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Improved Convective Heat Transfer Correlations for Two-Phase Two-Component Pipe Flow

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In this study, six two-phase nonboiling heat transfer correlations obtained from the recommendations of our previous work were assessed. These correlations were modified using 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 improvement of the six identified correlations. Based on the tabulated and graphical results of the comparisons between the predictions of the modified heat transfer correlations and the available experimental data, appropriate improved correlations for different flow patterns, tube orientations, and liquid-gas combinations were recommended.

Key Words : Heat Transfer Correlation, Convective Heat Transfer, Two-Phase (Two-Component) Flow, Flow Pattern

Nomenclature

A : Cross sectional area, ft^2 or m^2

c : Specific heat at constant pressure, Btu/(lbm-°F) or J/(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

$\Delta P_M/\Delta L$: Momentum pressure drop per unit length, lbf/ft^3 or Pa/m

$\Delta P/\Delta L$: Total pressure drop per unit length, lbf/ft^3 or Pa/m

Pr : Prandtl number ($=$cμ/k), dimensionless

Q : Volumetric flow rate, ft^3/min or m^3/s

q'' : Heat flux per unit area, Btu/(hr-ft^2) or W/m^2

Re : Reynolds number ($=\rho$VD/μ), dimensionless

Re_M : Mixture Reynolds number ($=\rho_L U_M{}^* D/\mu_L$ in (Ueda and Hanaoka(1967)), 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(1980) $= G_F D/\mu_F$ where G_F=mass flow rate of froth and $\mu_F = (\mu_W + \mu_A)/2$ in Dusseau (1968) $= Re_{SL} + Re_{SG}$ in Elamvaluthi and Srimivas(1984) and Groothuis and

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Hendal(1959)

R_L : Liquid volume fraction $(=1-\alpha)$, dimensionless

T : Temperature, °F or °C

V : Average velocity in the test section, ft/s or m/s

x : Flow quality $(=\dot{m}_G/\dot{m}_{TP})$, dimensionless

X_{TT} : Martinelli parameter $\left[=\left(\frac{1-x}{x}\right)^{0.9}\left(\frac{\rho_G}{\rho_L}\right)^{0.5}\left(\frac{\mu_L}{\mu_G}\right)^{0.1}\right]$, dimensionless

α : Void fraction $[=A_G/(A_G+A_L)]$, dimensionless

μ : Dynamic viscosity, lbm/(hr-ft) or Pa-s

ϕ_g, ϕ_l : Lockhart-Martinelli (1949) two-phase gas and liquid multipliers, dimensionless

ρ : Density, lbm/ft^3 or kg/m^3

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

$F12$: Freon 12

G : Glycerin

H : Helium or horizontal

M : Mist flow

S : Slug flow or silicone

V : Vertical

W : Water

1. Introduction

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 gas and liquid in tubes can be classified as bubbly, slug, froth, annular, and churn flows. The main flow patterns that might exist in two-phase gas-liquid flow in horizontal tubes can be classified as bubbly, stratified, slug, and annular flows. 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. These correlations for the two-phase flow convective heat transfer were developed based on limited experimental data and are only applicable to certain flow patterns. Kim et al. (1999) identified 38 two-phase flow heat transfer correlations. These correlations were compared against a large set of two-phase flow heat transfer experimental data, for vertical and horizontal tubes and different flow patterns and fluids. Table 1 shows twenty of the 38 heat transfer correlations that were identified and tested by Kim et al. (1999). The rest of the two-phase flow heat transfer correlations were not tested since the required information for the correlations was not available through the available experimental studies. The limitations of the twenty correlations presented in Table 1 as proposed by the original authors are tabulated in Table 2. While most of the identified heat transfer correlations were derived empirically based on a small set of experimental data, some of the heat

Table 1 Heat transfer correlations chosen for this study

Source	Heat Transfer Correlations	Source	Heat Transfer Correlations
Aggour (1978)	$h_{TP}/h_L = (1-\alpha)^{-1/3}$ Laminar (L) $Nu_L = 1.615\,(Re_{SL}Pr_L\,D/L)^{1/3}(\mu_B/\mu_W)^{0.14}$ (L) $h_{TP}/h_L = (1-\alpha)^{-0.83}$ Turbulent (T) $Nu_L = 0.0155\,Re_{SL}^{0.83}Pr_L^{0.5}(\mu_B/\mu_W)^{0.33}$ (T)	Knott et al. (1959)	$\frac{h_{TP}}{h_L} = \left(1+\frac{V_{SG}}{V_{SL}}\right)^{1/3}$ where h_L is from Sieder & Tate (1936)
Chu & Jones (1980)	$Nu_{TP} = 0.43\,(Re_{TP})^{0.55}(Pr_L)^{1/3}\left(\frac{\mu_B}{\mu_W}\right)^{0.14}\left(\frac{Pa}{P}\right)^{0.17}$	Kudirka et al. (1965)	$Nu_{TP} = 125\left(\frac{V_{SG}}{V_{SL}}\right)^{1/8}\left(\frac{\mu_G}{\mu_L}\right)^{0.6}(Re_{SL})^{1/4}(Pr_L)^{1/3}\left(\frac{\mu_B}{\mu_W}\right)^{0.14}$
Davis & David (1964)	$Nu_{TP} = 0.060\left(\frac{\rho_L}{\rho_G}\right)^{0.28}\left(\frac{DG_t x}{\mu_L}\right)^{0.87}Pr_L^{0.4}$	Martin & Sims (1971)	$\frac{h_{TP}}{h_L} = 1+0.64\sqrt{\frac{V_{SG}}{V_{SL}}}$ where h_L is from Sieder & Tate (1936)
Dorresteijn (1970)	$h_{TP}/h_L = (1-\alpha)^{-1/3}$ (L) $h_{TP}/h_L = (1-\alpha)^{-0.8}$ (T) $Nu_L = 0.0123\,Re_{SL}^{0.9}Pr_L^{0.33}(\mu_B/\mu_W)^{0.14}$	Oliver & Wright (1964)	$Nu_{TP} = Nu_L\left(\frac{1.2}{R_L^{0.36}}-\frac{0.2}{R_L}\right)$ $Nu_L = 1.615\left[\frac{(Q_G+Q_L)\rho D}{A\mu}Pr_L\,D/L\right]^{1/3}(\mu_B/\mu_W)^{0.14}$
Dusseau (1968)	$Nu_{TP} = 0.029\,(Re_{TP})^{0.87}(Pr_L)^{0.4}$	Ravipudi & Godbold (1978)	$Nu_{TP} = 0.56\left(\frac{V_{SG}}{V_{SL}}\right)^{0.3}\left(\frac{\mu_G}{\mu_L}\right)^{0.2}(Re_{SL})^{0.6}(Pr_L)^{1/3}\left(\frac{\mu_B}{\mu_W}\right)^{0.14}$
Elamvaluthi & Srinivas (1984)	$Nu_{TP} = 0.5\left(\frac{\mu_G}{\mu_L}\right)^{1/4}(Re_{TP})^{0.7}(Pr_L)^{1/3}\left(\frac{\mu_B}{\mu_W}\right)^{0.14}$	Rezkallah & Sims (1987)	$h_{TP}/h_L = (1-\alpha)^{-0.9}$ where h_L is from Sieder & Tate (1936)]
Groothuis & Hendal (1959)	$Nu_{TP} = 0.029\,(Re_{TP})^{0.87}(Pr_L)^{1/3}(\mu_B/\mu_W)^{0.14}$ (for water-air) $Nu_{TP} = 2.6\,(Re_{TP})^{0.39}(Pr_L)^{1/3}(\mu_B/\mu_W)^{0.14}$ (for (gas-oil)-air)	Serizawa et al. (1975)	$\frac{h_{TP}}{h_L} = 1+462X_{TT}^{-1.27}$ where h_L is from Sieder & Tate (1936)
Hughmark (1965)	$Nu_{TP} = 1.75\,(R_L)^{-1/2}\left(\frac{\dot{m}_L c_L}{R_L k_L L}\right)^{1/3}\left(\frac{\mu_B}{\mu_W}\right)^{0.14}$	Shah (1981)	$\frac{h_{TP}}{h_L} = \left(1+\frac{V_{SG}}{V_{SL}}\right)^{1/4}$ $Nu_L = 1.86\,(Re_{SL}\,Pr_L\,D/L)^{1/3}(\mu_B/\mu_W)^{0.14}$ (L) $Nu_L = 0.023\,Re_{SL}^{0.8}Pr_L^{0.4}(\mu_B/\mu_W)^{0.14}$ (T)
Khoze et al. (1976)	$Nu_{TP} = 0.26\,Re_{SG}^{0.2}\,Re_{SL}^{0.55}\,Pr_L^{0.4}$	Ueda & Hanaoka (1967)	$Nu_{TP} = 0.075(Re_M)^{0.6}\frac{Pr_L}{1+0.035(Pr_L-1)}$
King (1952)	$\frac{h_{TP}}{h_L} = \frac{R_L^{-0.52}}{1+0.025\,Re_{SG}^{0.5}}\left[\left(\frac{\Delta P}{\Delta L}\right)_{TP}/\left(\frac{\Delta P}{\Delta L}\right)_L\right]^{0.32}$ $Nu_L = 0.023\,Re_{SL}^{0.8}Pr_L^{0.4}$	Vijay et al. (1982)	$h_{TP}/h_L = (\Delta P_{TPF}/\Delta P_L)^{0.451}$ $Nu_L = 1.615\,(Re_{SL}Pr_L\,D/L)^{1/3}(\mu_B/\mu_W)^{0.14}$ (L) $Nu_L = 0.0155\,Re_{SL}^{0.83}Pr_L^{0.5}(\mu_B/\mu_W)^{0.33}$ (T)
		Sieder & Tate (1936)	$Nu_L = 1.86\,(Re_{SL}\,Pr_L\,D/L)^{1/3}(\mu_B/\mu_W)^{0.14}$ (L) $Nu_L = 0.027\,Re_{SL}^{0.8}Pr_L^{0.33}(\mu_B/\mu_W)^{0.14}$ (T)

Note: α and R_L are taken from the original experimental data for this study. $Re_{SL} < 2000$ implies laminar flow, otherwise turbulent; and for Shah (1981), replace 2000 by 170. With regard to the eqs. given for Shah (1981) above, the laminar two-phase correlation was used along with the appropriate single phase correlation, since Shah (1981) recommended 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	Orient.	$\dot{m}_G / \dot{m}_L$	V_{SG}/V_{SL}	Re_{SG}	Re_{SL}	Pr_L	Flow Pattern(s)
Aggour (1978)	A-W, Helium-W, Freon12-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 & Jones (1980)	W-A	34	V		0.12-4.64	540-2700	16000-112000		B, S, F-A
Davis & David (1964)	Gas-Liquid		H & V						A, M-A
Dorresteijn (1970)	A-Oil	16	V		0.004-4500		300-66000		B, S, A
Dusseau (1968)	A-W	67	V	45-350		0-4.29×10^{4}	1.4×10^{4}-4.9×10^{4}		F
Elamvaluthi & Srinivas (1984)	A-W A-Glycerin	86	V		0.3-2.5 0.6-4.6		300-14300		B, S
Groothuis & Hendal (1959)	A-W Gas-Oil-A	14.3	V	244-977 269-513	1-250 0.6-80		>5000 1400-3500		
Hughmark (1965)	Gas-Liquid		H						S
Khoze et al. (1976)	A-W, A-Poly methylsiloxane, A-Diphenyl oxide	60-80	V			4000-37000	3.5-210	4.1-90	A
King (1952)	A-W	252	H		0.327-7.648	1570-8.28×10^{4}	22500-11.9×10^{4}		S
Knott et al. (1959)	Petroleum oil-Nitrogen gas	119	V	1.57×10^{-3}-1.19	0.1-4	6.7-162	126-3920		B
Kudirka et al. (1965)	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} 380-1700	140 @ 37.8°C	B, S, F
Martin & Sims (1971)	A-W	17	H						B, S, A
Oliver & Wright (1964)	A-85% Glycol, A-1.5% SCMC, A-0.5% Polyox		H				500-1800		S
Ravipudi & Godbold (1978)	A-W, A-Toluene, A-Benzene, A-Methanol		V		1-90	3562-82532	8554-89626		F
Rezkallah & Sims (1987)	A, W, Oil, etc.; 13 Liquid-Gas combinations	52.1	V		0.01-7030		1.8-1.3×10^{5}	4.2-7000	B, S, C, A, F, B-S, B-F, S-C, S-A, C-A, F-A
Serizawa et al. (1975)	A-W	35	V						B
Shah (1981)	A, W, Oil, Nitrogen, Glycol, etc.; 10 combinations		H & V		0.004-4500		7-170		B, S, F, F-A, M
Ueda & Hanaoka (1967)	A-Liquid	67	V	9.4×10^{-4}-0.059	4-50			4-160	S, A
Vijay et al. (1982)	A-W, A-Glycerin, Helium-W, Freon12-W	52.1	V		0.005-7670		1.8-130000	5.5-7000	B, S, F, A, M, B-F, S-A, F-A, A-M

transfer correlations were based on either the liquid acceleration model concept, the pressure drop model concept, the separated flow model concept, or the dimensional analysis concept. The two-phase heat transfer correlations developed based on these different concepts may be divided into three main groups. A brief description of each group is as follows.

2. Explicit Void Fraction Parameter in Two-Phase Flow Heat Transfer Correlations

This type of correlation uses the liquid acceleration model concept. This approach is based on the assumptions that the introduction of the gas phase into the two-phase heated test section acts only to accelerate the liquid phase, and that the heat is transferred and carried away mainly by the liquid phase. Thus, the two-phase heat transfer mechanism could be considered as heat transfer to a single-phase liquid flow, with the liquid flowing with the actual mean (not the superficial) velocity in the heated test section. Therefore, the void fraction parameter explicitly appears in the two-phase heat transfer correlation. However, researchers used different single-phase heat transfer correlations in their two-phase heat transfer coefficient correlations which has resulted in slightly different non-dimensional parameters and exponent values. Also, some researchers assumed that the two-phase heat transfer mechanism was directly related to the instantaneous amount of the ratio of liquid and gas. Thus, they used void fraction (α) or liquid volume fraction (R_L) as a parameter in the two-phase heat transfer correlations. Aggour (1978), Dorresteijn (1970), Hughmark (1965), and Rezkallah & Sims (1987) used this method of approach.

3. Two-Phase Heat Transfer Correlations from Dimensional Analysis / Separated Flow Model Concepts

In this case, the single-phase heat transfer correlation developed by Sieder and Tate (1936) was employed and modified for the two-phase heat transfer data, since several researchers assumed that the two-phase flow heat transfer mechanisms are quite similar to those of single-phase flow. During the procedures of modifying the single-phase heat transfer correlation to a two-phase heat transfer correlation, additional parameters were introduced using dimensional analysis or separated flow model concepts. From the dimensional analysis considerations, the dimensionless parameters (ρ_L/ρ_G), (μ_G/μ_L), and (V_{SG}/V_{SL}) were introduced in the correlations of Davis and David (1964), Kudirka et al. (1965), and Ravipudi and Godbold (1978). Also, several researchers considered that the increase in the value of two-phase heat transfer coefficient was attributed to the increase of the effective mixture velocity, and the effective mixture velocity was defined as the sum of the single-phase liquid and gas velocities. They introduced Re_{TP} or ($1+V_{SG}/V_{SL}$) in their suggested two-phase heat transfer correlations. These are the correlations of Elamvaluthi and Srinivas (1984), Groothuis and Hendal (1959), Knott et al. (1959), Martin and Sims (1971), and Shah (1981).

4. Lockhart-Martinelli [1949] Type Two-Phase Heat Transfer Correlations

In this approach, the two-phase heat transfer data were correlated using the relationship between the two-phase and single-phase pressure drops suggested by Lockhart and Martinelli (1949). This approach characterizes the flow features by two parameters: two-phase to single-phase liquid pressure drop ratio, defined as $\phi=\Delta P_{TP}/\Delta P_L$; and ratio of two-phase to single-phase heat transfer coefficients, $\Psi=h_{TP}/h_L$. The researchers tried to predict Ψ using the Lackhart-Martinelli multiplier, ϕ^2, with a leading coefficient and different exponent numbers. This approach appears in the correlations of Fried (1954), Serizawa et al. (1975), and Vijay et al. (1982).

Table 3 shows the recommended two-phase heat transfer correlations based on the results of the general validity test performed by Kim et al. (1999). These correlations have some of 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} or $1+V_{SG}/V_{SL}$). Since there is no single correlation capable of predicting heat transfer rate for all fluid combinations in vertical pipes, there appears to be at

Table 3 Recommended correlations with regard to pipe orientation, fluids, and flow patterns from Kim et al. (1999) (See Nomenclature for Abbreviations)

Source	Correlation	Vertical Experimental Pipe													Horizontal	
		Water-Air (Vijay, 1978)				Glycerin-Air (Vijay, 1978)				Silicone-Air (Rezkallah, 1987)					W-A (Rezkallah, 1987; King, 1952)	
		B	S	F	A	B	S	F	A	B	S	C	A	F	A	S
Aggour (1978)	$h_{TP}/h_L = (1-\alpha)^{-1/3}$ Laminar (L) $Nu_L = 1.615\,(Re_{SL}Pr_L\,D/L)^{1/3}(\mu_B/\mu_W)^{0.14}$ (L) $h_{TP}/h_L = (1-\alpha)^{-0.83}$ Turbulent (T) $Nu_L = 0.0155\,Re_{SL}^{0.83}Pr_L^{0.5}(\mu_B/\mu_W)^{0.33}$ (T)	√	√			√	√	√	√							
Chu & Jones(1980)	$Nu_{TP} = 0.43\,(Re_{TP})^{0.55}(Pr_L)^{1/3}\left(\frac{\mu_B}{\mu_W}\right)^{0.14}\left(\frac{Pa}{P}\right)^{0.17}$				√											√
King(1952	$\frac{h_{TP}}{h_L} = \frac{R_L^{-0.52}}{1+0.025\,Re_{SG}^{0.5}}\left[\left(\frac{\Delta P}{\Delta L}\right)_{TP}/\left(\frac{\Delta P}{\Delta L}\right)_L\right]^{0.32}$ $Nu_L = 0.023\,Re_{SL}^{0.8}Pr_L^{0.4}$	insufficient experimental information provided				insufficient experimental information provided				insufficient experimental information provided						√
Knott et al. (1959)	$\frac{h_{TP}}{h_L} = \left(1+\frac{V_{SG}}{V_{SL}}\right)^{1/3}$ where h_L is from Sider & Tate (1936)	√		√										√		
Kudirka et al. (1965)	$Nu_{TP} = 125\left(\frac{V_{SG}}{V_{SL}}\right)^{1/8}\left(\frac{\mu_G}{\mu_L}\right)^{0.6}(Re_{SL})^{1/4}(Pr_L)^{1/3}\left(\frac{\mu_B}{\mu_W}\right)^{0.14}$															√
Martin & Sims (1971)	$\frac{h_{TP}}{h_L} = 1+0.64\sqrt{\frac{V_{SG}}{V_{SL}}}$ where h_L is from Sider & Tate(1936)	√														√
Ravipudi & Godbold (1978)	$Nu_{TP} = 0.56\left(\frac{V_{SG}}{V_{SL}}\right)^{0.3}\left(\frac{\mu_G}{\mu_L}\right)^{0.2}(Re_{SL})^{0.6}(Pr_L)^{1/3}\left(\frac{\mu_B}{\mu_W}\right)^{0.14}$				√							√	√			√
Rezkallah & Sims (1987)	$h_{TP}/h_L = (1-\alpha)^{-0.9}$ where h_L is from Sider & Tate (1936)	√								√	√	√				
Shah (1981)	$\frac{h_{TP}}{h_L} = \left(1+\frac{V_{SG}}{V_{SL}}\right)^{1/4}$ $Nu_L = 1.86\,(Re_{SL}\,Pr_L\,D/L)^{1/3}(\mu_B/\mu_W)^{0.14}$ (L) $Nu_L = 0.023\,Re_{SL}^{0.8}Pr_L^{0.4}(\mu_B/\mu_W)^{0.14}$ (T)	√		√		√				√				√	√	

√ = Recommended Correlation based on the predictions of the experimental data within ±30% deviations.

least 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 order to improve the applicability of these correlations to different flow patterns, liquid combinations, and pipe orientation, six of the recommended correlations in Table 3 that showed the best overall performance were chosen for further study. The six selected correlations (Aggour, 1978 ; Knott et al., 1959 ; Kudirka et al., 1965 ; Ravipdi and Godbold, 1978 ; Rezkallah and Sims, 1987 ; Shah, 1981) represent the three groups of two-phase heat transfer correlations discussed above. The exponents of the key parameters that appear in these six two-phase heat transfer correlations were varied in order to get the best agreement between these correlations and an extensive set of experimental data available from the literature. The key parameters that were studied included $(1-\alpha)$, $(1+V_{SG}/V_{SL})$, and (V_{SG}/V_{SL}). Seven sets of experimental data (a total of 524 data points) from five available experimental studies (Aggour, 1978 ; King, 1952 ; Vijay, 1978 ; Rezkallah, 1987 ; Pletcher, 1966) were used in this study. 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 orientation. The ranges of these seven sets of experimental data are provided in Table 4.

5. Results and Discussion

Table 5 gives a summary of the optimal values for the exponent (n) of the key parameter in each of the six selected two-phase heat transfer correlations. These values were obtained by varying the exponents of the key parameters in the

Table 4 Ranges of the experimental data used in this study

Water-Air	$16.71 \le \dot{m}_L \text{ (lbm/hr)} \le 8996$	$0.06 \le V_{SL}\text{(ft/sec)} \le 34.80$	$231.83 \le Re_{SL} \le 126630$
Vertical	$0.058 \le \dot{m}_G \text{ (lbm/hr)} \le 216.82$	$0.164 \le V_{SG}\text{(ft/sec)} \le 460.202$	$43.42 \le Re_{SG} \le 163020$
Data (139 Points)	$0.007 \le X_{TT} \le 433.04$	$59.64 \le T_{MIX}\text{ (°F)} \le 83.94$	$14.62 \le P_{MIX}\text{ (psi)} \le 74.44$
of Vijay (1978)	$0.061 \le \Delta P_{TP}\text{ (psi)} \le 17.048$	$0.007 \le \Delta P_{TPF}\text{ (psi)} \le 16.74$	$0.033 \le \alpha \le 0.997$
	$5.503 \le Pr_L \le 6.982$	$0.708 \le Pr_G \le 0.710$	$11.03 \le Nu_{TP} \le 776.12$
	$101.5 \le h_{TP}\text{ (Btu/hr-ft}^2\text{-°F)} \le 7042.3$	$0.813 \le \mu_W/\mu_B \le 0.933$	$L/D = 52.1,\ D = 0.46$ in.
Glycerin-Air	$100.5 \le \dot{m}_L \text{ (lbm/hr)} \le 1242.5$	$0.31 \le V_{SL}\text{(ft/sec)} \le 3.80$	$1.77 \le Re_{SL} \le 21.16$
Vertical	$0.085 \le \dot{m}_G \text{ (lbm/hr)} \le 99.302$	$0.217 \le V_{SG}\text{(ft/sec)} \le 117.303$	$63.22 \le Re_{SG} \le 73698$
Data (57 Points)	$0.15 \le X_{TT} \le 407.905$	$80.40 \le T_{MIX}\text{ (°F)} \le 82.59$	$17.08 \le P_{MIX}\text{ (psi)} \le 62.47$
of Vijay (1978)	$1.317 \le \Delta P_{TP}\text{ (psi)} \le 20.022$	$1.07 \le \Delta P_{TPF}\text{ (psi)} \le 19.771$	$0.0521 \le \alpha \le 0.9648$
	$6307.04 \le Pr_L \le 6962.605$	$0.708 \le Pr_G \le 0.709$	$12.78 \le Nu_{TP} \le 37.26$
	$54.84 \le h_{TP}\text{ (Btu/hr-ft}^2\text{-°F)} \le 159.91$	$0.513 \le \mu_W/\mu_B \le 0.610$	$L/D = 52.1,\ D = 0.46$ in.
Silicone-Air	$17.3 \le \dot{m}_L \text{ (lbm/hr)} \le 196$	$0.072 \le V_{SL}\text{(ft/sec)} \le 30.20$	$47.0 \le Re_{SL} \le 20930$
Vertical	$0.07 \le \dot{m}_G \text{ (lbm/hr)} \le 157.26$	$0.17 \le V_{SG}\text{(ft/sec)} \le 363.63$	$52.1 \le Re_{SG} \le 118160$
Data (162 points)	$72.46 \le T_W\text{ (°F)} \le 113.90$	$66.09 \le T_B\text{ (°F)} \le 89.0$	$13.9 \le P_{MIX}\text{ (psi)} \le 45.3$
of Rezkallah (1987)	$0.037 \le \Delta P_{TP}\text{ (psi)} \le 9.767$	$0.094 \le \Delta P_{TPF}\text{ (psi)} \le 9.074$	$0.011 \le \alpha \le 0.996$
	$61.0 \le Pr_L \le 76.5$	$0.079 \le Pr_G \le 0.710$	$17.3 \le Nu_{TP} \le 386.8$
	$29.9 \le h_{TP}\text{ (Btu/hr-ft}^2\text{-°F)} \le 683.0$		$L/D = 52.1,\ D = 0.46$ in.
Water-Helium	$267 \le \dot{m}_L \text{ (lbm/hr)} \le 8996$	$1.03 \le V_{SL}\text{(ft/sec)} \le 34.70$	$3841 \le Re_{SL} \le 125840$
Vertical	$0.020 \le \dot{m}_G \text{ (lbm/hr)} \le 33.7$	$0.423 \le V_{SG}\text{(ft/sec)} \le 483.6$	$14.0 \le Re_{SG} \le 23159$
Data (53 Points)	$0.16 \le X_{TT} \le 769.6$	$67.4 \le T_{MIX}\text{ (°F)} \le 82.0$	$15.5 \le P_{MIX}\text{ (psi)} \le 53.3$
of Aggour (1978)	$0.3 \le \Delta P_{TP}\text{ (psi)} \le 13.2$	$0.01 \le \Delta P_{TPF}\text{ (psi)} \le 12.5$	$0.038 \le \alpha \le 0.958$
	$5.78 \le Pr_L \le 7.04$	$0.6908 \le Pr_G \le 0.691$	$86.6 \le Nu_{TP} \le 668.2$
	$794 \le h_{TP}\text{ (Btu/hr-ft}^2\text{-°F)} \le 6061$	$83.9 \le T_W\text{ (°F)} \le 95.7$	$L/D = 52.1,\ D = 0.46$ in
Water-Freon 12	$267 \le \dot{m}_L \text{ (lbm/hr)} \le 3598$	$1.03 \le V_{SL}\text{(ft/sec)} \le 13.89$	$4190 \le Re_{SL} \le 51556$
Vertical	$0.84 \le \dot{m}_G \text{ (lbm/hr)} \le 206.59$	$0.51 \le V_{SG}\text{(ft/sec)} \le 117.7$	$859.5 \le Re_{SG} \le 209430$
Data (44 Points)	$0.16 \le X_{TT} \le 226.5$	$75.26 \le T_{MIX}\text{ (°F)} \le 83.89$	$15.8 \le P_{MIX}\text{ (psi)} \le 27.8$
of Aggour (1978)	$0.04 \le \Delta P_{TP}\text{ (psi)} \le 4.92$	$0.02 \le \Delta P_{TPF}\text{ (psi)} \le 4.48$	$0.035 \le \alpha \le 0.934$
	$5.63 \le Pr_L \le 6.29$	$0.769 \le Pr_G \le 0.77$	$87.1 \le Nu_{TP} \le 472.4$
	$800 \le h_{TP}\text{ (Btu/hr-ft}^2\text{-°F)} \le 4344$	$90.36 \le T_W\text{ (°F)} \le 94.89$	$L/D = 52.1,\ D = 0.46$ 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	$0.22 \le \Delta P_M/L\text{ (lbf/ft}^3\text{)} \le 26.35$	$0.021 \le X_{TT} \le 0.490$	$1.45 \le \phi_g \le 3.54$
Data (48 points)	$7.23 \le \phi_l \le 68.0$	$73.6 \le T_W\text{ (°F)} \le 107.1$	$64.9 \le T_{MIX}\text{ (°F)} \le 99.4$
of Pletcher (1966)	$7372 \le q''\text{ (Btu/hr-ft}^2\text{)} \le 11077$	$433 \le h_{TP}\text{ (Btu/hr-ft}^2\text{-°F)} \le 1043.8$	$L/D = 60.0,\ D = 1.0$ in.
Water-Air	$1375 \le \dot{m}_L \text{ (lbm/hr)} \le 6410$	$0.82 \le \dot{m}_G \text{ (SCFM)} \le 43.7$	$22500 \le Re_{SL} \le 119000$
Horizontal	$1570 \le Re_{SG} \le 84200$	$0.41 \le X_{TT} \le 29.10$	$0.117 \le R_L \le 0.746$
Data (21 points)	$136.8 \le T_{MIX}\text{ (°F)} \le 144.85$	$184.3 \le T_W\text{ (°F)} \le 211.3$	$15.8 \le P_{MIX}\text{ (psi)} \le 55.0$
of King (1952)	$1.027 \le \Delta P_{TP}\text{ (psi)} \le 22.403$	$1462 \le h_{TP}\text{ (Btu/hr-ft}^2\text{-°F)} \le 4415$	$0.33 \le V_{SG}/V_{SL} \le 7.65$
	$1.35 \le h_{TP} / h_L \le 3.34$	$1.35 \le \phi_l \le 8.20$	$L/D = 252,\ D = 0.737$ in.

correlations in order to get the best agreement (based on mean and r. m. s. deviations) between the correlations and the experimental data. The two-phase heat transfer experimental data used for this purpose were the 139 water-air experimental data points of Vijay (1978), 57 glycerin-air experimental data points of Vijay (1978), 162 silicone-air experimental data points of Rezkallah (1987), 53 water-helium experimental data points of Aggour (1978), and the 44 water-freon 12 experimental data points of Aggour (1978) in vertical pipes, and the 48 water-air experimental data points of Pletcher (1966) and the 21 water-air experimental data points of King (1952) in horizontal pipes. Table 5, aside from the optimal n values for each flow pattern, gives the percent overall mean, r. m. s. , and range of deviations of the predictions from the data for

Table 5 Different values for the exponent of the key parameters of six two-phase heat transfer correlations (See Nomenclature for Abbreviations)

Aggour (1978) Correlation with the Optimal n Values for Each Flow Pattern, $h_{TP} = \text{fctn}(Re_{SL}, Pr_L, \ldots)(1-\alpha)^n$

Flow Pattern	Vijay (1978) W-A	Vijay (1978) G-A	Rezkallah (1987) S-A	Aggour (1978) W-H	Aggour (1978) W-F12	Pletcher (1966) W-A	King (1952) W-A
Bubbly	0.595	-0.240	5.303	-0.174	-0.741		
Slug	-0.60	-0.111	-0.733	-0.603	-0.849		-0.442
Froth	-0.172	-0.242	-0.641	-0.339	-0.414		
Annular	-0.645	-0.351	-0.366	-0.608	-0.859	-0.851	
Churn			-0.673				
Bubbly-Slug		-0.095	0.077	-0.874	-1.144		
Bubbly-Froth	-0.090		1.872	0.70	0.70		
Slug-Annular	-0.683	-0.235		0.773	-0.787		
Slug-Churn			-0.551				
Froth-Annular	-0.542		0.211				
Annular-Mist	-0.530		-0.428	-0.413			
Churn-Annular			-0.663				
Mean Dev. (%)	1.50	-0.49	-5.57	-0.85	1.03	28.62	4.70
rms Dev. (%)	29.49	6.27	66.98	17.29	8.22	52.48	13.53
Dev. Range (%)	-126.0 & 70.8	-18.2 & 19.4	-226.8 & 74.8	-27.7 & 47.7	-15.7 & 13.5	-125.0 & 77.3	-36.1 & 33.3

Aggour (1978) Correlation with the Original n Values for All Flow Patterns, n = -1/3 (Laminar) and -0.83 (Turbulent)

Mean Dev. (%)	-14.28	-13.82	-5.57	-45.20	-1.04	-233.85	-57.46
rms Dev. (%)	56.27	18.44	74.95	72.51	14.35	316.86	66.21
Dev. Range (%)	-380.5 & 85.4	-39.0 & 19.3	-226.8 & 74.8	-369.3 & 12.8	-28.6 & 36.8	-770.8 & 71.4	-138.2 & -14.6

Rezkallah & Sims (1987) Correlation with the Optimal n Values for Each Flow Pattern, $h_{TP} = \text{fctn}(Re_{SL}, Pr_L, \ldots)(1-\alpha)^n$

Flow Pattern	Vijay (1978) W-A	Vijay (1978) G-A	Rezkallah (1987) S-A	Aggour (1978) W-H	Aggour (1978) W-F12	Pletcher (1966) W-A	King (1952) W-A
Bubbly	-0.571	0.467	-1.282	-0.953	-1.243		
Slug	-0.623	0.059	-0.664	-0.653	-0.90		-0.473
Froth	-0.411	-0.151	-0.374	-0.502	-0.637		
Annular	-0.664	-0.30	-0.480	-0.637	-0.880	-0.401	
Churn			-0.628				
Bubbly-Slug		0.133	-0.898	-0.996	-1.280		
Bubbly-Froth	-0.463		-0.556	0.013	-1.50		
Slug-Annular	-0.661	-0.161		-0.660	-0.825		
Slug-Churn			-0.548				
Froth-Annular	-0.664		-0.318				
Annular-Mist	-0.519		-0.393	-0.431			
Churn-Annular			-0.662				
Mean Dev. (%)	1.36	-1.15	6.73	0.34	1.74	9.14	4.59
rms Dev. (%)	33.69	10.51	37.68	11.72	7.55	30.99	16.39
Dev. Range (%)	-145.4 & 67.6	-24.9 & 19.0	-147.5 & 59.6	-27.1 & 34.6	-20.6 & 20.0	-56.5 & 57.4	-34.7 & 31.9

Rezkallah & Sims (1987) Correlation with the Original n Value for All Flow Patterns, n = -0.9

Mean Dev. (%)	-35.36	-51.49	-20.02	-47.53	-0.12	-333.49	-46.47
rms Dev. (%)	80.03	54.86	52.55	87.39	11.90	405.60	57.37
Dev. Range (%)	-473.0 & 37.5	-82.9 & 2.46	-204.1 & 42.9	-457.6 & 16.6	-27.3 & 35.9	-996.1 & -43.5	-120.9 & 3.6

Table 5 (Cont'd.) Different values for the exponent of the key parameters of six two-phase heat transfer correlations (See Nomenclature for Abbreviations)

Knott et al. (1959) Correlation with the Optimal n Values for Each Flow Pattern, $h_{TP} = \text{fctn}(Re_{SL}, Pr_L, \ldots)(1 + V_{SG}/V_{SL})^n$

Flow Pattern	Vijay (1978) W-A	Vijay (1978) G-A	Rezkallah (1987) S-A	Aggour (1978) W-H	Aggour (1978) W-F12	Pletcher (1966) W-A	King (1952) W-A
Bubbly	0.529	-0.402	1.273	0.829	1.082		
Slug	0.334	-0.034	0.368	0.381	0.560		0.521
Froth	0.288	0.088	0.325	0.323	0.486		
Annular	0.374	0.162	0.280	0.337	0.505	0.477	
Churn			0.336				
Bubbly-Slug		-0.092	0.815	0.727	0.993		
Bubbly-Froth	0.371		0.591	0.650	1.370		
Slug-Annular	0.358	0.088		0.364	0.50		
Slug-Churn			0.382				
Froth-Annular	0.435		0.237				
Annular-Mist	0.308		0.233	0.222			
Churn-Annular			0.367				
Mean Dev. (%)	2.21	-1.56	7.22	0.20	2.29	23.40	1.74
rms Dev. (%)	20.35	8.59	26.77	10.80	7.99	48.70	11.76
Dev. Range (%)	-161.4 & 62.6	-23.0 & 17.3	-130.6 & 65.4	-26.9 & 30.0	-20.9 & 23.5	-125.0 & 77.3	-38.3 & 22.0
Knott et al. (1959) Correlation with the Original n Value for All Flow Patterns, n = 1/3							
Mean Dev. (%)	3.76	-85.93	-4.09	0.74	27.20	-80.79	21.44
rms Dev. (%)	33.95	96.64	57.41	27.07	30.85	101.76	26.03
Dev. Range (%)	-139.5 & 65.8	-163.9 & -5.7	-235.7 & 67.0	-150.1 & 33.2	6.4 & 55.9	-231.0 & 10.3	-15.8 & 40.8

Shah (1981) Correlation with the Optimal n Values for Each Flow Pattern, $h_{TP} = \text{fctn}(Re_{SL}, Pr_L, \ldots)(1 + V_{SG}/V_{SL})^n$

Flow Pattern	Vijay (1978) W-A	Vijay (1978) G-A	Rezkallah (1987) S-A	Aggour (1978) W-H	Aggour (1978) W-F12	Pletcher (1966) W-A	King (1952) W-A
Bubbly	0.703	-0.402	0.094	0.952	1.216		
Slug	0.399	-0.034	0.365	0.395	0.625		0.589
Froth	0.314	0.088	0.968	0.346	0.531		
Annular	0.398	0.162	0.265	0.346	0.515	0.218	
Churn			0.330				
Bubbly-Slug		-0.092	0.517	0.765	1.041		
Bubbly-Froth	0.422		-0.116	0.70	1.60		
Slug-Annular	0.402	0.088		0.375	0.517		
Slug-Churn			0.367				
Froth-Annular	0.454		0.126				
Annular-Mist	0.303		0.178	0.227			
Churn-Annular			0.361				
Mean Dev. (%)	1.26	-1.56	6.91	0.67	2.75	4.89	1.93
rms Dev. (%)	28.91	10.38	39.10	10.85	8.69	24.14	13.95
Dev. Range (%)	-129.2 & 46.0	-23.0 & 17.3	-152.0 & 76.2	-27.3 & 29.7	-22.5 & 24.3	-47.2 & 44.2	-35.7 & 22.0
Shah (1981) Correlation with the Original n Value for All Flow Patterns, n = 1/3							
Mean Dev. (%)	24.86	-50.12	9.28	20.88	37.89	-13.92	37.42
rms Dev. (%)	31.51	54.0	42.96	26.70	41.65	31.98	39.65
Dev. Range (%)	-29.4 & 72.8	-86.7 & -1.3	-235.9 & 80.0	-42.1 & 56.3	14.1 & 70.6	-76.4 & 33.8	6.2 & 54.6

Table 5 (Cont'd.) Different values for the exponent of the key parameters of six two-phase heat transfer correlations (See Nomenclature for Abbreviations)

Kudirka et al. (1965) Correlation with the Optimal n Values for Each Flow Pattern, $Nu_{TP} = fctn(Re_{SL}, Pr_L, \ldots)(V_{SG}/V_{SL})^n$

Flow Pattern	Vijay (1978) W-A	Vijay (1978) G-A	Rezkallah (1987) S-A	Aggour (1978) W-H	Aggour (1978) W-F12	Pletcher (1966) W-A	King (1952) W-A
Bubbly	-0.045	-0.399	-0.060	-0.015	-0.063		
Slug	-0.246	0.527	-0.198	-0.222	-0.380		0.083
Froth	-0.184	0.437	-0.305	-0.098	-0.208		
Annular	0.032	0.335	-0.017	0.053	0.218	-0.024	
Churn			-0.109				
Bubbly-Slug		1.131	0.021	-0.730	-0.018		
Bubbly-Froth	-0.195		-0.160	-2.620	-0.174		
Slug-Annular	-0.144	0.343		-0.039	-0.016		
Slug-Churn			-0.162				
Froth-Annular	0.247		0.298				
Annular-Mist	-0.006		-0.054	-0.037			
Churn-Annular			-0.041				
Mean Dev. (%)	-4.62	21.63	-5.30	2.70	3.82	-0.12	-2.56
rms Dev. (%)	52.27	37.12	39.68	30.72	24.37	18.50	26.63
Dev. Range (%)	-227.9 & 53.4	-51.4 & 87.0	-158.1 & 60.7	-130.2 & 46.9	-60.7 & 49.9	-48.9 & 48.4	-59.7 & 28.6
Kudirka et al. (1965) Correlation with the Original n Value for All Flow Patterns, n = 1/8							
Mean Dev. (%)	-71.82	61.62	-65.83	-39.18	10.76	-52.30	-4.30
rms Dev. (%)	240.25	61.86	130.59	80.45	40.39	59.92	27.61
Dev. Range (%)	-1330.6 & 55.3	45.1 & 72.2	-423.9 & 64.5	-236.8 & 48.9	-80.1 & 51.5	-157.6 & 8.5	-61.9 & 27.5

Ravipudi & Godbold (1978) Correlation with the Optimal n Values for Each Flow Pattern, $Nu_{TP} = fctn(Re_{SL}, Pr_L, \ldots)(V_{SG}/V_{SL})^n$

Flow Pattern	Vijay (1978) W-A	Vijay (1978) G-A	Rezkallah (1987) S-A	Aggour (1978) W-H	Aggour (1978) W-F12	Pletcher (1966) W-A	King (1952) W-A
Bubbly	-0.032	-0.425	-0.024	-0.002	-0.045		
Slug	0.070	0.897	0.344	0.164	0.309		0.463
Froth	-0.001	0.570	-0.135	0.061	-0.103		
Annular	0.268	0.515	0.224	0.224	0.395	0.123	
Churn			0.282				
Bubbly-Slug		-1.190	0.299	0.519	-0.149		
Bubbly-Froth	-0.072		-0.075	-2.751	-0.088		
Slug-Annular	0.20	0.599		0.205	0.312		
Slug-Churn			0.312				
Froth-Annular	0.393		0.236				
Annular-Mist	0.184		0.099	0.119			
Churn-Annular			0.290				
Mean Dev. (%)	4.04	24.40	3.66	5.85	8.42	2.05	3.16
rms Dev. (%)	29.77	40.92	29.50	15.73	17.48	19.23	13.36
Dev. Range (%)	-171.5 & 42.0	-48.9 & 89.8	-143.5 & 74.9	-35.3 & 31.1	-17.3 & 41.7	-40.4 & 44.7	-22.8 & 24.3
Ravipudi & Godbold (1978) Correlation with the Original n Value for All Flow Patterns, n = 0.3							
Mean Dev. (%)	-14.66	66.18	-12.06	-10.69	28.72	-193.51	15.72
rms Dev. (%)	86.60	66.69	85.25	58.86	33.61	212.15	18.39
Dev. Range (%)	-371.0 & 66.5	53.7 & 87.5	-501.8 & 79.2	-275.0 & 61.8	-9.5 & 67.5	-379.1 & -45.3	-3.7 & 32.1

each experimental data set based on the optimal and original n values. The flow pattern identification for the experimental data was based on the procedures suggested by Govier and Aziz (1973), Griffith and Wallis (1961), Hewitt and Hall-Taylor (1970), Taitel et al. (1980), Taitel and Dukler (1976), and visual observation as appropriate. For the seven sets of different experimental fluid combinations and pipe orientation, this table also highlights the optimal n values of certain correlations that best predicted the experimental data. The results of predictions for the water-air experimental data of Vijay (1978) in a vertical pipe shown in Table 5 indicate that the correlations of Aggour (1978), Rezkallah and Sims (1987), and Shah (1981) did a good job with different exponent (n) values for each flow pattern. The mean and r. m. s. deviations of the predictions for the optimal n values for these correlations are much lower than those based on the original n value(s). Considering the performance of the correlations for all of the flow patterns and keeping in mind the values of the overall mean and r. m. s. deviations, the heat transfer correlation of Shah (1981), $h_{TP}/h_L=(1+V_{SG}/V_{SL})^{1/4}$, with the different exponent (n) values for the parameter $(1+V_{SG}/V_{SL})$ is recommended for the water-air experimental data of Vijay (1978).

As shown in Table 5, for the glycerin-air experimental data of Vijay (1978) in a vertical pipe, the correlations of Aggour (1978), Rezkallah and Sims (1987), Knott et al. (1959), and Shah (1981) were capable of predicting the experimental data with good accuracy. Considering the overall performance of the correlations for all flow patterns, the correlation of Aggour (1978), $h_{TP}/h_L=(1-\alpha)^{-0.83}$, with different exponent (n) values for the parameter $(1-\alpha)$ is recommended for this set of experimental data with extremely high liquid Prandtl number (6300~7000).

For the silicone-air experimental data of Rezkallah (1987) in a vertical pipe, the correlations of Ravipudi and Godbold (1978) and Knott et al. (1959) predicted the experimental data reasonably well with good r. m. s. deviation. The r. m. s. and max. deviations based on the different values of exponent n are much improved compared to those based on the original n value. Again, considering the overall performance of the correlations for all flow patterns, the correlation of Knott et al. (1959), $h_{TP}/h_L=(1+V_{SG}/V_{SL})^{1/3}$, with the exponent (n) values for the parameter $(1+V_{SG}/V_{SL})$ is recommended for this experimental data set with moderately high liquid Prandtl number (61 ~ 77).

The results of predictions for the water-helium experimental data of Aggour (1978) in a vertical pipe with the different exponent (n) values are also given in Table 5. The correlations of Rezkallah and Sims (1987), Knott et al. (1959), and Shah (1981) predicted the experimental data very accurately with good mean, r. m. s. and max. deviations. The magnitudes of the mean, r. m. s. and max. deviations for the optimal n values are much smaller than those calculated from the original n values. Among the three correlations, the correlation of Knott et al. (1959) with the different exponent (n) values for the parameter $(1+V_{SG}/V_{SL})$ is recommended for the water-helium experimental data of Aggour (1978) in which the gas density change from air to helium is approximately a factor of 10.

Most of the six two-phase heat transfer correlations shown in Table 5 predicted the water-freon 12 experimental data of Aggour (1978) in a vertical pipe very accurately with good mean and r. m. s. deviations. The magnitudes of the r. m. s. deviations with the optimal n values were about two times better than those with the original n values. Among the six correlations, the correlation of Aggour (1978) with the different exponent (n) values for the parameter $(1-\alpha)$ is recommended for this experimental data set.

The water-air experimental data of Pletcher (1966) in a horizontal pipe with annular flow were accurately predicted by the correlations of Kudirka et al. (1965) and Ravipudi and Godbold (1978). Between these two correlations which belong to the same heat transfer correlation group and were developed based on the dimensional analysis concept, the correlation of Kudirka et al. (1965), $Nu_{TP}=125(V_{SG}/V_{SL})^{1/8}(\mu_G/\mu_L)^{0.6}(Re_{SL})^{1/4}(Pr_L)^{1/3}(\mu_B/\mu_W)^{0.14}$, with n=-0.024 for the exponent of (V_{SG}/V_{SL}) is recommended for this set of experimental data.

Table 5 also shows the results of the predictions

Table 6 Recommended modified two-phase heat transfer correlations for five fluid combinations and four major flow patterns in a vertical pipe (See Nomenclature for Abbreviations)

Recommended Exponent Values for Parameters [Shown in Table 5] of the Two-Phase Heat Transfer Correlations

Correlation	Shah (1981)	Aggour (1978)	Knott et al. (1959)	Knott et al. (1959)	Aggour (1978)
Flow Pattern	Vijay (1978) W-A	Vijay (1978) G-A	Rezkallah (1987) S-A	Aggour (1978) W-H	Aggour (1978) W-F12
Bubbly	0.70	-0.24	1.27	0.83	-0.74
Slug	0.40	-0.11	0.37	0.38	-0.85
Froth	0.31	-0.24	0.33	0.32	-0.41
Annular	0.40	-0.35	0.28	0.34	-0.86
Mean Dev. (%)	1.66	-0.61	6.80	-0.03	0.65
rms Dev. (%)	25.19	8.49	35.07	10.23	7.83
Dev. Range (%)	-128.4 & 39.6	-18.4 & 19.4	-130.6 & 65.4	-17.7 & 30.0	-15.7 & 20.4
Original n Value Results for Each Correlation Taken from Table 5					
Mean Dev. (%)	24.86	-13.82	-4.09	0.74	-1.04
rms Dev. (%)	31.51	18.44	57.41	27.07	14.35
Dev. Range (%)	-29.4 & 72.8	-39.0 & 19.3	-235.7 & 67.0	-150.1 & 33.2	-28.6 & 36.8
Optimal n Value Results for Each Correlation Taken from Table 5					
Mean Dev. (%)	1.26	-0.49	7.22	0.20	1.03
rms Dev. (%)	28.91	6.27	26.77	10.80	8.22
Dev. Range (%)	-129.2 & 46.0	-18.2 & 19.4	-130.6 & 65.4	-26.9 & 30.0	-15.7 & 13.5

Table 7 Recommended simplified two-phase heat transfer correlations for five fluid combinations and four major flow patterns in a vertical pipe (See Nomenclature for Abbreviations)

Recommended Simplified Exponent Values for Parameters [Shown in Table 5] of the Two-Phase Heat Transfer Correlations

Correlation	Shah (1981)	Aggour (1978)	Knott et al. (1959)	Knott et al. (1959)	Aggour (1978)
Flow Pattern	Vijay (1978) W-A	Vijay (1978) G-A	Rezkallah (1987) S-A	Aggour (1978) W-H	Aggour (1978) W-F12
Bubbly	0.39	-0.28	0.29	0.34	-0.82
Slug					
Froth					
Annular					
Mean Dev. (%)	2.56	-5.14	12.11	3.21	-1.69
rms Dev. (%)	23.92	14.87	36.59	12.31	14.23
Dev. Range (%)	-117.6 & 40.2	-27.8 & 31.7	-142.6 & 69.1	-20.2 & 32.1	-27.9 & 23.1

Table 8 Simplified two-phase heat transfer correlations, with recommendations, predicting all five fluid combinations for each of the four major flow patterns in a vertical pipe (See Nomenclature for Abbreviations)

Aggour (1978) Correlation with Different n Values for Flow Patterns, $h_{TP} = \text{fctn}(Re_L, Pr_L, \ldots)(1-\alpha)^n$								
Flow Pattern (Data Pts.)	Vijay (1978) W-A	Vijay (1978) G-A	Rezkallah (1987) S-A	Aggour (1978) W-H	Aggour (1978) W-F12	Mean Dev. (%)	rms Dev. (%)	Dev. Range (%)
Bubbly (71)	0.47					-7.62	10.63	-59.7 & 76.9
Slug (74)	-0.60					-4.72	36.72	-90.2 & 67.0
Froth (82)	-0.21					-10.07	25.04	-60.5 & 20.5
Annular (81)	-0.63					-16.72	68.88	-278.0 & 50.8
Rezkallah & Sims (1987) Correlation with Different n Values for Flow Patterns, $h_{TP} = \text{fctn}(Re_L, Pr_L, \ldots)(1-\alpha)^n$								
Bubbly	-0.76					2.07	13.83	-43.3 & 42.5
Slug	-0.62					-12.15	24.08	-129.7 & 61.3
Froth	-0.43					-10.42	26.46	-68.2 & 15.4
Annular	-0.65					-21.94	82.63	-357.4 & 49.8
Knott et al. (1959) Correlation with Different n Values for Flow Patterns, $h_{TP} = \text{fctn}(Re_L, Pr_L, \ldots)(1 + V_{SG}/V_{SL})^n$								
Bubbly	0.70					2.30	13.72	-44.1 & 43.9
Slug	0.35					-6.71	50.01	-161.0 & 66.2
Froth	0.27					-10.89	33.13	-79.6 & 18.5
Annular	-0.36					-20.02	79.52	-297.4 & 51.3
Shah (1981) Correlation with Different n Values for Flow Patterns, $h_{TP} = \text{fctn}(Re_L, Pr_L, \ldots)(1 + V_{SG}/V_{SL})^n$								
Bubbly	0.80					-4.48	12.99	-47.7 & 17.0
Slug	0.39					-8.52	50.09	-130.5 & 75.4
Froth	0.29					-14.71	37.0	-90.6 & 20.0
Annular	0.37					-24.58	85.63	-320.0 & 51.2
Kudirka et al. (1965) Correlation with Different n Values for Flow Patterns, $Nu_{TP} = \text{fctn}(Re_L, Pr_L, \ldots)(V_{SG}/V_{SL})^n$								
Bubbly	-0.04					-10.21	52.88	-156.6 & 65.0
Slug	-0.24					-1.14	55.52	-194.0 & 77.5
Froth	-0.15					38.77	46.69	-14.7 & 89.2
Annular	0.04					5.46	57.87	-190.3 & 83.6
Ravipudi & Godbold (1978) Correlation with Different n Values for Flow Patterns, $Nu_{TP} = \text{fctn}(Re_L, Pr_L, \ldots)(V_{SG}/V_{SL})^n$								
Bubbly	-0.02					1.21	21.13	-45.4 & 78.8
Slug	0.15					25.69	49.22	-135.6 & 86.9
Froth	-0.01					33.06	41.91	-3.9 & 87.8
Annular	0.26					5.25	38.82	-113.7 & 77.1

for the water-air slug flow experimental data of King (1952) in a horizontal pipe. The correlations of Knott et al. (1959) and Shah (1981) accurately predicted the horizontal slug flow water-air experimental data. Between these two correlations which were based on the separated flow model concept, the correlation of Knott et al. (1959) with the exponent (n) value of 0.521 for the parameter $(1 + V_{SG}/V_{SL})$ is recommended for this set of experimental data.

Table 6 summarizes this study's recommended modified two-phase heat transfer correlations for five fluid combinations (W-A, G-A, S-A, W-H, W-F12) and four major flow patterns (bubbly, slug, froth, annular) in a vertical pipe. In this table, the optimal values of n listed in Table 5 for the four major flow patterns have been rounded off to two significant digits without significant loss of accuracy. For comparison purposes, the table also provides the original and the optimal n values for each correlation. Referring to Table 6, it is interesting to observe that generally for three of the four major flow patterns: slug, froth, and annular, the reported exponent n values for a given fluid combination show a weaker dependence on flow pattern than for fluid combination. It should also be mentioned that Table 6 does not provide information on horizontal pipe

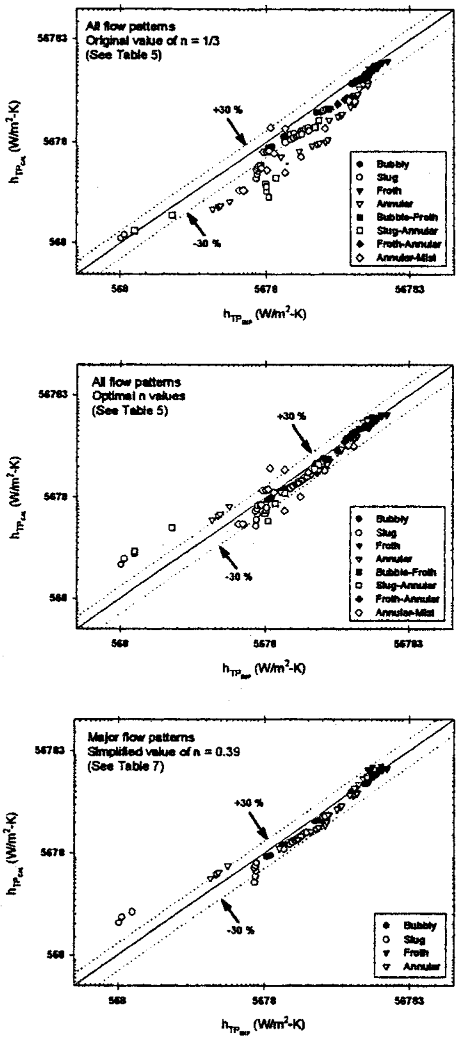

Fig. 1 Comparison of Shah (1981) Original and Modified Correlations with Vijay (1978) Water-Air Experimental Data in a Vertical Pipe (See Tables 5 and 7)

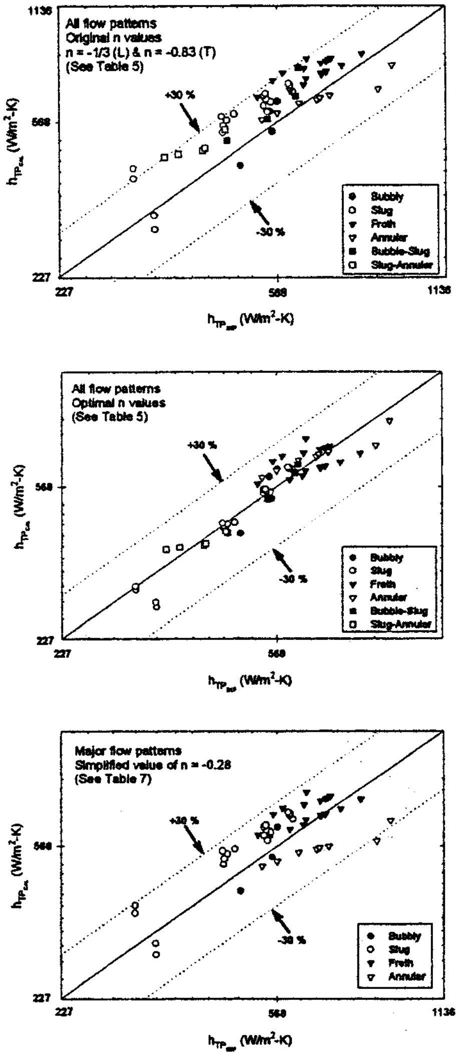

Fig. 2 Comparison of Aggour (1978) Original and Modified Correlations with Vijay (1978) Glycerin-Air Experimental Data in a Vertical Pipe (See Tables 5 and 7)

flows and the transitional vertical pipe flows. For horizontal pipe flows, this study has information on only two flow patterns (slug and annular); and for transitional flows, there is an insufficient number of data points in each transitional flow pattern to plot and determine appropriate n values.

Table 7 shows the results of our attempt to unify the exponent n values provided in Table 6 for each fluid combination and different flow patterns. The mean and r. m. s. deviations reported in Table 7 for the simplified exponent n values show only a slight increase over those given in Table 6 for the modified exponent n values. As can be seen from the results of Table 7, the flow pattern dependency of the two-phase heat transfer correlations for a vertical pipe can be overcome by using an appropriate key parameter in the heat transfer correlation with an optimal exponent n value. For prediction of water-air, silicone-air, and water-helium two-phase heat transfer, the

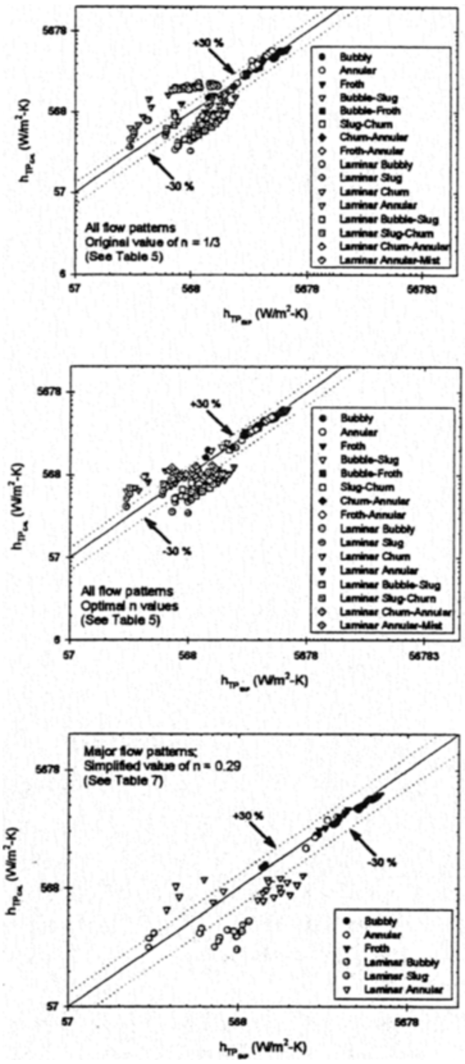

Fig. 3 Comparison of Knott et al. (1959) Original and Modified Correlations with Rezkallah (1987) Silicone-Air Experimental Data in a Vertical Pipe (See Tables 5 and 7)

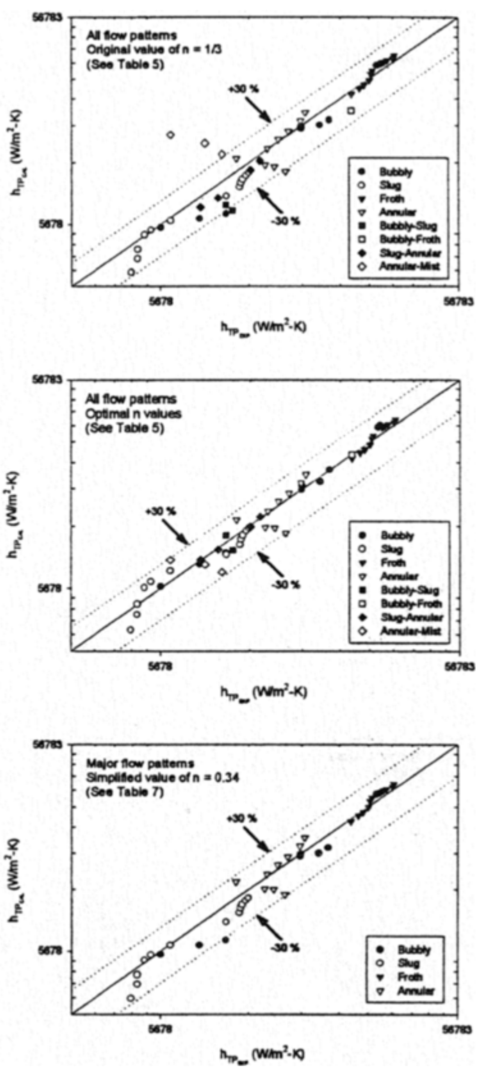

Fig. 4 Comparison of Knott et al. (1959) Original and Modified Correlations with Aggour (1978) Water-Helium Experimental Data in a Vertical Pipe (See Tables 5 and 7)

parameter $(1+V_{SG}/V_{SL})$ and an appropriate exponent n should be used in the heat transfer correlations. Similarly, for prediction of glycerin-air and water-freon 12 two-phase heat transfer, the parameter $(1-\alpha)$ and an appropriate exponent n value should be used in the heat transfer correlations.

Figures 1 to 5 compare the performance of the identified two-phase heat transfer correlations for the vertical pipe flow experimental data for each of the five fluid combinations. These figures show the results of predictions from the correlations with the original n values (see Table 5), optimal n values (see Table 5), and the simplified n values (see Table 7). The comparison results for the horizontal pipe flow experimental data of Pletcher (1966) and King (1952) with the two-phase heat transfer correlations are given in Figs. 6 and 7. These figures show results for both the original and the optimal exponent n values.

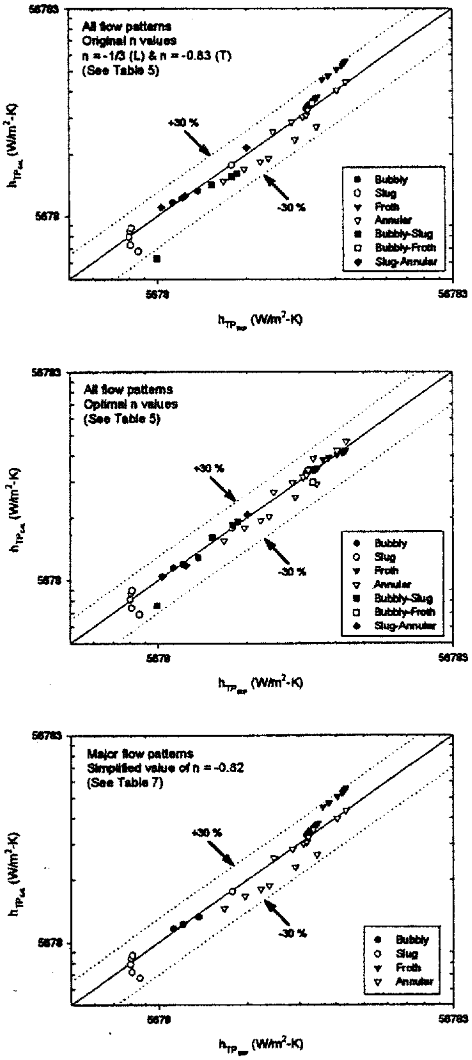

Fig. 5 Comparison of Aggour (1978) Original and Modified Correlations with Aggour (1978) Water-Freon 12 Experimental Data in a Vertical Pipe (See Tables 5 and 7)

Table 8 shows the results of our attempts to overcome the fluid combination dependency of the two-phase heat transfer correlations for a vertical pipe. For this purpose, this study combined the experimental data for each of the four major flow patterns (bubbly, slug, froth, annular) and the five different fluid combinations (W-A, G-A, S-A, W-H, W-F12). With this combined data, this study obtained the optimal value of the exponent n for the key parameters in

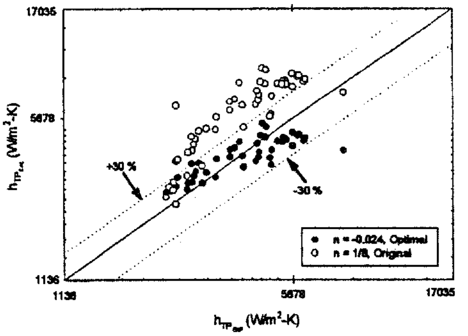

Fig. 6 Comparison of Kudirka et al. (1965) Original and Modified Correlations with Pletcher (1966) Water-Air Experimental Data in a Horizontal Pipe (See Table 5)

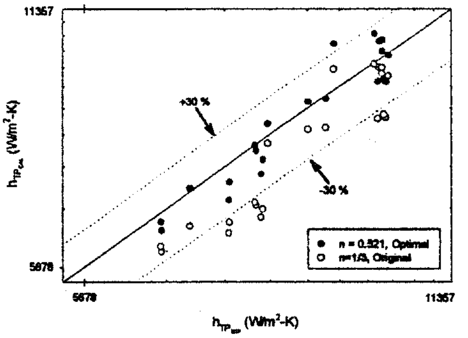

Fig. 7 Comparison of Knott et al. (1959) Original and Modified Correlations with King (1952) Water-Air Experimental Data in a Horizontal Pipe (See Table 5)

the six recommended correlations by Kim et al. (1999). Comparing the overall performance (by mean and r. m. s. deviations) of the predictions for each flow pattern for all five fluid combinations, the correlation of Aggour (1978), $h_{TP}/h_L=(1-\alpha)^{-0.83}$, with an n=-0.6 for the parameter $(1-\alpha)$ is recommended for slug flow, the correlation of Rezkallah and Sims (1987), $h_{TP}/h_L=(1-\alpha)^{-0.9}$, with n=-0.43 for the parameter $(1-\alpha)$ is recommended for froth flow, the correlation of Shah (1981), $h_{TP}/h_L=(1+V_{SG}/V_{SL})^{1/4}$, with n=0.8 for the parameter $(1+V_{SG}/V_{SL})$ is recommended for bubbly flow, and the correlation of Ravipudi and Godbold (1978), $Nu_{TP}=0.56(V_{SG}/V_{SL})^{0.3}(\mu_G/\mu_L)^{0.2}(Re_{SL})^{0.6}(Pr_L)^{1/3}(\mu_B/\mu_W)^{0.14}$, with n =0.26 for the parameter (V_{SG}/V_{SL}) is recommended for

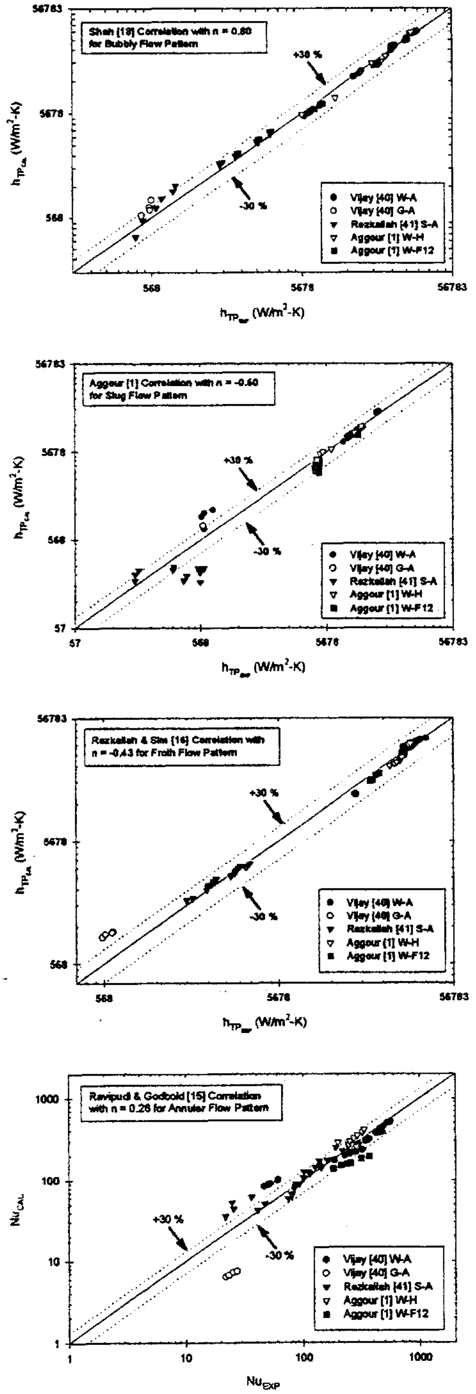

Fig. 8 Comparison of the Modified Shah (1981), Aggour (1978), Rezkallah & Sims (1987), and Ravipudi & Godbold (1978) Correlations with the Experimental Data of Four Major Flow Patterns in a Vertical Pipe

annular flow. Figure 8 shows how well these four recommended heat transfer correlations predict the vertical pipe two-phase heat transfer data for each flow pattern and all five fluid combinations. As can be seen from the figure, the correlations with the recommended n values do a very good job of predicting the majority of the heat transfer data with a ±30% deviation. The experimental data that completely fell outside of the ±30% band were the glycerin-air froth flow data of Vijay (1978) using Rezkallah and Sims' (1987) correlation, the water-air slug flow data of Vijay (1978) using Aggour's (1978) correlation, and the water-air annular flow data of Vijay (1978) using Ravipudi and Godbold's (1978) correlation. To further improve the predictive capabilities of the recommended correlations in predicting the two-phase heat transfer coefficient in each flow pattern regardless of the fluid combination, there appears to be at least one additional parameter [ratio], which is related to the effects of different fluid combinations on two-phase heat transfer, that must be added to the recommended correlations.

6. Summary and Conclusions

This study has modified the ability of the six two-phase heat transfer correlations recommended by Kim et al. (1999) to predict seven sets of experimental data that are available in the open literature. Five of these experimental data sets are for various flow patterns of water-air (Vijay, 1978), glycerin-air (Vijay, 1978), silicone-air (Rezkallah, 1987), water-helium (Aggour, 1978), and water-freon 12 (Aggour, 1978) in vertical pipes. The other two data sets are from the flow of water-air for slug (King, 1952) and annular (Pletcher, 1966) flow patterns in horizontal pipes.

Based on the improvements of the predictability of the two-phase heat transfer correlations shown in Table 5, this study makes the following recommendations: for glycerin-air and water-freon 12 flows within vertical pipes, this study recommend use of the Aggour (1978) correlation along with the optimal n values listed in Table 5 for the different fluid combinations; use of the Knott et al. (1959) correlation with the optimal n values listed in Table 5 for silicone-air and water-helium flows within vertical pipes and water-air slug flow within horizontal pipes; use of the Shah (1981) correlation along with the optimal n values listed in Table 5 for water-air flow within vertical pipes; and use of the Kudirka et al. (1965) correlation with the optimal n values for water-air annular flow within horizontal pipes.

Simplifying the modified exponent n values listed in Table 6 which depend on the four major flow patterns (bubbly, slug, froth, annular) in vertical pipes was successfully completed without significant loss of accuracy (see Table 7). The simplified exponent n values are 0. 39 for the parameter $(1+V_{SG}/V_{SL})$ in the Shah (1981) correlation for predicting the water-air flow; -0. 28 for the parameter $(1-\alpha)$ in the Aggour (1978) correlation for glycerin-air flow; 0.29 for the parameter $(1+V_{SG}/V_{SL})$ in the Knott et al. (1959) correlation for silicone-air flow; 0.34 for the parameter $(1+V_{SG}/V_{SL})$ in the Knott et al. (1978) correlation for water-helium flow; and -0. 82 for the parameter $(1-\alpha)$ in the Aggour (1978) correlation for water-freon 12 flow.

Attempts to simplify the exponent values in the six two-phase heat transfer correlations according to the major flow patterns regardless of the fluid combinations for predicting the five sets of two-phase heat transfer experimental data in vertical pipes were also made (see Table 8). Recommended exponent n values are 0.8 for the parameter $(1+V_{SG}/V_{SL})$ in the Shah (1981) correlation for bubbly flow; -0.6 for the parameter $(1-\alpha)$ in the Aggour (1978) correlation for slug flow; -0.43 for the parameter $(1-\alpha)$ in the Rezkallah and Sims (1987) correlation for froth flow; and 0.26 for the parameter (V_{SG}/V_{SL}) in the Ravipudi and Godbold (1978) correlation for annular flow. To further improve the predictive capabilities of the recommended correlations in predicting the two-phase heat transfer coefficient in each flow pattern, there appears to be at least one additional parameter, related to the effects of different fluid combinations on two-phase heat transfer, that might be required.

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

Acknowledgments

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