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An Assessment of Some Predictive Methods for In-tube Condensation Heat Transfer of Refrigerant Mixtures

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ABSTRACT

Condensation heat transfer coefficient of non-azeotropic mixtures is significantly lower than that of single-component fluids due to mass transfer resistances. Several correction factors have been proposed for modifying the predictions of single fluid correlations for use with multicomponent refrigerant mixtures. A comprehensive study evaluating these correction factors against a wide range of experimental data has not been undertaken previously. This research aims at presenting an assessment of such predictive methods to fulfill this need in industry and academia. Analyzable data for miscible mixtures condensing in plain tubes were compared with the predictions of the general correlation of Shah (2009) modified by correction factors proposed by three researchers. The data included 529 test points for 36 refrigerant mixtures from 22 studies in horizontal and vertical tubes and included temperature glides up to 35.5°C (63.9 °F). These were predicted with a mean deviation of 18% using the correction factors of Bell and Ghaly (1973) and McNaught (1979).

INTRODUCTION

In compliance with the Montreal Protocol, the use of many chlorofluorocarbons (CFC) refrigerants such as R-11 and R-12 has already been prohibited in new equipment. The phasing out of many hydrochlorofluorocarbons (HCFC) such as R-22 is in progress. New mixtures are being proposed in an effort to obtain better thermal performance while minimizing Global Warming Potential (GWP) and Ozone Depletion Potential (ODP). For the design of condensers using these new mixtures, methods for calculating heat transfer are required. As is well known, heat transfer coefficients during condensation of non-azeotropic mixtures are lower than those of the components due to mass transfer resistance at the vapor-liquid interface. Heat transfer coefficients of non-azeotropic mixtures cannot be calculated with correlations for pure fluids simply by using mixture mean properties. To predict the heat transfer performance of mixtures, many theoretical and empirical methods have been proposed. The most common approach used in practical design applications is to apply correction factors to the predictions of reliable correlations for single-component fluids. Many such correction factors have been developed.

The classical method used for correcting the performance of binary mixtures is the film theory method proposed by Colburn and Drew (1937) which subsequently has been extended to multicomponent mixtures. Such methods are described in Taylor and Krishna (1993). These methods are quite tedious, especially when there are more than two components. Much more commonly used is the equilibrium method proposed by Bell and Ghaly (1973), which assumes that the mass transfer resistance is proportional to the resistance to sensible cooling in the vapor phase. Several modifications to the Bell and Ghaly method have been proposed. These include those by Del Col et al. (2005), McNaught (1979), and Sardesai et al. (1983). While these methods have been verified with a few data sets, there has been no comprehensive comparison with data from many sources. Such a study is needed to know which methods are reliable in what range of parameters. This research was done in an attempt to fulfill this need.

During this research, a comprehensive database for mixture condensation was compared to a correlation well-verified for single-component fluids, modifying this correlation's predictions by three published correction factors for mixture effects. The results of this comparison are presented in the following.

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CORRELATIONS FOR SINGLE-COMPONENT FLUIDS

As is well known, condensation at higher flow rates is independent of heat flux while at lower flow rates it becomes increasingly affected by heat flux. Numerous correlations, empirical and analytical, have been proposed for heat transfer during condensation of single-component fluids inside tubes. Many of them are applicable only to higher flow rates where heat flux has no significant effect. Examples of successful correlations of this type are Shah (1979), Traviss et al. (1973), and Moser et al. (1998). Very few well-verified correlations include the entire range, heat flux dependent and independent. Among these are the correlations of Dobson and Chato (1998), Cavallini et al. (2006), and Shah (2009). The last two are applicable only to horizontal tubes while the Shah correlation is applicable to both horizontal and vertical tubes (2009). The Shah correlation takes into account heat flux implicitly and hence heat flux need not be known to be compared with test data. The correlations known to us that have been demonstrated to be applicable to heat flux dependent regime, such as that of Cavallini et al. (2006), include heat flux explicitly and hence heat flux has to be known in order to compare with the data. The majority of researchers have not reported heat flux for their data points. Such data can be compared to the Shah correlation but not to the others (2009).

As shown in Shah (2009), the Shah correlation is well-verified, is applicable to all orientations, and can be compared to all data (even if they do not report heat flux). It was decided to use it as the single-component correlation for the evaluation of mixture correction factors.

The Shah Correlation (2009)

The Shah correlation (2009) has three heat transfer regimes. The condensation heat transfer coefficient is given by the following relations:

In Regime I (turbulent regime),

$$h_{TP} = h_I \tag{1}$$

In Regime II (mixed regime),

$$h_{TP} = h_I + h_{Nu} \tag{2}$$

In Regime III (laminar regime),

$$h_{TP} = h_{Nu} \tag{3}$$

where h_I and h_{Nu} in the above equations are obtained from the following equations:

$$h_I = h_{LS}\left(1 + \frac{3.8}{Z^{0.95}}\right)\left(\frac{\mu_f}{14\mu_g}\right)^{(0.0058 + 0.557 p_r)} \tag{4}$$

$$h_{Nu} = 1.32 \mathrm{Re}_{LS}^{-1/3}\left[\frac{\rho_l(\rho_l - \rho_g) g k_f^3}{\mu_f^2}\right]^{1/3} \tag{5}$$

Equation 5 is the Nusselt equation for laminar film condensation in vertical tubes; the constant has been increased by 20% as recommended by McAdams (1954) on the basis of comparison with test data. The same is used here also for horizontal tubes. Equation 5 is a modification of Shah's earlier correlation (1979), the difference being that the 1979 version did not have the viscosity ratio term. This term becomes significant only at higher p_r.

In Equation 4, h_{LS} is the heat transfer of the liquid phase flowing alone in the tube. It is calculated by the following equation:

$$h_{LS} = 0.023 \mathrm{Re}_{LS}^{0.8} \mathrm{Pr}_f^{0.4} k_f / D \tag{6}$$

Regime I is called the turbulent regime as it uses Equations 1 through 4, which are for turbulent flow. Regime III is called the laminar regime as it exclusively uses the Nusselt formula for laminar flow (Equation 5). Regime II is called the mixed regime as it adds the predictions for the laminar and turbulent regimes.

The heat transfer regimes are determined as follows.

Vertical and inclined tubes: Regime I occurs when

$$J_g \geq \frac{1}{2.4Z + 0.73} \tag{7}$$

The boundary between Regimes II and III is given by the following relation: Regime III prevails when

$$J_g \leq 0.89 - 0.93 \exp(-0.087 Z^{-1.17}) \tag{8}$$

J_g is the dimensionless vapor velocity defined as

$$J_g = \frac{xG}{(gD\rho_g(\rho_l - \rho_g))^{0.5}} \tag{9}$$

Horizontal tubes: The boundary between Regimes I and II is given by the following relation: Regime I occurs when

$$J_g \geq 0.98(Z + 0.263)^{-0.62} \tag{10}$$

A third regime is expected at very low flow rates. Analyzable data were not available for such conditions. Tentatively and conservatively, Regime III is defined to occur when both Re_{LS} and Re_{GS} is less than 1000. This is the criteria of Lockhart and Martinelli (1949) for their laminar-laminar regime.

The Shah correlation was validated by comparison with 1189 data points for 22 fluids (water, organics, halocarbon refrigerants) from 39 studies in horizontal, vertical, and inclined tubes. These included tube diameters from 2 to 49 mm (0.079 to 1.93 in.), p_r from 0.0005 to 0.9, and G from 4 to 820 kg/m^{2}s (49 to 10086 lb./ft^{2}s). Complete details of this validation and data analysis are given in Shah (2009).

CORRECTION FACTORS FOR MIXTURE EFFECTS

Three of the available correction methods for mixtures were selected for evaluating their ability to correct the predictions of the Shah (2009) general correlation for a wide range of experimental data. These methods are described below.

The Bell and Ghaly (1973) method calculates the mixture condensing heat transfer coefficient as

$$\frac{1}{h_{mix}} = \frac{1}{h_c} + \frac{Y_G}{h_{GS}} \tag{11}$$

where:

$$Y_G = xC_{pg}\frac{dT_{glide}}{dI} \tag{12}$$

h_c is the condensing heat transfer coefficient calculated with mixture properties using a correlation for pure fluids. h_{GS} is the superficial heat transfer coefficient of the vapor phase, i.e., assuming vapor phase to be flowing alone in the tube, calculated by the following equation,

$$h_{GS} = 0.023\left(\frac{u_{GS}\rho_g D}{\mu_g}\right)^{0.8}\frac{Pr_g^{0.4}k_g}{D} \tag{13}$$

Del Col et al. (2005) have presented two methods applicable to different flow pattern groups. For the intermittent, annular, and mist flow patterns, they reasoned that the heat transfer coefficient of the vapor phase is increased by means of interfacial waves and interfacial shear. To take these factors into account, they modified Equation 11 to the following:

$$\frac{1}{h_{mix}} = \frac{1}{h_c} + \frac{Y_G}{h_{GS}f_i} \tag{14}$$

where h_G is the heat transfer coefficient of vapor phase in the tube cross section occupied by vapor and is calculated by using Equation 13 but replacing u_{GS} with the vapor velocity through the area occupied by the vapor. The interfacial friction factor, f_i, is calculated using a number of equations that include those for the calculation of flow patterns and void fraction. Their correction factor for the stratified and stratified-wavy flow patterns requires that heat flux be known. The Shah correlation (2009) does not include heat flux explicitly; it is included in Regimes II and III implicitly through the liquid Reynolds number in Equation 5. Further, most of the data sets available in the open literature do not provide the heat flux. Therefore, the Del Col et al. (2005) correction factor method for stratified and stratified-wavy flow patterns was not tested here.

According to McNaught (1979), the mass transfer resistance can be significantly higher than that calculated through the Bell and Ghaly method (1973). McNaught replaced h_{GS} in Equation 11 by $h_{GS,mod}$ given by the following equation:

$$h_{GS,\,mod} = \frac{h_{GS}\phi}{(\exp\phi - 1)} \tag{15}$$

ϕ is the Ackermann factor given by:

$$\phi = \sum_{i=1}^{n}\frac{(m_i C_{pg,i})}{h_{GS}} \tag{16}$$

where m is the individual mass flux of a component. The subscript i indicates for component i. The summation is carried out for all n components of the mixture. The predicted heat transfer coefficient by the McNaught method (1979) is always equal or lower than that by the Bell and Ghaly method (1973).

COMPARISON WITH TEST DATA

Data Collection

Vigorous attempts were made to collect test data for in-tube condensation of mixtures of miscible fluids. While a large number of studies for mixtures were found, many of them did not provide sufficient information (such as pressure) to be included in this analysis. While numerous studies on R-404A and R-410A with analyzable data were available, the temperature glides of these fluids are so small that comparison with them does not give a meaningful test of the capabilities of the correction factors. Only one data set of each of these fluids has been included in this study to demonstrate the applicability of these predictive methods to this class of fluid mixtures. Most of the data was collected by analyzing graphs in research papers or reports. Only a few data sets are available in tabular form.

Table 1 lists the range of the data analyzed. It can be seen in Table 1 that the majority of data sets are for horizontal tubes with the exception of two which are for vertical tubes (downflow).

Methodology

The compositions of vapor and liquid phases were calculated at each value of vapor quality. The properties of vapor and liquid phases were calculated at these compositions. The critical pressure was calculated for the vapor-phase composition. All calculations were done using these local properties. The condensing heat transfer coefficient h_c in Equations 11 and 14 was calculated by the Shah (2009) correlation at each value of vapor quality, x, using these local values of properties. The correction factors by the three methods evaluated were also calculated the same way with properties at the local vapor quality. Flow patterns were calculated using the correlation of El Hajal et al. (2003). This method was used as Del Col et al. (2005) had

Table 1. Range of Data Analyzed and Deviations of Shah Correlation Alone and with Various Correction Factors

Author	Diameter mm (in.)	Fluids in Mixture, Percent Mass Concentration of Components	p_r	Glide °C (°F)	G kg/m^{2}s (lb/ft^{2}s)	x	Re$_{LT}$	Re$_{GT}$	Number of Data	Deviation,%, Mean/Average			
										Shah 2009	Bell and Ghaly with Shah	Del Col with Shah (see Note 2)	Mc-Naught with Shah
Lambrechts et al. (2006)	8.1 (0.032)	R-407C	0.33	5.1 (9.2)	310 (3813) 800 (9840)	0.5	18,625 48,065	187,441 482,946	6	29.7 29.7	15.3 14.4	25.7 25.7	15.2 14.3
Vardhan (1997)	1.49 (0.059)	R-407C	0.446	4.6 (8.3)	434 (5338) 650 (7995)	0.5	5,260 8,456	45,367 68,071	2	27.4 27.4	13.4 13.4	21.9 21.9	10.2 10.2
Inoue et al. (1988)	16 (0.63)	R-113/-114, 27-73	0.053	11.5 (20.7)	80 (984) 100 (1230)	0.5	4,158 5,198	114,881 143,600	2	51.1 51.1	16.6 16.6	NA	11.8 11.8
		R-113/-114, 48-52	0.050	14.8 (26.6)	65 (799) 140 (1722)	0.5	3,046 6,561	90,845 145,667	4	78.2 78.2	21.7 21.7	NA	14.7 14.7
		R-113/-114, 76-24	0.036	12.0 (21.6)	75 (922) 120 (1476)	0.2	2,706 4,331	104,966 167,946	3	50.8 50.8	5.1 -0.3	NA	6.7 -6.4
Moichzugi et al. (1990)	16.0 (0.63)	R-11/R-113, 20-80	0.0309	4.3 (7.7)	147 (1808)	0.05 0.95	5,023 5216	211,481 214,155	11	7.8 4.2	12.3 -7.8	4.6 -4.3	13.6 -10.0
Kogawa (1993)	8.44 (0.33)	R-134a/R-123, 35-65	0.11	26.1 (47.0)	300 (3690)	0.05 0.98	9,662 10,862	195,854 208,558	13	35.3 35.3	21.2 0.8	15.7 15.7	23.5 -3.9
Afroz et al. (2008)	4.35 (0.17)	CO2/DME 39-61	0.25	35.5 (63.9)	200 (2460) 500 (6150)	0.11 0.97	5,263 15,064	58,906 152,077	17	48.1 47.7	15.5 -11.0	12.8 12.8	19.6 -17.2
		CO2/DME 21-79	0.20	25.7 (46.3)	200 (2460) 500 (6150)	0.05 0.98	4,986 16,349	60,331 161,281	27	13.8 11.3	35.2 -34.8	20.2 -20.2	39.6 -39.6
Eckels-Pate (1991)	8.0 (0.31)	R-22/R124/R152a 36-24-40	0.157 0.268	3.5 (6.3) 3.8 (6.8)	135 (1660) 400 (4920)	0.49	5,886 19,065	88,555 247,893	12	19.8 19.0	12.5 8.8	20.0 20.0	10.8 6.7

Table 1. Range of Data Analyzed and Deviations of Shah Correlation Alone and with Various Correction Factors *(continued)*

Author	Diameter mm (in.)	Fluids in Mixture, Percent Mass Concentration of Components	p_r	Glide °C (°F)	G kg/m^{2}s (lb/ft^{2}s)	x	Re$_{LT}$	Re$_{GT}$	Number of Data	Deviation,%, Mean/Average			
										Shah 2009	Bell and Ghaly with Shah	Del Col2 with Shah (see Note 2)	Mc-Naught with Shah
Doer et al. (1994)	7.5 (0.29)	R125/R143a/R134a 44-52-04	0.382	0.4 (0.72)	127 (1562) 371 (4563)	0.46 0.48	7,994 23,261	76471 221,801	4	10.0 8.9	9.5 7.9	12.5 10.8	9.3 7.7
		R-32/R-125/R134a 30-10-60	0.266 0.334	5.3 (9.5) 5.6 (18.7)	130 (1599) 371 (4563)	0.45 0.47	6,729 21,779	76,814 215,059	10	38.5 38.5	20.9 20.9	30.7 30.7	16.8 16.8
		R-32/R-134a 25-75	0.242 0.30	5.2 (9.4) 5.5 (9.9)	131 (1611) 362 (4453)	0.45 0.46	6,397 19,543	80,499 222,139	16	36.5 36.5	17.9 17.9	27.6 27.6	13.8 13.8
		R-134a/R-32 90-10	0.212 0.283	3.6 (6.5) 4.6 (8.3)	129 (1587) 381 (4686)	0.45 0.48	5,613 18,999	80,370 2229,907	17	30.2 30.2	16.9 16.9	24.8 24.8	14.1 14.1
Cavallini et al. (2000)	8.0 (0.31)	R125-R236ea, 28-72	0.242	21.6 (38.9)	100 (1230) 750 (9225)	0.08 0.69	3,511 27,873	57,772 441,075	15	53.2 52.9	29.4 7.35	3.7 3.7	29.4 1.7
		R125-236ea, 63-73	0.402	16.8 (30.2)	100 (1230) 750 (9225)	0.16 0.81	5,278 41,087	55,094 420,694	23	47.2 47.2	15.7 13.1	20.9 20.9	14.7 4.7
		R-125-R236ea, 46-54	0.319	21.3 (38.3)	100 (1230) 750 (9225)	0.09 0.75	4,420 34,449	56,680 432,394	24	37.4 37.1	18.8 1.1	9.3 9.1	20.6 -4.2
Cavallini et al. (1999)	8.0 (0.31)	R-407C	0.365	5.0 (9.0)	100 (1230) 750 (9225)	0.24 0.81	6,267 46,948	58,558 439,442	28	13.5 9.7	10.7 -4.3	12.9 7.2	11.8 -7.8
Chang et al. (2000)	8.0 (0.31)	R-290/R-600, 50-50	0.219	12.3 (22.1)	57 (701) 159 (1956)	0.5	4,426 12,346	51,535 143,755	4	65.1 65.1	29.3 29.3	48.6 48.6	23.9 23.9
		R-290/R-600, 75-25	0.294	8.3 (14.9)	88 (1082) 170 (2091)	0.5	8,035 15,522	77,689 150,081	5	43.8 43.8	26.2 26.2	41.2 41.2	22.9 22.9
		R-290/R-600, 25-75	0.17	10.5 (18.9)	63 (775) 117 (1439)	0.5	4,275 7,940	58,127 107,951	3	48.8 48.8	16.1 16.1	48.4 48.4	11.3 11.3
		R-290/R-600A, 75-25	0.323	4.6 (8.3)	95 (1168) 190 (2337)	0.5	9,041 18,082	82,382 166,565	4	41.4 41.4	30.1 30.1	41.7 41.7	27.8 27.8
		R-290/R-600a, 50-50	0.266	6.5 (11.7)	70 (861) 155 (1906)	0.5	5,889 13,041	62,968 139,429	3	39.5 39.5	22.0 22.0	44.6 44.6	19.0 19.0
		R-290/R-600A, 25-75	0.222	5.6 (10.1)	62 (763) 152 (1870)	0.5	4,640 11,376	57,403 140,731	3	52.3 52.3	31.2 31.2	41.6 41.6	27.7 27.7

Table 1. Range of Data Analyzed and Deviations of Shah Correlation Alone and with Various Correction Factors *(continued)*

Author	Diameter mm (in.)	Fluids in Mixture, Percent Mass Concentration of Components	p_r	Glide °C (°F)	G kg/m^{2}s (lb/ft^{2}s)	x	Re$_{LT}$	Re$_{GT}$	Number of Data	Deviation,%, Mean/Average			
										Shah 2009	Bell and Ghaly with Shah	Del Col2 with Shah (see Note 2)	Mc-Naught with Shah
Hinton and Conklin (1995)	16.8 (0.66)	R143A/R124 75-25	0.488	3.5 (6.3)	220 (2706) 375 (4612)	0.5	38,049 64,857	289,9494 94,230	4	16.7 16.7	8.0 8.0	10.3 10.3	7.2 6.3
DeGrush and Stoecker (1987)	12.7 (0.50)	R12/R114 30-70	0.117	8.3 (14.9)	183 (2251) 233 (2866)	0.5	10,388 13,729	193,844 244,195	3	25.8 25.8	1.7 0.9	20.0 20.0	3.4 -3.4
		R-12/R-114, 70-30	0.175	6.0 (10.8)	183 (2251) 233 (2866)	0.5	12,637 16,388	189,267 239,647	4	26.2 26.2	11.5 11.5	18.7 18.9	8.7 8.7
		R-12/R-114, 50-50	0.146	8.2 (14.8)	183 (2251) 233 (2866)	0.5	11,551 14,708	192,272 242,954	4	40.4 40.4	15.3 15.3	27.6 27.6	10.8 10.8
Kenney et al. (1994)	7.04 (0.28)	R407C	0.29	5.3 (9.5)	75 (922) 650 (7995)	0.09 0.92	3,651 32,108	40,213 349,231	46	35.0 34.7	23.7 18.1	25.0 25.0	23.2 24.5
Smit et al. (2002)	8.1 (0.32)	R22/R142B 90-10	0.483	2.7 (4.9)	40 (492) 600 (7380)	0.11 0.85	2,998 44,981	21,533 323,455	34	9.5 1.2	11.2 -4.5	8.5 2.0	11.5 -5.2
		R-22/R142B 70-30	0.488	5.9 (10.6)	40 (492) 600 (7380)	0.1 0.90	3,013 45,329	21,249 319,522	31	20.3 18.3	13.8 3.3	16.7 16.7	14.9 -1.3
		R-22/R142b 50-50	0.507	6.7 (12.1)	40 (492) 600 (7380)	0.11 0.82	3,071 46,397	21,098 316,830	26	24.4 21.2	16.2 1.6	19.2 19.2	17.3 -1.8
Wen et al. (2006)	2.56 (0.1)	Propane/Butane 57-43	0.15	13.1 (23.6)	205 (2521) 320 (3936)	0.1 0.84	4,372 6,969	62,307 99,631	17	11.1 -10.8	27.4 -27.4	17.6 -17.6	29.7 -29.7
Jung et al. (2004)	8.8 (0.35)	R407C	0.332	5.1 (9.2)	200 (2460) 300 (3690)	0.1 0.97	12,979 19,811	131,360 197,440	19	12.1 11.9	7.9 -11.3	9.5 8.1	8.5 -4.5
Jiang and Garimella (2003)	9.4 (0.37)	R-404A	0.798 0.896	0.2 (0.36)	200 (2460) 500 (6150)	0.13 0.86	27,976 83,158	98,142 278,243	37	8.7 -3.9	7.9 -4.7	7.4 -2.8	7.8 -5.0
Wilson et al. (2003)	3.7 (0.14)	R-410A	0.435	0.1 (0.18)	75 (922) 400 (4920)	0.10 0.79	2,702 14,413	19,392 103,503	12	11.2 9.0	11.1 8.6	7.7 4.6	11.0 8.5

Table 1. Range of Data Analyzed and Deviations of Shah Correlation Alone and with Various Correction Factors *(continued)*

Author	Diameter mm (in.)	Fluids in Mixture, Percent Mass Concentration of Components	p_r	Glide °C (°F)	G kg/m^{2}s (lb/ft^{2}s)	x	Re$_{LT}$	Re$_{GT}$	Number of Data	Deviation,%, Mean/Average			
										Shah 2009	Bell and Ghaly with Shah	Del Col2 with Shah (see Note 2)	Mc-Naught with Shah
Boisseux et al. (2000)	9.5 (0.37)	R-407C	0.214	5.6 (10.1)	175 (2152)	0.04 0.96	9,931 10,227	131,956 132,398	13	24.1 23.7	13.7 6.7	35.2 35.2	12.2 3.1
		R-417A	0.290	3.1 (5.6)	207 (2546)	0.02 0.95	12,882 12,904	151,612 152,281	10	50.5 50.5	38.8 38.8	53.8 53.8	36.2 36.2
Moichizugi et al. (1984)1	13.9 (0.55)	R-114/R-11, 71-29	0.076	2.7 (4.9)	82 (1009)	0.5	4,381	100,554	1	15.8 15.8	9.2 9.2	NA	8.1 8.1
		R-114/R-11, 37-63	0.06	3.5 (6.3)	81 (996)	0.5	3,825	98,619	1	11.7 11.7	1.9 1.9	NA	0.3 0.3
Kozitskiy et al. (1971)1	40.0 (1.57)	R-22/R-12, 75-25	0.253	0.3 (0.54)	1.1 (13.5) 3.7 (45.5)	0.5	284 973	3,371 11,549	4	17.1 -17.1	31.8 -31.8	NA	33.0 -33.0
		R-22/R-12, 12-88	0.200	2.3 (4.1)	0.9 (11.1) 3.3 (40.6)	0.5	211 768	2,939 10,707	4	55.6 55.6	53.2 -53.2	NA	56.2 -56.2
All data for horizontal tubes	1.49 (0.06) 16.8 (0.66)	32 mixtures	0.039 0.896	0.2 (0.36) 35.5 (63.9)	40 (492) 800 (9840)	0.02 0.98	2,702 83,659	19,322 483,000	527	26.9 23.4	17.7 4.1	20.1 6.3	17.6 0.5

1 Data for vertical tube. All other data are for horizontal tubes.

2 The deviations given for Del Col et al. correction factor are only for horizontal tubes and mist, annular, and intermittent flow patterns.

developed their correction factor using this correlation. As stated earlier, the Del Col et al. correction was applied only to the data with annular, mist, and intermittent flow patterns. Further, it was applied only to horizontal tubes as it is not applicable to vertical tubes. For the data sets which gave only the mean heat transfer coefficients, the arithmetic mean of the inlet and outlet qualities was used for evaluation. All properties were calculated using the NIST software REFPROP Version 8.0 (Lemmon et al. 2007).

Results of Data Analysis

Table 1 lists the range of all data analyzed and the mean and average deviations of the data sets with the predictions of the Shah correlation (2009) alone as well as with corrections factors by the three methods. Deviations are defined as follows.

The mean deviation is defined as

$$\delta_m = \frac{\sum_{N}^{1} ABS((h_{predicted} - h_{measured})/h_{measured})}{N} \qquad (17)$$

Average deviation is defined as

$$\delta_{avg} = \frac{\sum_{N}^{1} ((h_{predicted} - h_{measured})/h_{measured})}{N} \qquad (18)$$

N is the number of data points.

Table 2 gives the breakdown of deviations of horizontal tube data in the three heat transfer regimes of the Shah correlation as well as for the various flow patterns. Figures 1 to 5 provide graphical representation of some results to highlight some of the findings of this research.

DISCUSSION

As seen in Table 1, the data analyzed in this study include 529 data points from 22 studies, for 36 fluid mixtures and temperature glides up to 35.5°C (63.9°F) for a wide range of reduced pressures and mass flow rates. The three correction factors gave mean deviations of about 17% to 20%. This is reasonably good, considering the wide range of data. Some aspects of the results are discussed in the following to give better insight into them.

Heat Transfer Regimes of Shah Correlation

Considering the heat transfer regimes that correspond to the Shah correlation (2009), the Bell and Ghaly correction factor (1973) has the least mean deviation in Regime I at 17.0%, while that of the McNaught factor is a little higher at 17.5%. Mean deviation with the Del Col et al. (2005) correction factor is significantly higher at 20.2%. Hence the Bell and Ghaly method (1973) is the best choice for Regime I. In Regime II, there are only two data points which had the flow patterns to which Del Col et al. (2005) factor could be applied. In this regime, the McNaught factor (1979) comes out best with a mean deviation of 18.6%, compared to 19.8% with the Bell and Ghaly method (1973). In Regime II, mass velocities are lower than in Regime I. So the interfacial friction is likely to be lower in Regime II, leading to greater mass transfer resistance as assumed by McNaught (1979). This may be the reason for the better performance of the McNaught correction factor.

While the mean deviations considering all data are reasonably good, discrepancies were noticed in some cases in prediction of heat transfer regimes at the lowest flow rates. This is illustrated in Figure 1. According to the criterion of Equation 10, these data are in Regime II. However, good agreement is obtained, assuming them to be in Regime I. The glide in these data was 21.6°C (38.9°F). Figure 2 shows data of Smit et al. (2002) at the same flow rate but with a glide of 6.7°C (12.1°F). These data are seen to be correctly predicted. Further, their mean heat transfer coefficient data at $G = 40$ kg/m^{2}s (492 lb/ft^{2}s) are also satisfactorily predicted. This appears to suggest that the boundary between Regime I and II changes at high values of glide. It is therefore desirable to further investigate this point, considering all data at low flow rates. The development of a new criterion for this boundary, however, is beyond the scope of the present study.

Flow Patterns

In the stratified flow pattern, the mean deviations of predictions by both McNaught (1979) and Bell and Ghaly (1973) methods are high. It is mainly due to two data points which have very high deviations; one of these is included in Figure 1. If these two are disregarded, the mean deviation of the remaining points is 17%. These two data points are at the boundary of Regimes I and II, and were predicted to be in Regime II. If they were in Regime I, good agreement will be obtained with both correction factors. Such scatter is not unusual near the boundaries. The possibility of the boundary being affected by glide has been discussed in the previous section. It is to be noted that the Shah correlation was verified with a very wide range of data that included very low flow rates and hence must have included many data in the stratified regime.

In the annular flow regime, the mean deviation with the Del Col et al. (2005) method is somewhat higher than that with the other two methods. It should be noted that Del Col et al. optimized their method using the model of Thome et al. (2003) for pure fluids. If that model were used instead of the Shah correlation, it is possible that the mean deviation could be lower than what was obtained here.

In the mist flow pattern, 19 of the 22 data points are for R-404A, which has a glide of only 0.2°C (0.36°F). So it is really a test of only the Shah correlation (2009). It is, however, satisfying to note the correct trend of the predictions of the three correction factors. As expected from their models, McNaught (1979) predicts lowest and Del Col et al. (2005) highest, with Bell and Ghaly (1973) in between the two.

Table 2. Summary of data analysis for various regimes and flow patterns

Correlation	Per Heat Transfer Regimes in Shah (2009)								On the Basis of Flow Patterns (See Footnote 3)									
	Number of Data in Heat Transfer Regimes				Deviation %, Absolute. Mean/Average				Number of Data in Flow Pattern					Deviation %, Absolute. Mean/Average				
	Regime I	Regime II	Regime III	All	Regime I	Regime II	Regime III	All	ST	SW	INT	ANN	MIST	ST	SW	INT	A	MIST
Shah (2009)	384	137	8	529	20.3 15.6	38.9 36.8	36.4 19.3	25.4 21.1	6	183	54	254	22	71.3 71.3	33.2 31.0	14.4 3.9	22.2 18.8	8.9 -3.7
Shah with Bell and Ghaly (1973)	384	137	8	528	17.0 -2.0	19.8 13.9	42.5 -42.5	18.1 1.5	6	183	54	254	22	43.7 40.0	18.6 7.4	17.3 -4.7	17.2 -0.1	11.6 -7.6
Shah with Del Col et al. (2005)	338	2	0	340	20.2 6.3	7.2 1.8	NA	20.1 6.3	6	183	54	254	22	NA	NA	15.4 1.7	19.0 12.5	9.7 -4.9
Shah with McNaught (1979)	384	137	8	529	17.5 -5.3	18.6 10.5	44.6 -44.6	18.2 -1.8	6	183	54	254	22	41.5 35.8	18.2 3.8	17.8 -6.4	17.6 -3.9	12.1 -8.5

1 All Regime III data are from one set for vertical tube
2 All flow patterns are for horizontal tubes
3 ST = Stratified, SW = Stratified-Wavy, INT = Intermittent, ANN = Annular, MIST = Mist flow

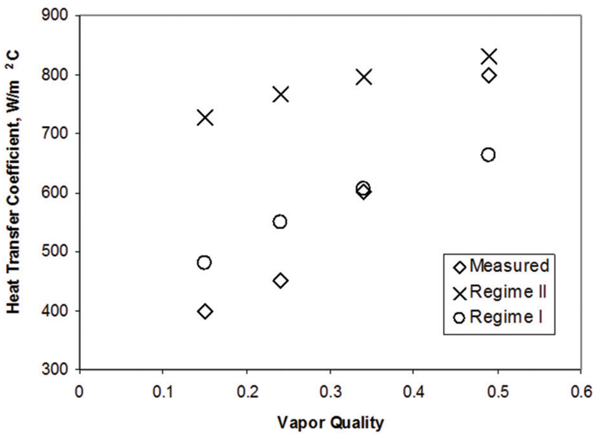

Figure 1 *Data of Cavallini et al. (2000a) for mixture of 28%–72% R-125 with R-236ea compared with Shah correlation predictions modified by the McNaught correction factor, alternately considering data to be in Regime I and II. Glide is 21.6°C (38.9°F).*

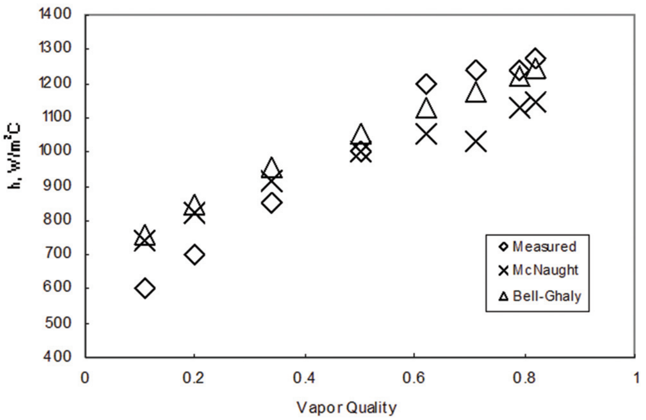

Figure 2 *Data of Smit et al. (2002) for 50-50 mixture of R-22 with R-142b and the predictions using the correction factors of McNaught (1979) and Bell and Ghaly (1973).* G = *100 kg/m^{2}s (1230 lb/ft^{2}s),* T$_{BP}$ *= 86.5°C (155.7°F), glide = 6.7°C (12.1°F).*

Data Showing Large Deviations

The data of Chang et al. (2000) for mixtures of R-290 with R-600 and R-600A are overpredicted, especially with the Del Col et al. (2005) method. In another paper, Chang et al. (1997) reported that their single component data in the same test apparatus were overpredicted 25% to 55% by the correlations of Shah (1979), Cavallini and Zecchin (1966), and Traviss et al. (1973), while it gave reasonable agreement with the correlation of Dobson and Chato (1998). During the present study, their single-component data were compared to the Shah (2009) correlation. The correlation was found to considerably overpredict the data. Thus the overprediction of mixture data is due to overprediction of h_c by the Shah correlation. It should be noted that the Shah correlation was found to be in good agreement with data for these fluids from several other sources investigated in this study. Del Col et al. (2005) have reported good agreement with data for mixtures of R-290 and R-600 using their correction factor. These data appear to be from the same source. They calculated h_c by the model of Thome et al. (2003). Apparently, this model gave lower predictions of h_c, resulting in good prediction of mixture data.

The data of Boisseux et al. (2000) for R-417A are grossly overpredicted with the three correction factors. In their paper they presented data from only one experimental run. They report that all of the data presented for this fluid had a mean deviation of 20.1% with the Shah (1979) correlation. During the present study, it was found that the data set analyzed had a mean deviation of 32.4% with the Shah (1979) correlation. Hence the data set included in this study is not representative of the entire data set evaluated by Boisseux et al. (2000). Better agreement is likely if all data were available for the purpose of this analysis.

Temperature Glide

The mixture effects increase with increasing glide as seen in the formulas for the three correction factors presented in the foregoing. The magnitude of mixture effects depends on various parameters such as mass flux, quality, fluid properties, etc., as seen in the equations for these corrective factors. If the glide is near zero, mass transfer effects are negligible as seen for the cases of R-404A and R-410A in Table 1. Hence, while many parameters affect the mass transfer effects, temperature glide is the most important factor. In Figure 3, mean deviations of data sets for horizontal tubes are plotted against temperature glide. It is seen that the deviations do not appear to be related to glide. The data at the highest glide, 35.5°C (63.9°F), are satisfactorily predicted. While there are some high deviation points at smaller glides, there are many more that give satisfactory agreement. Possible reasons for some of the data showing large deviations have been discussed earlier. If those data are disregarded, almost all mean deviations will be under 25%.

Mass Flux

Figure 4 shows the deviations for mean heat transfer coefficients (i.e. mean or average of the heat transfer coefficients along the tube length) from some of the tests with near 100% quality change in the tube, using the correction factor of McNaught (1979). The results with the Bell and Ghaly (1973) method are about the same. As seen, the mass flux in these data ranged from 40 to 800 kg/m^{2}s (492 to 9840 lb/ft^{2}s). All data show fair to excellent agreement. There is no indication of any relation between mass flux and deviation. The maximum glide in these data was 14.8°C (26.6°F). All other mean heat transfer data not included in this figure also show good agreement.

Vertical Tubes

Only two sets of analyzable data could be found for vertical tubes, both for downflow. That of Moichizugi et al. (1984) gives good agreement with the McNaught (1979) and Bell and Ghaly (1973) methods. The data of Kozitskiy et al. (1971) for R-22 and R-12 mixtures give poor agreement with both methods. These data are at extremely low flow rates, 0.9 to 3.7 kg/m^{2}s (11.1 to 45.5 lb/ft^{2}s), and are in Regime III of the Shah correlation (2009). The data is presented in Figure 5 and an unusual trend is observed. As the concentration of R-22 in the mixture increases, the heat transfer coefficient is observed to decrease with increasing flow rate (corresponding to increasing heat flux) as predicted by the Nusselt analysis. At low concentrations of R-22, the heat transfer coefficient is observed to increase with mass flux, contrary to the trend according to Nusselt analysis. The data of Bokhanovskiy (1980) for the same fluid mixture in a coil shows the same trend. None of the correction factors evaluated in this study account for this behavior. It is to be noted that the measurements of Kozitsky et al. (1971) for pure R-12 and R-22 in the same tube are in good agreement with the Nusselt analysis. Thus, there is a need for more research at these very low flow rates.

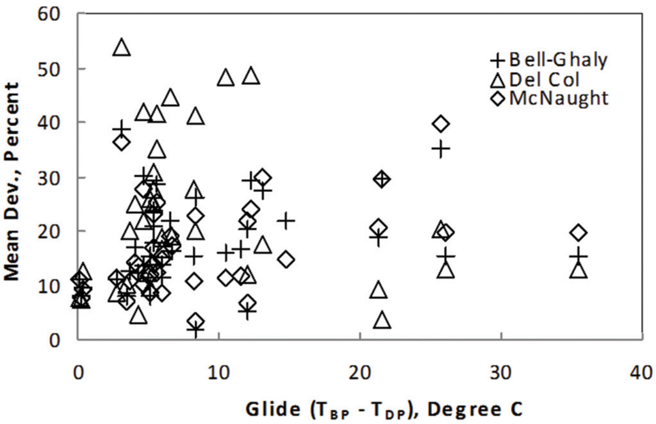

Figure 3 *Mean deviations of data sets versus temperature glide by applying the correction factors of McNaught (1979), Bell and Ghaly (1979), and Del Col et al. (2005).*

SUMMARY & CONCLUSIONS

1. A database consisting of 39 mixtures from 22 studies for condensation in horizontal and vertical tube was compared to the Shah correlation (2009) for pure fluids with its predictions modified by three published correction factors for mixture effects.
2. For horizontal tubes, the Bell and Ghaly (1973) correction factor gave the least mean deviation (17%) in Shah's Regime I. The McNaught correction factor (1979) gave the least deviation (18.6%) in Regime II. While a closer agreement is desirable, this level of agreement can be considered satisfactory in view of the wide range of data. These two are therefore recommended for use with the Shah correlation (2009) in these two regimes. For flow rates of 100 kg/m^{2}s (1230 lb/ft^{2}s) and lower, these are recommended only for temperature glides less than 15°C (27°F). Further study is needed at larger glides.
3. For vertical tubes, there were only two data sets, one in Regime I and one in Regime III. Those in Regime I agree well with both Bell and Ghaly (1973) and McNaught (1979) correction factors. Considering the good agreement with these methods with horizontal tubes in Regime I and II, similar results are expected with vertical tubes also, but direct verification with test data is desirable.
4. The data in Regime III show different trends as the mixture composition changes and predictions are poor using the correction factors. Hence application to

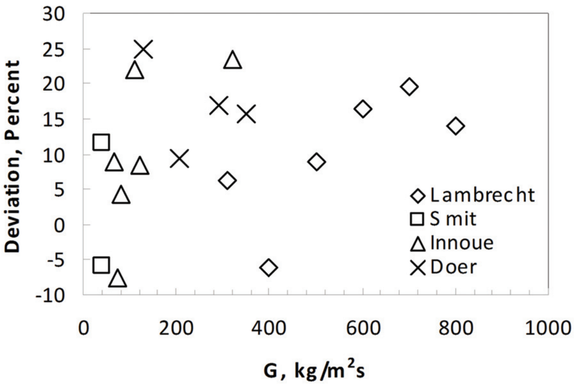

Figure 4 *Deviations of mean heat transfer data from four researchers versus mass flux.*

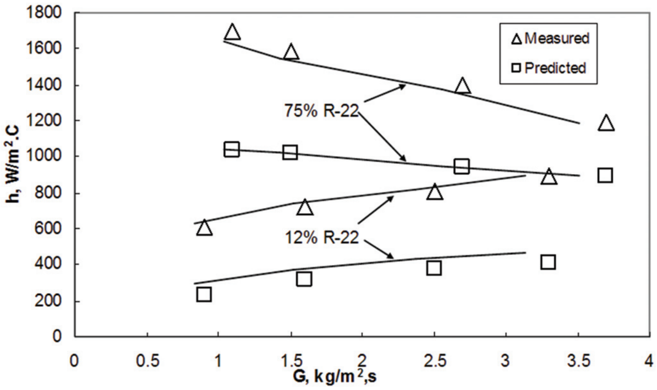

Figure 5 *Data of Kozitskiy et al. (1971) with mixtures of R-22 with R-12.* T_{BP} *at entrance 32°C (57.6°F). Predictions are with the correction factor of McNaught (1979).*

Regime III is not recommended for any tube orientation. More experimental and theoretical research is needed for condensation of mixtures at very low flow rates (Regime III) to gain understanding of the mechanisms and developing methods to predict heat transfer.

5. It is expected that the application of the correction factors for mixture effects evaluated in this study, to the predictions of reliable general correlations for pure fluids other than the Shah correlation (2009) will give similar results; verification is desirable.

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NOMENCLATURE

C_{pg} = specific heat of vapor at constant pressure (J kg^{-1} K^{-1}) (Btu/lb·°F)
D = inside diameter of tube (m) (ft)
G = total mass flux (liquid + vapor) (kg m^{-2} s^{-1}) (lb ft^{-2}s^{-1})
g = acceleration due to gravity (m s^{-2}) (ft s^{-2})
h = heat transfer coefficient (W m^{-2} K^{-1}) (Btu ft^{-2}·°F^{-1} s^{-1})
h_c = condensing heat transfer coefficient of mixture considering it to be a single fluid with mixture properties (W m^{-2} K^{-1}) (Btu ft^{-2}·°F^{-1} s^{-1})
h_I = heat transfer coefficient given by Equation 4 (W m^{-2} K^{-1}) (Btu ft^{-2}·°F^{-1} s^{-1})
h_G = heat transfer coefficient of vapor phase flowing in the cross-section occupied by vapor (W m^{-2} K^{-1}) (Btu ft^{-2}·°F^{-1} s^{-1})
h_{GS} = heat transfer coefficient of vapor phase flowing alone in the tube (W m^{-2} K^{-1}) (Btu ft^{-2}·°F^{-1} s^{-1})
h_{LS} = heat transfer coefficient assuming liquid phase flowing alone in the tube (W m^{-2} K^{-1}) (Btu ft^{-2}·°F^{-1} s^{-1})
h_{LT} = heat transfer coefficient assuming all mass flowing as liquid (W m^{-2} K^{-1}) (Btu ft^{-2}·°F^{-1} s^{-1})
h_{mix} = condensing heat transfer coefficient of mixture (W m^{-2} K^{-1}) (Btu ft^{-2}·°F^{-1} s^{-1}) (Btu ft^{-2}·°F^{-1} s^{-1})
h_{Nu} = heat transfer coefficient given by Equation 5, the Nusselt relation (W m^{-2} K^{-1}) (Btu ft^{-2}·°F^{-1} s^{-1})
h_{TP} = condensation heat transfer coefficient (W m^{-2} K^{-1}) (Btu ft^{-2}·°F^{-1} s^{-1})
I = enthalpy of mixture (J kg^{-1}) (Btu lb^{-1})
J_g = dimensionless vapor velocity defined by Equation 9
k = thermal conductivity of fluid (W/m K) (Btu/ft s)
p_r = reduced pressure
Pr = Prandtl number
Re_{GT} = Reynolds number assuming total mass flowing as vapor, $= GD/\mu_g$
Re_{LS} = Reynolds number assuming liquid phase flowing alone, $= G\,(1 - x)\,D/\mu_f$
Re_{LT} = Reynolds number assuming total mass flowing as liquid $= GD/\mu_f$
u_{GS} = vapor velocity assuming vapor phase flowing alone in the tube (m s^{-1})
T_{BP} = bubble point temperature of mixture (K) (R)
T_{DP} = dew point temperature of mixture (K) (R)
T_{glide} = temperature glide, $\mathrm{T_{DP} - T_{BP}}$, (K) (R)
x = vapor quality
Z = Shah's correlating parameter $= (1/x - 1)^{0.8}\, p_r^{0.4}$

Greek

ϕ = Ackermann factor, defined by Equation 15
μ = dynamic viscosity, kg/(m.s) (lb/ft s)
ρ = density, kg/m^3 (lb/ft^3)

Subscripts

f = of liquid
g = of vapor

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