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Heat transfer by nucleate pool boiling—general correlation based on thermodynamic similarity

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Abstract—A 'general' equation for nucleate boiling heat transfer valid for various fluids is assumed to exist according to the hypothesis of thermodynamic similarity, modified by taking into account fluid specific parameters. The physical quantities are nondimensionalized in the new type of equation by fluid-specific scaling units being critical data or power products of critical data of the fluid. The equation and the fluid-specific reference values α_0 of the heat transfer coefficient presented by Gorenflo for nearly 50 fluids are the empirical basis, to which the new equation is fitted. A resulting 'general' heat transfer correlation for nucleate boiling represents the reference values α_0 of Gorenflo with a mean deviation of about 14%, depending on the number of fluid specific parameters taken into account for. The correlation is supposed to allow for estimating nucleate boiling heat transfer coefficients in poorly known fluids. Fluid properties at the actual boiling condition or specific reference values of the heat transfer coefficient are not required to apply the new type of correlation.

1. HEAT TRANSFER IN NUCLEATE POOL BOILING

IN NUCLEATE pool boiling the convection of latent heat by separating vapor bubbles and of sensible heat by the drift flow of superheated liquid following the bubbles are commonly assumed to be the dominating mechanisms of heat transfer. Measurements of boiling heat transfer typically conceal the thermal fluctuations by discrete bubbles and yield surface and time averaged values of the heat flux $\dot{q}$ and of the temperature difference ΔT between heater (or heated wall, respectively) and bulk liquid. The temperature of the bulk liquid is nearly that of vapor–liquid equilibrium at the actual pressure in steady-state (saturated) pool boiling.

The mean heat flux $\dot{q}$ in nucleate pool boiling may be described approximately by a power function of the temperature difference ΔT:

$$\dot{q} = E\Delta T^{\varepsilon}; \quad 2.5 \leqslant \varepsilon \leqslant 6. \tag{1}$$

E and ε are empirical constants in equation (1).

Most of the investigators correlate experimental data of boiling heat transfer by describing the heat transfer coefficient $\alpha = \dot{q}/\Delta T$ as a function of the heat flux $\dot{q}$:

$$\alpha = F\dot{q}^{n}; \quad n = 1-1/\varepsilon; \quad 0.6 \leqslant n \leqslant 0.83. \tag{2}$$

The factor F and the exponent n in equation (2), as well as E and ε in equation (1), depend on the pressure of the boiling fluid. The functions $\dot{q}(\Delta T)$ or $\alpha(\dot{q})$, respectively, describing the heat transfer depend on physical parameters of the coupled transport process: on properties of the fluid, on the roughness and material properties of the heater, on size and geometric proportions of the vessel and heater, and on the gravitational acceleration. Because of the proximity to vapor–liquid equilibrium, the fluid properties are approximately functions of only the pressure of the liquid.

Material properties of the heater are not considered here; results from well-conducting (nearly isothermal) well-wetted copper surfaces are regarded preferably.

The surface structure or roughness of the heater is characterized by only one length, the maximum peak height of the profile (Glättungstiefe) R_p defined by the former standard DIN 4762 [2] or by the arithmetical mean deviation of the profile (Mittenrauhwert) $R_a \simeq 0.4R_p$ defined by the standard ISO 4287/1 : 1984 and by the actual DIN 4762 [1].

2. HEAT TRANSFER EQUATIONS BEING FUNCTIONS OF THE REDUCED PRESSURE

Gorenflo [3] presents the following correlation for the heat transfer coefficient α at pool boiling of various pure fluids (organic and inorganic liquids, liquefied noble gases, but no liquid metals and no molten salts):

$$\alpha/\alpha_0 = F(p^*)(\dot{q}/\dot{q}_0)^{n}(R_a/R_{a0})^{0.133}. \tag{3}$$

The roughness of the heater is characterized in equation (3) by the mean deviation of the profile R_a defined by ISO 4287/1: 1984 and by DIN 4762 [1]. The exponent $\varphi = 0.133$ for the influence of roughness is taken from Stephan [4]. The reference values $\dot{q}_0 = 20\,000\ \mathrm{W\ m^{-2}}$ and $R_{a0} = 0.4\ \mu\mathrm{m}$ of heat flux and of roughness, respectively, are arbitrarily fixed to define the reference values α_0 of the heat transfer coefficient in equation (3).

NOMENCLATURE

A	fluid-specific factor in equation (14)
a	thermal diffusivity [$\text{m}^2\ \text{s}^{-1}$]
c_p	specific heat capacity [$\text{J kg}^{-1}\ \text{K}^{-1}$]
C	caloric parameter, equation (9), $c_{\text{pL},p^*=0.1}/(R_\text{mol}M_\text{mol})$
E	factor in equation (1)
F	$F(p^*)$, $F_\text{N}(p^*)$, $F'(p^*)$ factors in equations (2), (3), (6) and (14) depending on pressure
g	gravitational acceleration [m s^{-2}]
k	Boltzmann-constant [J K^{-1}]
K	vapor-pressure-parameter, equation (10)
L	length [m]
M_mol	molar mass (molecular weight) [kg kmol^{-1}]
n	exponent of heat flux in equations (2) and (3), $1-1/\varepsilon$
N_mol	Avogadro-constant [kmol^{-1}]
p	pressure [Pa]
$\dot{q}$	heat flux [W m^{-2}]
$\mathfrak{R}$	specific gas constant, $\mathfrak{R}_\text{mol}/M_\text{mol}$ [$\text{J kg}^{-1}\ \text{K}^{-1}$]
R^*	scaled roughness, R_a/L_{00}
R_a	arithmetical mean deviation of the profile (Mittenrauhwert), ISO 4287/1 : 1984/DIN 4762 [1] [m]
R_p	maximum peak height of the profile (Glättungstiefe), DIN 4762 [2] [m]
T	temperature [K]
V_mol	molar volume, M_mol/ρ [$\text{m}^3\ \text{kmol}^{-1}$]
Z_c	critical parameter.

Greek symbols

α	heat transfer coefficient, $\dot{q}/\Delta T$ [$\text{W m}^{-2}\ \text{K}^{-1}$]
γ	exponent of influence of gravity
$\Delta h_\text{L,V}$	heat of evaporation [J kg^{-1}]
ΔT	surface superheat of the heater, $T_\text{W}-T_\text{sat}$ [K]
ε	exponent of ΔT in equation (1)
ρ	density [kg m^{-3}]
σ	surface tension [N m^{-1}]
Σ	surface tension parameter, $\sigma_{p^*=0.1}/(p_\text{c}L_{00})$
φ	exponent of influence of roughness in equation (14)
ω	acentric factor $-\log_{10}(p^*_{T^*=0.7})-1$.

Subscripts and superscripts

c	at the critical point of the fluid
corr	calculated from a correlation
exp	experimental, from Gorenflo [3]
ig	ideal gas, vapor at low pressure $p \ll p_\text{c}$
L	liquid
m	mean value
mol	molar, related to 1 kmol
N	from Nishikawa
sat	saturation, liquid–vapor equilibrium at actual pressure
V	vapor
W	heated wall, heater surface
0	reference quantity according to Gorenflo
00	fluid-specific scaling unit of Table 1
*	nondimensionalized by scaling units of Table 1
RMS	root mean square (deviation).

$F(p^*)$ and n are functions of the reduced pressure p^*; these functions are found to be common for the examined fluids except for water:

$$F(p^*) = 1.2p^{*0.27} + \left(2.5 + \frac{1}{1-p^*}\right)p^* \tag{4}$$

$$n(p^*) = 0.9 - 0.3p^{*0.3}. \tag{5}$$

By definition, $F(p^*) = 1$ for $p^* = p_0^* = 0.1$.

The specific reference value α_0 of the heat transfer coefficient in a fluid considered is typically obtained by boiling experiments made at or extrapolated to the standard reference boiling condition ($\dot{q}_0$; p_0^*; R_a0). Gorenflo presents a list of values α_0 for 47 examined fluids. The values α_0 and the equations (3)–(5) correlate experimental data of nucleate boiling heat transfer from many investigators. Most of these data have been measured in devices with horizontal cylindric heaters similar to an experimental facility designed by Goetz [5].

Equation (3) cannot be used to estimate a boiling heat transfer coefficient in any fluid, for which the reference value α_0 has not been determined before by experiments or from another correlation. Gorenflo suggests for such fluids to calculate a reference value α_0 of the boiling heat transfer coefficient from a correlation of Stephan and Preußer [6]. The evaluation of this correlation requires one to know the values of 6 fluid properties at the reference condition.

Nishikawa *et al.* [7] have measured heat transfer in nucleate pool boiling of the refrigerants R21, R113 and R114 at horizontal flat plate heaters of different roughness. Assuming 'thermodynamic similarity' as discussed below, they propose a common heat transfer correlation for these refrigerants. Their correlation is used here in a dimensionally correct notation according to Leiner [8],

$$\alpha = 12.7\,(p_c^2 \Re_{\mathrm{mol}} T_c / M_{\mathrm{mol}})^{1/10} \times F_N(p^*)\dot{q}^{4/5}(8R_p/R_{p0})^{(1-p^*)/5} \quad (6)$$

where

$$F_N(p^*) = p^{*0.23}(1-0.99p^*)^{0.9}. \quad (7)$$

In equation (6) the roughness of the heater is characterized by R_p as defined by the earlier edition of DIN 4762 [2] with the reference value $R_{p0} = 1\ \mu\mathrm{m}$. For technical surfaces R_p can be substituted easily by R_a defined in ISO 4287/1 :1984 or to the actual DIN 4762 (1989) by setting $(R_p/R_{p0}) = (R_a/R_{a0})$ with $R_{a0} = 0.4\ \mu\mathrm{m}$ (Gorenflo [3]). An essential feature of equation (6) of Nishikawa is that it is supposed to be common for different fluids.

The aim of the present study is to find a nondimensional universal heat transfer correlation being valid for nucleate pool boiling of various fluids. The correlation equation (3) and the reference values α_0 of Gorenflo for nucleate pool boiling heat transfer from horizontal cylindric heaters represent a good empirical basis for a very large variety of fluids. In the case of inconsistent experimental data and for some poorly examined fluids, the reference values α_0 given by Gorenflo may be relatively low with regard to safe heat exchanger design. Equation (6) of Nishikawa, based on measurements with horizontal flat plate heaters in three refrigerants, is particularly well established for varying values of boiling pressure and roughness.

3. THERMODYNAMIC SIMILARITY AND FLUID-SPECIFIC SCALING UNITS DERIVED FROM CRITICAL DATA

Wukalovich and Nowikow [9] and Borishanskii *et al.* [10] have suggested to extend the principle of corresponding states to other fluid properties than properties of state and to boiling heat transfer, respectively, as 'thermodynamic similarity'. The validity of thermodynamic similarity has not been verified very strictly and suggestions were missing, how to overcome evident inconsistencies with experimental results.

Considerations of thermodynamic similarity are facilitated by scaling fluid properties and other physical quantities, which depend on fluid properties, by fluid-specific scaling units of the same dimensions. Critical data and power products of two of the three critical data, preferably T_c and p_c, of the molar gas constant $\Re_{\mathrm{mol}}$, the molar mass M_{mol} and the Avogadro constant N_{mol} are suggested here as fluid-specific scaling units. A scaled description of pool boiling heat transfer requires a sufficient set of such scaling units to nondimensionalize the essential physical parameters, e.g.

- the temperature difference ΔT between heater and bulk fluid,
- the heat flux $\dot{q}$ from the heater surface,
- the heat transfer coefficient $\alpha = \dot{q}/\Delta T$,
- the size R_a or R_p of roughness or any characteristic length of the heater-and-vessel-configuration and
- the acceleration g by gravity;

see Table 1.

4. FLUID-SPECIFIC PARAMETERS

Specific features of a fluid, which do not fit the principle of corresponding states or of thermodynamic similarity, can be characterized by fluid-specific nondimensional parameters. Such parameters may be defined by specific properties of the fluid at corresponding states. Three such parameters will be considered in this study:

- the *critical factor*

$$Z_c = p_c V_{\mathrm{mol,c}}/(\Re_{\mathrm{mol}} T_c) = p_c/(\rho_c \Re T_c) \quad (8)$$

- the *caloric parameter* or scaled specific heat capacity of the liquid

$$C = c_{pL}/\Re = c_{pL} M_{\mathrm{mol}}/\Re_{\mathrm{mol}} \quad (9)$$

- the *vapor-pressure-parameter* characterizing the slope of the p–T-curve of vapor–liquid equilibrium and the latent heat of evaporation

$$\begin{aligned} K &= -T^* \ln p^*/(1-T^*) \\ &\simeq -[\mathrm{d}(\ln p^*)/\mathrm{d}(1/T^*)]_{\mathrm{sat}} \\ &\simeq [\Delta h_{LV}/(\Re T_c)]_{p^* \ll 1}. \end{aligned} \quad (10)$$

The vapor-pressure-parameter K is nearly independent of p^* or T^*, respectively, for almost any fluid and linearly linked to the acentric factor defined as

$$\omega = -\log_{10}(p^*_{T^*=0.7}) - 1$$

(see, e.g. Lukas *et al.* [11]), by:

$$K = 5.37\,(1-\omega). \quad (11)$$

C and K are defined here with the values of c_{pL} and T^*, respectively, at phase equilibrium at the reference pressure $p_0^* = 0.1$. The values Z_c, C and K of the fluids examined by Gorenflo are within the ranges

$$0.18 < Z_c < 0.32, \quad 2.5 < C < 39,$$

with the geometrically averaged values:

$$Z_{c,m} \simeq 0.269, \quad C_m \simeq 15.5, \quad K_m \simeq 6.62.$$

The parameters Z_c, C and K depend on each other. The critical factor Z_c can be correlated approximately by a power function of C and K for the fluids examined by Gorenflo, except helium,

$$Z_c = 0.6872\,C^{0.0656}\,K^{-0.5908} \quad (12)$$

with a RMS-deviation of only 4.1% (peak 13.8% for acetone). As a consequence, Z_c can be substituted easily by C and K.

The vapor-pressure-parameter K and the caloric

Table 1. Fluid-specific scaling units defined by T_c and p_c

Physical quantity	SI-unit	Fluid-specific unit
Temperature difference ΔT	K	$T_{00} = T_c$
Heat flux $\dot{q}$	$\mathrm{W\,m^{-2}}$	$\dot{q}_{00} = p_c(\Re T_c)^{1/2}$
Heat transfer coefficient α	$\mathrm{W\,m^{-2}\,K^{-1}}$	$\alpha_{00} = p_c(\Re/T_c)^{1/2}$
Size of roughness or any length L	m	$L_{00} = (kT_c/p_c)^{1/3}$
Gravitational acceleration	$\mathrm{m\,s^{-2}}$	$g_{00} = \Re T_c/L_{00}$

$k = \Re_{\mathrm{mol}}/N_{\mathrm{mol}}, \quad \Re = \Re_{\mathrm{mol}}/M_{\mathrm{mol}}$.

parameter C depend on each other too. Both may be correlated by a power function

$$K = 3.948\,C^{0.189} \tag{13}$$

with a RMS-deviation of 8.1%.

5. NONDIMENSIONAL EQUATIONS OF NUCLEATE POOL BOILING HEAT TRANSFER

Scaling equation (3) of Gorenflo by fluid-specific units of Table 1 yields a nondimensional heat transfer equation, in simplified notation:

$$\alpha^* = AF'(p^*)\dot{q}^{*n}R^{*\varphi} \tag{14}$$

with

$$\alpha^* = \alpha/\alpha_{00}; \quad \dot{q}^* = \dot{q}/\dot{q}_{00};$$

$$R^* = R_a/L_{00} \quad \text{and} \quad \varphi = 0.133.$$

The exponent n in equation (14), as in equation (3), is given by equation (5) and is supposed to be valid for all fluids examined by Gorenflo except water and helium.

The nondimensional factor A in equation (14) is linked to the reference value α_0 given by Gorenflo by

$$A = \frac{\alpha_0 T_c}{\dot{q}_0^{n_0}\dot{q}_{00}^{1-n_0}}(L_{00}/R_{a0})^{0.133} \tag{15}$$

with

$$n_0 = n(p_0^* = 0.1) = 0.75.$$

The value of the factor $F'(p^*)$ in equation (14) at the reference pressure $p_0^* = 0.1$ is by definition:

$$F'(p_0^*) = F(p_0^*) = 1 \quad \text{with} \quad n = n_0.$$

The factor $F'(p^*)$ in equation (14) differs for $p^* \neq p_0^*$ from $F(p^*)$ in Gorenflo's equation (3) because of the pressure dependence of n:

$$F'(p^*) = (\dot{q}_{00}/\dot{q}_0)^{n-n_0}F(p^*) \tag{16}$$

$F'(p^*)$ depends on the type of fluid at $p^* \neq p_0^*$, because the scaling unit $\dot{q}_{00}$ of the heat flux in equation (16) is strongly fluid-specific.

However, the small exponent $n - n_0 \ll 1$ in equation (16) allows us to replace $\dot{q}_{00}$ by its geometric mean value $\dot{q}_{00,\mathrm{m}} = 0.86 \times 10^9\ \mathrm{W\,m^{-2}}$ yielding

$$F'(p^*) = 43\,000^{n-n_0}F(p^*) \tag{17}$$

with

$$n - n_0 = 0.15 - 0.3p^{*0.3}. \tag{18}$$

Equation (17) is equivalent to equation (16) within $\pm 15\%$ at reduced pressures $0.001 \leqslant p^* \leqslant 0.9$ for the fluids considered by Gorenflo except water and ammonia because of their extremely high values of $\dot{q}_{00}$. For water $\dot{q}_{00}$ exceeds the mean value $\dot{q}_{00,\mathrm{m}}$ by a factor 14. This could explain, why Gorenflo has found a particular function $F(p^*)$ for water instead of equation (4). The general pressure function $F'(p^*)$ in equation (14) is assumed to be given by equation (17).

The factor A would be a universal constant in equations (14) in the case of full thermodynamic similarity. In fact the values of A, calculated by equation (15) from the α_0-values of Gorenflo (for copper heaters), differ from fluid to fluid (not including He) by a factor 3,

$$1.38 \leqslant A \leqslant 3.72$$

with the geometric mean $A_{\mathrm{m}} = 2.351$ (He: $A = 0.36$). The scaled heat transfer coefficient A evidently depends on the type of fluid and on fluid-specific properties, respectively.

In an earlier approach (Leiner and Gorenflo [8]), values of fluid properties were taken or interpolated from the VDI-Wärmeatlas, part D (Lucas *et al.* [11]) to calculate the fluid-specific scaling units and the parameters Z_c, C and K. On this basis the values A (named α_0^* by Leiner and Gorenflo [8]) were calculated by equation (15) for 42 fluids and correlated by a power product of two parameters, C and K, yielding:

$$A = 0.376\,C^{0.077}K^{0.85} \tag{19}$$

with a RMS-deviation of 13.8% (14.2% after including R 226, RC 318 and water). The correlation equation (19) had been established omitting the fluids R 227, RC 318 and SF_6 because of missing values of fluid properties, and without including water and helium because of their different thermal behavior.

After strictly revising the fluid property data and including data of Perry and Green [12], Shimmok *et al.* [13], Vargaftik [14] and of the *Handbook of Chemistry and Physics* [15], the values A of 45 fluids now including R 227, RC 318 and water have again been correlated with different parameter combinations, yielding the correlations and mean value listed in Table 2.

Inserting the correlations for A from Table 2 into the general equation (14) yields the following heat transfer correlations presented here in the order of

Table 2. Parameter correlations for the fluid-specific constant A in the boiling heat transfer equation (14)

Number/type of parameters		Parameter correlation/mean value for fluid-specific factor A	RMS-deviation %
3	C, K, Z_c	$A = 0.4368\,C^{0.2113}K^{-0.0521}Z_c^{-0.9166}$	13.6
2	C, K	$A = 0.6161\,C^{0.1512}\,K^{0.4894}$	14.2
1	C	$A = 1.2063\,C^{0.2437}$	14.6
0	—	$A = A_m = 2.351$	40

decreasing number of parameters and increasing RMS-deviation from Gorenflo's data

with 3 parameters, Z_c, C, K,

$$\alpha^* = 0.4368\,C^{0.2113}K^{-0.0521}Z_c^{-0.9166}F'(p^*) \times q^{*n}R^{*0.133} \pm 13.6\% \quad (20)$$

with 2 parameters, C, K,

$$\alpha^* = 0.6161\,C^{0.1512}K^{0.4894}F'(p^*)q^{*n}R^{*0.133} \pm 14.2\% \quad (21)$$

or with only one parameter, C,

$$\alpha^* = 1.2063\,C^{0.2437}F'(p^*)q^{*n}R^{*0.133} \pm 14.6\%. \quad (22)$$

The pressure function $F'(p^*)$ in equations (20)–(22) is given by equation (17). Equations (20)–(22) are formally 'general' and seem appropriate to estimate nucleate boiling heat transfer coefficients in fluids, for which no α_0-values nor values of fluid properties at the considered boiling condition are available.

The use of the 3-parameter- (3p-) correlation, equation (20), is handicapped for poorly investigated fluids, for which the critical volume and critical factor, respectively, are not known accurately. The 1p-correlation equation (22) represents Gorenflo's reference values and equation with an RMS-deviation of 14.6%, just 0.4% more than the 2p-correlation, equation (21).

The 2p-correlation equation (21) is actually regarded as particularly suitable for physical interpretation and for further considerations including liquid metals and salt melts. The parameters C and K represent the specific heat capacity of the liquid and the heat of evaporation, both being essential properties in the two dominating mechanisms of heat transfer: drift flow and convection of latent heat. Heat transfer coefficients calculated from equation (21) for the reference condition (p_0, $\dot{q}_0$, R_{a0}) are plotted in Fig. 1 vs the α_0-values of Gorenflo.

The coefficients and exponents in both 2p-correlations for A, equation (19) and the 2p-correlation given in Table 2, differ strongly, though based on only slightly different sets of data. This fact asks for more examination: equating the right hand sides of both correlations yields

$$K = 3.935\,C^{0.2058}, \quad (23)$$

which reflects the interdependence of K and C and is nearly equal to equation (13). We conclude, that the interdependence between C and K shown by equation (13) is sufficiently strong to allow for a series of correlations $A = A(C, K)$ of almost equal accuracy.

Particularly high deviations of the different parameter correlations in Table 2 from the A-values calculated by equation (15) from Gorenflo's data occur mainly for the same fluids, iso-pentane, isopropanol and *n*-butanol. The specific deviations for these fluids are positive and of the order of 30% (about 2.5 times the value of mean RMS-deviations) and may be due to conservative, low or safe estimations of α_0 by Gorenflo or to impurities in the experimental specimens reducing the experimental heat transfer coefficients.

Inserting the mean value $A_m = 2.351$ into equations (14) would yield a correlation corresponding to pure thermodynamic similarity with an RMS-deviation of about 40%.

Gorenflo suggests an upper and a lower value α_0 for some fluids represented by bars in Fig. 1 to define an α_0-interval instead of giving one definite value. For these fluids the geometric mean of both α_0-values is used to fit the correlations.

6. COMPARING THE NEW CORRELATION TO CORRELATIONS OF OTHER INVESTIGATORS

Equation (6) of Nishikawa *et al.* may equally be rewritten in the non-dimensional notation of equation

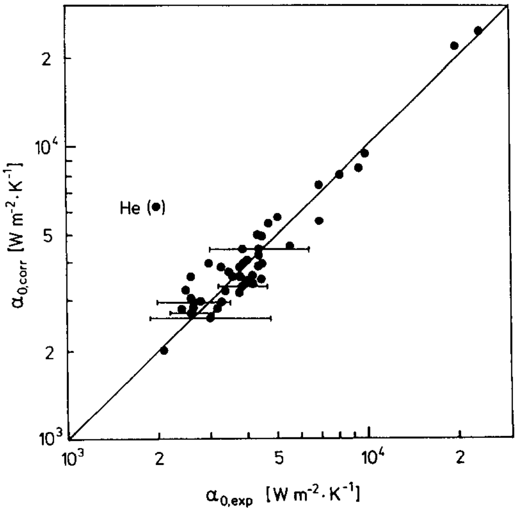

FIG. 1. Heat transfer coefficient $\alpha_{0,corr} = \alpha(p_0, \dot{q}_0, R_{a0})$ at the reference condition, calculated from equation (21), plotted vs the experimental reference value α_0 of Gorenflo for pool boiling.

(14) with $R_p/R_{p0} = R_a/R_{a0}$, $R_{a0} = 0.4$ μm:

$$\alpha^* = 12.7\frac{p^{*0.23}}{(1-0.99p^*)^{0.9}}\dot{q}^{*4/5} \times (8L_{00}/R_{a0})^{(1-p^*)/5}R^{*(1-p^*)/5}. \quad (24)$$

The arbitrary value of R_{p0} in equation (6) or of $R_{a0} = 0.4$ mm in equation (24) does not fit into the claimed universal character. However, a mean value of L_{00} can be used for the examined refrigerants and the term ($8\,L_{00}/R_{a0}$) in equation (24) can be regarded as approximately constant because of its small exponent:

$$L_{00,m} = 1.172\times10^{-9}\,\text{m};$$

$$(8\,L_{00}/R_{p0})^{1/5} = 0.472\pm0.014;$$

$$\alpha^* = 12.7\,F_N(p^*)\dot{q}^{*4/5}R^{*(1-p^*)/5} \quad (25)$$

with

$$F_N(p^*) = \frac{p^{*0.23}0.472^{(1-p^*)}}{(1-0.99p^*)^{0.9}}. \quad (26)$$

Three essential differences exist between equations (20)–(22) and equation (25).

- The functions $F(p^*)$ in equations (20)–(22) and $F_N(p^*)$ in equation (25), respectively, which describe the influence of the reduced pressure are different.
- The exponent n describing the influence of $\dot{q}$ or $\dot{q}^*$ depends on p^* in equations (20)–(22) but is constant, $n = 4/5$, in equation (25).
- Fluid-specific parameters occur in equations (20)–(22) but do not in equation (25).

The modified correlation of Nishikawa, equation (25), can be compared with equations (20)–(22) for the examined refrigerants, if mean values of C, K, and Z_c or of A are used in equations (20)–(22) and in equation (14), respectively. The 2p-correlation equation (21) and equation (25) are plotted in Fig. 2 in the form $\alpha^*(\dot{q}^*)$ for $p^* = 0.1$ and $R^* = 400$ (equivalent to $R_a = 0.47$ μm, $R_p = 1.17$ μm). Differences between the values α^* calculated from equations (21) and (25), respectively, are small: the graph of equation (25) (from Nishikawa *et al.*) for flat plate heaters has a slightly greater slope than the graph of equation (21) based mainly on measurements with horizontal rod heaters (from Gorenflo). This effect of the heater configurations on nucleate boiling heat transfer has been found much earlier by Stephan [4] for refrigerant R11.

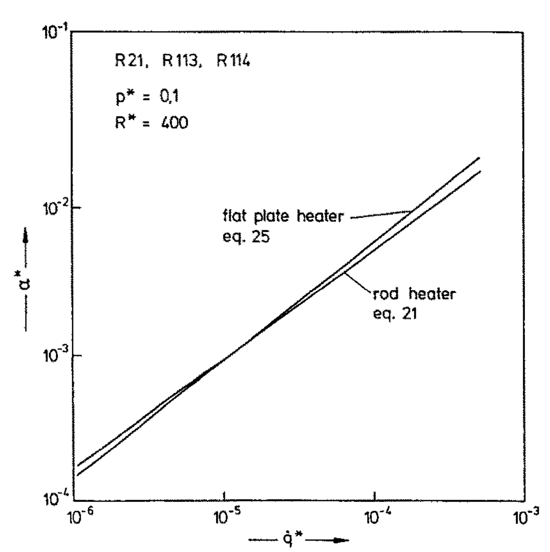

FIG. 2. Comparison of pool boiling heat transfer coefficient calculated from equation (21) (correlating data of Gorenflo, mainly for cylindric heaters) and from equation (25) (from Nishikawa, flat plate heaters), respectively, plotted vs heat flux.

The absence of fluid-specific parameters in equation (25) (derived from Nishikawa) suggests, that this equation, though established by explicitly assuming thermodynamic similarity, is not generally suitable to calculate heat transfer coefficients for other fluids than the examined refrigerants. The validity of equation (25) found for flat plate heaters can probably be extended to other fluids than the considered refrigerants by introducing a subfunction of fluid-specific parameters as any parameter correlation for the factor A from Table 2 is in equation (14).

7. ADDITIONAL ASPECTS

Three aspects of a general heat transfer equation for nucleate pool boiling based on considerations of thermodynamic similarity have been studied additionally.

Nucleate pool boiling is a free convection process and depends on gravitation or system acceleration. The scaled value of acceleration g^* by terrestrial gravity differs from fluid to fluid because of the different values of the fluid-specific scaling unit g_{00}. A power-product correlation of the type $A \sim g^{*\gamma}$ yields from Gorenflo's data: $\gamma < 0.02$. The accuracy of the correlations for A as given in Table 2 is only improved negligibly by less than 0.2%, if g^* is introduced as additional parameter. Clearer information is expected from considering heat transfer data obtained by centrifuge and space experiments.

The surface tension of the liquid controls nucleation. By introducing an additional surface tension parameter,

$$\Sigma = \sigma/(p_c L_{00}) \quad (27)$$

the accuracy of A-correlations is improved only by less than 0.2%, probably because the parameter Σ is correlated with good accuracy by a function of the parameters C and K already taken into account.

Different approaches to establish a 'general' heat transfer equation yield the greatest deviations, about +30% at the reference condition, from Gorenflo's data for the same fluids: isopentane, isopropanol and n-butanol. New measurements should verify, whether this is due to inaccurate experimental data or whether the correlations are not sufficiently accurate.

Boiling metals and salt melts are not yet included in this study.

8. SUMMARY

The concept of describing a transport process by a general equation scaled by the critical data T_c and p_c and by scaling units defined with T_c or p_c is successful for nucleate boiling heat transfer.

Pure thermodynamic similarity is no valid assumption for establishing a general heat transfer equation; it is to be modified by fluid-specific parameters to fit experimental data satisfyingly.

The influence of nondimensional gravity may be neglected for heat transfer by terrestrial nucleate pool boiling, though this is a free convection process.

The concept is formally not restricted to nucleate pool boiling heat transfer: it also seems suitable for other complex transport phenomena in fluids, e.g. for heat transfer in heat pipes.

The parameters C and K are linked to each other, probably because both depend on properties of the condensed liquid phase. Replacing C by a new parameter based on the specific heat capacity $c_{p,ig}$ of the ideal gas (vapor at low pressure) instead of that of the liquid allows us to expect a higher degree of independence from the second parameter K and a still more efficient 2-parameter correlation for the empirical A-values. This will be the next step in future work.

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