Heat Transfer Engineering

Investigations of Pool Boiling Heat Transfer of Binary Refrigerant Mixtures

CHUNG-BIAU CHIOU [a] , DING-CHONG LU [b] & CHI-CHUAN WANG [c]

[a] Teco Electric & Machinery Co., Ltd , Tao-Yuan, Taiwan

[b] Department of Mechanical Engineering , National Chiao Tung University , Hsinchu, Taiwan

[c] Energy and Research Laboratories, Industrial Technology Research Institute , Hsinchu, Taiwan
Published online: 27 Mar 2007.

PLEASE SCROLL DOWN FOR ARTICLE

Investigations of Pool Boiling Heat Transfer of Binary Refrigerant Mixtures

CHUNG-BIAU CHIOU

Teco Electric & Machinery Co., Ltd., Tao-Yuan, Taiwan

DING-CHONG LU

Department of Mechanical Engineering, National Chiao Tung University, Hsinchu, Taiwan

CHI-CHUAN WANG

Energy and Research Laboratories, Industrial Technology Research Institute, Hsinchu, Taiwan

Pool boiling data for binary mixtures of R-22 / R-124 on plain tubes are reported at reduced pressures of 0.1, 0.15, and 0.2. Significant reductions of heat transfer coefficients for mixtures are found as compared to pure refrigerant, and the reduction of heat transfer coefficient is especially pronounced in the vicinity of the pure component. This phenomenon is strongly related to the nonlinear variation of physical properties of liquid viscosity and latent heat of the mixtures. The available empirical and semiempirical correlations developed for mixtures are compared with the present data. In addition, a correlation based on the present R-22 / R-124 experimental data is proposed. This correlation not only predicts the deterioration of heat transfer coefficients for the present data with success but also predicts the experimental data from other investigators with reasonably good accuracy.

Nucleate boiling of binary mixtures has become of great interest in recent years. The boiling of mixtures is quite different from single-component boiling in that the driving force for heat transfer is in turn governed by mass transfer [1]. Therefore, the heat transfer rate may be severely reduced for binary mixtures because the rate of mass diffusion is considerably slower than that of heat diffusion in the liquid. Numerous investigations have been directed toward understanding the physical mechanism, and especially the deterioration observed in heat transfer. On the other hand, a number of correlations have been developed to predict the degree of heat transfer deterioration for mixtures. Palen and Small [2] presented the first functional

relationship among h, h_{id}, and ΔT_{db} as

$$\frac{h}{h_{id}} = \exp(-0.027 \Delta T_{db})$$ (1)

where the ideal heat transfer coefficient, h_{id}, is calculated using the McNelly [3] correlation. Stephan and Körner [4] suggested using an excess function formulation to determine the wall superheat and heat transfer coefficient:

$$\frac{h}{h_{id1}} = \frac{1}{1 + A_0(y - x)[0.88 + 0.12p(\text{bar})]}$$ (2)

where A_0 is an empirical constant, ranging from 0.42 to 3.56, that was determined from 17 mixtures by regression. The ideal transfer coefficient, h_{id1}, is given as $xh_1 + (l - x)h_2$.

Jungnickel et al. [5] proposed a similar form of Eq. (2), suggesting that the coefficient A_0 is dependent on the heat flux:

$$\frac{h}{h_{id\,1}} = \frac{1}{1 + K_0(y - x)q^{(0.48 + 0.1x)}\rho_g/\rho_f} \qquad (3)$$

The first completely analytical expression for predicting the wall superheat in a boiling mixture appears to have been derived by Calus and Leonidopoulos [6]. Starting from the pioneer work of Scriven [7], their analysis showed that

$$\frac{h}{h_{id\,2}} = \frac{1}{1 + (x - y)(\alpha/D)^{0.5}(Cp_f/i_{fg})(dT/dx)} \qquad (4)$$

Based on the film theory of mass transfer, Schlünder [8] arrived at the following expression:

$$\frac{h}{h_{id\,2}} = \frac{1}{1 + (h_{id\,2}/q'')(T_{s2} - T_{s1})(y - x)} \times \left[1.0 - \exp(-B_0 q''/\rho_f \beta_f i_{fg})\right] \qquad (5)$$

where the ideal heat transfer coefficient, $h_{id\,2}$, is calculated based on the ideal mixing temperature, $\Delta T_{id} = x \Delta T_1 + (1 - x) \Delta T_2$. Schlünder [8] assumed that $B_0 = 1.0$ and set the liquid mass transfer coefficient, β_f, equal to a constant value of 0.0002 m/s in correlating experimental data from other investigators. The ideal heat transfer coefficient, $h_{id\,2}$, is calculated by $q''/\Delta T_{id}$.

Thome and Shakir [9] eliminated the two approximations; that is, they used the exact expression for the vapor/liquid mole fraction difference of the more volatile component at the interface and the slope of the bubble-point curve by means of the boiling range,

$$\frac{dT}{dx} \approx \frac{T_d - T_b}{x - y} = \frac{\Delta T_{db}}{x - y} \qquad (6)$$

Consequently, they arrived at the correlation

$$\frac{h}{h_{id\,2}}$$

$$= \frac{1}{1 + (h_{id\,2}/q'')\,\Delta T_{db}\left[1 - \exp(-B_0 q''/\rho_f i_{fg}\,\beta_f)\right]} \qquad (7)$$

Based on an empirical procedure of dimensional analysis, Ünal [10] proposed a correlation that requires only knowledge of phase equilibrium data, which is given as follows:

$$\frac{h_{id\,2}}{h} = \left[1 + (b_2 + b_3)(1 + b_4)\right](1 + b_5) \qquad (8)$$

where

$$b_2 = (1 - x)\ln\left(\frac{1.01 - x}{1.01 - y}\right) + x\ln\left(\frac{x}{y}\right) + |y - x|^{1.5} \qquad (9)$$

$$b_3 = 0 \qquad \text{for } x \geq 0.01 \qquad (10)$$

$$b_3 = \left(\frac{y}{x}\right)^{0.1} - 1 \qquad \text{for } x \geq 0.01 \qquad (11)$$

$$b_4 = 152 P_r \qquad (12)$$

$$b_3 = 0.92|y - x|^{0.001} P_r \qquad (13)$$

$$\frac{y}{x} = 1 \qquad \text{for } x = y = 0 \qquad (14)$$

However, due to the extremely complex nature of the boiling phenomena in a binary mixture, none of these correlations could predict the heat transfer coefficients in all practical ranges of conditions with reasonable accuracy. In addition, the databank for the above-mentioned correlations are mainly from paraffins, aromatics, and olefins. Experimental data related to halogenated paraffins, which are commonly used as the working fluid in the air-conditioning and refrigeration industry, are very rare. Furthermore, systematic verification of the previous correlations to experimental data have not been conducted. Therefore, the main purpose of this study is to present new experimental data for R-22/R-124 mixtures, and to evaluate the applicability of the above-mentioned correlations to experimental data related to halogenated paraffins. In addition, a correlation based on the present experimental data is proposed. This correlation not only predicts the deterioration of heat transfer coefficients for the present data with success but also predicts the heat transfer data of halogenated paraffins from other investigators with reasonably good accuracy.

EXPERIMENTAL APPARATUS

The schematic of the single-tube pool boiling apparatus is shown in Figure 1a. It consists of a

CV: charging valve
DC: power supplier
P: pressure gauge
RV: relieve valve
TL1–TL2: liquid RTDs
Tw1–Tw3: wall TCs
W1–W2: view windows

(a)

Units: mm

(b)
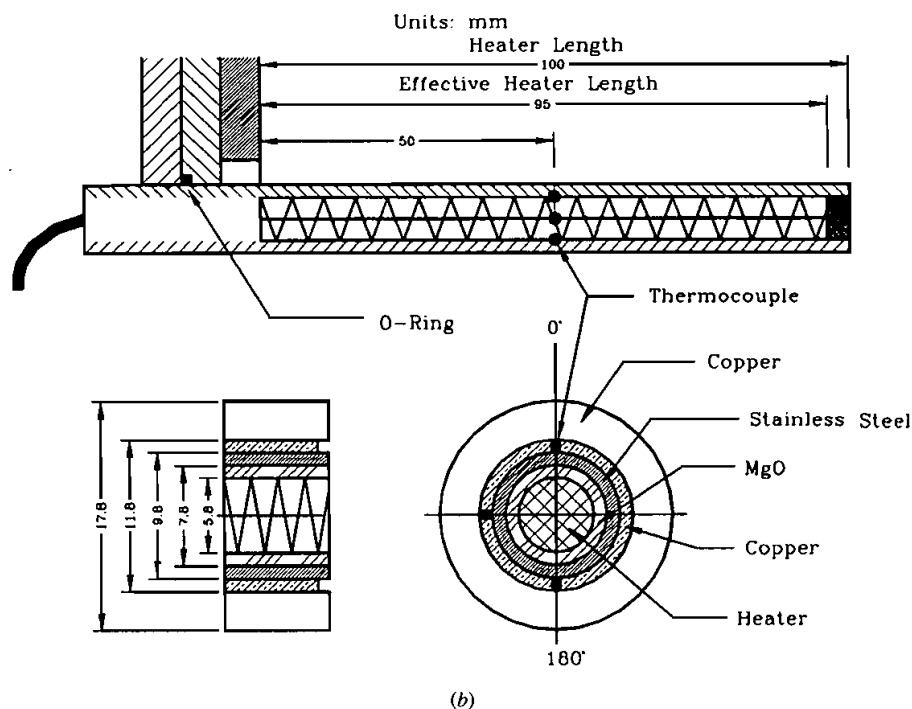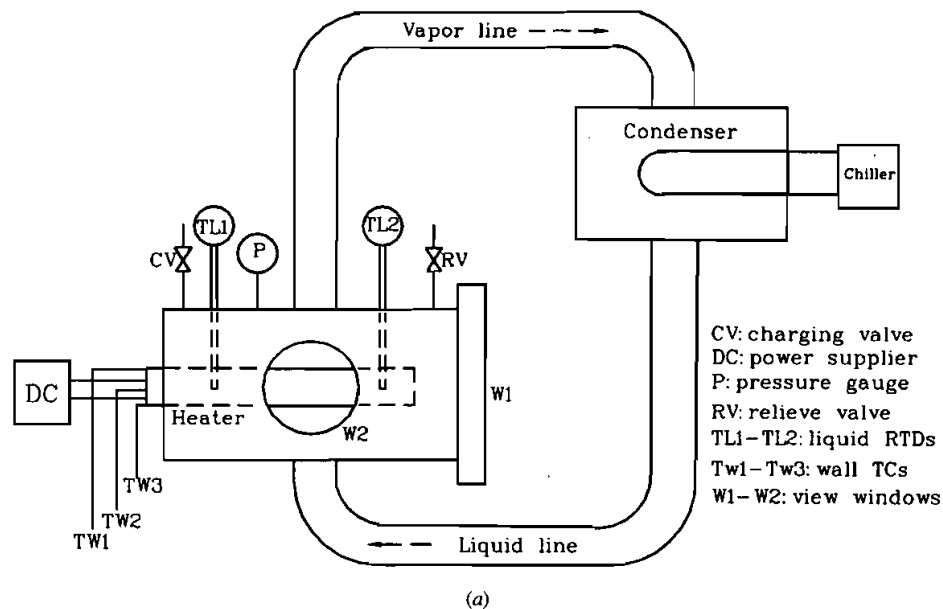
Figure 1 (a) Schematic diagram of experimental setup. (b) Detailed geometries of the test and test tube.

cylindrical test vessel, a condenser, and relevant connecting pipes made of stainless steel. Actually, the test setup is a natural-circulation-type apparatus. Heat is supplied to the copper tube by an internal cartridge heater; the evaporated vapor refrigerant leaves the test section through the vapor pipe line and condenses in a separate condenser. The cylindrical boiling cell is made of stainless steel with a diameter of 88 mm and a length of 140 mm. The test vessel has a side-view window and a frontal-view window to observe the boiling phenomena.

The detailed geometry of the test tube is shown in Figure 1b. The length of the test tube is 100 mm and it has an outside diameter of 17.8 mm. Inside the test tube, a cartridge heater with a diameter of 5.8 mm and an effective length of 95 mm is installed in the test tube. The cartridge heater, having a maximum power of 670 W, is coated with magnesium oxide and is covered by stainless steel. The stainless steel tube has a copper sleeve with three grooves in which to locate the thermocouples. Three T-type thermocouples to measure the temperature variations around the

tube wall are installed in the copper sleeve at a location 50 mm from the flange. Note that the locations of the thermocouples are 90° apart as shown in Figure 1b.

A pressure gauge calibrated with an accuracy of ±0.2% is placed at the top of the test vessel to measure the system pressure. The liquid refrigerant temperature is recorded by two resistance temperature devices (RTDs). All the thermocouples and RTDs are precalibrated by a quartz thermometer having a calibrated accuracy of 0.1°C. A high-resolution power supply capable of measuring the current to 0.01 A is used to provide the power source of the heater.

Both thermodynamic and transport properties of the mixtures were evaluated using a computer program [11].

EXPERIMENTAL PROCEDURES

The test section was cleaned and made leak-free before it was evacuated. Then the system was evacuated using a turbomolecular vacuum pump. The vacuum pump continued working for another 2 h after the vacuum gauge manometer reached 10^{-4} torr to ensure that the system contained no noncondensable gases. The experimental setup was cleaned thoroughly prior to filling the vessel with an experimental mixture. Pool boiling experiments were conducted for refrigerant mixtures of R-22/R-124 at reduced pressures of 0.1, 0.15, and 0.2. The liquid refrigerant mixtures were gradually preheated to the corresponding saturated state before running each test. Power was then adjusted to a prior setting. The criterion for steady-state condition was that the variation of system pressure was within ±3 kPa and the temperature variations of the wall surface were less than ±0.1°C over 5 min. All the data signals are collected and converted by a data acquisition system (a hybrid recorder). The data acquisition system

then transmitted the converted signals through a GPIB interface to the host computer for further operation.

The experimental uncertainties reported in the present investigation, following the single-sample method proposed by Moffat [12], are tabulated in Table 1. The maximum and minimum uncertainties of the heat transfer coefficients were estimated to be approximately 16.8% for $\dot{Q} = 2.6$ W and 1.37% for $\dot{Q} = 668$ W. The ranges of the present test data are as follows:

P_r: 0.1–0.2
q'': 0.1–120 kW/m²
ΔT_{db}: 1–8°C
$y-x$: 0.04–0.32

DATA REDUCTION

The heat transfer coefficient for each power input was calculated as follows:

$$h = \frac{\dot{Q}}{A(T_{wall} - T_f)} \tag{15}$$

where $\dot{Q}$ is the electric heating power and T_f is the average mixture temperature detected by the RTDs. The outside surface area, A, is evaluated as $\pi D_o l$. Note that D_o is the outside tube diameter, and l is the effective length of the cartridge heater ($l = 95$ mm; the length of the cartridge heater is 100 mm). T_{wall} is the mean average wall temperature at the outer surface, which can be calculated from the measurement of inside temperatures and is given by

$$T_{wall} = T_{wi} - \dot{Q}\frac{\ln(D_o/D_i)}{2\pi k_w l} \tag{16}$$

Table 1 Summary of estimated uncertainties

Primary measurements	Uncertainty	Derived quantities	$\dot{Q} = 2.6W$ (minimum)	$\dot{Q} = 668W$ (maximum)
l	10^{-3} m	ΔT	14.1%	0.94%
D_0	10^{-5} m	A	0.83%	0.83%
T	0.1°C	$\dot{Q}$	9.17%	0.57%
I	0.01 A	q''	9.21%	1.00%
Voltage	1 V	h	16.8%	1.37%

where T_{wi} is the arithmetic mean of three inside wall temperatures:

$$T_{wi} = \frac{T_{w1} + 2T_{w2} + T_{w3}}{4} \qquad (17)$$

where T_{w1}, T_{w2}, and T_{w3} are the inside wall temperature readings, respectively.

EXPERIMENTAL RESULTS

Figure 2 shows the comparison of heat transfer coefficients versus heat flux for R-22 refrigerant between the present data and those of Webb and Pais [13] and Gorenflo and Fath [14]. The saturation temperatures shown in the figure are 4.4 and 26.7°C, respectively, which are identical to the test conditions of Webb and Pais [13]. As seen, the present data agree favorably with those of Webb and Pais [13] and Gorenflo and Fath [14]. Figure 2 also shows the heat transfer coefficients predicted by Cooper [15], Stephan and Abdelsalam [16], and

Figure 2 Comparison of R-22 data with Webb and Pais [14] and correlations of Cooper [15], Stephan and Abdelsalam [16] and Mostinski [17].

Mostinski [17]. The Cooper [15] correlation is given as

$$h = 90(q'')^{0.67}M^{-0.5}P_r^m(-\log_{10} P_r)^{-0.55} \qquad (18)$$

$$m = 0.12 - 0.2\log_{10} R_p \qquad (19)$$

As reported by Stephan and Abdelsalam [16], commercial-finish copper tubes generally have a surface roughness of 0.4 μm. Therefore, the surface roughness, R_p, is given as 0.4 μm in the present calculation. The choice of surface roughness, R_p, has a slight effect on heat transfer rate as depicted by Cooper [15]. For comparison purposes, the Stephan and Abdelsalam [16] correlation and the Mostinski correlation [17] are also drawn on the figure. As can be seen, the Stephan and Abdelsalam [16] correlation and the Mostinski [17] correlation considerably underpredict the experimental data. Generally, about 20–30% underpredictions for the Stephan and Abdelsalam [16] correlation are reported; and approximately 40–100% underpredictions for the Mostinski [17] correlation are shown. Webb and Pais [13] also reported an underprediction of 20–25% of the Stephan and Abdelsalam [16] correlation.

The relationship between heat transfer coefficients and mass fraction at various heat fluxes for reduced pressures of 0.1, 0.15, and 0.2 were shown in Figure 3. As expected, the heat transfer coefficients for binary mixtures are considerably lower than the ideal heat transfer coefficient. It is evident that the deterioration of heat transfer coefficients increases sharply with increasing heat flux, particularly in the vicinity of the pure component. In addition to the explanation of mass transfer resistance, this phenomenon may be due to the nonlinear variation of physical properties. Table 2 lists the thermodynamic and transport properties of R-22, R-124, R-114, R-134a, and their corresponding binary mixtures with mass concentrations of 0.1, 0.5, and 0.9 under a given pressure of 800 kPa. It is seen from this table that some of the properties reveal highly nonlinear characteristics versus mass concentration—for example, liquid viscosity, latent heat, and liquid density. With close examination of the variation of these physical properties of R-22/R-124 in Table 2, one can easily find that the changes of some of the physical properties such as liquid viscosity and latent heat are more pronounced near the vicinity of a single component. The variations of the physical properties with concentration become less sensitive with further changes of concentration. This
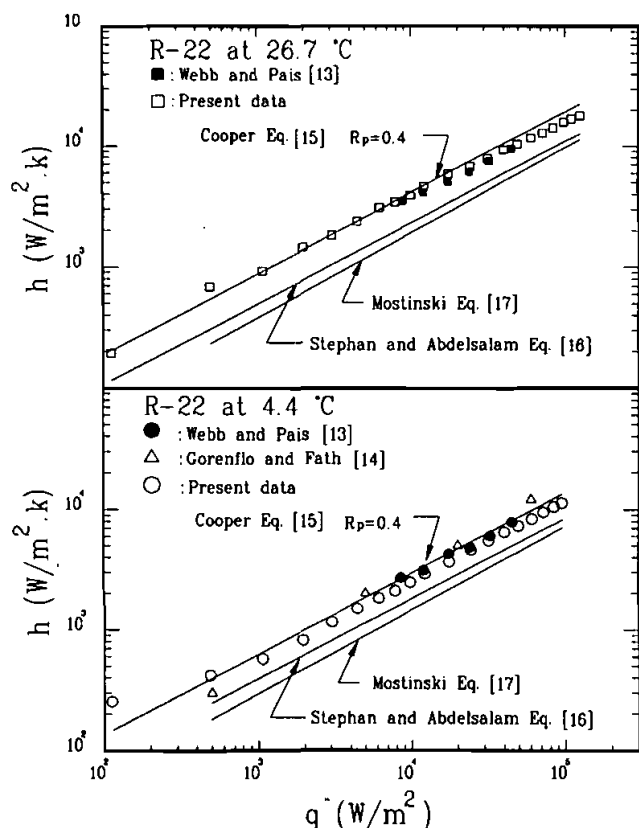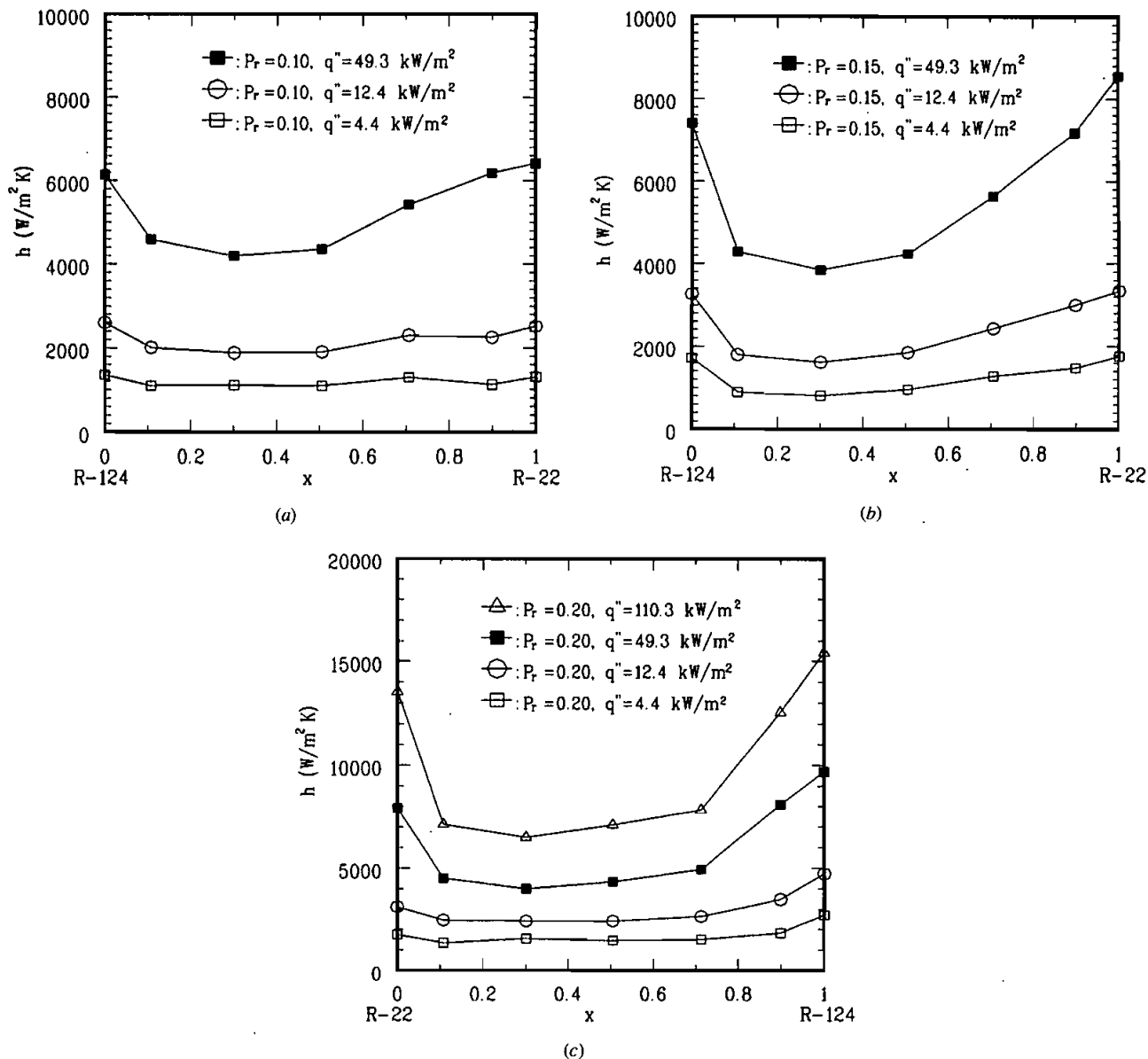
Figure 3 Pool boiling data for R-22/R-124 mixtures: (a) at $P_r = 0.1$; (b) at $P_r = 0.15$; (c) at $P_r = 0.2$.

Table 2 Thermodynamic and transport properties of five pure refrigerants and their mixtures evaluated at 800 kPa

	X	M (kg/kmol)	i_{fg} (kJ/kg)	k_f (mW/m² K)	k_g (mW/m²K)	μ_f (μPa s)	μ_g (μPa s)	Cp_f (kJ/kg K)	Cp_g (kJ/kg K)	ρ_f (kg/m³)	ρ_g (kg/m³)
R-22	1	86.48	193.2	90.85	10.74	192.6	12.8	1.199	0.739	1226.9	33.6
R-114	0	170.94	104.2	49.0	13.43	211.3	14.1	1.092	0.828	1287.0	58.9
R-124	0	136.47	130.7	59.57	13.68	196.9	13.6	1.193	0.859	1257.9	49.2
R-134a	0	102.03	175.8	77.25	14.22	200.8	12.8	1.439	0.957	1180.6	38.4
R-22/R-114	0.1	162.49	125.9	57.03	12.89	240.9	14.0	1.075	0.813	1328.0	53.8
R-22/R-124	0.1	131.47	141.2	63.86	13.15	205.5	13.5	1.181	0.843	1270.6	46.7
R-22/R-114	0.5	128.71	163.4	77.16	11.52	238.5	13.5	1.110	0.772	1302.0	41.3
R-22/R-124	0.5	111.48	169.7	77.98	11.68	210.2	13.2	1.172	0.791	1270.6	39.2
R-32/R-134a	0.5	77.03	263.0	120.10	12.35	186.8	12.2	1.527	0.921	1144.1	24.5
R-22/R-114	0.9	94.93	186.5	88.67	10.79	200.8	12.9	1.181	0.745	1239.1	35.0
R-22/R-124	0.9	91.48	189.1	88.58	10.89	196.8	12.9	1.193	0.749	1236.1	34.5

suggests that the sharp change of heat transfer coefficients near the vicinity of pure component may attribute to the nonlinear variation of the physical properties.

The maximum deterioration of the heat transfer coefficient occurs at approximately the same concentration where the greatest difference of $y - x$ is found ($x \approx 0.3$) for all the reduced pressures tested. The deterioration of heat transfer coefficients due to the change of reduced pressure is somewhat minor compared to the increase of heat flux. For a given heat flux, the change of slopes (dh/dx) of the curves seems insensitive to the change of reduced pressure for a mass concentration between 0.2 and 0.8. However, dh/dx increases with reduced pressure in the vicinity of the pure component. Similar results were reported by Inoue and Monde [18] and by Jungnickel et al. [5].

CONSTRUCTING OF THE CORRELATION BASED ON THE PRESENT EXPERIMENTAL DATA FOR R-22 / R124

Some inherent difficulties are associated with the analytical expression derived by Calus and Leonidopoulos [Eq. (4)], namely, the dT/dx and liquid mass diffusivity D. Thome and Shakir [9] approximated the temperature gradient, dT/dx, by Eq. (6). However, it is still very difficult to determine the mass diffusivity of D, since the mass diffusivity varies considerably with change of mixture composition and this property is generally not available in the open literature. Therefore, it

is necessary to eliminate D in Eq. (4) for practical engineering application. From the analysis of large spherical molecules diffusing in a dilute solution, hydrodynamic theory [19] indicates that

$$D_{AB} = \frac{RT}{6\pi\mu_B r_A} \tag{20}$$

where r_A is the radius of the "spherical solute," and μ_B is the viscosity of the solvent. Actually, Eq. (20) is the so-called Stokes-Einstein equation. Although this equation was derived for a very special situation, many investigators have used the form in developing correlations. For instance, an older but still widely used correlation for D_{AB}, the empirical Wilke-Chang correlation [20], is given as

$$D_{AB} = \frac{7.4 \times 10^{-8}(\phi M_B)^{0.5} T}{\mu_B V_A^{0.6}} \tag{21}$$

where M_B is the molecular weight of solvent B (g/mol) and V_A is the molar volume of solute A at its normal boiling point temperature (cm^3/mol).

Accordingly, the mass diffusion coefficient is assumed to be the following function of temperature, viscosity, and molecular weight, i.e.,

$$D \propto C_0\left(\frac{T_f}{\mu_f M}\right) \tag{22}$$

where C_0 is correlation parameter related to other physical properties that can be determined from the experimental data. Rearranging Eq. (4) using Eqs. (6) and (22), one arrives at

$$\frac{h}{h_{id2}} = \frac{1}{1 + (\Delta T_{db}/\Delta T_{id})(\rho_g/\rho_f)(k_f\mu_f M/\rho_f Cp_f T_f)^{0.5} C_0(Cp_f \rho_f \Delta T_{id}/i_{fg} \rho_g)} \tag{23}$$

The function $Cp_f \rho_f \Delta T_{id}/i_{fg} \rho_g$ on the right hand side of denominator in Eq. (23) can be considered as the ratio of sensible heat and latent heat. As described in the analysis by Tong et al. [21], the function should be dependent on the wall superheat, which may be interpreted as a function of heat flux. Eventually, it is assumed that the term $C_0(Cp_f \rho_f \Delta T_{id}/i_{fg} \rho_g)$ is a function of heat flux

and reduced pressure, and additional parameter ΔT_{db} characterized the refrigerant mixtures are included in this term, namely,

$$C_0\frac{Cp_f \rho_f \Delta T_{id}}{i_{fg} \rho_g} = \text{fn}(q'', P_r, \Delta T_{db}) \tag{24}$$

A best fit of the present experimental data (R-22/R-124) gives the following expression:

$$\mathrm{fn}(q'', P_r, \Delta T_{db}) = \left(1.5 \times 10^{-5}\,\frac{q''}{p_r} + \frac{25}{\Delta T_0}\right) \times 10^6$$

(25)

where

$$\Delta T_0 = \Delta T_{db} \qquad \text{for } \Delta T_{db} > 5 \tag{26}$$

$$\Delta T_0 = 5 \qquad \text{for } \Delta T_{db} \leq 5 \tag{27}$$

$$\Delta T_{db} = T_d - T_b \tag{28}$$

Eventually, the correlation has the following form:

$$\frac{h}{h_{id2}} = \frac{1}{1 + (\Delta T_{db}/\Delta T_{id})(PF)\,\mathrm{fn}(q'', P_r, \Delta T_{db})}$$

(29)

where PF is a property index and is given by

$$PF = \frac{\rho_g}{\rho_f}\left(\frac{k_f \mu_f M}{\rho_f C p_f T_f}\right)^{0.5} \tag{30}$$

Figure 4 presents the prediction of heat transfer coefficient by Eq. (29) and the present data. As seen, 93.7% of the experimental data are correlated within ±20%. In addition to the correlation proposed in this article, several other correlations were tested against the present R-22/R-124 data. These correlations include those from Palen and Small [2], Stephan and Körner [4], Jungnickel et al. [5], Schlünder [8], Thome and Shakir [9], and Ünal [10]. The results of the comparison of the correlations with the present R-22/R-124 data are shown in Table 3. As seen, the standard deviation of the present correlation, the Palen and Small correlation [2], the Stephan and Körner
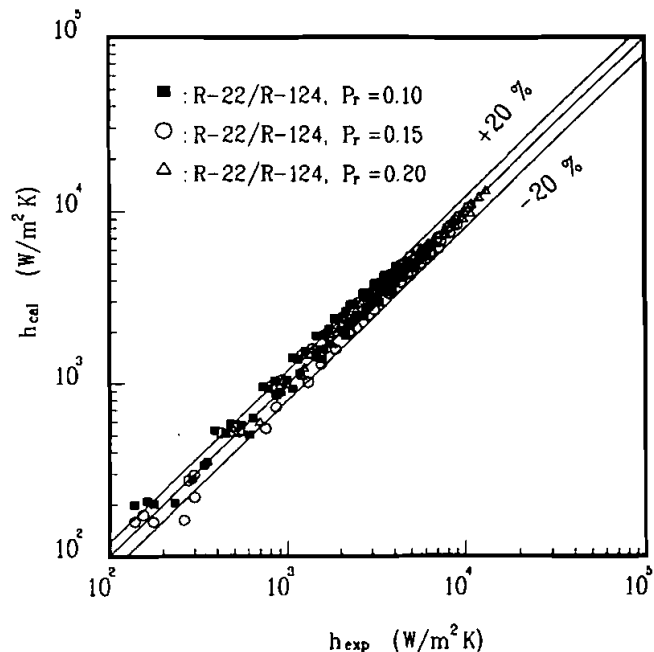

Figure 4 Comparison of the present correlation with present experimental data.

correlation [4], the Jungnickel correlation [5], the Schlünder correlation [8], the Ünal correlation [10], and the Thome and Shakir correlation [9] are 12.5%, 37.4%, 46.3%, 46.6%, 59.1%, and 26.9%, respectively. The Ünal correlation [10] gives the highest standard deviation. This may be due to the lack of the effect of the physical properties in the Ünal correlation [10]. The Jungnickel correlation [5] and Schlünder correlation considerably underpredict the present data. The Thome and Shakir correlation [9] can predict 81.5% of the present data within 20%, and gives acceptable predictions of the present data.

TESTS OF THE VARIOUS CORRELATIONS AGAINST THE DATA

An attempt has been made to collect data from a wide range of refrigerant binary mixtures from

Table 3 Standard deviations and mean absolute errors of the existing correlations with the present experimental data

Correlation	Percent of the predicted data that fall within ±20%	Mean absolute errors (%)	Standard deviation (%)
Present correlation [Eq. (29)]	93.70	3.48	12.48
Palen and Small [2]	51.68	26.92	37.41
Stephan and Körner [4]	42.86	−34.23	46.27
Jungnickel et al. [5]	27.31	−42.71	56.62
Schlünder correlation [8]	39.50	−27.43	46.56
Ünal correlation [11]	30.25	−50.63	59.14
Thome and Shakir [9]	81.51	13.51	25.92

Table 4 Operating parameters for boiling refrigerant mixtures on plain tube

Refrigerants and investigators	Heat flux, q'' (kW/m^2)	Pressure, P (kPa) or reduced pressure, P_r	Data points
R-22/R-124 (present investigation)	0.1–120	$P_r = 0.1, 0.15, 0.2$	238
R-22/R-12 (Jungnickel et al. [5])	40	$P = 200, 400, 1,000$	33
R-23/R-13 (Jungnickel et al. [5])	40	$P = 200, 1,000, 2,000$	22
R-22/R-115 (Gorenflo and Bieling [22])	5, 20	$P_r = 0.1, 0.2, 0.35, 0.5$	49
R-22/R-114 (Gorenflo et al. [23])	1, 10	$P_r = 0.2, 0.4$	22
R-11/R-113 (Ohta and Fujita, [24])	100	$P = 100, 200, 400, 800, 1,500$	29
R-11/R-113 (Trewin et al. [25])	30	$P = 103$	5
R-22/R-11 (Inoue and Monde [18])	40, 70, 100	$P = 400$	42
R-22/R-113 (Inoue and Monde [18])	40, 70, 100	$P = 400$	21
R-134a/R-113 (Inoue and Monde [18])	40, 70, 100	$P = 250, 400$	42
R-12/R-113 (Inoue and Monde [18])	40, 70, 100	$P = 400, 700$	33

other investigators. In Table 4, a complete list of the refrigerant mixtures and the relevant operating conditions is given. The data are from Jungnickel et al. [5] (R-22/R-13 and R-23/R-13, 1980), Gorenflo and Bieling [22] (R-22/R-115, 1987), Gorenflo et al. [23] (R-22/R-114, 1988), Ohta and Fujita [24] (R-11/R-113, 1994), Trewin et al. [25] (R-11/R-113, 1994), and Inoue and Monde [18] (R-22/R-11, R-22/R-113, R-134a/R-113, R-12/R-113, 1994). Note that the refrigerant mixtures of R-23/R-13 and R-22/R-115 are azetropic mixtures. Some of the experimental data (Gorenflo et al. [23], R-22/R-114, for reduced pressures of 0.6, 0.8, and 0.9) are not included in the comparisons due to the failure of the property calculation of the REFPROP program [11]. In using these correlations, it is necessary to incorporate the ideal heat transfer coefficients, h_{id1} or h_{id2}. This can be accomplished using the original experimental data from these investigators. Figure 5 shows the predictions of the present correlation with the experimental data from the above-mentioned investigators. As seen, the present correlation can predict 83.4% of the experimental data within ±20%. The predictions for R-134a/R-113 mixtures are much higher than the experimental data of Inoue and Monde [18]. However, the current correlation gives favorable predictions of the R-12/R-113 data from Inoue and Monde [18]. From carefully examination of the phase diagram and physical properties of R-12/R-113 and R-134a/R-113 mixtures, we find that there are no clear distinctions between these two mixtures. Accordingly, the significant deviations between the experimental data of R-12/R-113 and R-134a/R-113 are not clear, and are likely due to experimental errors.

The results of the predictions by other investigators with the existing data are tabulated in
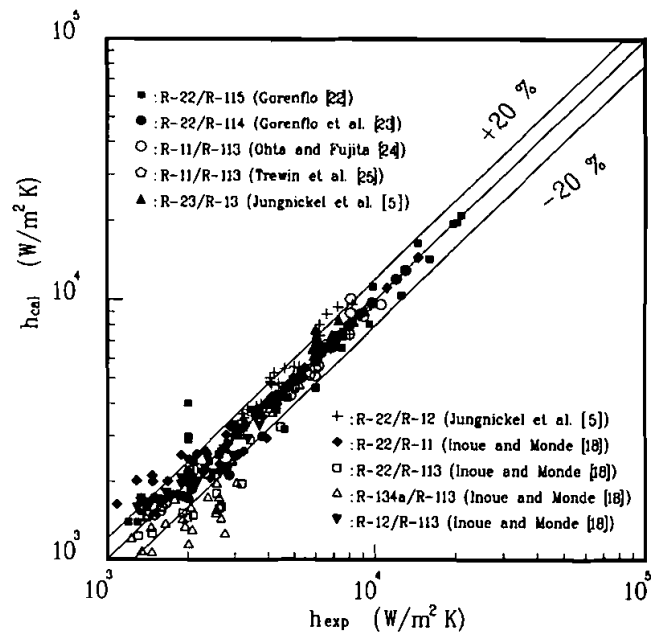
Figure 5 Comparison of the present correlation with existing experimental data.

Table 5. As shown, the standard deviation of the present correlation, the Palen and Small correlation [2], the Stephan and Körner correlation [4], the Jungnickel correlation [5], the Schlünder correlation [8], the Ünal correlation [10], and the Thome and Shakir correlation [9] are 16.9%, 30.1%, 29.9%, 21.1%, 25.9%, and 18.7%, respectively. The present correlation also gives the smallest mean absolute deviation, −1.12%. Again, the Thome and Shakir [9] correlation also gives acceptable predictions against the existing data.

CONCLUSIONS

Pool boiling data for binary mixtures of R-22/R-124 on a plain tube are reported at reduced

Table 5 Standard deviations and mean absolute errors of the existing correlations with other investigators

Correlation	Percent of the predicted data that fall within ±20%	Mean absolute deviation (%)	Standard deviation (%)
Present investigation [Eq. (29)]	83.43	−1.12	16.98
Palen and Small [2]	67.24	5.63	30.05
Stephan and Körner [4]	62.46	8.59	29.91
Jungnickel et al. [5]	42.32	−24.26	39.87
Schlünder [8]	72.35	−1.71	21.01
Ünal [11]	68.26	−5.14	25.95
Thome and Shakir [9]	70.65	−4.87	18.69

pressures of 0.1, 0.15, and 0.2. For pure refrigerants of R-22 and R-124, it is shown that the Cooper [15] correlation can predict the present pool boiling heat transfer coefficients quite satisfactorily. Significant reduction of heat transfer coefficients were found for the refrigerant mixtures, and the reductions of heat transfer coefficients are especially vivid in the vicinity of the single component. This phenomenon is strongly related to the nonlinear variation of physical properties of liquid viscosity and latent heat of the mixtures. The available empirical and semiempirical correlations developed for mixtures were compared with the present data. Among them, the correlation proposed by Thome and Shakir [9] gives fairly good predictions. In addition, a correlation based on the present R-22/R-124 experimental data is proposed. This correlation not only predicts the deterioration of heat transfer coefficients for the present data with success but also gives the best predictions with the existing experimental data of mixture refrigerants from other investigators.

NOMENCLATURE

A	heat transfer area
A_0	empirical constant
b_2, b_3, b_4, b_5	parameter
B_0	empirical constant
C_p	specific heat
C_0	empirical constant
D	mass diffusion coefficient
D_0	outside diameter
D_i	inside diameter
h	heat transfer coefficient
h_{id1}	ideal heat transfer coefficient evaluated as $xh_1 + (l - x)h_2$
h_{id2}	ideal heat transfer coefficient, evaluated using as $\dfrac{1}{(x/h_1) + [(1 - x)/h_2]}$
i_{fg}	latent heat
k	thermal conductivity
K_0	mixture-dependent constant
l	heating length
m	parameter
M	molecular weight
P	pressure
P_c	critical pressure $[= xP_{c1} + (1 - x)P_{c2}]$
P_r	reduced pressure $(= P/P_c)$
PF	property index, $\mathrm{PF} = \dfrac{\rho_g}{\rho_f}\left(\dfrac{k_f \mu_f M}{\rho_f Cp_f T_f}\right)^{0.5}$
q''	heat flux
Q	heat flow rate
r_A	molecular radius
R	gas constant
R_p	surface roughness
T	temperature
T_s	saturation temperature
T_{satl}	saturation temperature
T_{wall}	wall surface temperature
T_{wi}	average inner wall temperature
T_{w1}	top wall temperature
T_{w2}	side wall temperature
T_{w3}	bottom wall temperature
ΔT_{db}	temperature glide
ΔT_{id}	ideal mixing temperature
ΔT_0	reference temperature difference
V	molar volume
x	liquid concentration of more volatile component
y	vapor concentration of more volatile component
α	thermal diffusion coefficient

β	mass transfer coefficient
ρ	density
ϕ	parameter for the solvent

Subscripts

A	Solution
B	Solvent
b	bubble point
cal	calculated
d	dew point
exp	experimental
f	fluid (liquid)
g	gas (vapor)
w	wall
1	more volatile component
2	less volatile component

REFERENCES

[1] Thome, J. R., and Shock, R. A. W., Boiling of Multicomponent Liquid Mixtures, In J. P. Hartnett and T. F. Irvine, Jr., (Eds.), *Advances in Heat Transfer*, vol. 16, pp. 59–156, 1984.

[2] Palen, J. W., and Small, W., A New Way to Design Kettle and Internal Reboilers, *Hydrocarbon Proc.*, vol. 43, no. 11, pp. 199–208, 1964.

[3] McNelly, M. J., A Correlation of Rates of Heat Transfer to Nucleate Boiling of Liquids, *J. Imp. Coll. Chem. Soc.*, vol. 7, pp. 18–34, 1953.

[4] Stephan, K., and Körner, M., Calculation of Heat Transfer in Evaporating Binary Liquid Mixtures, *Chemie-Ingr-Tech.*, vol. 41, no. 7, pp. 409–417, 1969.

[5] Jungnickel, H., Wassilew, P. and Kraus, W. E., Investigation on the Heat Transfer of Boiling Binary Refrigerant Mixtures, *Int. J. Refrig.*, vol. 3, pp. 129–133, 1980.

[6] Calus, W. F., and Leonidopoulos, D. J., Pool Boiling-Binary Liquid Mixture, *Int. J. Heat Mass Transfer*, vol. 17, pp. 249–256, 1974.

[7] Scriven, L. E., On Dynamics of Phase Growth, *Chem. Eng. Sci.*, vol. 10, pp. 1–13, 1959.

[8] Schlünder, E. U., Heat Transfer in Nucleate Boiling of Mixtures, *Int. Chem. Eng.*, vol. 23, no. 4, pp. 589–599, 1983.

[9] Thome, J. R., and Shakir, S., A New Correlation for Nucleate Pool Boiling of Aqueous Mixtures, *AIChE Symp. Ser.*, vol. 83, no. 257, pp. 46–51, 1987.

[10] Ünal, H. C., Prediction of Nucleate Boiling Heat Transfer Coefficient for Binary Mixtures, *Int. J. Heat Mass Transfer*, vol. 29, pp. 637–640, 1986.

[11] National Institute of Standards and Technology, REFPROP 5.0, NIST, Gaithersburg, MD, 1996.

[12] Moffat, R. J., Describing the Uncertainties in Experimental Results, *Exp. Thermal Fluid Sci.*, vol. 1, pp. 3–17, 1988.

[13] Webb, R. L., and Pais, C., Nucleate Pool Boiling Data for Five Refrigerants on Plain, Integral-Fin and Enhanced Tube Geonertries, *Int. J. Heat Mass Transfer*, vol. 35, no. 8, pp. 1893–1904, 1992.

[14] Gorenflo, D., and Fath, W., Heat Transfer at Pool Boiling Outside of Finned Tubes at High Saturation Pressures, *Proc. XVIIth Int. Cong. Refrigeration*, Wien, vol. B, pp. 955–960, 1987.

[15] Cooper, M. G., Heat Flow Rates in Saturated Nucleate Pool Boiling—A Wide-Ranging Examination Using Reduced Properties, *Adv. Heat Transfer*, vol. 16, pp. 157–239, 1984.

[16] Stephan, K., and Abdelsalam, M., Heat Transfer Correlations for Natural Convection Boiling, *Int. J. Heat Mass Transfer*, vol. 23, pp. 73–87, 1980.

[17] Mostinski, I. L., Calculation of Heat Transfer and Critical Heat Flux in Boiling Liquids Based on the Law of Corresponding States, *Teploenergetika*, vol. 10, no. 4, pp. 66–71, 1963.

[18] Inoue, T., and Mode, M., Nucleate Pool Boiling Heat Transfer in Binary Mixtures, *Thermo and Fluid Dynamics*, vol. 29, pp. 171–180, 1994.

[19] Bird, R. B., W. E. Stewart, and Lightfoot, E. N., *Transport Phenomena*, John Wiley, New York, chap. 16, 1960.

[20] Wilke, C. R., and Chang, P., Correlation of Diffusion Coefficients in Dilute Solutions, *AIChE J.*, vol. 1, p. 264, 1955.

[21] Tong, W., Bar-Cohen, A., and Simon, T. W., Thermal Transport Mechanisms in Nucleate Pool Boiling of Highly-Wetting Liquids, *Proc. 9th Int. Heat Transfer Conf.*, vol. 2, pp. 27–32, 1990.

[22] Gorenflo, D., and Beiling, V., Heat Transfer at Pool Boiling of Mixtures with R22 and R115, in N. H. Afgan and J. Bougard (Eds.), *Heat and Mass Transfer in Refrigeration and Cryogenics*, pp. 243–257, Hemisphere, Washington, DC, 1987.

[23] Gorenflo, D., Blein, P., Herres, G., Rott, W., Schömann, H. and Sokol, P., Heat Transfer at Pool Boiling of Mixtures with R-22 and R-114, *Rev. Int. Froid*, vol. 11, pp. 257–263, 1988.

[24] Ohta, H., and Fujita, Y. Nucleate Pool Boiling of Binary Mixtures, *Proc. 10th Int. Heat Transfer Conf.*, vol. 5, pp. 129–134, 1994.

[25] Trewin, R. R., Jensen, M. K., and Bergles, A. E., Pool Boiling from Enhanced Surfaces in Pure and Binary Mixtures of R-113 and R-11, *Proc. 10th Int. Heat Transfer Conf.*, vol. 5, pp. 165–170, 1994.

Chung-Biau Chiou received his B.S. from Fen-Cha University of Mechanical Engineering, Taiwan. He got his M.S. and Ph.D. of mechanical engineering from National Chiao-Tung University, Hsinchu, Taiwan. He is currently an engineer at the Teco Electric & Machinery Co., Ltd., Tao-Yuan, Taiwan. His primary works are in refrigeration and air conditioning system design. Also, he is interested in multiphase heat transfer and thermoelectric system design.

Ding-Chong Lu received his B.S. from National Taiwan University of Mechanical Engineering, Taiwan. He holds M.S. and Ph.D. degrees in mechanical engineering from the University of New Mexico, USA. He is currently a professor in the Mechanical Engineering Department at National Chiao-Tung University, Hsinchu, Taiwan. His research areas are advanced heat exchanger design, two-phase heat transfer, and heat pipes.

Chi-Chuan Wang is currently a researcher at the Energy & Resources Lab., Industrial Technology Research Institute (ITRI), Hsinchu, Taiwan. He got his B.S., M.S., and Ph.D. in mechanical engineering from National Chiao Tung University Hsinchu, Taiwan, during 1977–1989. He joined ITRI in 1989. His research areas include enhanced heat transfer, multiphase systems, and heat pump technology. He has published more than 60 articles in the past few years.