Int. J. Heat Mass Transfer. Vol. 25, No. 6, pp. 753–757, 1982
Printed in Great Britain

0017-9310/82 060753–05 $03.00/0

CORRELATION OF FORCED CONVECTION BOILING HEAT TRANSFER DATA

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(Received 14 December 1981)

Abstract—The method of superposition for correlating forced convection boiling heat transfer data is extended to cover subcooled to high quality ranges using single phase and two phase forced convection equations, a pool boiling equation, and an incipient boiling criterion. Only one empirically determined coefficient is needed. Agreement with water data is better than that provided by the Chen correlation.

NOMENCLATURE

B_M, dimensional constant in equation (11);
C_p, specific heat [J kg^{-1} K^{-1} (Btu lbm^{-1} °F^{-1})];
D, tube diameter [m (ft)];
$F(X_{tt})$, parameter in equation (5);
F_2, parameter in equation (5);
G, mass flux [kg s^{-1} m^{-2} (lbm h^{-1} ft^{-2})];
g, gravitational acceleration [m s^{-2} (ft h^{-2})];
g_0, constant [1 kg m N^{-1} s^{-2} (4.17 × 10^8 lbm ft lbf^{-1} h^{-2})];
h_{fg}, enthalpy of vaporization [J kg^{-1} (Btu lbm^{-1})];
h, heat transfer coefficient [W m^{-2} (Btu h^{-1} ft^{-2} °F^{-1})];
k, thermal conductivity [W m^{-1} K^{-1} (Btu h^{-1} ft^{-1} °F^{-1})];
p, absolute pressure [Pa (lbf ft^{-2})];
Pr, Prandtl number;
q, heat flux [W m^{-2} (Btu h^{-1} ft^2)];
r, bubble radius [m (ft)];
Re_l, liquid Reynolds number, defined by equation (8);
T, temperature [K (°F)];
ΔT, temperature difference [K (°F)];
v_{fg}, vapor–liquid specific volume difference [m^3 kg^{-1} (ft^3 lbm^{-1})];
x, quality;
X_{tt}, Martinelli parameter, defined by equation (7);
y, distance from heating surface [m (ft)].

Greek symbols
μ, dynamic viscosity [kg s^{-1} m^{-1} (lbm h^{-1} ft^{-1})];
ρ, density [kg m^{-3} (lbm ft^{-3})];
σ, surface tension [N m^{-1} (lbf ft^{-1})].

Subscripts
B, boiling;
Bi, value obtained from fully developed boiling correlation at the incipient boiling point;
FC, forced convection;
ib, value at the incipient boiling point;
l, liquid;
meas, measured;
pred, predicted;
sat, saturation, or, with respect to saturation;
tang, point of tangency;
v, vapor;
w, wall.

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INTRODUCTION

FORCED convection boiling data has been recorrelated, using previously proposed superposition equations.

For the high quality region ($x > 0.05$)

$$q = q_{FC} + q_B - q_{Bi}. \quad (1)$$

For the subcooled and low quality region ($x < 0.05$)

$$q = [q_{FC}^2 + (q_B - q_{Bi})^2]^{1/2}. \quad (2)$$

These are a superposition of q_{FC} and q_B, modified by subtracting q_{Bi} in order to make $q = q_{FC}$ at the incipience of boiling. The quantities in equations (1) and (2) are shown in Fig. 1.

A different superposition equation is used for each region to obtain better agreement with data in each region. Equation (2) lies closer to the q_{FC} and q_B curves than equation (1). This is probably due to the fact that in the subcooled region bubbles do not depart, but grow and collapse near the wall.

The q_B curve is the fully developed boiling curve and has a slope of about 3 ($q_B \sim \Delta T_{sat}^3$). In this case, equations (1) and (2) may be written as follows, for $\Delta T_{sat} \geq \Delta T_{sat,ib}$:

high quality region:

$$q = q_{FC} + q_B\left[1 - \left(\frac{\Delta T_{sat,ib}}{\Delta T_{sat}}\right)^3\right]; \quad (3)$$

subcooled and low quality region:

$$q = \left\{q_{FC}^2 + q_B^2\left[1 - \left(\frac{\Delta T_{sat,ib}}{\Delta T_{sat}}\right)^3\right]^2\right\}^{1/2}. \quad (4)$$

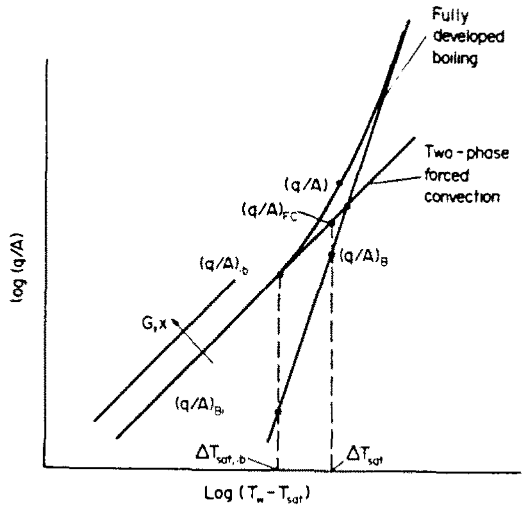

FIG. 1. Superposition technique.

The term multiplying q_B is in effect a boiling suppression factor which replaces the factor S used by Chen [1].

Equations (3) and (4) have been proposed previously. Relations for q_{FC}, q_B and q_{Bi} not previously used in these equations are proposed here.

Forced convection contribution, q_{FC}

High quality region. Traviss *et al.* [2] developed a correlation for annular flow forced convection condensation inside tubes. The same analytical model applies to annular flow evaporation without nucleation. This equation was tested against non-nucleating forced convection data by Hall [3], who suggested a slight modification of the coefficients in the Traviss equation. The recommended equation for q_{FC} in equation (3) is

$$q_{FC} = \frac{Re_l^{0.9}\, Pr_l F(X_{tt}) k_l}{F_2 D} \Delta T_{sat}, \tag{5}$$

where

$$F(X_{tt}) = 0.15\left[\frac{1}{X_{tt}} + 2.0\left(\frac{1}{X_{tt}}\right)^{0.32}\right], \tag{6}$$

where

$$X_{tt} = \left(\frac{\rho_v}{\rho_l}\right)^{0.5}\left(\frac{\mu_l}{\mu_v}\right)^{0.1}\left(\frac{1-x}{x}\right)^{0.9}, \tag{7}$$

$$Re_l = \frac{GD(1-x)}{\mu_l}, \tag{8}$$

and

$$F_2 = 5Pr_l + 5\ln(1 + 5Pr_l) + 2.5\ln(0.0031\, Re_l^{0.812}) \quad (Re_l > 1125) \tag{9a}$$

$$F_2 = 5Pr_l + 5\ln[1 + Pr_l(0.0964\, Re_l^{0.585} - 1)] \quad (50 < Re_l < 1125) \tag{9b}$$

$$F_2 = 0.0707 Pr_l Re_l^{0.5} \quad (Re_l < 50). \tag{9c}$$

Subcooled and low quality region. The recommended equation for q_{FC} in equation (4) is that of Colburn [4]:

$$\left(\frac{h_{FC}D}{k_b}\right) = 0.023\left(\frac{GD}{\mu_f}\right)^{0.8}\left(\frac{\mu_f C_{pb}}{k_b}\right)^{1/3}, \tag{10}$$

$$q_{FC} = h_{FC}(\Delta T_{sat} + \Delta T_{sc}).$$

Here the subscript f indicates that the property should be evaluated at the film temperature, $(T_w + T_b)/2$, and the subscript b indicates that the property should be evaluated at the liquid bulk temperature, T_b.

Boiling contribution, q_B

The Mikic–Rohsenow [5] correlation, used successfully for pool boiling data, was used to determine q_B in both equations (3) and (4):

$$\frac{q_B}{\mu_l h_{fg}}\left(\frac{g_0 \sigma}{g(\rho_l - \rho_v)}\right)^{1/2} = B_M \frac{k_l^{1/2}\rho_l^{17/8} C_{pl}^{19/8} \rho_v^{1/8}}{\mu_l h_{fg}^{7/8} (\rho_l - \rho_v)^{9/8} \sigma^{5/8} T_{sat}^{1/8}} \Delta T_{sat}^3 \tag{11}$$

where B_M is a dimensional constant which for pool boiling depends only upon boiling surface cavity size distribution and fluid properties. Brown and Bergles [6] showed that forced convection heat transfer is not influenced by cavity size distribution. Therefore, it was expected that a single value of B_M in equation (11) should be sufficient for a given fluid. This was determined from data to be $B_M = 1.89 \times 10^{-14}$ in SI units (0.0000213 in engineering units) for forced convection boiling of water.

Incipient boiling, $\Delta T_{sat,ib}$

High quality region. Using the procedure of Bergles and Rohsenow [7], the wall superheat at the incipience of boiling is

$$\Delta T_{sat,ib} = \frac{8\sigma T_{sat} v_{fg} h_{FC}}{k_l h_{fg}}. \tag{12}$$

In pool boiling at low pressures with low convection heat transfer coefficients, the procedure for predicting the incipient boiling conditions must be modified to account for the effect of a maximum cavity size. However, in annular flow forced convection boiling where there are thin liquid films, Mesler and Mailen [8] have shown the existence of vapor bubbles which remain in the film after a larger vapor bubble has broken through the liquid–vapor interface. These bubbles act like nucleation sites of diameter larger than the maximum cavity in the solid surface.

Subcooled and low quality region. In subcooled boiling, the flow is bubbly, and a thin liquid film is not present. Thus, the effect of a maximum cavity size must be accounted for in determining the incipient boiling point. There are two equations for the incipient boiling heat flux, q_{ib}, with the true value depending on whether the radius at which tangency between the bubble equilibrium equation and the temperature profile near the wall occurs, r_{tang}, is greater or less than the radius of the largest cavity, r_{max}.

The radius of the point of tangency is given by

$$r_{tang} = \frac{4\sigma T_{sat} v_{fg}}{h_{fg} \Delta T_{sat,ib}}. \qquad (13)$$

Davis and Anderson [9] found good agreement with data using $r_{max} = 10^{-6}$ m(3.28×10^{-6} ft). This value is used here.

The incipient boiling criterion for subcooled conditions is derived by Bjorge [10]:

for $r_{tang} > r_{max}$,

$$\Delta T_{sat,ib} = \frac{1}{1-N}\left(\frac{1}{4\Gamma N} - N\Delta T_{sc}\right); \qquad (14a)$$

for $r_{tang} < r_{max}$,

$$\Delta T_{sat,ib} = \frac{1}{2\Gamma}[1 + (1 + 4\Gamma \Delta T_{sc})^{1/2}], \qquad (14b)$$

$$\Gamma \equiv \frac{k_l h_{fg}}{8\sigma T_{sat} v_{fg} h_{FC}}, \qquad (14c)$$

$$N \equiv \frac{h_{FC} r_{max}}{k_l}. \qquad (14d)$$

Equation (14b) reduces to equation (12) for $\Delta T_{sc} = 0$.

Comparison with data

High quality region. The correlation for the high quality region was compared with eight sets of water data [11–16]. The range of variables covered is

- D 0.295–2.54 cm (0.116–1.0 in.),
- G 54.2–3930 kg s^{-1} m^{-2} (4.0×10^4–2.9×10^6 lbm h^{-1} ft^{-2}),
- p 0.0624–7.43 MPa (9–1072 psia),
- x 1–65%,
- q 2.2×10^4–4.57×10^6 W m^{-2} (7.0×10^3–1.45×10^6 Btu h^{-1} ft^{-2}).

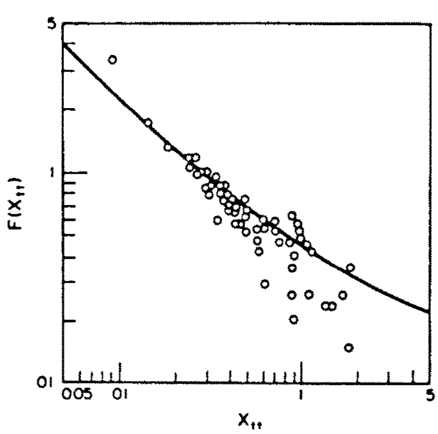

FIG. 2. Comparison of Hall–Traviss equations (5) and (6) with non-boiling data.

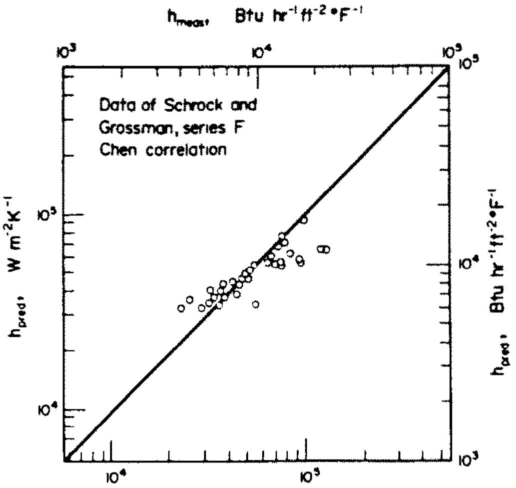

FIG. 3. Comparison with data: Chen correlation.

The incipient boiling criterion, equation (12), was used to determine which data were non-boiling. These data are compared with the Hall–Traviss forced convection relation, equation (5) and (6) in Fig. 2. The average deviation is 13.9%.

All of the high quality data were compared with the proposed prediction method, equation (3), and also with the Chen [1] correlation. In both cases, the heat flux was assumed to be specified and the wall superheat was calculated. To illustrate the nature of the results, Figs. 3 and 4 show the comparison of the two predictions with series F data of Schrock and Grossman [14]. Similar graphs are shown by Bjorge [10] for all data used [11–16].

The average deviation of the data from the prediction is as follows [10]: equation (3), 15.0%; Chen, 17.4%.

It is evident that the proposed correlation provides

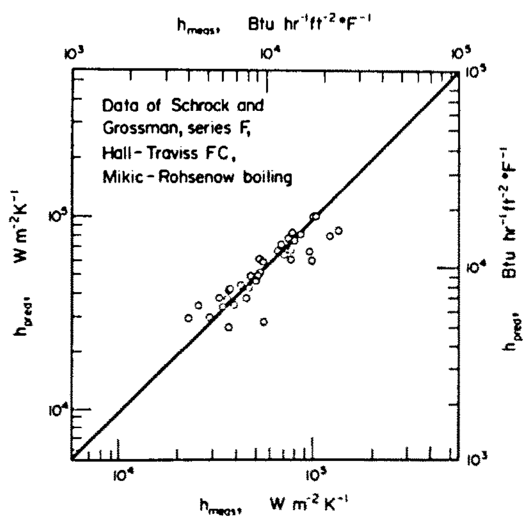

FIG. 4. Comparison with data: Hall–Traviss/Mikic–Rohsenow superposition correlation.

better agreement with the water data examined than does the Chen correlation. Also, the data crosses over the correlation line for the Chen correlation, Fig. 3, but follows along the correlation line of the proposed correlation, equation (3), Fig. 4.

Subcooled and low quality region. The correlation for the subcooled and low quality region was compared with water data of Cheng *et al.* [17], Latsch *et al.* [18], and McAdams *et al.* [19]. The range of variables covered is

D 1.0–1.32 cm (0.39–0.52 in.),
G 470–1880 kg s^{-1} m^{-2} (3.47 × 10^5–1.39 × 10^6 lbm h^{-1} ft^{-2}),
p 0.2–0.41 MPa (29–60 psia),
ΔT_{sc} 10–70 K (50–126°F),
q 1.5 × 10^5–2.1 × 10^6 W m^{-2} (4.75 × 10^4–6.65 × 10^5 Btu h^{-1} ft^{-2}).

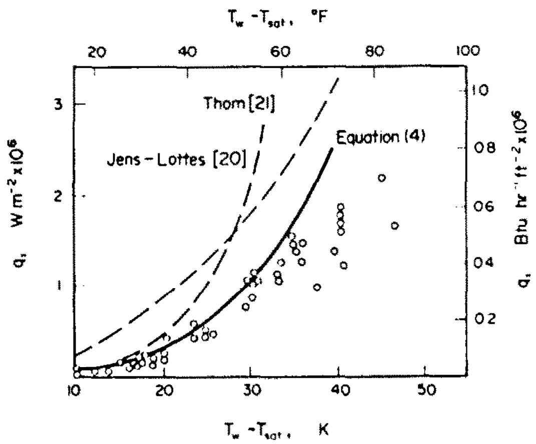

FIG. 5. Comparison of equation (4) with data of Cheng *et al.* [17].

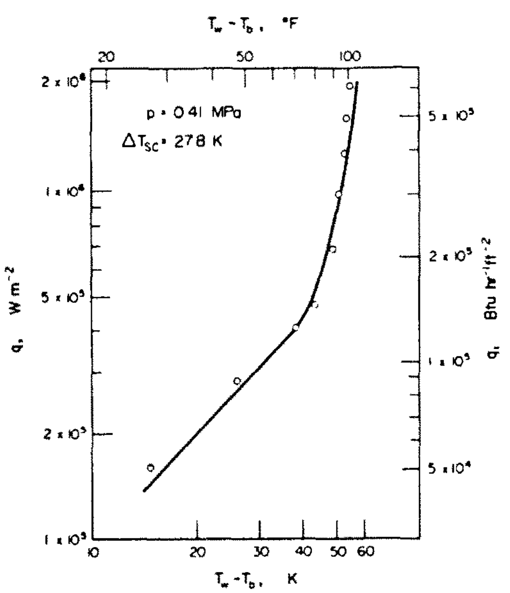

FIG. 6. Comparison of equation (4) with data of McAdams *et al.* [19].

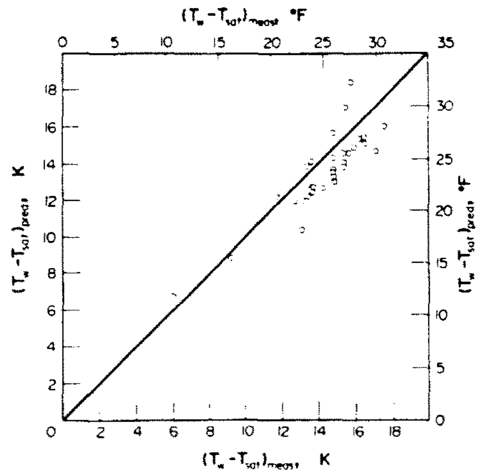

FIG. 7. Comparison of equation (4) with subcooled boiling data.

The proposed prediction method, equation (4), is compared with fully developed subcooled forced convection boiling data of Cheng *et al.* [17] in Fig. 5. Also, shown are the correlations of Jens and Lottes [20], and Thom *et al.* [21]. The present correlation is seen to be a marked improvement over the previous ones. The discrepancy between equation (4) and the data at high heat fluxes is due to the fact that the critical heat flux is being approached.

Equation (4) is compared with partial boiling data of McAdams *et al.* [19] in Fig. 6. A plot of predicted versus measured wall superheat for the boiling data points of McAdams *et al.* [19] and Latsch *et al.* [18] is given in Fig. 7. Good agreement is seen between the correlation and the data.

CONCLUSIONS

It is recommended that the prediction methods described here be used to predict heat transfer in forced convection boiling of water in tubes. The method may be extended for use with other fluids by determining the value of the dimensional constant B_M which applies to each fluid.

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FORMULATION DES DONNEES THERMIQUES EXPERIMENTALES SUR L'EBULLITION AVEC CONVECTION FORCEE

Résumé—La méthode de superposition pour regrouper des données de transfert thermique par ébullition avec convection forcée est étendue pour couvrir des domaines depuis le sous-refroidissement jusqu'aux qualités élevées, en utilisant des équations de phase unique ou de convection biphasique, une équation d'ébullition en réservoir, et un critère d'ébullition naissante. Seul est nécessaire un coefficient empirique. L'accord avec les données sur l'eau est meilleur que ce qui est fourni par la formule de Chen.

KORRELATION DES WÄRMEÜBERGANGS BEIM SIEDEN BEI ERZWUNGENER KONVEKTION

Zusammenfassung—Das Superpositions-Verfahren zur Korrelation des Wärmeübergangs beim Sieden bei erzwungener Konvektion wird auf die Bereiche des unterkühlten Siedens und des Siedens bei hohen Dampfgehalten ausgedehnt. Dazu werden Ein- und Zwei-Phasen-Korrelationen für erzwungene Konvektion, eine Korrelation für Behältersieden und ein Kriterium für den Siedebeginn verwendet. Nur ein empirisch bestimmter Koeffizient wird benötigt. Die Übereinstimmung mit den Daten für Wasser ist besser als die der Chen-Korrelation.

ОБОБЩЕНИЕ ДАННЫХ ПО ТЕПЛООБМЕНУ ПРИ КИПЕНИИ В УСЛОВИЯХ ВЫНУЖДЕННОЙ КОНВЕКЦИИ

Аннотация — Метод суперпозиции, с помощью которого проводится обобщение данных по теплообмену при кипении в условиях вынужденной конвекции, распространен на случай, включающий диапазоны от недогрева до высокого уровня паросодержания, для чего использованы уравнения одно- и двухфазной вынужденной конвекции, уравнение, описывающее кипение в открытом объеме, и критерий возникновения кипения. При этом требуется только один коэффициент, определяемый эмпирически. Результаты лучше описывают данные по кипению воды, чем соотношение Чена.