig. 5. The agreement is somewhat better than that with the Shah correlation, with respect to both underprediction and scatter.

The Steiner correlation (equation (4)) in Fig. 6 appears to be better than the preceding equations. Although it still underpredicts the experimental data by 22.2% on average, most of the data points are within the ±30% deviation range.

The correlation by Stephan and Auracher (equation (5)) yields a mean deviation of 10.2% and an average deviation of only 1.2% (see Table 3). As

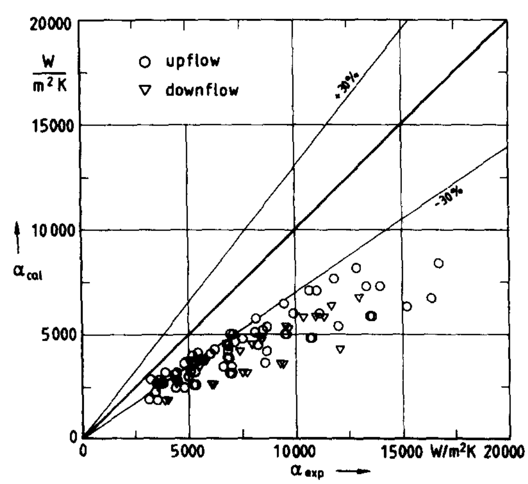

FIG. 4. The Shah correlation compared with our data.

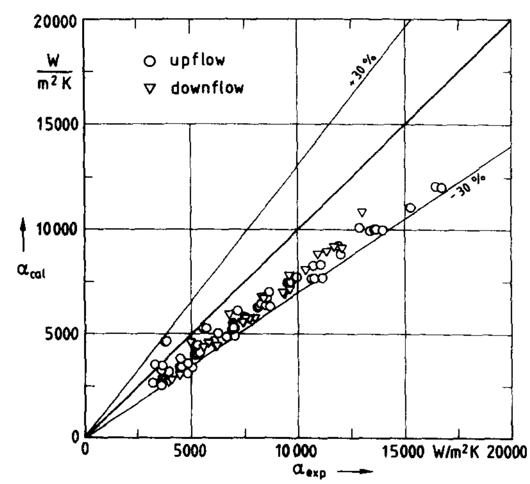

FIG. 6. The Steiner correlation compared with our data.

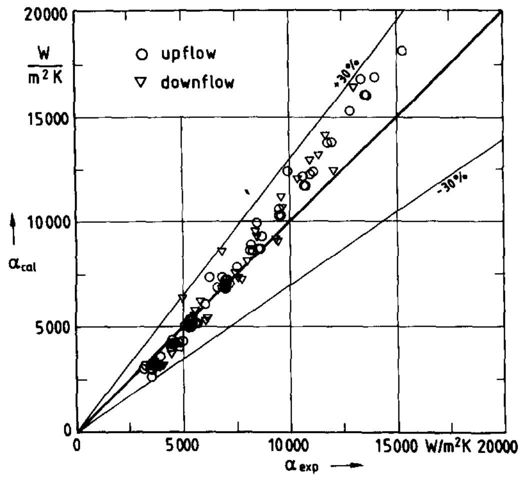

FIG. 7. The correlation by Stephan and Auracher compared with our data.

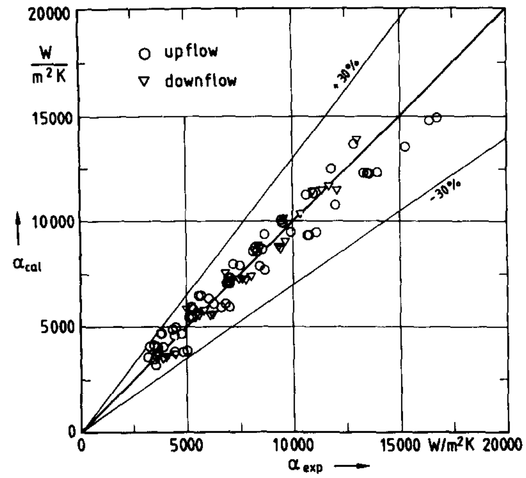

FIG 9. The correlation by Bjorge *et al.* compared with our data.

shown in Fig. 7, the correlation slightly underpredicts in the region of low heat transfer coefficients, corresponding to low heat flux and low pressure, and it overpredicts in the region of high heat transfer coefficients, i.e. high heat flux and high pressure. This tendency can be corrected, if the exponent of the dimensionless number $(\dot{q}d/\lambda_l T_s)$ in equation (5b) is changed from 0.745 to 0.59.

The Styushin correlation (equation (6)) compared in Fig. 8 appears quite satisfactory, although it still underpredicts by 8.9% on the average.

The constant B_M in the correlation of Bjorge *et al.* (equation (7)) is optimized with our experimental data by minimizing the mean deviation. The value obtained is $B_M = 4.0 \times 10^{-13}\,\mathrm{s}^{9/4}\,\mathrm{m}^{-9/8}$. As shown in Fig. 9, the result is quite satisfactory as compared with our data. According to Bjorge *et al.*, only one value of B_M should be given for a specific fluid. Therefore, their correlation with $B_M = 4.0 \times 10^{-13}\,\mathrm{s}^{9/4}\,\mathrm{m}^{-9/8}$ was compared with the 143 experimental heat transfer coefficients of R12 measured by Vaihinger and Kaufmann [12, 13]. As shown in Fig. 10, the value of B_M also appears satisfactory for the experimental data of Vaihinger and Kaufmann, but the points are more scattered. One cause may be that their operating parameters had a larger range:

$$p = 1150\text{–}3370\,\mathrm{kPa}$$

$$\dot{m} = 660\text{–}5600\,\mathrm{kg\,m^{-2}\,s^{-1}}$$

$$\dot{q} = 9\text{–}111\,\mathrm{kW\,m^{-2}}$$

$$\dot{x} = 0\text{–}0.209.$$

The Chen correlation is one of the most widely used correlations for flow boiling, but Chen only tested his correlation against the experimental data of water and

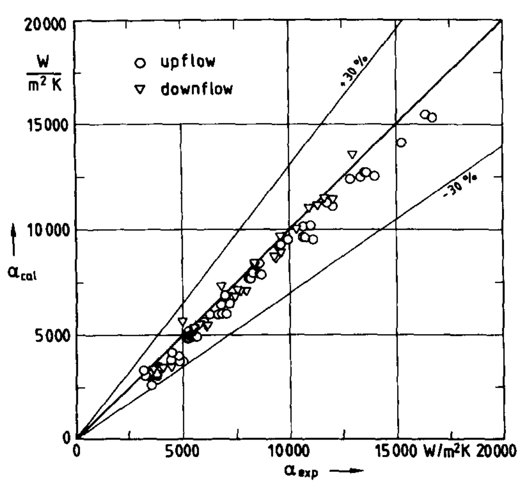

FIG. 8. The Styushin correlation compared with our data.

Table 3. Mean and average deviations between calculated and measured heat transfer coefficients

Correlation	Mean deviation (%)	Average deviation (%)
Chen	47.8	−47.8
Shah	41.6	−41.6
Gungor and Winterton	38.1	−38.1
Steiner	23.1	−22.2
Stephan and Auracher	10.2	1.2
Styushin	9.4	−8.9
Bjorge *et al.*	7.2	−1.0
Bjorge *et al.*, compared with the data of Vaihinger and Kaufmann	14.3	3.5
Modified Chen	6.1	4.4

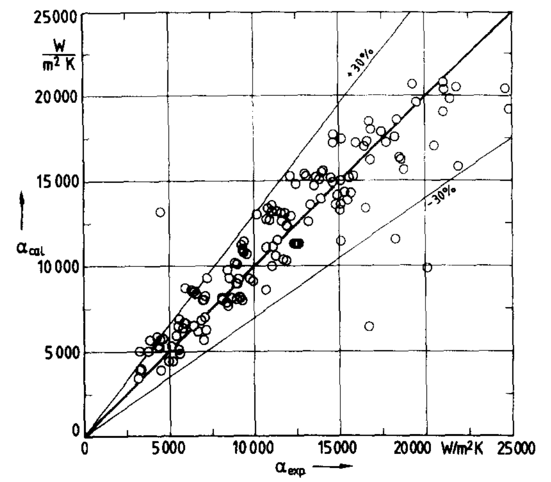

FIG. 10. The correlation by Bjorge *et al.* compared with the data of Vaihinger and Kaufmann.

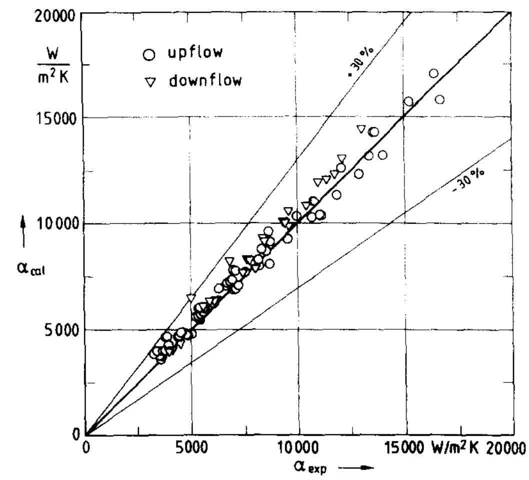

FIG. 11. The modified Chen correlation compared with our data.

some hydrocarbons. For other fluids, an underprediction was observed [14, 15], just as in our case.

Some authors [14, 16] have suggested that other correlations be used for F, S and α_B in the Chen equation (equation (1)). Several correlations were tried out with our experimental data. The best result is obtained by taking α_B as proposed by Gorenflo [17] and the suppression factor S as developed by Bennett *et al.* [16]. The original function F is maintained, as well as α_{FC}. These correlations are given in Table 4. The result is shown in Fig. 11 and Table 3; it is better than that of all other correlations.

In all of Figs. 3–9 and 11 an obvious effect of flow direction cannot be observed, with the superficial liquid velocity ranging from 0.25 to 1.25 m s^{-1}. This agrees with the observation of Bartolini *et al.* [11].

In order to demonstrate the differences among the correlations and the effect of heat flux and pressure, the eight correlations are compared with each other in Figs. 12 and 13. The parameter range corresponds approximately to the range of our measurements. The curve of the modified Chen correlation may represent the position of our measured data. The discrepancy between the correlations is quite large and different at different pressures. While at 600 kPa the difference between the Styushin correlation and the correlation of Bjorge *et al.* is obvious, at 1100 kPa these correlations give similar results.

5. CONCLUSION

Correlations for fully developed nucleate flow boiling in the literature give discrepant results. Compared with our experimental data for R12 in upflow and downflow boiling, the correlations by Chen, by Shah, by Gungor and Winterton, and by Steiner yield large

Table 4. The modified Chen correlation

Correlations	Annotations
$\alpha = \alpha_{FC}F + \alpha_B S$ [1]	$\alpha_{FC} = \frac{\lambda}{D} 0.023 Re_l^{0.8} Pr_l^{0.4}$
$\alpha_B = \alpha_0 \left(\frac{\dot{q}}{\dot{q}_0}\right)^m \left[2.1\left(\frac{p}{p_c}\right)^{0.27} + \left(4.4 + \frac{1.8}{(1-p/p_c)}\right)\left(\frac{p}{p_c}\right)\right]\left(\frac{R_p}{R_{p0}}\right)^{0.133}$ [17]	$q_0 = 20\,000$ W m^{-2}
$S = \frac{\lambda_l}{0.041\alpha_{FC}b}\left[1 - \exp\left(-\frac{0.041\alpha_{FC}b}{\lambda_l}\right)\right]$ [16]	$R_{p0} = 1 \times 10^{-6}$ m
	for organic fluids
$F = 1$ $(1/X_{tt} \leqslant 0.1)$	$m = 0.9 - 0.3\left(\frac{p}{p_c}\right)^{0.3}$
$F = 2.35(1/X_{tt} + 0.213)^{0.736}$ $(1/X_{tt} > 0.1)$	
	for R12
	$\alpha_0 = 2300$ W m^{-2} K^{-1}
	$X_{tt} = \left(\frac{\rho_g}{\rho_l}\right)^{0.5}\left(\frac{\eta_l}{\eta_g}\right)^{0.1}\left(\frac{1-\dot{x}}{\dot{x}}\right)^{0.9}$

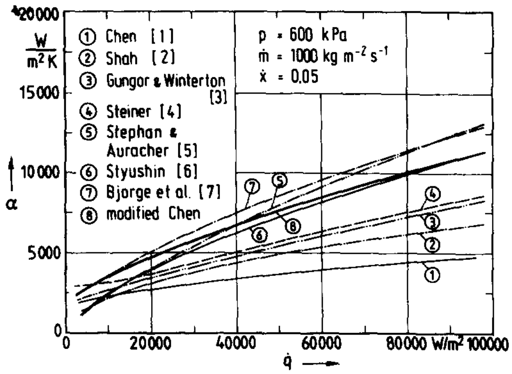

FIG. 12. Comparison of flow boiling correlations at 6×10^5 Pa.

average deviations of -22 to -48%. The correlations by Stephan and Auracher, by Styushin, and by Bjorge *et al.* give much smaller average deviations of 1.2, -8.9 and -1.0% and mean deviations of 10.2% at most.

The correlation by Stephan and Auracher yields better agreement with our measurements, if the exponent of the dimensionless number $(\dot{q}d/\lambda_l T_s)$ is changed from 0.745 to 0.59.

The correlation of Bjorge *et al.* should be used with the constant $B_M = 4.0 \times 10^{-13}\,s^{9/4}\,m^{-9/8}$ for R12. This value was determined from our data, and it also fits the data of Vaihinger and Kaufmann well.

The Chen correlation may be modified using the pool boiling equation by Gorenflo and the suppression factor S by Bennett *et al.* This modified Chen correlation predicts our measurements with an average deviation of 4.4% and a mean deviation of 6.1%. The pool boiling equation by Gorenflo is applicable to many substances with different constants given in ref. [17].

The flow direction has no obvious effect on the heat transfer coefficient for fully developed nucleate boiling.

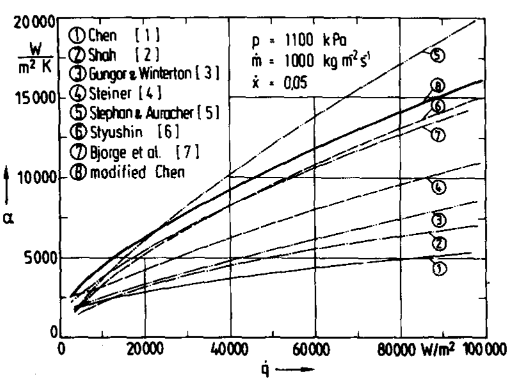

FIG. 13. Comparison of flow boiling correlations at 11×10^5 Pa.

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EBULLITION NUCLEE ETABLIE DANS UN ECOULEMENT ASCENDANT OU DESCENDANT

Résumé—Des coefficients de transfert thermique pour l'ébullition en écoulement du R12 sont obtenus pour un large domaine de pression de flux de chaleur, de débit et de qualité du fluide. Les résultats expérimentaux sont comparés avec sept formules différentes connues. On trouve un bon accord seulement avec quelques unes. Le meilleur accord concerne la formule de Chen modifiée qui utilise l'équation d'ébullition en réservoir de Gorenflo et le facteur de surpression de Bennett et alii. Dans la formule proposée par Bjorge et alii une valeur numérique de la constante B_M est recommendée pour R12. Pour une vitesse minimale du liquide égale à 0,25 m s^{-1}, on ne peut pas observer clairement un effet de la direction ascendante ou descendante de l'écoulement.

VOLLAUSGEBILDETES BLASENSIEDEN BEI AUFWÄRTS- UND ABWÄRTSSTRÖMUNG

Zusammenfassung—In einem weiten Bereich von Druck, Massenstromdichte, Wärmestromdichte und Massendampfgehalt werden Messungen zum Wärmeübergang beim Strömungssieden von R12 durchgeführt. Die Ergebnisse werden mit sieben verschiedenen Korrelationen aus der Literatur verglichen. Nur für einige Korrelationen wurde eine gute Übereinstimmung festgestellt. Beste Übereinstimmung wird mit einer modifizierten Chen-Gleichung erhalten, wenn die Behältersiedegleichung von Gorenflo und der Blasenunterdrückungsfaktor von Bennett *et al.* verwendet wird. Für die Fluidkonstante B_M der Korrelation von Bjorge *et al.* wird ein Wert für R12 angegeben. Ein deutlicher Einfluß der Stömungsrichtung (aufwärts oder abwärts) auf den Wärmeübergang wurde nicht beobachtet. Die kleinste Leerrohrgeschwindigkeit der Flüssigkeit war dabei 0,25 m s^{-1}.

ПОЛНОСТЬЮ РАЗВИТОЕ ПУЗЫРЬКОВОЕ КИПЕНИЕ В ВОСХОДЯЩЕМ И НИСХОДЯЩЕМ ПОТОКАХ

Аннотация—В экспериментах по кипению в потоке фреона 12 получены коэффициенты теплопереноса для широкого диапазона давлений, потоков массы и тепла и паросодержания. Сравниваются экспериментальные результаты с данными, полученными по семи известным из литературы различным обобщающим соотношениям. Хорошее совпадение наблюдалось только для нескольких соотношений, а наилучшее — для модифицированной зависимости Чена, использующей уравнение Горенфло для описания кипения в большом объеме и фактор подавления кипения Беннетта и др. В соотношении, предложенном Бъёрге и др., постоянная B_M для фреона 12 выражена численно. При минимальной скорости жидкости в 0.25 м сек$^{-1}$ нельзя различить четкого влияния на результаты направления течения (вверх или вниз).