Comparison of 20 Two-Phase Heat Transfer Correlations with Seven Sets of Experimental Data, Including Flow Pattern and Tube Inclination Effects

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In this study, the validity of 20 nonboiling heat transfer correlations obtained from a comprehensive literature review are assessed. These correlations were tested against seven extensive sets of two-phase flow experimental data available from the literature, for vertical and horizontal tubes and different flow patterns and fluids. A total of 524 data points from five available experimental studies (which included the seven sets of data) were used for these comparisons. Based on the tabulated and graphical results of the comparisons with and without considering author-specified ranges of applicability, appropriate correlations for different flow patterns and tube orientations are recommended.

In many industrial applications, such as the flow of natural gas and oil in flow lines and wellbores, the knowledge of nonboiling two-phase, two-component (liquid and permanent gas) heat transfer is required. When a gas–liquid mixture flows in a pipe, a variety of flow patterns may occur, depending primarily on flow rates, the physical properties of the fluids, and the pipe inclination angle. The main flow patterns that generally exist in vertical upward flow of a gas and liquid in tubes can be classified as bubbly flow, slug flow, froth flow, and annular flow. The main flow patterns that might exist in two-phase gas–liquid flow in horizontal tubes can be classified as stratified flow, slug flow, annular flow, and mist flow. The variety of flow patterns reflects the different ways that the gas and liquid phases are distributed in a pipe. This causes the heat transfer mechanism to be different in the different flow patterns.

Numerous heat transfer correlations and experimental data for forced convective heat transfer during gas–liquid two-phase flow in vertical and horizontal pipes have been published over the past 40 years. In this study,

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Table 1 Heat transfer correlations chosen for this study

Source	Heat transfer correlations		Source	Heat transfer correlations	
Aggour [1]	$\frac{h_{\mathrm{TP}}}{h_L} = (1-\alpha)^{-1/3}$	Laminar (L)	Knott et al. [11]	$\frac{h_{\mathrm{TP}}}{h_L} = \left(1 + \frac{V_{\mathrm{SG}}}{V_{\mathrm{SL}}}\right)^{1/3}$ where h_L is from Sieder and Tate [21]	
	$\mathrm{Nu}_L = 1.615\left(\mathrm{Re}_{\mathrm{SL}}\,\mathrm{Pr}_L \frac{D}{L}\right)^{1/3}\left(\frac{\mu_B}{\mu_W}\right)^{0.14}$	(L)	Kudirka et al. [12]	$\mathrm{Nu}_{\mathrm{TP}} = 125\left(\frac{V_{\mathrm{SG}}}{V_{\mathrm{SL}}}\right)^{1/8}\left(\frac{\mu_G}{\mu_L}\right)^{0.6}(\mathrm{Re}_{\mathrm{SL}})^{1/4}(\mathrm{Pr}_L)^{1/3}\left(\frac{\mu_B}{\mu_W}\right)^{0.14}$	
	$\frac{h_{\mathrm{TP}}}{h_L} = (1-\alpha)^{-0.83}$	Turbulent (T)	Martin and Sims [13]	$\frac{h_{\mathrm{TP}}}{h_L} = 1 + 0.64\sqrt{\frac{V_{\mathrm{SG}}}{V_{\mathrm{SL}}}}$ where h_L is from Sieder and Tate [21]	
	$\mathrm{Nu}_L = 0.0155\,\mathrm{Re}_{\mathrm{SL}}^{0.83}\,\mathrm{Pr}_L^{0.5}\left(\frac{\mu_B}{\mu_W}\right)^{0.33}$	(T)	Oliver and Wright [14]	$\mathrm{Nu}_{\mathrm{TP}} = \mathrm{Nu}_L\left(\frac{1.2}{R_L^{0.36}} - \frac{0.2}{R_L}\right)$	
Chu and Jones [2]	$\mathrm{Nu}_{\mathrm{TP}} = 0.43(\mathrm{Re}_{\mathrm{TP}})^{0.55}(\mathrm{Pr}_L)^{1/3}\left(\frac{\mu_B}{\mu_W}\right)^{0.14}\left(\frac{\mathrm{Pa}}{\mathrm{P}}\right)^{0.17}$			$\mathrm{Nu}_L = 1.615\left(\frac{(Q_G+Q_L)\,\rho D}{A\mu}\mathrm{Pr}_L \frac{D}{L}\right)^{1/3}\left(\frac{\mu_B}{\mu_W}\right)^{0.14}$	
Davis and David [3]	$\mathrm{Nu}_{\mathrm{TP}} = 0.060\left(\frac{\rho_L}{\rho_G}\right)^{0.28}\left(\frac{DG_t x}{\mu_L}\right)^{0.87}\mathrm{Pr}_L^{0.4}$		Ravipudi and Godbold [15]	$\mathrm{Nu}_{\mathrm{TP}} = 0.56\left(\frac{V_{\mathrm{SG}}}{V_{\mathrm{SL}}}\right)^{0.3}\left(\frac{\mu_G}{\mu_L}\right)^{0.2}(\mathrm{Re}_{\mathrm{SL}})^{0.6}(\mathrm{Pr}_L)^{1/3}\left(\frac{\mu_B}{\mu_W}\right)^{0.14}$	
Dorresteijn [4]	$\frac{h_{\mathrm{TP}}}{h_L} = (1-\alpha)^{-1/3}$	(L)	Rezkallah and Sims [16]	$\frac{h_{\mathrm{TP}}}{h_L} = (1-\alpha)^{-0.9}$ where h_L is from Sieder and Tate [21]	
	$\frac{h_{\mathrm{TP}}}{h_L} = (1-\alpha)^{-0.8}$	(T)	Serizawa et al. [17]	$\frac{h_{\mathrm{TP}}}{h_L} = 1 + 462X_{\mathrm{TT}}^{-1.27}$ where h_L is from Sieder and Tate [21]	
	$\mathrm{Nu}_L = 0.0123\,\mathrm{Re}_{\mathrm{SL}}^{0.9}\,\mathrm{Pr}_L^{0.33}\left(\frac{\mu_B}{\mu_W}\right)^{0.14}$		Shah [18]	$\frac{h_{\mathrm{TP}}}{h_L} = \left(1 + \frac{V_{\mathrm{SG}}}{V_{\mathrm{SL}}}\right)^{1/4}$	
Dusseau [5]	$\mathrm{Nu}_{\mathrm{TP}} = 0.029(\mathrm{Re}_{\mathrm{TP}})^{0.87}(\mathrm{Pr}_L)^{0.4}$			$\mathrm{Nu}_L = 1.86\left(\mathrm{Re}_{\mathrm{SL}}\mathrm{Pr}_L \frac{D}{L}\right)^{1/3}\left(\frac{\mu_B}{\mu_W}\right)^{0.14}$	(L)
Elamvaluthi and Srinivas [6]	$\mathrm{Nu}_{\mathrm{TP}} = 0.5\left(\frac{\mu_G}{\mu_L}\right)^{1/4}(\mathrm{Re}_{\mathrm{TP}})^{0.7}(\mathrm{Pr}_L)^{1/3}\left(\frac{\mu_B}{\mu_W}\right)^{0.14}$			$\mathrm{Nu}_L = 0.023\,\mathrm{Re}_{\mathrm{SL}}^{0.8}\,\mathrm{Pr}_L^{0.4}\left(\frac{\mu_B}{\mu_W}\right)^{0.14}$	(T)

Table 1 (*Cont.*)

Source	Heat transfer correlations	Source	Heat transfer correlations	
Groothuis and Hendal [7]	$\mathrm{Nu_{TP}} = 0.029(\mathrm{Re_{TP}})^{0.87}(\mathrm{Pr}_L)^{1/3}\left(\frac{\mu_B}{\mu_W}\right)^{0.14}$ (for water–air)	Ueda and Hanaoka [19]	$\mathrm{Nu_{TP}} = 0.075(\mathrm{Re}_M)^{0.6}\frac{\mathrm{Pr}_L}{1+0.035(\mathrm{Pr}_L - 1)}$	
	$\mathrm{Nu_{TP}} = 2.6(\mathrm{Re_{TP}})^{0.39}(\mathrm{Pr}_L)^{1/3}\left(\frac{\mu_B}{\mu_W}\right)^{0.14}$ [for (gas–oil)–air]	Vijay et al. [20]	$\frac{h_{\mathrm{TP}}}{h_L} = \left(\frac{\Delta P_{\mathrm{TPF}}}{\Delta P_L}\right)^{0.451}$	
Hughmark [8]	$\mathrm{Nu_{TP}} = 1.75(\mathrm{R}_L)^{-1/2}\left(\frac{\dot{m}_L c_L}{R_L k_L L}\right)^{1/3}\left(\frac{\mu_B}{\mu_W}\right)^{0.14}$		$\mathrm{Nu}_L = 1.615\left(\mathrm{Re_{SL}}\,\mathrm{Pr}_L\frac{D}{L}\right)^{1/3}\left(\frac{\mu_B}{\mu_W}\right)^{0.14}$	(L)
Khoze et al. [9]	$\mathrm{Nu_{TP}} = 0.26\,\mathrm{Re_{SG}^{0.2}}\,\mathrm{Re_{SL}^{0.55}}\,\mathrm{Pr}_L^{0.4}$		$\mathrm{Nu}_L = 0.0155\,\mathrm{Re_{SL}^{0.83}}\mathrm{Pr}_L^{0.5}\left(\frac{\mu_B}{\mu_W}\right)^{0.33}$	(T)
King [10]	$\frac{h_{\mathrm{TP}}}{h_L} = \frac{\mathrm{R}_L^{-0.52}}{1+0.025\,\mathrm{Re_{SG}^{0.5}}}\left[\left(\frac{\Delta P}{\Delta L}\right)_{\mathrm{TP}}\Big/\left(\frac{\Delta P}{\Delta L}\right)_L\right]^{0.32}$	Sieder and Tate [21]	$\mathrm{Nu}_L = 1.86\left(\mathrm{Re_{SL}}\mathrm{Pr}_L\frac{D}{L}\right)^{1/3}\left(\frac{\mu_B}{\mu_W}\right)^{0.14}$	(L)
	$\mathrm{Nu}_L = 0.023\,\mathrm{Re_{SL}^{0.8}}\mathrm{Pr}_L^{0.4}$		$\mathrm{Nu}_L = 0.027\,\mathrm{Re_{SL}^{0.8}}\,\mathrm{Pr}_L^{0.33}\left(\frac{\mu_B}{\mu_W}\right)^{0.14}$	(T)

Note: α and R_L are taken from the original experimental data for this study. $\mathrm{Re_{SL}} < 2{,}000$ implies laminar flow, otherwise turbulent; and for Shah [18], replace 2,000 by 170. With regard to the equations given for Shah [18] above, the laminar two-phase correlation was used along with the appropriate single-phase correlation, since Shah [18] recommends a graphical turbulent two-phase correlation.

Table 2. Author-specified limitations of the heat transfer correlations used in this study (see Nomenclature for abbreviations)

Source	Fluids	L/D	Orientation	$\dot{m}_G/\dot{m}_L$	V_{SG}/V_{SL}	Re_{SG}	Re_{SL}	Pr_L	Flow pattern(s)
Aggour [1]	A–W, helium–W, Freon 12–W	52.1	V	7.5×10^{-5}–5.72×10^{-2}	0.02–470	13.95–2.95×10^5		5.78–7.04	B, S, A, B–S, B–F, S–A, A–M
Chu and Jones [2]	W–A	34	V		0.12–4.64	540–2,700	16,000–112,000		B, S, F–A
Davis and David [3]	Gas–Liquid		H & V						A, M–A
Dorresteijn [4]	A–oil	16	V		0.004–4,500		300–66,000		B, S, A
Dusseau [5]	A–W	67	V	45–350		0–4.29×10^4	1.4×10^4–4.9×10^4		F
Elamvaluthi and Srinivas [6]	A–W A–glycerin	86	V		0.3–2.5 0.6–4.6		300–14,300		B, S
Groothuis and Hendal [7]	A–W Gas–oil–A	14.3	V	244–977 269–513	1–250 0.6–80		>5,000 1,400–3,500		
Hughmark [8]	Gas–liquid		H						S
Khoze et al. [9]	A–W, A-poly-methylsiloxane, A–diphenyl oxide	60–80	V			4,000–37,000	3.5–210	4.1–90	A
King [10]	A–W	252	H		0.327–7.648	1,570–8.28×10^4	22,500–11.9×10^4		S
Knott et al. [11]	Petroleum oil–nitrogen gas	119	V	1.57×10^{-3}–1.19	0.1–4	6.7–162	126–3,920		B
Kudirka et al. [12]	A–W, A-ethylene glycol	17.6	V	1.92×10^{-4}–0.1427 0–0.11	0.16–75 0.25–67		5.5×10^4–49.5×10^4 380–1,700	140@ 37.8°C	B, S, F
Martin and Sims [13]	A–W	17	H						B, S, A
Oliver and Wright [14]	A–85% glycol, A–1.5% SCMC, A–0.5% polyox		H				500–1,800		S
Ravipudi and Godbold [15]	A–W, A–toluene, A–benzene, A–methanol		V		1–90	3,562–82,532	8,554–89,626		F
Rezkallah and Sims [16]	A, W, oil, etc.; 13 liquid–gas combinations	52.1	V		0.01–7,030		1.8–1.3×10^5	4.2–7,000	B, S, C, A, F, B–S, B–F, S–C, S–A, C–A, F–A
Serizawa et al. [17]	A–W	35	V						B
Shah [18]	A, W, oil, nitrogen, glycol, etc.; 10 combinations		H&V		0.004–4,500		7–170		B, S, F, F–A, M
Ueda and Hanaoka [19]	A–liquid	67	V	9.4×10^{-4}–0.059	4–50			4–160	S, A
Vijay et al. [20]	A–W, A–glycerin, helium–W, Freon 12–W	52.1	V		0.005–7,670		1.8–130,000	5.5–7,000	B, S, F, A, M, B–F, S–A, F–A, A–M

a comprehensive literature search was carried out and a total of 38 two-phase flow heat transfer correlations [1–39] were identified. The validity of these correlations and their ranges of applicability have been documented by the original authors; [1–39]. In most cases, the identified heat transfer correlations were derived empirically and were based on a small set of experimental data with a limited range of variables and liquid–gas combinations. In order to assess the validity of those correlations, they were compared against seven extensive sets of two-phase flow heat transfer experimental data available from the literature, for vertical and horizontal tubes and different flow patterns and fluids. A total of 524 data points from five available experimental studies [1, 10, 40–42] were used for these comparisons. The experimental data included five different liquid–gas combinations (water–air, glycerin–air, silicone–air, water–helium, water–Freon 12), and covered a wide range of variables, including liquid and gas flow rates and properties, flow patterns, pipe sizes, and pipe inclination.

Table 1 shows 20 of the 38 heat transfer correlations that were identified and tested in this study. The rest of the two-phase flow heat transfer correlations [22–39] were not tested, since the required information for the correlations was not available through the identified experimental studies. The limitations of the 20 correlations used in this study as proposed by the original authors are tabulated in Table 2. The ranges of the seven sets of experimental data used to assess the validity of

Table 3. Ranges of experimental data used in this study

Water–air	$16.71 \le \dot{m}_L \text{ (lbm/hr)} \le 8{,}996$	$0.06 \le V_{\mathrm{SL}} \text{ (ft/sec)} \le 34.80$	$231.83 \le \mathrm{Re}_{\mathrm{SL}} \le 126{,}630$
Vertical	$0.058 \le \dot{m}_G \text{ (lbm/hr)} \le 216.82$	$0.164 \le V_{\mathrm{SG}} \text{ (ft/sec)} \le 460.202$	$43.42 \le \mathrm{Re}_{\mathrm{SG}} \le 163{,}020$
Data (139 points)	$0.007 \le X_{\mathrm{TT}} \le 433.04$	$59.64 \le T_{\mathrm{MIX}} \text{ (°F)} \le 83.94$	$14.62 \le P_{\mathrm{MIX}} \text{ (psi)} \le 74.44$
of Vijay [40]	$0.061 \le \Delta P_{\mathrm{TP}} \text{ (psi)} \le 17.048$	$0.007 \le \Delta P_{\mathrm{TPF}} \text{ (psi)} \le 16.74$	$0.033 \le \alpha \le 0.997$
	$5.503 \le \mathrm{Pr}_L \le 6.982$	$0.708 \le \mathrm{Pr}_G \le 0.710$	$11.03 \le \mathrm{Nu}_{\mathrm{TP}} \le 776.12$
	$101.5 \le h_{\mathrm{TP}} \text{ (Btu/hr ft}^2\text{ °F)} \le 7{,}042.3$	$0.813 \le \mu_W/\mu_B \le 0.933$	$L/D = 52.1,\ D = 0.46$ in.
Glycerin–air	$100.5 \le \dot{m}_L \text{ (lbm/hr)} \le 1{,}242.5$	$0.31 \le V_{\mathrm{SL}} \text{ (ft/sec)} \le 3.80$	$1.77 \le \mathrm{Re}_{\mathrm{SL}} \le 21.16$
Vertical	$0.085 \le \dot{m}_G \text{ (lbm/hr)} \le 99.302$	$0.217 \le V_{\mathrm{SG}} \text{ (ft/sec)} \le 117.303$	$63.22 \le \mathrm{Re}_{\mathrm{SG}} \le 73{,}698$
Data (57 points)	$0.15 \le X_{\mathrm{TT}} \le 407.905$	$80.40 \le T_{\mathrm{MIX}} \text{ (°F)} \le 82.59$	$17.08 \le P_{\mathrm{MIX}} \text{ (psi)} \le 62.47$
of Vijay [40]	$1.317 \le \Delta P_{\mathrm{TP}} \text{ (psi)} \le 20.022$	$1.07 \le \Delta P_{\mathrm{TPF}} \text{ (psi)} \le 19.771$	$0.0521 \le \alpha \le 0.9648$
	$6307.04 \le \mathrm{Pr}_L \le 6{,}962.605$	$0.708 \le \mathrm{Pr}_G \le 0.709$	$12.78 \le \mathrm{Nu}_{\mathrm{TP}} \le 37.26$
	$54.84 \le h_{\mathrm{TP}} \text{ (Btu/hr ft}^2\text{ °F)} \le 159.91$	$0.513 \le \mu_W/\mu_B \le 0.610$	$L/D = 52.1,\ D = 0.46$ in.
Silicone–air	$17.3 \le \dot{m}_L \text{ (lbm/hr)} \le 196$	$0.072 \le V_{\mathrm{SL}} \text{ (ft/sec)} \le 30.20$	$47.0 \le \mathrm{Re}_{\mathrm{SL}} \le 20{,}930$
Vertical	$0.07 \le \dot{m}_G \text{ (lbm/hr)} \le 157.26$	$0.17 \le V_{\mathrm{SG}} \text{ (ft/sec)} \le 363.63$	$52.1 \le \mathrm{Re}_{\mathrm{SG}} \le 118{,}160$
Data (162 points)	$72.46 \le T_W \text{ (°F)} \le 113.90$	$66.09 \le T_B \text{ (°F)} \le 89.0$	$13.9 \le P_{\mathrm{MIX}} \text{ (psi)} \le 45.3$
of Rezkallah [41]	$0.037 \le \Delta P_{\mathrm{TP}} \text{ (psi)} \le 9.767$	$0.094 \le \Delta P_{\mathrm{TPF}} \text{ (psi)} \le 9.074$	$0.011 \le \alpha \le 0.996$
	$61.0 \le \mathrm{Pr}_L \le 76.5$	$0.079 \le \mathrm{Pr}_G \le 0.710$	$17.3 \le \mathrm{Nu}_{\mathrm{TP}} \le 386.8$
	$29.9 \le h_{\mathrm{TP}} \text{ (Btu/hr ft}^2\text{ °F)} \le 683.0$		$L/D = 52.1,\ D = 0.46$ in.
Water–helium	$267 \le \dot{m}_L \text{ (lbm/hr)} \le 8{,}996$	$1.03 \le V_{\mathrm{SL}} \text{ (ft/sec)} \le 34.70$	$3{,}841 \le \mathrm{Re}_{\mathrm{SL}} \le 125{,}840$
Vertical	$0.020 \le \dot{m}_G \text{ (lbm/hr)} \le 33.7$	$0.423 \le V_{\mathrm{SG}} \text{ (ft/sec)} \le 483.6$	$14.0 \le \mathrm{Re}_{\mathrm{SG}} \le 23{,}159$
Data (53 points)	$0.16 \le X_{\mathrm{TT}} \le 769.6$	$67.4 \le T_{\mathrm{MIX}} \text{ (°F)} \le 82.0$	$15.5 \le P_{\mathrm{MIX}} \text{ (psi)} \le 53.3$
of Aggour [1]	$0.3 \le \Delta P_{\mathrm{TP}} \text{ (psi)} \le 13.2$	$0.01 \le \Delta P_{\mathrm{TPF}} \text{ (psi)} \le 12.5$	$0.038 \le \alpha \le 0.958$
	$5.78 \le \mathrm{Pr}_L \le 7.04$	$0.6908 \le \mathrm{Pr}_G \le 0.691$	$86.6 \le \mathrm{Nu}_{\mathrm{TP}} \le 668.2$
	$794 \le h_{\mathrm{TP}} \text{ (Btu/hr ft}^2\text{ °F)} \le 6{,}061$	$83.9 \le T_W \text{ (°F)} \le 95.7$	$L/D = 52.1,\ D = 0.46$ in
Water–Freon 12	$267 \le \dot{m}_L \text{ (lbm/hr)} \le 3{,}598$	$1.03 \le V_{\mathrm{SL}} \text{ (ft/sec)} \le 13.89$	$4{,}190 \le \mathrm{Re}_{\mathrm{SL}} \le 51{,}556$
Vertical	$0.84 \le \dot{m}_G \text{ (lbm/hr)} \le 206.59$	$0.51 \le V_{\mathrm{SG}} \text{ (ft/sec)} \le 117.7$	$859.5 \le \mathrm{Re}_{\mathrm{SG}} \le 209{,}430$
Data (44 points)	$0.16 \le X_{\mathrm{TT}} \le 226.5$	$75.26 \le T_{\mathrm{MIX}} \text{ (°F)} \le 83.89$	$15.8 \le P_{\mathrm{MIX}} \text{ (psi)} \le 27.8$
of Aggour [1]	$0.04 \le \Delta P_{\mathrm{TP}} \text{ (psi)} \le 4.92$	$0.02 \le \Delta P_{\mathrm{TPF}} \text{ (psi)} \le 4.48$	$0.035 \le \alpha \le 0.934$
	$5.63 \le \mathrm{Pr}_L \le 6.29$	$0.769 \le \mathrm{Pr}_G \le 0.77$	$87.1 \le \mathrm{Nu}_{\mathrm{TP}} \le 472.4$
	$800 \le h_{\mathrm{TP}} \text{ (Btu/hr ft}^2\text{ °F)} \le 4{,}344$	$90.36 \le T_W \text{ (°F)} \le 94.89$	$L/D = 52.1,\ D = 0.46$ in.
Water–air	$0.069 \le \dot{m}_L \text{ (lbm/sec)} \le 0.3876$	$0.03 \le \dot{m}_G \text{ (lbm/sec)} \le 0.2568$	$7.84 \le \Delta P/L \text{ (lbf/ft}^3\text{)} \le 137.5$
Horizontal	$0.22 \le \Delta P_M/L \text{ (lbf/ft}^3\text{)} \le 26.35$	$0.021 \le X_{\mathrm{TT}} \le 0.490$	$1.45 \le \phi_g \le 3.54$
Data (48 points)	$7.23 \le \phi_l \le 68.0$	$73.6 \le T_W \text{ (°F)} \le 107.1$	$64.9 \le T_{\mathrm{MIX}} \text{ (°F)} \le 99.4$
of Pletcher [42]	$7{,}372 \le q'' \text{ (Btu/hr ft}^2\text{)} \le 11{,}077$	$433 \le h_{\mathrm{TP}} \text{ (Btu/hr ft}^2\text{ °F)} \le 1{,}043.8$	$L/D = 60.0,\ D = 1.0$ in.
Water–air	$1{,}375 \le \dot{m}_L \text{ (lbm/hr)} \le 6{,}410$	$0.82 \le \dot{m}_G \text{ (SCFM)} \le 43.7$	$22{,}500 \le \mathrm{Re}_{\mathrm{SL}} \le 119{,}000$
Horizontal	$1{,}570 \le \mathrm{Re}_{\mathrm{SG}} \le 84{,}200$	$0.41 \le X_{\mathrm{TT}} \le 29.10$	$0.117 \le R_L \le 0.746$
Data (21 points)	$136.8 \le T_{\mathrm{MIX}} \text{ (°F)} \le 144.85$	$184.3 \le T_W \text{ (°F)} \le 211.3$	$15.8 \le P_{\mathrm{MIX}} \text{ (psi)} \le 55.0$
of King [10]	$1.027 \le \Delta P_{\mathrm{TP}} \text{ (psi)} \le 22.403$	$1{,}462 \le h_{\mathrm{TP}} \text{ (Btu/hr ft}^2\text{ °F)} \le 4{,}415$	$0.33 \le V_{\mathrm{SG}}/V_{\mathrm{SL}} \le 7.65$
	$1.35 \le h_{\mathrm{TP}}/h_L \le 3.34$	$1.35 \le \phi_l \le 8.20$	$L/D = 252,\ D = 0.737$ in.

the correlations listed in Table 1 are provided in Table 3. It should be noted that for consistency, the validity of the identified heat transfer correlations were based on the comparison between the predicted and experimental two-phase heat transfer coefficients meeting the ±30% criterion. For this reason, all of the $\mathrm{Nu}_{\mathrm{TP}}$ correlations in Table 1 were converted to h_{TP} correlations using the following simple two-phase mixture thermal conductivity relation: $k_{\mathrm{TP}} = xk_G + (1 - x)k_L$.

RESULTS FROM COMPARISON WITH CORRELATION LIMITATIONS

The author-proposed limitations for the 20 heat transfer correlations used in this study have been tabulated in Table 2. This table lists the ranges of the five dimensionless parameters $\dot{m}_G/\dot{m}_L$, $V_{\mathrm{SG}}/V_{\mathrm{SL}}$, $\mathrm{Re}_{\mathrm{SG}}$, $\mathrm{Re}_{\mathrm{SL}}$, and Pr_L that were mainly used in the development of these correlations. Among the listed parameters, only $V_{\mathrm{SG}}/V_{\mathrm{SL}}$ and $\mathrm{Re}_{\mathrm{SL}}$ have been most consistently supplied. For this reason, only these two parameters were chosen to check the validity of the identified heat transfer correlations with the seven sets of experimental data. Tables 4–10 give a summary of the results obtained by comparing the 20 identified two-phase flow heat transfer correlations with the 139 water–air experimental data of Vijay [40], 57 glycerin–air experimental data of Vijay [40], 162 silicone–air experimental data of Rezkallah [41], 53 water–helium experimental data of Aggour [1], 44 water–Freon 12 experimental data of Aggour [1], 48 water–air experimental data of Pletcher [42], and 21 water–air experimental data of King [10], respectively. Since some of the identified heat transfer correlations did not provide ranges for $\mathrm{Re}_{\mathrm{SL}}$ or $V_{\mathrm{SG}}/V_{\mathrm{SL}}$, those correlations were not listed in the comparison tables. Each

Table 4 Comparison of water–air experimental data (139 data points) of Vijay [40] with the studied correlations (see Nomenclature for abbreviations)

Source	Mean dev. (%)	rms dev. (%)	Data points within ±30%/data points for each flow pattern within $\mathrm{Re}_{\mathrm{SL}}$ range of correlation							
			B (25)	S (25)	F (25)	A (25)	B–F (7)	S–A (10)	F–A (4)	A–M (18)
Chu and Jones [2]	6.17	15.49	17/17	9/9	19/19	7/7	6/6	1/1	4/4	
Dorresteijn [4]	−17.19	61.33	7/7	20/22	1/2	11/21	0/1	2/8	0/4	0/15
Dusseau [5]	99.29	99.29	0/5	0/9	0/2	0/10	0/1	0/1	0/4	0/1
Elamvaluthi and Srinivas [6]	−123.76	183.21	0/2	0/13		1/14		2/7		0/15
Groothuis and Hendal [7]	−103.78	116.24	0/25	1/16	0/25	4/14	0/7	1/2	0/4	0/2
Khoze et al. [9]										
Knott et al. [11]	−19.65	68.50	0/3			4/4		0/7		7/13
Kudirka et al. [12]	−1.47	47.53	4/25	6/22	6/25	18/21	2/7	2/8	4/4	12/15
Oliver and Wright [14]	3798.2	4673.2						0/5		0/9
Ravipudi and Godbold [15]	18.02	23.61	0/13	16/16	10/10	14/14	4/5	2/2	4/4	2/2
Rezkallah and Sims [16]	−35.33	79.99	25/25	22/25	17/25	14/25	7/7	5/10	4/4	4/18
Shah [18]										

Note: Correlations not listed in the table did not provide an $\mathrm{Re}_{\mathrm{SL}}$ range. Blanks indicate that no data points fell within the $\mathrm{Re}_{\mathrm{SL}}$ range of the correlation.

Source	Mean dev. (%)	rms dev. (%)	Data points within ±30%/data points for each flow pattern within $V_{\mathrm{SG}}/V_{\mathrm{SL}}$ range of correlation							
			B (25)	S (25)	F (25)	A (25)	B–F (7)	S–A (10)	F–A (4)	A–M (18)
Aggour [1]	−25.33	54.75	25/25	25/25	2/25	14/21	4/7	4/9	1/4	0/6
Chu and Jones [2]	2.19	19.09	10/11	17/19	23/25	1/1	6/6	1/1	4/4	
Dorresteijn [4]	−28.79	63.33	7/25	20/25	1/25	11/25	0/7	2/10	0/4	0/15
Elamvaluthi and Srinivas [6]	−86.62	90.44	0/2	0/18	0/24	0/1	0/4	0/1	0/4	
Groothuis and Hendal [7]	−74.82	106.50		7/17	0/11	11/21	0/1	6/8	0/4	0/4
Knott et al. [11]	7.29	12.91	15/15	16/18	24/24		7/7	1/1	3/3	
Kudirka et al. [12]	−16.60	137.92	3/6	6/23	6/25	17/20	2/6	2/4	4/4	2/2
Ravipudi and Godbold [15]	−0.91	43.40		13/15	11/11	20/20	1/1	4/5	4/4	2/2
Rezkallah and Sims [16]	−34.73	80.04	25/25	22/25	17/25	14/25	7/7	5/10	4/4	4/16
Shah [18]	24.27	30.91	25/25	15/25	25/25	3/25	7/7	3/10	4/4	6/15
Ueda and Hanaoka [19]	−13.99	23.37		1/4	1/1	14/15		1/3	1/1	

Note: Correlations not listed in the table did not provide a $V_{\mathrm{SG}}/V_{\mathrm{SL}}$ range. Blanks indicate that no data points fell within the $V_{\mathrm{SG}}/V_{\mathrm{SL}}$ range of the correlation.

Table 5 Comparison of glycerin–air experimental data (57 data points) of Vijay [40] with the studied correlations (see Nomenclature for abbreviations)

			Data points within ±30%/data points for each flow pattern within Re_{SL} range of correlation					
Source	Mean dev. (%)	rms dev. (%)	B (4)	S (19)	F (17)	A (8)	B–S (4)	S–A (5)
Chu and Jones [2]								
Dorresteijn [4]								
Dusseau [5]								
Elamvaluthi and Srinivas [6]								
Groothuis and Hendal [7]								
Khoze et al. [9]	−621.68	645.37	0/4	0/15	0/17		0/4	
Knott et al. [11]								
Kudirka et al. [12]								
Oliver and Wright [14]								
Ravipudi and Godbold [15]								
Rezkallah and Sims [16]	−52.84	55.75	1/4	0/18	0/17	5/7	0/4	0/4
Shah [18]	−40.78	43.36	3/3	2/10	0/8		2/3	

Note: Correlations not listed in the table did not provide an Re_{SL} range. Blanks indicate that no data points fell within the Re_{SL} range of the correlation.

			Data points within ±30%/data points for each flow pattern within V_{SG}/V_{SL} range of correlation					
Source	Mean dev. (%)	rms dev. (%)	B (4)	S (19)	F (17)	A (8)	B–S (4)	S–A (5)
Aggour [1]	−13.76	18.39	4/4	17/19	15/17	8/8	4/4	4/5
Chu and Jones [2]	−91.98	98.19	1/3	2/15	0/2		0/4	
Dorresteijn [4]	89.69	89.93	0/4	0/19	0/17	0/8	0/4	0/5
Elamvaluthi and Srinivas [6]	−536.11	669.32	0/1	1/15	0/2		0/4	
Groothuis and Hendal [7]				0/13	0/17	0/7	0/2	0/5
Knott et al. [11]	−40.11	44.41	2/3	2/14	0/1		2/4	
Kudirka et al. [12]	61.59	61.82	0/3	0/19	0/17		0/4	0/5
Ravipudi and Godbold [15]	64.06	64.35		0/13	0/17	0/1	0/2	0/5
Rezkallah and Sims [16]	−51.41	54.78	1/4	1/19	0/17	6/8	0/4	0/5
Serizawa et al. [17]								
Shah [18]	−50.04	53.92	4/4	4/19	0/17	0/8	3/4	0/5
Ueda and Hanaoka [19]	−31.47	34.57		5/5	2/15			0/4

Note: Correlations not listed in the table did not provide a V_{SG}/V_{SL} range. Blanks indicate that no data points fell within the V_{SG}/V_{SL} range of the correlation.

table shows the total number of experimental data points for each flow pattern, the ratio of the number of data points in each flow pattern that were predicted to within ±30% by the individual heat transfer correlations to the total number of data points that fell within the restrictions for Re_{SL} or V_{SG}/V_{SL} (Table 2) that accompanied the correlations, and the percent overall mean and root-mean-square (rms) deviations of the predictions from the data for each correlation. The flow pattern identification for the experimental data was based on the procedures suggested by Govier and Aziz [44], Griffith and Wallis [45], Hewitt and Hall-Taylor [46], Taitel et al. [47], Taitel and Dukler [48], and visual observation as appropriate. The procedures employ complex flow maps depending on V_{SL} and V_{SG}, and tube orientation; these are not reproduced here. For each flow pattern, the tables also highlight (see shaded cells of the tables) the number of data points predicted by the correlation(s) that best satisfied the ±30% two-phase heat transfer coefficient criterion.

From the comparison results shown in Table 4, several water–air data points of Vijay [40] were within the accompanying Re_{SL} and V_{SG}/V_{SL} parameter ranges of the heat transfer correlations. Considering the author-specified ranges of Re_{SL} and V_{SG}/V_{SL} along with the overall performance for all flow patterns and mean and rms deviations, the correlation of Chu and Jones [2] is recommended for all the flow patterns except the annular–mist flow pattern. Also, the correlation of Ravipudi and Godbold [15] is recommended for all of the flow patterns except the bubbly flow pattern. The performances of Chu and Jones' [2] and Ravipudi and

Table 6 Comparison of silicone–air experimental data (162 data points) of Rezkallah [41] with the studied correlations (see Nomenclature for abbreviations)

Source	Mean dev. (%)	rms dev. (%)	Data points within ±30%/data points for each flow pattern within $\mathrm{Re_{SL}}$ range of correlation										
			B (26)	S (13)	C (11)	A (25)	F (18)	B–S (7)	B–F (10)	S–C (13)	C–A (12)	F–A (6)	A–M (21)
Chu and Jones [2]	−18.92	20.21	13/13				10/10		4/4				
Dorresteijin [4]	−5.61	45.65	25/26	0/1	0/5	0/13	4/18	2/7	9/10	1/8	1/5	0/6	4/9
Dusseau [5]	98.75	98.75	0/13				0/10		0/4				
Elamvaluthi and Srinivas [6]	−294.86	608.60	0/13	1/1	0/5	0/13	0/8	0/7	0/6	1/8	0/5	0/6	0/9
Groothuis and Hendal [7]	−140.42	157.62	0/20			0/2	0/18		0/10			0/6	
Khoze et al. [9]	−66.50	85.61		0/9	0/5	0/9				0/4	0/4		5/9
Knott et al. [11]	14.46	57.60	2/6	0/7	0/8	9/17		3/7		1/10	2/10		2/15
Kudirka et al. [12]	−17.11	73.96	4/26	0/1	0/5	5/13	8/18	2/7	5/10	1/8	1/5	6/6	0/9
Oliver and Wright [14]	900.85	1880.5	0/4	0/1	0/5	0/8		0/4		0/7	0/4		0/9
Ravipudi and Godbold [15]	40.74	48.53	0/17			2/2	8/16		0/7			4/4	
Rezkallah and Sims [16]	−20.01	52.54	26/26	8/13	9/11	14/25	10/18	6/7	10/10	12/13	10/12	0/6	6/21
Shah [18]	−5.97	34.37		3/6	0/3	2/6				2/3	2/2		5/6

Note: Correlations not listed in the table did not provide an $\mathrm{Re_{SL}}$ range. Blanks indicate that no data points fell within the $\mathrm{Re_{SL}}$ range of the correlation.

Source	Mean dev. (%)	rms dev. (%)	Data points within ±30%/data points for each flow pattern within V_{SG}/V_{SL} range of correlation										
			B (26)	S (13)	C (11)	A (25)	F (18)	B–S (7)	B–F (10)	S–C (13)	C–A (12)	F–A (6)	A–M (21)
Aggour [1]	−8.36	78.72	0/22	3/13	2/11	1/21	0/18	0/7	0/10	1/13	1/12	0/6	5/9
Chu and Jones [2]	−68.44	76.83	0/5	1/3		0/3	10/18	0/7	3/9	0/6	0/1	0/6	
Dorresteijn [4]	22.35	59.02	25/26	0/13	0/11	0/25	4/18	2/7	9/10	1/13	1/12	0/6	4/20
Elamvaluthi and Srinivas [6]	−93.71	110.52	0/3	2/3		0/3	0/14	0/7	0/1	1/6	0/1	0/6	
Groothuis and Hendal [7]	−368.94	866.34	0/1	5/13	2/11	0/18	0/4	3/3		5/13	0/12	0/6	0/7
Knott et al. [11]	15.09	28.67	3/7	0/3		2/2	18/18	3/7	10/10	1/6	1/1	6/6	
Kudirka et al. [12]	−43.0	87.73	0/5	0/13	0/8	5/13	8/18	2/7	5/6	1/12	1/9	6/6	
Ravipudi and Godbold [15]	4.34	21.54	1/1	4/13	8/8	11/13	4/4	3/3		11/12	10/10	6/6	
Rezkallah and Sims [16]	−20.19	52.70	25/25	8/13	9/11	14/25	10/18	6/7	10/10	12/13	10/12	0/6	6/21
Shah [18]	9.35	43.09	25/26	3/13	1/11	11/25	18/18	3/7	10/10	6/13	4/12	6/6	9/20
Ueda and Hanaoka [19]	−205.46	218.96		0/8	0/8	0/8				0/4	0/7		

Note: Correlations not listed in the table did not provide a V_{SG}/V_{SL} range. Blanks indicate that no data points fell within the V_{SG}/V_{SL} range of the correlation.

Godbold's [15] correlations in different flow patterns with respect to the parameters of $\mathrm{Re_{SL}}$ and V_{SG}/V_{SL} plotted on the horizontal axis and the dimensionless value of $h_{\mathrm{TP_{CAL}}}/h_{\mathrm{TP_{EXP}}}$ plotted on the vertical axis are given in Figures 1 and 2, respectively. For bubbly and slug flow patterns, the correlation of Aggour [1] is recommended, based on the comparison results with and without (see Table 11) the restriction on V_{SG}/V_{SL} accompanying the correlation, even though there was no author-specified $\mathrm{Re_{SL}}$ restriction.

Comparison results of several heat transfer correlations with the glycerin–air experimental data of Vijay [40], along with the restrictions on $\mathrm{Re_{SL}}$ and V_{SG}/V_{SL} suggested by the authors of the correlations, are given in Table 5. Only a few of the tested correlations, used within the specified limitations on $\mathrm{Re_{SL}}$ and V_{SG}/V_{SL}, were capable of accurately predicting the glycerin–air experimental data. Considering the overall performance of predicting the experimental heat transfer coefficients, only the correlation of Aggour [1] is recommended for all of the flow patterns in this set of experimental data. Figure 3 shows the comparison results between the correlation of Aggour [1] and the glycerin–air experimental data of Vijay [40] in terms of the dimensionless values of $h_{\mathrm{TP_{CAL}}}/h_{\mathrm{TP_{EXP}}}$ plotted versus $\mathrm{Re_{SL}}$ and V_{SG}/V_{SL}.

For the silicone–air experimental data of Rezkallah [41], along with the restrictions on $\mathrm{Re_{SL}}$ and V_{SG}/V_{SL} from the correlations, only a few of the correlations predicted the experimental data reasonably well, even though several of the silicone–air experimental data points fell within the author-specified $\mathrm{Re_{SL}}$ and V_{SG}/V_{SL} ranges of the correlations (see Table 6). Considering the

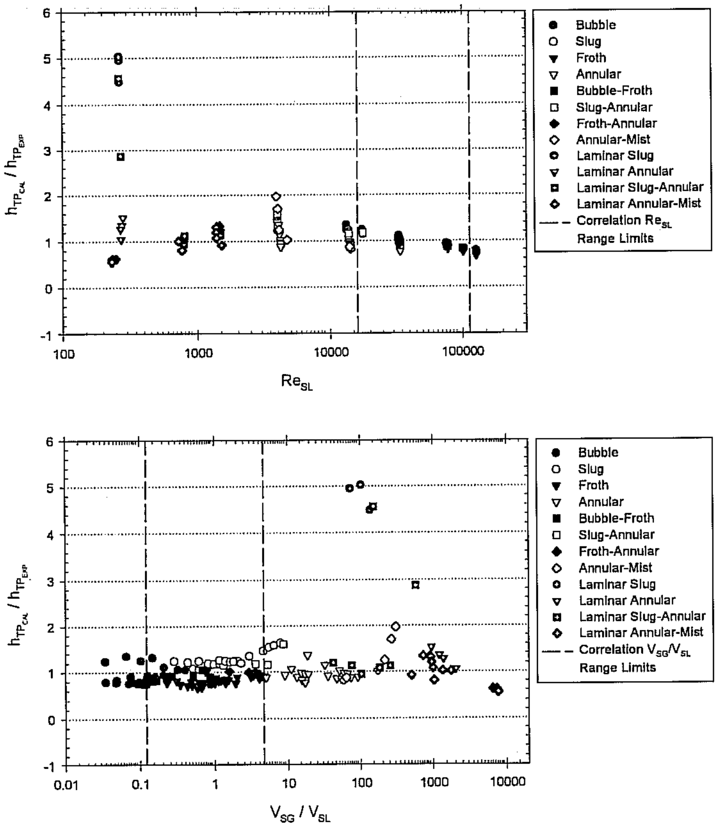

Figure 1. Comparison of Chu and Jones's [2] correlation with Vijay's [40] water–air experimental data.

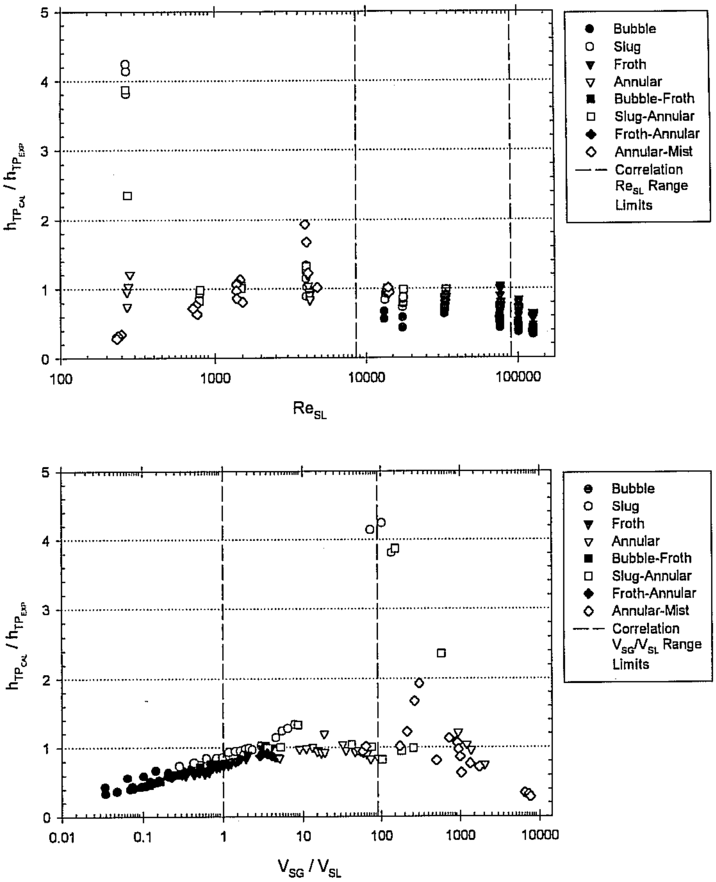

Figure 2. Comparison of Ravipudi and Godbold [15] correlation with Vijay's [40] water–air experimental data.

Table 7 Comparison of water–helium experimental data (53 data points) of Aggour [1] with the studied correlations (see Nomenclature for abbreviations)

Source	Mean dev. (%)	rms dev. (%)	Data points within ±30%/data points for each flow pattern within Re_{SL} range of correlation							
			B (10)	S (12)	F (12)	A (9)	B–S (2)	B–F (1)	S–A (4)	A–M (3)
Chu and Jones [2]	7.21	8.63	4/4		6/6			1/1		
Dorresteijn [4]	−53.17	76.13	4/7	5/12	0/6	2/9	2/2	0/1	1/4	0/3
Dusseau [5]	99.64	99.64				0/2				
Elamvaluthi and Srinivas [6]	−41.49	66.88	0/3	1/12		8/9	0/2		3/4	0/3
Groothuis and Hendal [7]	−60.56	85.58	1/10	6/6	0/12	5/5	2/2	0/1	2/2	
Khoze et al. [9]										
Knott et al. [11]	−152.28	152.28								0/1
Kudirka et al. [12]	−38.18	78.60	4/10	0/12	6/12	3/9	0/2	1/1	0/4	0/3
Ravipudi and Godbold [15]	2.26	26.80	3/7	6/6	6/6	0/5	2/2	0/1	2/2	
Rezkallah and Sims [16]	−47.52	88.24	10/10	6/12	6/12	1/9	2/2	1/1	0/4	0/3
Shah [18]										

Note: Correlations not listed in the table did not provide an Re_{SL} range. Blanks indicate that no data points fell within the Re_{SL} range of the correlation.

Source	Mean dev. (%)	rms dev. (%)	Data points within ±30%/data points for each flow pattern within V_{SG}/V_{SL} range of correlation							
			B (10)	S (12)	F (12)	A (9)	B–S (2)	B–F (1)	S–A (4)	A–M (3)
Aggour [1]	−45.41	73.89	7/10	6/12	0/12	2/9	2/2	1/1	0/4	0/3
Chu and Jones [2]	−3.0	22.58	4/5	4/5	9/9		2/2	1/1		
Dorresteijn [4]	−55.40	74.57	4/10	5/12	0/12	2/9	2/2	0/1	1/4	0/3
Elamvaluthi and Srinivas [6]	−59.38	62.29	0/3	0/5	0/5		0/2	0/1		
Groothuis and Hendal [7]	0.14	28.13		12/12	0/6	6/9	1/1		2/4	1/1
Knott et al. [11]	10.0	16.47	4/5	4/4	9/9		1/2	1/1		
Kudirka et al. [12]	−41.30	76.43	2/4	0/12	6/10	2/5	0/2	1/1	0/4	
Ravipudi and Godbold [15]	−22.42	31.51		7/12	6/6	0/5	1/1		2/4	
Rezkallah and Sims [16]	−47.52	88.24	10/10	6/12	6/12	1/9	2/2	1/1	0/4	0/3
Shah [18]	20.89	26.71	9/10	8/12	12/12	6/9	0/2	1/1	2/4	2/3
Ueda and Hanaoka [19]	98.20	98.20		0/8	0/3	0/5			0/3	

Note: Correlations not listed in the table did not provide a V_{SG}/V_{SL} range. Blanks indicate that no data points fell within the V_{SG}/V_{SL} range of the correlation.

overall performance of the correlations for all flow patterns and the values of the mean and rms deviations, two of the tested heat transfer correlations are recommended. These are the correlation of Ravipudi and Godbold [15] for churn, annular, bubbly–slug, slug–churn, churn–annular, and froth–annular flows and the correlation of Rezkallah and Sims [16] for bubbly, slug, churn, bubbly–slug, bubbly–froth, slug–churn, and churn–annular flows. Figures 4 and 5 show the comparison between the predictions of the correlation of Ravipudi and Godbold [15] and the correlation of Rezkallah and Sims [16] with the silicone–air experimental data of Rezkallah [41], along with the authors' specified ranges of Re_{SL} and V_{SG}/V_{SL}, in terms of the dimensionless values of $h_{TP_{CAL}}/h_{TP_{EXP}}$ plotted versus Re_{SL} and V_{SG}/V_{SL}.

The results of comparison of the water–helium experimental data of Aggour [1] with the identified heat transfer correlations, along with the authors' specified parameter ranges of Re_{SL} and V_{SG}/V_{SL}, are given in Table 7. Several of the experimental data points were within the author-specified ranges of Re_{SL} and V_{SG}/V_{SL}. Among the tested heat transfer correlations, three correlations are recommended. The correlation of Knott et al. [11] predicted well the heat transfer experimental data for three of the main flow patterns (bubbly, slug, and froth) with or without considering the restriction on V_{SG}/V_{SL} (see Table 14). Even though the experimental data points did not fall within the range of Re_{SL} accompanying the correlation of Knott et al. [11], it appears to be a reasonable recommendation that the correlation is good for predicting results for all of those three main flow patterns. The correlation of Chu and Jones [2] is recommended for bubbly, slug, froth, and bubbly–slug flow patterns. The correlation of Shah [18] is also recommended for bubbly, froth, and annular–mist flow

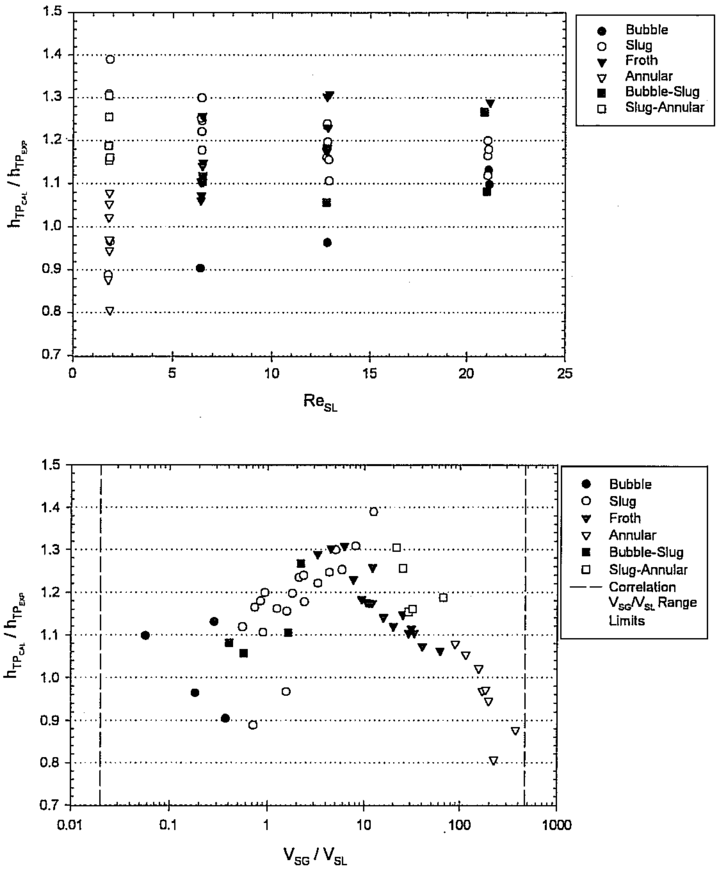

Figure 3. Comparison of Aggour [1] correlation with Vijay's [40] glycerin–air experimental data.

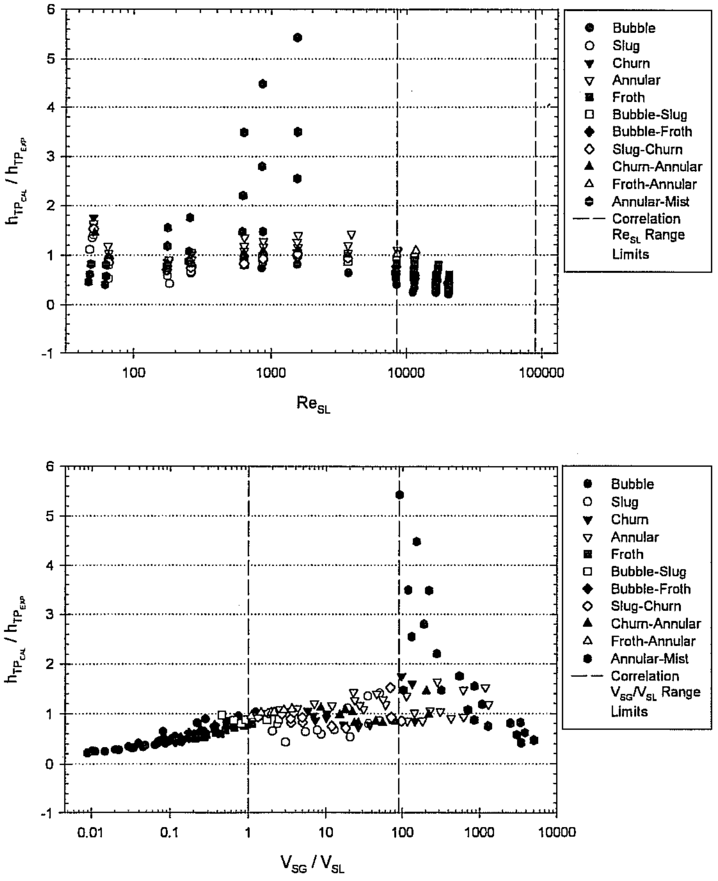

Figure 4. Comparison of Ravipudi and Godbold [15] correlation with Rezkallah's [41] silicone–air experimental data.

Table 8 Comparison of water–Freon 12 experimental data (44 data points) of Aggour [1] with the studied correlations (see Nomenclature for abbreviations)

			Data points within ±30%/data points for each flow pattern within Re_{SL} range of correlation						
Source	Mean dev. (%)	rms dev. (%)	B (6)	S (6)	F (10)	A (14)	B–S (4)	B–F (1)	S–A (3)
Chu and Jones [2]	8.39	8.66	3/3		10/10			1/1	
Dorresteijn [4]	−9.86	24.56	6/6	6/6	3/10	14/14	3/4	1/1	3/3
Dusseau [5]	99.73	99.73				0/2			
Groothuis and Hendal [7]	−115.41	123.60	0/6	0/1	0/10	0/7	0/3	0/1	0/1
Khoze et al. [9]									
Knott et al. [11]									
Kudirka et al. [12]	14.71	42.21	3/6	1/6	0/10	5/14	4/4	0/1	2/3
Ravipudi and Godbold [15]	37.41	39.48	0/6	1/1	2/10	3/7	0/3	0/1	1/1
Rezkallah and Sims [16]	−0.12	11.90	6/6	6/6	10/10	14/14	3/4	1/1	3/3
Shah [18]									

Note: Correlations not listed in the table did not provide an Re_{SL} range. Blanks indicate that no data points fell within the Re_{SL} range of the correlation.

			Data points within ±30%/data points for each flow pattern within V_{SG}/V_{SL} range of correlation						
Source	Mean dev. (%)	rms dev. (%)	B (6)	S (6)	F (10)	A (14)	B–S (4)	B–F (1)	S–A (3)
Aggour [1]	−0.99	14.35	6/6	6/6	10/10	14/14	3/4	1/1	3/3
Chu and Jones [2]	−8.61	21.85	2/3	2/6	10/10		4/4	1/1	1/1
Dorresteijn [4]	−9.86	24.56	6/6	6/6	3/10	14/14	3/4	1/1	3/3
Groothuis and Hendal [7]	−118.35	132.53		1/6	0/4	0/14	1/2		0/3
Knott et al. [11]	20.88	24.0	3/3	4/6	10/10		1/4	1/1	1/1
Kudirka et al. [12]	9.17	40.74	3/3	1/6	0/9	5/13	4/4		2/3
Ravipudi and Godbold [15]	24.90	29.28		6/6	2/4	5/13	0/2		3/3
Rezkallah and Sims [16]	−0.12	11.90	6/6	6/6	10/10	13/14	3/4	1/1	3/3
Shah [18]	37.90	41.66	6/6	0/6	10/10	0/14	0/4	1/1	0/3
Ueda and Hanaoka [19]	98.85	98.85			□	0/11			0/2

Note: Correlations not listed in the table did not provide a V_{SG}/V_{SL} range. Blanks indicate that no data points fell within the V_{SG}/V_{SL} range of the correlation.

patterns, even though the experimental data points did not fall within the Re_{SL} range of the correlation (see Table 14). Figure 6 shows the performance of the correlation of Knott et al. [11] in predicting the experimental data of all flow patterns. The correlation of Groothuis and Hendal [7] is recommended for slug flow in the water–helium experimental data, and the correlation of Rezkallah and Sims [16] is recommended for bubbly and bubbly–slug flow patterns.

Several of the water–Freon 12 experimental data points of Aggour [1] were within the ranges of Re_{SL} and V_{SG}/V_{SL} accompanying the identified correlations, and the comparison results are given in Table 8. Considering the overall performance of the correlations for all of the flow patterns and the values of mean and rms deviations along with the restrictions on Re_{SL} and V_{SG}/V_{SL} from the correlations, only three of the heat transfer correlations are recommended. These are the correlation of Aggour [1], the correlation of Dorresteijn [4], and the correlation of Rezkallah and Sims [16] for all main flow patterns (bubbly, slug, froth, and annular) and the slug–annular transitional flow pattern, except that the correlation of Dorresteijn [4] does not accurately predict the froth flow. Even though the correlation of Aggour [1] did not specify a range for Re_{SL}, it appears reasonable to recommend the correlation, based on the comparison results in Table 15 for no restrictions on Re_{SL} and V_{SG}/V_{SL}. Figures 7 and 8 show how well the correlations of Aggour [1] and Rezkallah and Sims [16] predicted the water–Freon 12 experimental data in terms of the dimensionless values of $h_{TP_{CAL}}/h_{TP_{EXP}}$ plotted versus Re_{SL} and V_{SG}/V_{SL}.

Tables 9 and 10 show the results of comparisons for the annular flow water–air experimental data of Pletcher [42] and the slug flow water–air experimental data of King [10] in horizontal tubes with the identified heat transfer correlations, along with the suggested Re_{SL} and V_{SG}/V_{SL} parameter ranges of the correlations. For the results from the comparison of annular flow data (see Table 9), several of the experimental data points fell

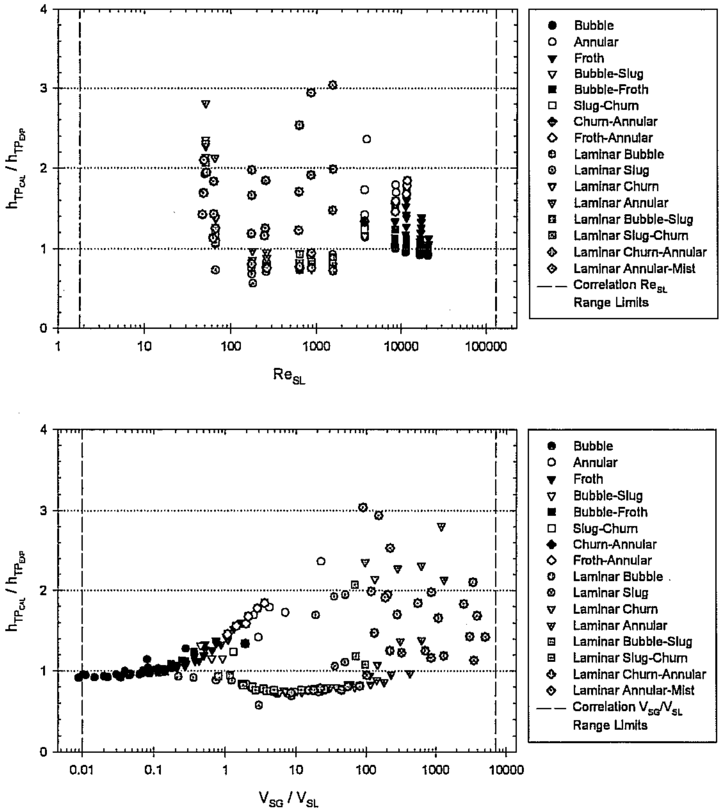

Figure 5. Comparison of Rezkallah and Sims [16] correlation with Rezkallah's [41] silicone–air experimental data.

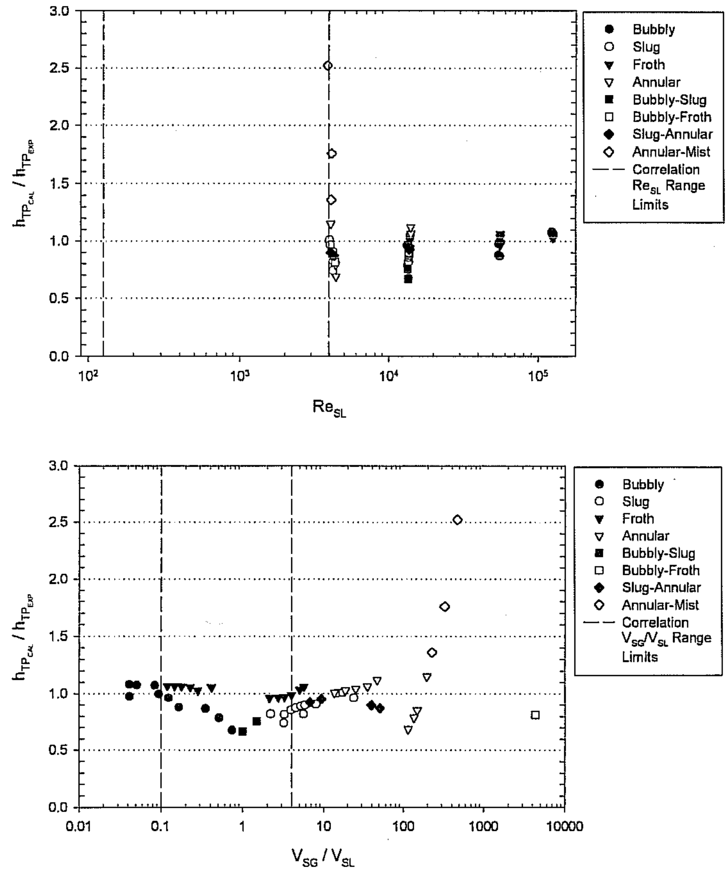

Figure 6. Comparison of Knott et al. [11] correlation with Aggour's [1] water–helium experimental data.

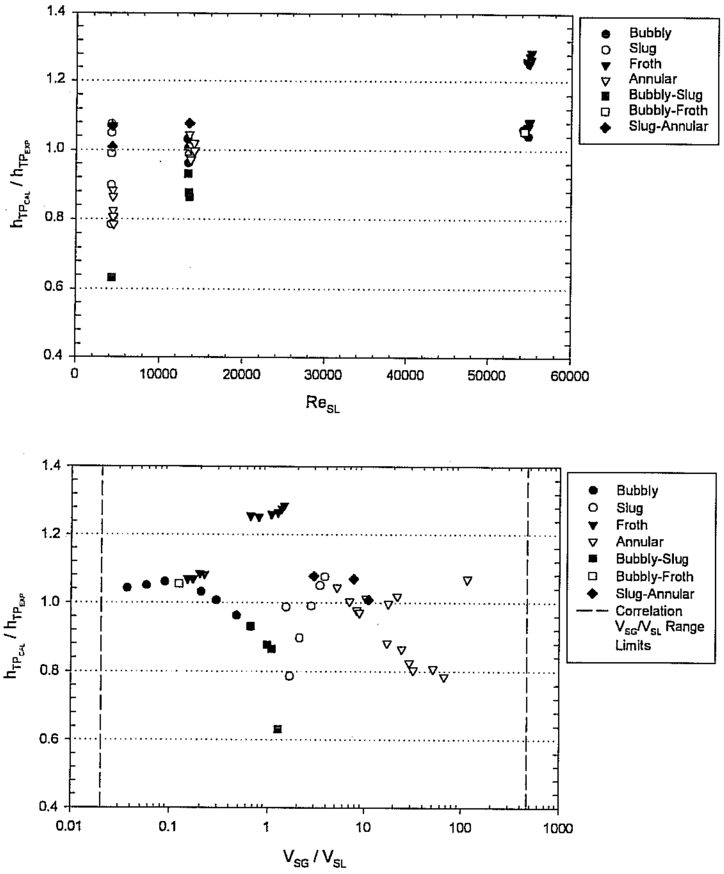

Figure 7. Comparison of Aggour [1] correlation with Aggour's [1] water–Freon 12 experimental data.

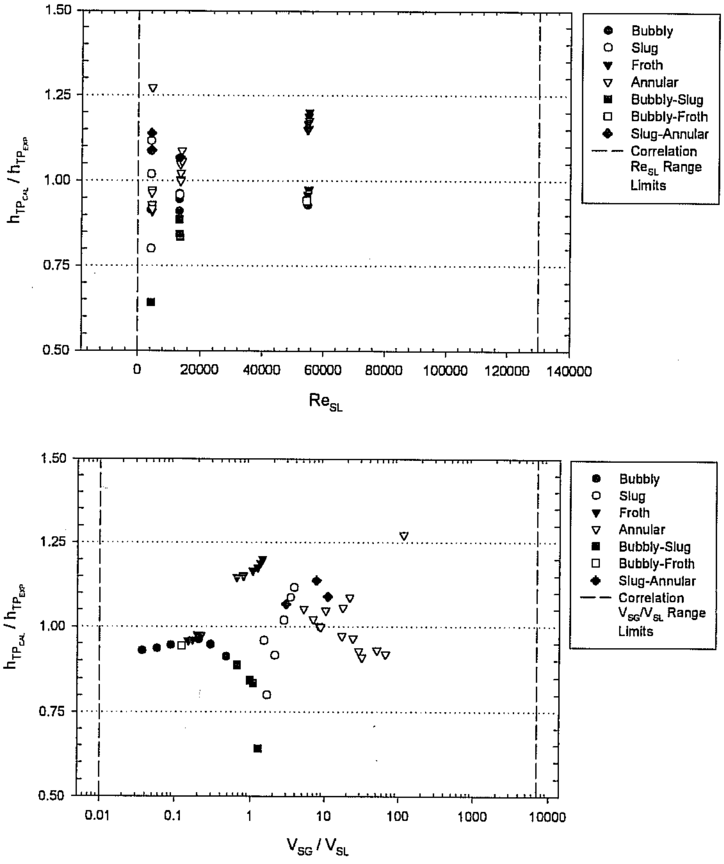

Figure 8. Comparison of Rezkallah and Sims [16] correlation with Aggour's [1] water–Freon 12 experimental data.

Table 9 Comparison of 48 water–air experimental data points of Pletcher [42] with the studied correlations (see Nomenclature for abbreviations)

	Annular flow from Pletcher [42]								
	Within correlation Re_{SL} limitation			Within correlation V_{SG}/V_{SL} limitation			Without correlation limitations		
Source	Mean dev. (%)	rms dev. (%)	±30%/total data points	Mean dev. (%)	rms dev. (%)	±30%/total data points	Mean dev. (%)	rms dev. (%)	No. of ±30% data points
Aggour [1]	No Re_{SL} limitation			−221.88	241.69	0/26	−233.85	314.86	
Davis and David [3]	No Re_{SL} limitation			No V_{SG}/V_{SL} limitation			97.53	97.56	
Dorresteijn [4]	−225.30	288.61	5/48	−225.30	288.61	5/48	−225.30	288.61	5
Dusseau [5]				No V_{SG}/V_{SL} limitation			98.92	98.92	
Elamvaluthi and Srinivas [6]	46.92	52.03	13/48				46.92	52.03	13
Groothuis and Hendal [7]	49.43	50.45	1/23	48.40	49.88	1/14	64.79	67.06	1
Khoze et al. [9]				No V_{SG}/V_{SL} limitation			100.0	100.0	
Knott et al. [11]	−67.18	95.91	5/19				−80.79	101.76	6
Kudirka et al. [12]	−52.30	59.93	11/48	−103.62	103.62	0/1	−52.30	59.92	11
Martin and Sims [13]	No Re_{SL} limitation			No V_{SG}/V_{SL} limitation			−246.76	278.68	
Oliver and Wright [14]				No V_{SG}/V_{SL} limitation			4693.	6604.	
Ravipudi and Godbold [15]	−97.62	101.21	0/11	−108.05	108.44	0/2	−77.14	86.27	4
Rezkallah and Sims [16]	−329.53	404.90	1/48	−329.53	404.90	1/48	−329.53	404.90	1
Serizawa et al. [17]	No Re_{SL} limitation			No V_{SG}/V_{SL} limitation			−256486.	314035.	
Shah [18]				−13.92	31.98	33/48	−13.92	31.98	33
Ueda and Hanaoka [19]	No Re_{SL} limitation						−186.16	198.71	
Vijay et al. [20]							4.34	37.11	26

Note: Blanks indicate that the correlation did not satisfy the ±30% criterion or no experimental data points fell within the Re_{SL} or V_{SG}/V_{SL} correlation limitations.

within the correlations' ranges of Re_{SL} and V_{SG}/V_{SL}. However, only the correlation of Shah [18] predicted the experimental data well. Figure 9 compares the performance of this correlation with the experimental data of Pletcher [42]. Table 10 shows the results of the comparison between the heat transfer correlations and the slug flow experimental data of King [10], along with the suggested Re_{SL} and V_{SG}/V_{SL} parameter ranges of the correlations. Several of the experimental data points of King [10] fell within the restrictions on Re_{SL} and V_{SG}/V_{SL} accompanying the correlations, and those data were predicted very well by four of the identified heat transfer correlations. These are the correlations of Chu and Jones [2], King [10], Kudirka et al. [12], and Ravipudi and Godbold [15].

RESULTS FROM COMPARISON WITHOUT CORRELATION LIMITATIONS

In this section, the author-proposed restrictions on V_{SG}/V_{SL} and Re_{SL} were not imposed on the identified heat transfer correlations in order to assess the general validity of the correlations. As in the previous section, the heat transfer correlations were compared with the same seven sets of experimental data, and are given in Tables 9–15. The difference between these tables and the previous tables of comparison results is that, for the previous comparisons (Tables 4–10), only the experimental data points that fell within the ranges of Re_{SL} and V_{SG}/V_{SL} suggested by the original authors of the correlations were used. Tables 9–15 give the total number of experimental data points used from each experimental study, the total number of data points for each flow pattern, the number of data points in each flow pattern that were predicted to within ±30% by the individual heat transfer correlations, and the percent overall mean and rms deviations for the predictions of each correlation. The percent mean and rms deviations were calculated using the difference of the heat transfer coefficients between experimental value and predicted value divided by the experimental value. Note that the magnitudes of mean and rms deviations in these tables range from 0.08% to 13,064% indicating a wide range of agreement/disagreement of the correlations with the experimental data. For each flow pattern, the tables also highlight the number of data points predicted by the correlation(s) that best satisfied the ±30% criterion. Further details on these comparisons may be found in Kim et al. [49].

Table 10 Comparison of 21 water–air experimental data points of King [10] with the studied correlations (see Nomenclature for abbreviations)

	Slug flow from King [10]								
	Within correlation $\mathrm{Re}_{\mathrm{SL}}$ limitation			Within correlation $V_{\mathrm{SG}}/V_{\mathrm{SL}}$ limitation			Without correlation limitations		
Source	Mean dev. (%)	rms dev. (%)	±30%/total data points	Mean dev. (%)	rms dev. (%)	±30%/total data points	Mean dev. (%)	rms dev. (%)	No. of ±30% data points
Aggour [1]	No $\mathrm{Re}_{\mathrm{SL}}$ limitation			−57.46	66.21	3/21	−57.46	66.21	3
Chu and Jones [2]	−4.01	17.47	14/15	1.21	17.27	17/18	0.08	16.33	20
Davis and David [3]	No $\mathrm{Re}_{\mathrm{SL}}$limitation			No $V_{\mathrm{SG}}/V_{\mathrm{SL}}$ limitation			−90.36	90.74	
Dorresteijn [4]	−81.22	88.54	0/11	−97.01	106.65	0/21	−97.01	106.65	
Dusseau [5]	98.49	98.70	0/9	No $V_{\mathrm{SG}}/V_{\mathrm{SL}}$ limitation			98.49	98.49	
Elamvaluthi and Srinivas [6]				−84.87	89.19	0/18	−89.46	95.87	
Groothuis and Hendal [7]	−65.33	77.95	5/21	−65.33	77.95	5/21	−65.33	77.95	5
Hughmark [8]	No $\mathrm{Re}_{\mathrm{SL}}$ limitation			No $V_{\mathrm{SG}}/V_{\mathrm{SL}}$ limitation			90.14	90.22	
Khoze et al. [9]				No $V_{\mathrm{SG}}/V_{\mathrm{SL}}$ limitation			−121.91	127.86	
King [10]	4.77	12.14	21/21	4.77	12.14	21/21	4.77	12.14	21
Knott et al. [11]				19.21	24.24	12/18	21.44	26.03	12
Kudirka et al. [12]	−4.30	27.60	18/21	−4.30	27.61	18/21	−4.30	27.61	18
Martin and Sims [13]	No $\mathrm{Re}_{\mathrm{SL}}$ limitation			No $V_{\mathrm{SG}}/V_{\mathrm{SL}}$ limitation			−3.82	19.34	19
Oliver and Wright [14]				No $V_{\mathrm{SG}}/V_{\mathrm{SL}}$ limitation			94.37	94.38	
Ravipudi and Godbold [15]	18.91	20.66	12/15	17.26	19.87	18/21	17.26	19.87	18
Rezkallah and Sims [16]	−66.56	76.32	3/21	−66.56	76.32	3/21	−66.56	76.32	3
Serizawa et al. [17]	No $\mathrm{Re}_{\mathrm{SL}}$ limitation			No $V_{\mathrm{SG}}/V_{\mathrm{SL}}$ limitation			−276.08	455.02	4
Shah [18]				28.22	40.42	6/21	38.22	40.42	6
Ueda and Hanaoka [19]	No $\mathrm{Re}_{\mathrm{SL}}$ limitation			15.87	17.93	3/3	−29.94	32.66	10
Vijay et al. [20]							−44.0	53.21	7

Note: Blanks indicate that the correlation did not satisfy the ±30% criterion or no experimental data points fell within the $\mathrm{Re}_{\mathrm{SL}}$ or $V_{\mathrm{SG}}/V_{\mathrm{SL}}$ correlation limitations.

Tables 9 and 10 also show the results of comparison for the 48 annular flow water–air experimental data of Pletcher [42] and the 21 slug-flow water–air experimental data of King [10] in horizontal tubes with the identified heat transfer correlations, ignoring the author-specified $\mathrm{Re}_{\mathrm{SL}}$ and $V_{\mathrm{SG}}/V_{\mathrm{SL}}$ ranges. For the annular flow data, only the correlation of Shah [18] performed well (see Table 9). Table 10 shows the results of comparing the heat transfer correlations with the slug-flow experimental data of King [10]. The experimental data of King [10] were predicted very well by five of the identified heat transfer correlations. Figure 10 shows how well the correlations of Chu and Jones [2], King [10], Kudrika et al. [12], Martin and Sims [13], and Ravipudi and Godbold [15] predicted the data of King [10].

The results shown in Table 11 indicate that, for bubbly, froth, annular, bubbly–froth, and froth–annular flow patterns, several of the heat transfer correlations did a very good job of predicting the experimental water–air data of Vijay [40] in a vertical tube. However, for slug, slug–annular, and annular–mist flows, only one correlation for each flow pattern provided good predictions. Considering the performance of the correlations for all flow patterns and keeping in mind the values of the overall mean and rms deviations, four heat transfer correlations are recommended for this set of experimental data. These are the correlation of Knott et al. [11] for bubbly, froth, bubbly–froth, and froth–annular flow patterns; the correlation of Ravipudi and Godbold [15] for annular, slug–annular, froth–annular, and annular–mist flow patterns; the correlation of Chu and Jones [2] for annular, bubbly–froth, slug–annular, and froth–annular flow patterns; and the correlation of Aggour [1] for bubbly and slug flow patterns. As an example, Figure 11 shows how well the recommended correlation of Knott et al. [11] performed with respect to the water–air experimental data of Vijay [40].

From the comparison results shown in Table 12, it can be seen that only a few of the tested heat transfer correlations were capable of accurately predicting the glycerin–air experimental data of Vijay [40] in a vertical tube. Considering the overall performance of the correlations for all flow patterns, only the correlation of Aggour [1] is recommended for this set of experimental data.

For the silicone–air experimental data of Rezkallah [41] in a vertical tube, a few of the correlations predicted the experimental data reasonably well, see Table 13.

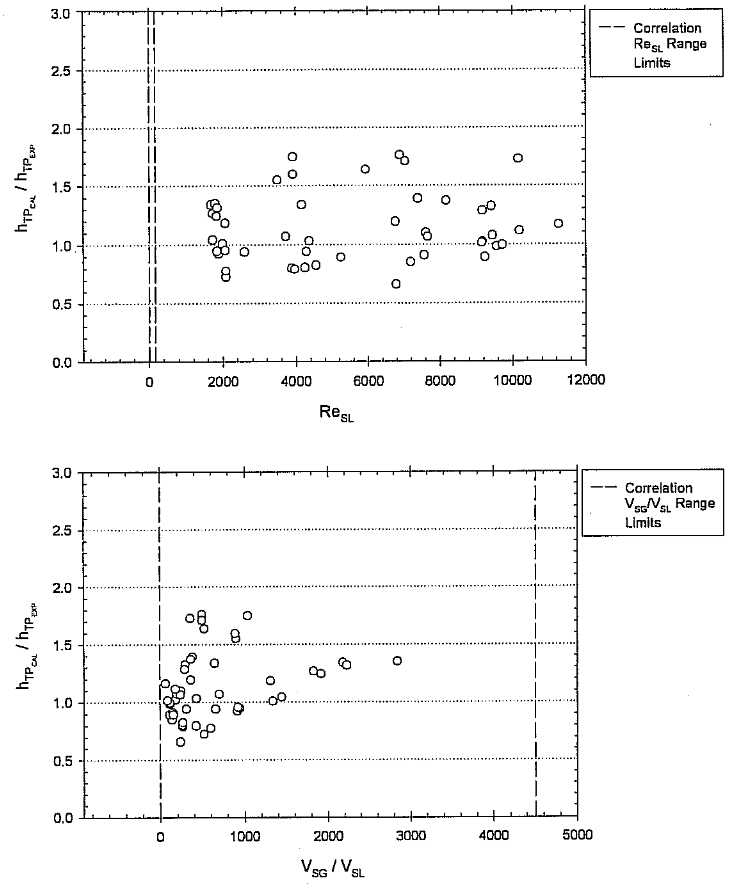

Figure 9. Comparison of Shah [18] correlation with Pletcher's [42] annular flow water–air experimental data.

Again, considering the overall performance of the correlations for all flow patterns and the values of the mean and rms deviations, only three of the tested heat transfer correlations are recommended. These are the correlation of Rezkallah and Sims [16] for bubbly, slug, churn, bubbly–slug, bubbly–froth, slug–churn, and churn–annular flow patterns; the correlation of Ravipudi and Godbold [15] for churn, annular, bubbly–slug, slug–churn, churn–annular, and froth–annular flow patterns; and the correlation of Shah [18] for bubbly, froth, bubbly–froth, froth–annular, and annular–mist flow patterns. Figure 12 provides a comparison of the predictions of Shah's [18] correlation with the silicone–air experimental data of Rezkallah [41].

For the water–helium experimental data of Aggour [1] in a vertical tube, several correlations predicted the experimental data fairly well, as can be seen from the results shown in Table 14. Considering not only

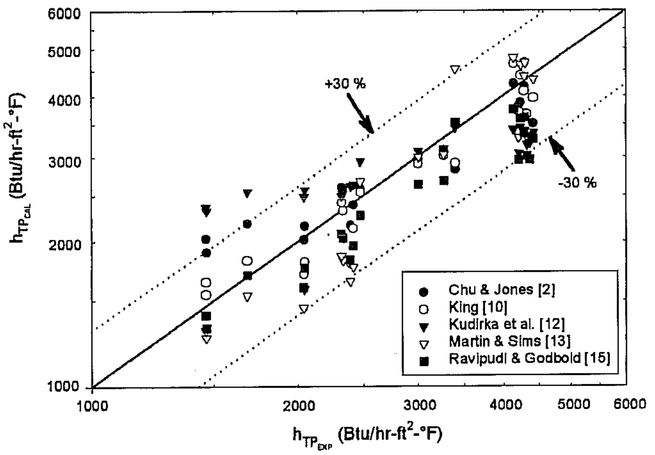

Figure 10. Comparison of correlations of [2, 10, 12, 13, 15] with King's [10] slug flow water–air experimental data.

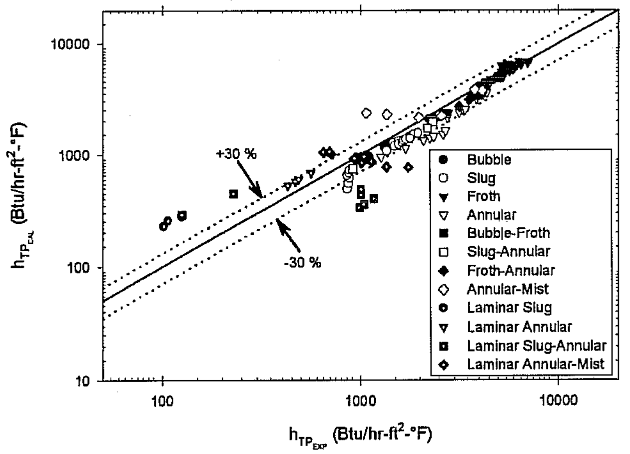

Figure 11. Comparison of Knott et al. [11] correlation with Vijay's [40] water–air experimental data.

Table 11 Comparison of water–air experimental data (139 data points) of Vijay [40] with the studied correlations (see Nomenclature for abbreviations)

Source	Mean dev. (%)	rms dev. (%)	Data points within ±30% for each flow pattern (pattern/total no. of data points) B (25)	S (25)	F (25)	A (25)	B–F (7)	S–A (10)	F–A (4)	A–M (18)
Aggour [1]	−14.28	56.27	25	25	2	14	4	4	1	
Chu and Jones [2]	−13.11	69.98	23	17	23	22	7	7	4	10
Davis and David [3]	−88.64	90.04								1
Dorresteijn [4]	−26.62	63.53	7	20	1	11		2		
Dusseau [5]	99.31	99.31								
Elamvaluthi and Srinivas [6]	−121.93	157.26				1		2		
Groothuis and Hendal [7]	−116.88	162.25		7		11		7		
Khoze et al. [9]	−133.21	159.97				4		4		6
Knott et al. [11]	3.76	33.95	25	20	25	19	7	3	4	11
Kudirka et al. [12]	−37.46	196.65	4	6	6	18	2	2	4	4
Martin and Sims [13]	−42.69	89.23	25	22	18	18	6	5	4	2
Oliver and Wright [14]	1500.	4349.								
Ravipudi and Godbold [15]	8.44	61.16		21	16	25	4	7	4	12
Rezkallah and Sims [16]	−35.36	80.03	25	22	17	14	7	5	4	4
Serizawa et al. [17]	−3459.	13064.	25	18	14		7		1	
Shah [18]	24.86	31.51	25	15	25	3	7	3	4	6
Ueda and Hanaoka [19]	−33.85	105.29	25	19	25	20	7	2	4	2
Vijay et al. [20]	46.26	58.59	21	2	23		6			

Note: Blanks indicate that the correlation did not satisfy the ±30% criterion.

the overall performance of the correlations for all flow patterns but also the values of the mean and rms deviations, three of the tested heat transfer correlations are recommended. These are the correlation of Chu and Jones [2] for bubbly, froth, and bubbly–slug flow patterns; the correlation of Knott et al. [11] for all of the main flow patterns (bubbly, slug, froth, and annular) and slug–annular transitional flow; and the correlation

Table 12 Comparison of glycerin–air experimental data (57 data points) of Vijay [40] with the studied correlations (see Nomenclature for abbreviations)

Source	Mean dev. (%)	rms dev. (%)	Data points within ±30% for each flow pattern (pattern/total no. of data points) B (4)	S (19)	F (17)	A (8)	B–S(4)	S–A (5)
Aggour [1]	−13.82	18.44	4	17	15	8	4	4
Chu and Jones [2]	−89.48	95.63	1	2		2		
Davis and David [3]	97.53	97.56						
Dorresteijn [4]	89.69	89.83						
Dusseau [5]	99.86	99.86						
Elamvaluthi and Srinivas [6]	−1256.	1580.	1	1				
Groothuis and Hendal [7]	−5550.	7508.						
Hughmark [8]	−120.0	136.98	4	1			2	
Khoze et al. [9]	−492.15	551.28						
Knott et al. [11]	−85.93	96.64	3	2			2	
Kudirka et al. [12]	63.38	63.75						
Martin and Sims [13]	−164.31	185.58						
Oliver and Wright [14]	776.74	1883.	4	4	4		2	
Ravipudi and Godbold [15]	67.95	68.45						
Rezkallah and Sims [16]	−51.49	54.78	1	1		6		
Serizawa et al. [17]	−734.01	1479.	4	4			2	
Shah [18]	−50.04	53.92	4	4			3	
Ueda and Hanaoka [19]	−14.22	39.48	1	17	3	1	1	
Vijay et al. [20]	26.58	33.12	4	17	9		4	

Note: Blanks indicate that the correlation did not satisfy the ±30% criterion.

Table 13 Comparison of silicone-air experimental data (162 data points) of Rezkallah [41] with the studied correlations (see Nomenclature for abbreviations)

			Data points within ±30% for each flow pattern (pattern/total no. of data points)										
Source	Mean dev. (%)	rms dev. (%)	B (26)	S (13)	C (11)	A (25)	F (18)	B–S (7)	B–F (10)	S–C (13)	C–A (12)	F–A (6)	A–M (21)
Aggour [1]	−5.57	74.95		3	2	4				1	1		10
Chu and Jones [2]	−96.07	140.24	13	3			10		4				1
Davis and David [3]	86.54	89.55											7
Dorresteijn [4]	22.73	59.21	25				4	2	9	1	1		4
Dusseau [5]	99.37	99.37											
Elamvaluthi and Srinivas [6]	−285.84	527.24		7						2			9
Groothuis and Hendal [7]	−406.01	820.35	1	5	2			4		5			
Hughmark [8]	−0.59	105.46		4	3	11				1	8		1
Khoze et al. [9]	−268.66	339.16		2									5
Knott et al. [11]	−4.09	57.41	22	3	1	11	18	3	10	3	3	6	2
Kudirka et al. [12]	−45.05	104.29	4			5	8	2	5	1	1	6	
Martin and Sims [13]	−63.47	149.26	21	3	3	9	11	2	10	3	9		
Oliver and Wright [14]	3282.	10086.											
Ravipudi and Godbold [15]	3.33	66.42	5	4	9	19	10	7	1	12	11	6	6
Rezkallah and Sims [16]	−20.02	52.55	26	8	9	14	10	6	10	12	10		6
Serizawa et al. [17]	−3864.	12574.	22		5	1	16	3	10	3	1	1	
Shah [18]	9.28	42.96	25	3	1	11	18	3	10	6	4	6	10
Ueda and Hanaoka [19]	−298.45	419.53											
Vijay et al. [20]	41.38	67.08	10			4	14	3	7	1	1	6	

Note: Blanks indicate that the correlation did not satisfy the ±30% criterion.

of Shah [18] for bubbly, froth, and annular–mist flow patterns. Figures 13 and 14 show the comparison between the predictions of Chu and Jones' [2] and Shah's [18] correlations with the water–helium experimental data of Aggour [1].

From the results shown in Table 15, it can be seen that several of the tested heat transfer correlations were capable of predicting the water–Freon 12 experimental data of Aggour [1] with good accuracy. Considering the overall performance of the correlations for all flow patterns and also the mean and rms deviations, three of the tested correlations demonstrated good accuracy in predicting all of the main flow patterns (bubbly, slug, froth, and annular) and slug–annular transitional flow. These are the correlation of Aggour [1], the correlation of Martin and Sims [13], and the correlation of Rezkallah and Sims [16]. Figure 15 shows the performance of the predictions of Martin and Sims' [13] correlation with the vertical tube water–Freon 12 experimental data of Aggour [1].

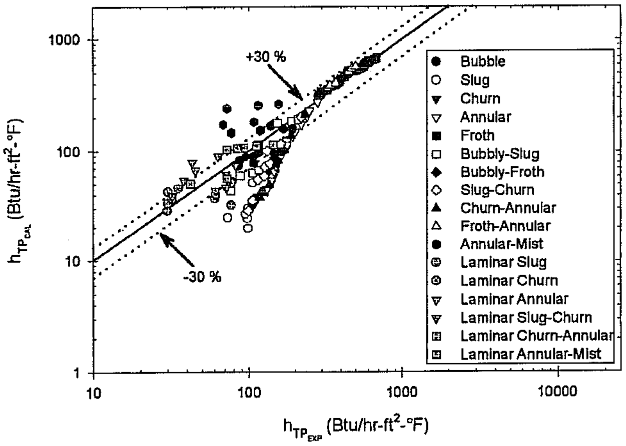

Figure 12. Comparison of Shah [18] correlation with Rezkallah's [41] silicone–air experimental data.

SUMMARY AND CONCLUSIONS

We have studied the ability of 20 two-phase heat transfer correlations to predict seven sets of experimental data that are available in the open literature. Five of these experimental data sets are concerned with flow patterns in vertical pipes: the air–water data of Vijay [40], the air–glycerin data of Vijay [40], the air–silicone data of Rezkallah [41], the water–helium data of Aggour [1], and the water–Freon 12 data of Aggour [1]. The other two data sets are for flow patterns within horizontal pipes: the air–water in slug flow data of King [10] and annular flow data of Pletcher [42].

In order to assess the validity of the 20 two-phase heat transfer correlations, their predictions were compared with the seven sets of experimental data, both with and without considering the restrictions on Re_{SL} and

Table 14 Comparison of water–helium experimental data (53 data points) of Aggour [1] with the studied correlations (see Nomenclature for abbreviations)

Source	Mean dev. (%)	rms dev. (%)	Data points within ±30% for each flow pattern (pattern/total no. of data points) B (10)	S (12)	F (12)	A (9)	B–S (2)	B–F (1)	S–A (4)	A–M (3)
Aggour [1]	−45.43	73.90	7	6		2	2	1		
Chu and Jones [2]	−24.63	50.77	9	4	12	4	2	1		
Davis and David [3]	35.31	138.62				5			1	
Dorresteijn [4]	−55.40	74.57	4	5		2	2		1	
Dusseau [5]	99.30	99.30								
Elamvaluthi and Srinivas [6]	−61.81	81.45		1		8			2	
Groothuis and Hendal [7]	−42.79	79.93	1	12		6	2		2	1
Hughmark [8]	72.21	76.65								2
Khoze et al. [9]	−71.59	89.31	1			3				
Knott et al. [11]	0.73	27.29	9	12	12	8	1	1	4	
Kudirka et al. [12]	−38.18	78.60	4		6	3		1		
Martin and Sims [13]	−37.48	70.45	10	9	8	2	2	1	2	
Ravipudi and Godbold [15]	−9.62	55.67	3	7	6	2	2		2	
Rezkallah and Sims [16]	−47.54	88.26	10	6	6	1	2	1		
Serizawa et al. [17]	−7968.	24990.								
Shah [18]	20.88	26.70	9	8	12	6		1	2	2
Ueda and Hanaoka [19]	98.23	98.24								
Vijay et al. [20]	44.83	55.62	7		7					

Note: Blanks indicate that the correlation did not satisfy the ±30% criterion.

V_{SG}/V_{SL} accompanying the correlations. The results comparing those heat transfer correlations and the seven sets of experimental data are summarized in Table 16 for major flow patterns and Table 17 for transitional flow patterns. There were no remarkable differences for the recommendations of the heat transfer correlations based on the results with and without the restrictions on Re_{SL} and V_{SG}/V_{SL}, except for the correlations of Chu and Jones [2] and Ravipudi and Godbold [15], as applied to the water–air experimental data of Vijay [40]. Based on the results without the authors' restrictions, the correlation of Chu and Jones [2] was recommended for only annular, bubbly–froth, slug–annular, and froth–annular flow patterns; and the correlation of Ravipudi and Godbold [15] was recommended for only annular, slug–annular, and froth–annular flow patterns of the vertical tube water–air experimental data. However, considering the Re_{SL} and V_{SG}/V_{SL} restrictions, the correlation of Chu and Jones [2] was recommended for all vertical tube water–air flow patterns including transitional flow patterns except the annular–mist flow pattern; and the correlation of Ravipudi and Godbold [15] was recommended for slug, froth, and annular flow patterns and for all of the transitional flow patterns of the water–air experimental data of Vijay [40].

With the data at hand, we make the following recommendations. For water–air flow within vertical pipes, we recommend use of the Knott et al. [11] correlation

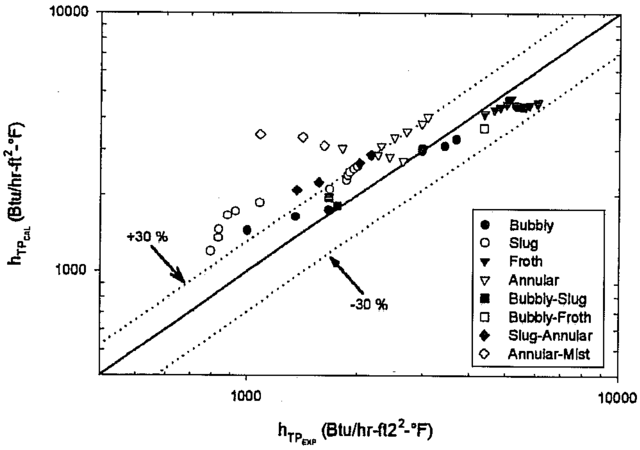

Figure 13. Comparison of Chu and Jones [2] correlation with Aggour's [1] water–helium experimental data.

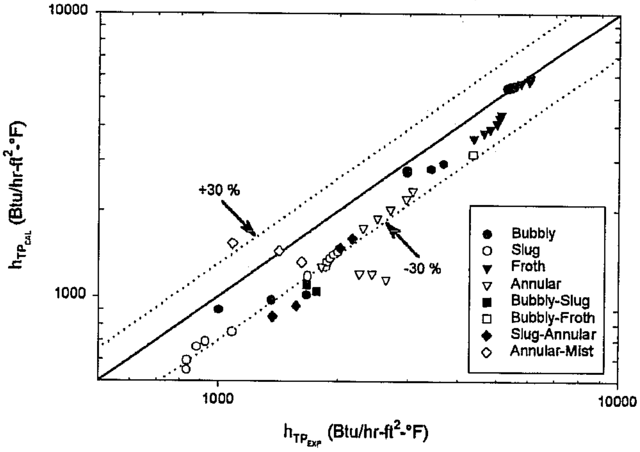

Figure 14. Comparison of Shah [18] correlation with Aggour's [1] water–helium experimental data.

Table 15 Comparison of water–Freon 12 experimental data (44 data points) of Aggour [1] with the studied correlations (see Nomenclature for abbreviations)

			Data points within ±30% for each flow pattern (pattern/total no. of data points)						
Source	Mean dev. (%)	rms dev. (%)	B (6)	S (6)	F (10)	A (14)	B–S (4)	B–F (1)	S–A (3)
Aggour [1]	−1.0	14.35	6	6	10	14	3	1	3
Chu and Jones [2]	1.41	23.25	5	2	10	10	4	1	2
Dorresteijn [4]	−9.87	24.57	6	6	3	14	3	1	3
Dusseau [5]	99.39	99.39							
Groothuis and Hendal [7]	−111.52	122.90		1			1		
Hughmark [8]	82.36	82.66							
Khoze et al. [9]	−176.40	192.15				3			
Knott et al. [11]	27.20	30.85	6	4	10		1	1	2
Kudirka et al. [12]	14.77	42.21	3	1		5	4		2
Martin and Sims [13]	5.25	15.28	6	6	10	13	3	1	3
Ravipudi and Godbold [15]	32.45	36.93		6	2	5			3
Rezkallah and Sims [16]	−0.12	11.90	6	6	10	14	3	1	3
Serizawa et al. [17]	−6234	11426							
Shah [18]	37.89	41.65	6		10			1	
Ueda and Hanaoka [19]	99.05	99.05							
Vijay et al. [20]	57.38	63.35	3		10			1	

Note: Blanks indicate that the correlation did not satisfy the ±30% criterion.

for froth and bubbly–froth flow patterns; use of the Chu and Jones [2] correlation for annular, bubbly–froth, slug–annular, and froth–annular flow patterns; use of the Ravipudi and Godbold [15] correlation for annular, slug–annular, froth–annular, and annular–mist flow patterns; use of the Aggour [1] correlation for bubbly and slug flow patterns; and use of the Rezkallah and Sims [16] correlation for bubbly, bubbly–froth, and froth–annular flow patterns. For glycerin–air flow within vertical pipes, we recommend use of the Aggour [1] correlation for bubbly, slug, froth, annular, bubbly–slug, and slug–annular flow patterns. For silicone–air flow within vertical pipes, we recommend use of the Rezkallah and Sims [16] correlation for bubbly, slug, churn, bubbly–slug, bubbly–froth, slug–churn, and churn–annular flow patterns; use of the Ravipudi and Godbold [15] correlation for churn, annular, bubbly–slug, slug–churn, churn–annular, and froth–annular; and use of the Shah [18] correlation for bubbly, froth, bubbly–froth, and froth–annular flow patterns. For water–helium flow within vertical pipes, we recommend use of the Knott et al. [11] correlation for bubbly, slug, and froth flow patterns; use of the Chu and Jones [2] correlation for bubbly, froth, and bubbly–slug flow patterns; and use of the Shah [18] correlation for bubbly, froth, and annular–mist flow patterns. For water–Freon 12 flow within vertical pipes, we recommend using one of the three correlations of Aggour [1], Martin and Sims [13], and Rezkallah and Sims [16] for bubbly, slug, froth, annular, and slug–annular flow patterns. With regard to air–water flow in horizontal pipes, we recommend use of the Shah [18] correlation for annular flow, and use of the Chu and Jones [2], Kudirka et al. [12], and Ravipudi and Godbold [15] correlations for slug flow.

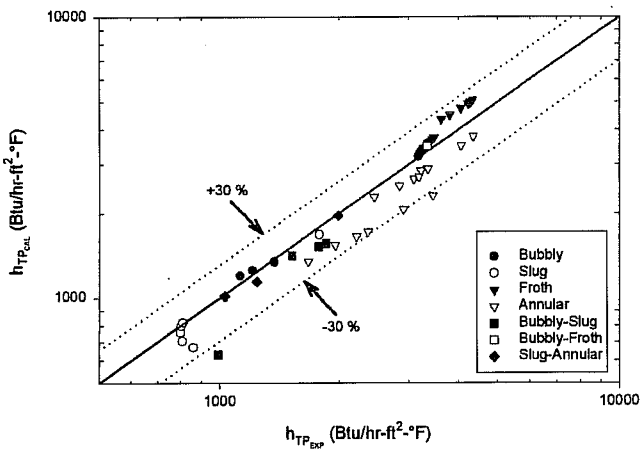

Figure 15. Comparison of Martin and Sims [13] correlation with Aggour's [1] water–Freon 12 experimental data.

The above recommended correlations all have the following important parameters in common: Re_{SL}, Pr_L, μ_B/μ_W and either void fraction (α) or superficial velocity ratio (V_{SG}/V_{SL}). It appears that void fraction and superficial velocity ratio, although not directly related, may serve the same function in two-phase heat transfer correlations. However, since there is no single correlation capable of predicting the flow for all fluid combinations in vertical pipes, there appears to be at least

Table 16 Recommended correlations from the general comparisons with regard to pipe orientation, fluids, and major flow patterns (see Nomenclature for abbreviations)

	Vertical experimental pipe																				Horizontal	
Correlations with restrictions on Re_{SL}	Water–air				Glycerin–air				Silicone–air					Water–helium				Water–Freon 12				Water–air	
and V_{SG}/V_{SL}	B	S	F	A	B	S	F	A	B	S	C	A	F	B	S	F	A	B	S	F	A	A	S
Aggour [1]	−V	−V			−V	−V	−V	−V										−V	−V	−V	−V		
Chu and Jones [2]	RV	RV	RV	RV					R				R	RV	V	RV		R		RV			RV
Knott et al. [11]	V	V	V	R									V	V	V	V		V		V			
Kudirka et al. [12]				RV														V					RV
Ravipudi and Godbold [15]		RV	RV	RV							V	RV	V		R	RV			V		RV		RV
Rezkallah and Sims [16]	RV	RV							RV	RV	RV			RV				RV	RV	RV	RV		
Shah [18]	V		V		RV				V				V	V		V		V		V		V	
Correlations with	Water–air				Glycerin–air				Silicone–air					Water–helium				Water–Freon 12				Water–air	
no restrictions	B	S	F	A	B	S	F	A	B	S	C	A	F	B	S	F	A	B	S	F	A	A	S
Aggour [1]	N	N			N	N	N	N										N	N	N	N		
Chu and Jones [2]				N										N		N				N			N
Knott et al. [11]	N		N										N	N	N	N	N	N		N			
Kudirka et al. [12]																							N
Martin and Sims [13]	N													N				N	N	N	N		N
Ravipudi and Godbold [15]				N							N	N							N				N
Rezkallah and Sims [16]	N								N	N	N			N				N	N	N	N		
Shah [18]	N		N		N				N				N	N		N		N		N		N	
Correlation recommendations based	Water–air				Glycerin–air				Silicone–air					Water–helium				Water–Freon 12				Water–air	
on comparisons above	B	S	F	A	B	S	F	A	B	S	C	A	F	B	S	F	A	B	S	F	A	A	S
Aggour [1]	√	√			√	√	√	√										√	√	√	√		
Chu and Jones [2]				√										√		√				√			√
Knott et al. [11]			√										√	√	√	√		√		√			
Kudirka et al. [12]																							√
Martin and Sims [13]	√													√				√	√	√	√		√
Ravipudi and Godbold [15]				√							√	√							√				√
Rezkallah and Sims [16]	√								√	√	√			√				√	√	√	√		
Shah [18]	√		√		√				√				√	√		√		√		√		√	

Notes: R = Recommended correlation with the range of Re_{SL}. V = Recommended correlation with the range of V_{SG}/V_{SL}. N = Recommended correlation with no restrictions. √ = Recommended correlation with and without restrictions. − = Correlation that did not provide ranges for either Re_{SL} or V_{SG}/V_{SL}. Correlation of Martin & Sims [13] did not provide ranges for Re_{SL} and V_{SG}/V_{SL}.

Table 17 Recommended correlations from the general comparisons with regard to experimental fluids and transition flow patterns (see Nomenclature for abbreviations)

	Vertical experimental pipe																		
Correlations with restrictions on Re_{SL} and V_{SG}/V_{SL}	Water–air				Glycerin–air		Silicone–air						Water–helium				Water–Freon 12		
	B–F	S–A	F–A	A–M	B–S	S–A	B–S	B–F	S–C	C–A	F–A	A–M	B–S	B–F	S–A	A–M	B–S	B–F	S–A
Aggour [1]					−V	−V													−V
Chu and Jones [2]	RV	RV	RV					R					V				V		
Knott et al. [11]	V							V			V								
Kudirka et al. [12]			RV	R				V			RV						RV		
Ravipudi and Godbold [15]	RV	RV	RV	RV			V		V	V	RV		R		R				V
Rezkallah and Sims [16]	RV		RV				RV	RV	RV	RV			RV						RV
Shah [18]	V		V					V			V	R				V			
Correlations with no restrictions	Water–air				Glycerin–air		Silicone–air						Water–helium				Water–Freon 12		
	B–F	S–A	F–A	A–M	B–S	S–A	B–S	B–F	S–C	C–A	F–A	A–M	B–S	B–F	S–A	A–M	B–S	B–F	S–A
Aggour [1]					N	N						N	N						N
Chu and Jones [2]	N	N	N										N				N		
Knott et al. [11]	N		N					N			N				N				
Kudirka et al. [12]			N								N						N		
Martin and Sims [13]			N										N						N
Ravipudi and Godbold [15]		N	N	N			N		N	N	N		N						N
Rezkallah and Sims [16]	N		N				N	N	N	N			N						N
Shah [18]	N		N		N			N			N	N				N			
Correlation recommendations based on comparisons above	Water–air				Glycerin–air		Silicone–air						Water–helium				Water–Freon 12		
	B–F	S–A	F–A	A–M	B–S	S–A	B–S	B–F	S–C	C–A	F–A	A–M	B–S	B–F	S–A	A–M	B–S	B–F	S–A
Aggour [1]					√	√													√
Chu and Jones [2]	√	√	√										√				√		
Knott et al. [11]	√							√			√								
Kudirka et al. [12]			√								√						√		
Martin and Sims [13]			√										√						√
Ravipudi and Godbold [15]		√	√	√			√		√	√	√		√						√
Rezkallah and Sims [16]	√		√				√	√	√	√			√						√
Shah [18]	√		√					√			√					√			

Notes: R = Recommended correlation with the range of Re_{SL}. V = Recommended correlation with the range of V_{SG}/V_{SL}. N = Recommended correlation with no restrictions. √ = Recommended correlation with and without restrictions. − = Correlation that did not provide ranges for either Re_{SL} or V_{SG}/V_{SL}. Correlation of Martin & Sims [13] did not provide ranges for Re_{SL} and V_{SG}/V_{SL}.

one parameter [ratio], which is related to fluid combinations, that is missing from these correlations. In addition, since, for the horizontal data available, the recommended correlations differ from those of vertical pipes, there must also be at least one additional parameter [ratio], related to pipe orientation, that is missing from the correlations.

In our future work, we plan to continue this study by investigating the development of a correlation that is robust enough to span all or most of the fluid combinations, pipe orientations, and flow patterns. This may require experimental data parameters that are not in the currently available data sets. In order to aid in this heat transfer correlation development, we plan to obtain additional horizontal flow pattern data, and to obtain experimental data, for other fluid combinations that are applicable to the oil/gas industry.

NOMENCLATURE

A	cross-sectional area, ft^2 or m^2
c	specific heat at constant pressure, Btu/lbm °F or kJ/kg K
D	inside diameter of the tube, ft or m
G_t	mass velocity of total flow ($= \rho V$), lbm/hr ft^2 or kg/s m^2
h	heat transfer coefficient, Btu/hr ft^2 °F or W/m^2 K
k	thermal conductivity, Btu/hr ft °F or W/m K
L	length of the heated test section, ft or m
$\dot{m}$	mass flow rate, lbm/hr or kg/s
Nu	Nusselt number ($= hD/k$), dimensionless
P	mean system pressure, psi or Pa
Pa	atmospheric pressure, psi or Pa
ΔP_M	momentum pressure drop, psi or Pa
$\Delta P/\Delta L$	total pressure drop per unit length, lbf/ft^3 or Pa/m
Pr	Prandtl number ($= \mu c/k$), dimensionless
q''	heat flux per unit area, Btu/hr ft^2 or W/m^2
Q	volumetric flow rate, ft^3/min or m^3/s
R_L	liquid volume fraction ($= 1 - \alpha$), dimensionless
Re	Reynolds number ($= \rho VD/\mu$), dimensionless
Re_M	mixture Reynolds number ($= \rho_L U_M^* D/\mu_L$ in Ueda and Hanaoka [19]), dimensionless where $U_M^* = V_L + 1.2(Re_S)^{-0.25} V_S$ $-12\,Fr_{ED} V_{ED} + 16(Fr_S)^{1.25} V_S$, $Re_S = \rho_L V_S D(1 - \sqrt{\alpha})/\mu_L$, $V_{ED} = V_{SL} + V_{SG}$, $Fr_{ED} = \alpha D(1 - \sqrt{\alpha})/V_{ED}^2$, $Fr_S = D(1 - \sqrt{\alpha})/V_S^2$, $V_L = V_{SL}/(1 - \alpha)$, $V_G = V_{SG}/\alpha$, V_S = slip velocity $= V_G - V_L$
Re_{TP}	two-phase flow Reynolds number, dimensionless $= Re_{SL}/(1 - \alpha)$ in Chu and Jones [2] $= G_F D/\mu_F$, where G_F = mass flow rate of froth and $\mu_F = (\mu_W + \mu_A)/2$ in Dusseau [5] $= Re_{SL} + Re_{SG}$ in Elamvaluthi and Srinivas [6] and Groothuis and Hendal [7]
T	temperature, °F or °C
V	average velocity in the test section, ft/s or m/s
x	flow quality ($= \dot{m}_G/\dot{m}$), dimensionless
X_{TT}	Martinelli parameter $\{= [(1 - x)/x]^{0.9}(\rho_G/\rho_L)^{0.5}(\mu_L/\mu_G)^{0.1}\}$, dimensionless
α	void fraction $[= A_G/(A_G + A_L)]$, dimensionless
μ	dynamic viscosity, lbm/hr ft or Pa s
ρ	density, lbm/ft^3 or kg/m^3
ϕ_g, ϕ_l	Lockhart-Martinelli [43] two-phase gas and liquid multipliers, dimensionless

Subscripts

A	air
B	bulk
CAL	calculated
EXP	experimental
G	gas
L	liquid
MIX	gas–liquid mixture
TP	two-phase
TPF	two-phase frictional
SG	superficial gas
SL	superficial liquid
W	wall

Abbreviations

A	air or annular flow
B	bubbly flow
B-S	bubbly-slug transitional flow (other combinations with dashes are also transitional flows)
C	churn flow
F	froth flow
H	horizontal
M	mist flow
S	slug flow
V	vertical
W	water

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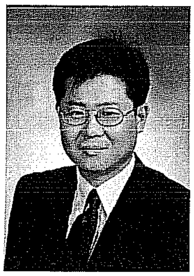

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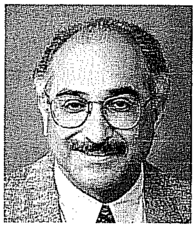

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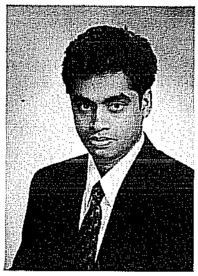

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