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Modeling of heat transfer coefficient for upward no-phase-change two-phase flow in inclined pipes

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HIGHLIGHT

- An extensive survey was performed to collect heat transfer data and existing correlations.
- None of existing correlations could predict the whole database satisfactorily.
- "Two-phase heat transfer multiplier" was proposed for two-phase heat transfer enhancement ratio.
- The dependence of two-phase heat transfer multiplier on pipe inclination angle was analysed.
- A heat transfer multiplier correlation was developed using Chilton-Colburn analogy.

ARTICLE INFO

Keywords:
No-phase-change two-phase flow
Heat transfer coefficient
Nusselt number
Inclined pipe
Chilton-Colburn analogy

ABSTRACT

This study aims at developing a robust and theoretically-supported correlation of two-phase heat transfer coefficient for upward no-phase-change two-phase flow in inclined pipes based on the concept of extended Chilton-Colburn analogy. Firstly, a comprehensive literature survey was conducted to gather over 1800 experimental data and 12 correlations of two-phase heat transfer coefficient. The comparison results indicated that none of the existing correlations could predict the entire database satisfactorily. Then, the dependence of two-phase heat transfer enhancement ratio (or two-phase heat transfer multiplier) on liquid fraction, two-phase pressure drop multiplier and inclination angle was analysed, and the two-phase heat transfer coefficient correlation was developed. The performance assessment indicated that the newly-developed correlation could predict 95% of the experimental data within ± 30% error with the mean absolute relative deviation of 12.9%. The newly-developed semi-theoretical correlation would be useful in designing no-phase-change two-phase heat transfer systems, such as petroleum pipelines and nuclear power plants.

1. Introduction

Upward no-phase-change two-phase flow in inclined pipes has extensive industrial and engineering applications in petroleum pipelines, chemical reactors and nuclear power plants [1]. Various flow patterns such as bubbly flow, intermittent flow, stratified flow and annular flow, occur in inclined pipes depending on different flow conditions [2]. Due to the significant interaction between gas and liquid phases, the flow characteristics of upward no-phase-change two-phase flow in inclined pipes are complicated. The thermal characteristics of no-phase-change two-phase flow in inclined pipes is attracting more and more attention recently. Substantial efforts have been made on understanding the flow and heat transfer characteristics of upward no-phase-change two-phase flow in inclined pipes.

Hetsroni et al. [3] investigated the local heat transfer coefficient of upward air-water flow in inclined pipes and claimed that the pipe inclination enhanced two-phase heat transfer. Mosyak and Hetsroni [4] also measured the temperature difference between the top and bottom of a horizontal pipe and slightly inclined pipes, and found that increasing pipe inclination could drastically reduce the temperature difference. Vaze and Banerjee [5] studied the effect of pipe inclination on flow and heat transfer characteristics of air-water two-phase flow experimentally. Trimble et al. [6] conducted experimental study on heat transfer characteristics of upward two-phase slug flow in inclined pipes.

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Nomenclature

a, A	empirical constant [–]
b	empirical constant [–]
C	Chisholm constant [–]
C_f	friction coefficient [–]
D	diameter [m]
D_H	hydraulic equivalent diameter [m]
f_D	Darcy friction factor [–]
f_F	Fanning friction factor [–]
Fr	Froude number [–]
G	mass flux[kg/(m^2 s)]
h	heat transfer coefficient[W/(m^2 K)]
j	superficial velocity [m/s]
k	exponent [–]
L	length [m]
m	exponent [–]
m_d	mean error [–]
m_{rel}	mean relative deviation [–]
$m_{rel,ab}$	mean absolute relative deviation [–]
n	exponent [–]
N	number of samples [–]
Nu	Nusselt number [–]
p	pressure Pa
Pr	Prandtl number [–]
Q	flow rate [m^3/s]
Re	Reynolds number [–]
R_f	liquid holdup [–]
s_d	standard deviation [–]
T	temperature [K]
v	velocity [m/s]
x	mass fraction [–]
X	Martinelli parameter [–]
y	direction perpendicular to a wall [–]
z	axial direction [–]

Greek symbols

α	void fraction [–]
θ	inclination angle [°]
μ	dynamic viscosity [Pa s]
ν	kinematic viscosity [m^2/s]
ρ	density [kg/m^3]
$\Delta\rho$	density difference [kg/m^3]
σ	surface tension [N/m]
τ	shear stress [Pa]
Φ_h	two-phase heat transfer multiplier [–]
Φ_f^2	two-phase multiplier [–]
ω	weighting function [–]

Subscripts

atm	atmospheric [–]
B	bulk [–]
cal	calculated [–]
D	developing region [–]
exp	experimental [–]
f,1Φ	liquid [–]
F	friction [–]
g	gas [–]
m	gas-liquid mixture [–]
sys	system [–]
W, w	wall [–]
2Φ	gas-liquid two-phase [–]

Superscripts

*	non-dimensional [–]
+	non-dimensional [–]

The experimental results indicated that the heat transfer increment could be 10% and 20% in 2°- and 5°-inclined pipes compared with that in horizontal pipes, respectively. Ghajar and Tang [7] investigated the flow and heat transfer characteristics of air-water two-phase flow in horizontal and slightly inclined pipes, and claimed that the effect of pipe inclination on heat transfer of two-phase flow varied with different flow regimes.

The mechanism of no-phase-change two-phase heat transfer is complicated due to the intricate two-phase interaction inside pipes. Several simple hypotheses have been proposed to explain the complicated mechanism of no-phase-change two-phase heat transfer in pipes. In Rezkallah and Sims's [8] and Aggour's [9] hypotheses, the introduction of air acted to accelerate the liquid phase, and the two-phase heat transfer coefficient was assumed to be equal to that of single-phase flow at the actual liquid velocity in two-phase flow. Void fraction was utilized to calculate the actual velocity of liquid phase. Besides, Knott et al. [10] and Ravipudi-Godbold [11] claimed that the two-phase heat transfer enhancement of two-phase flow was attributed to the increase of the average mixture velocity and developed two-phase heat transfer coefficient correlations based on the extension of single-phase heat transfer coefficient correlations. Several correction factors such as physical property ratios and velocity ratio between two phases were proposed in the modified two-phase heat transfer coefficient correlations.

Although several heat transfer coefficient or Nusselt number correlations of two-phase flow have been developed, most of the existing correlations were derived from limited experimental database in horizontal or vertical pipes. Therefore, the existing heat transfer coefficient correlations cannot be applied directly to estimating the thermal performance of the no-phase-change two-phase heat transfer systems with inclined pipes, such as petroleum pipelines and nuclear power plants. As discussed above, the pipe inclination plays an important role in two-phase heat transfer coefficient. Therefore, it is necessary to develop a robust and theoretically-supported heat transfer coefficient correlation for upward no-phase-change two-phase flow in inclined pipes with a wide range of applicability.

The purpose of this study is to develop a robust and theoretically-supported heat transfer coefficient correlation for upward no-phase-change two-phase flow in inclined pipes with a wide range of applicability. An extensive literature survey on upward no-phase-change two-phase heat transfer coefficients in inclined pipes is first conducted. More than 1800 experimental data of various flow regimes are collected from 11 sources. The literature survey identifies 12 heat transfer correlations of two-phase flow with 3 from horizontal pipes, 8 from vertical pipes and 1 from inclined pipes. To examine the applicability of the existing correlations, the comparison between collected database and existing correlations is conducted. The comparison results indicate that none of the existing correlations could predict the whole database with acceptable accuracy. Therefore, a new theoretically-supported heat transfer coefficient correlation for upward no-phase-change two-phase flow in inclined pipes is developed based on the concept of extended Chilton-Colburn analogy to two-phase flow. The resulting equation of the two-phase heat transfer multiplier is a function of void fraction, α, and two-phase multiplier, Φ_f^2. The newly-developed semi-theoretical correlation would be well applied in the design of no-phase-change two-phase heat transfer systems such as, petroleum pipelines and nuclear power plants, to accurately estimate the heat transfer coefficients.

2. Literature survey on existing database and correlations of heat transfer coefficient for upward no-phase-change two-phase flow in inclined pipes

2.1. Existing data of two-phase heat transfer coefficient

This study collects more than 1800 experimental data on heat transfer coefficients of upward no-phase-change two-phase flow in inclined pipes from 11 different sources. The detailed test conditions, fluid systems and flow parameters of the collected database are summarized in Table 1 [7,12–21]. The pipe diameter, D, ranges from 12.5 mm to 49.2 mm and the length of test sections ranges from 3.7D to 190D.

The superficial liquid velocity, j_f, ranges from 0.005 m/s to 3.17 m/s with the liquid Reynolds number, Re_f, ranging from 3.07×10^2 to 8.90×10^4, and the superficial gas velocity, j_g, ranges from 0.0195 m/s to 36.0 m/s with the gas Reynolds number, Re_g, ranging from 2.50×10^1 to 6.40×10^4 indicating that the data taken in both laminar and turbulent flows are collected. Here, the liquid Reynolds number at the transition between laminar and turbulent flows are assumed to be 2300. To investigate the effect of pipe inclination on two-phase heat transfer coefficient, the experimental data from different pipe inclination angles are collected, with the pipe inclination angles ranging from 0° to 90°. Here, the inclination angle, θ, is measured from a horizontal direction, and $\theta = 0°$and 90° correspond to horizontal and vertical directions, respectively. Fig. 1 shows the flow conditions of the collected database in the flow regime map proposed by Bhagwat and Ghajar [20]. The lines represent the flow regime transition boundaries of different flow regimes with the pipe diameter of 12.5 mm. The red dashed line, blue dotted line, pink short-dashed line and black solid line indicate the flow regime transition boundaries in inclined pipes with the inclination angles of 0°, 30°, 60° and 90°, respectively. Fig. 1 shows that the existing data are collected in various flow regimes such as dispersed bubbly flow (DB), plug/slug flow (P/S), stratified smooth flow (SS), wavy slug/wavy annular flow (SW/WA), and annular flow (A).

As mentioned above, the existing data are collected in a wide range of flow conditions from upward laminar and turbulent flow in inclined pipes with different pipe inclination angles. Almost all of the flow regimes such as dispersed bubbly flow, plug/slug flow, stratified smooth flow, wavy slug/ wavy annular flow and annular flow are included in the collected database.

2.2. Existing correlations of two-phase heat transfer coefficient

Continuous efforts have been made to investigate the mechanism of two-phase flow in pipes and several two-phase heat transfer coefficient correlations have been proposed. Table 2 summarizes the existing correlations of heat transfer coefficient for no-phase-change two-phase flow. In total, 12 two-phase heat transfer coefficient correlations from different sources are collected, including 3 from horizontal pipes, 8 from vertical pipes and 1 from inclined pipes. A brief description about the existing heat transfer coefficient correlations is given in the sequence of vertical (V), horizontal (H) and inclined (I) pipes.

2.2.1. Vertical upward flow correlation

Knott et al. [10] conducted an experimental study on the heat transfer characteristics of upward nitrogen-oil mixture in a vertical pipe and developed a correlation to predict the heat transfer coefficient of two-phase flow. Knott et al. [10] found that the main resistance of heat-to-liquids laid in the vicinity of the heat transfer surface.

Groothuis and Hendal [22] measured the heat transfer coefficients of upward air-water and gas-oil mixtures in vertical pipes and found that the gas added to liquid could enhance the heat transfer coefficient

Table 1
Summary of two-phase heat transfer coefficient database for upward no-phase-change two-phase flow in inclined pipes.

Sources	Fluids	Inclination angles [°]	Diameter, D [mm]	L/D [–]	L_D/D [–]	j_g [m/s]	j_f [m/s]	Re_g [–]	Re_f [–]	Flow regimes
Durant (2003) [12]	Air-Water	0, 5, 7	27.9	100	88	15.0–20.3	0.100–0.260	2.72×10^4–3.69×10^4	2.86×10^3–8.36×10^3	A
Hetsroni et al. (2003) [13]	Air-Water	8	49.2, 25.0	3.70, 7.20	152–300	20.0–36.0	0.005–0.099	5.85×10^4–6.40×10^4	3.07×10^2–3.09×10^3	SS, A
Ghajar (2004) [14]	Air-Water	0, 2, 5, 7	25.4	100	88.0	0.331–29.1	0.171–0.582	5.49×10^2–4.83×10^4	5.00×10^3–1.70×10^4	P/S, WS/WA, A, SS
Malhotra (2004) [15]	Air-Water	0, 2, 5, 7	27.9	100	88.0	0.325–3.40	0.113–2.03	6.34×10^2–6.63×10^3	3.16×10^3–2.86×10^4	PS, WS
Ghajar and Tang (2007) [7]	Air-Water	0, 2, 5, 7	27.9	100	88.0	0.310–26.5	0.108–0.934	5.64×10^2–4.80×10^4	3.00×10^3–2.60×10^4	P/S, WS/WA, A, SS, DB
Liu and Cheng (2013) [16]	Air-Water	8	40.0	75.0	150	1.63–5.94	0.520–1.46	4.41×10^2–1.60×10^4	3.17×10^4–8.90×10^4	S
Wang et al. (2014) [17]	Air-Water	0, 1, 3	25.4	190	88.0	1.00–19.0	0.100–1.20	1.65×10^3–3.14×10^4	3.17×10^3–3.81×10^4	S
Kalapatapu (2014) [18]	Air-Water	0, 5, 10, 20	12.5	80.0	110	0.340–24.2	0.150–0.960	2.74×10^2–1.94×10^4	1.87×10^3–1.20×10^4	DB, S, A, SS
Sources	Fluids	Inclination angles [°]	Diameter, D [mm]	L/D [–]	L_D/D [–]	j_g [m/s]	j_f [m/s]	Re_g [–]	Re_f [–]	Flow Regimes
Kashinsky et al. (2014) [19]	Air-Water	0, 10, 20, 30, 40, 50, 60, 70, 80, 90	20.0	93.4	–	0.0195–0.153	0.176–3.17	2.50×10^1-1.93×10^2	3.20×10^3–2.50×10^4	DB
Bhagwat and Ghajar (2016) [20]	Air-Water	0, 10, 20, 30, 45, 60, 75, 90	12.5	81.3	100	0.100–18.7	0.150–1.35	8.40×10^1-1.56×10^4	1.88×10^3–1.69×10^4	DB, S, WS, WA, A
Chinak et al. (2018) [21]	Air-Water	0, 10, 20, 30, 40, 50, 60, 70, 80, 90	20.0	93.4	–	0.0305–0.153	0.275–1.37	3.96×10^1-1.98×10^2	5.00×10^3–2.50×10^4	DB

Notes: A: annular flow, DB: dispersed bubbly flow, P: plug flow, S: slug flow, SS: stratified smooth flow, WS: wavy slug flow, WA: wavy annular flow.

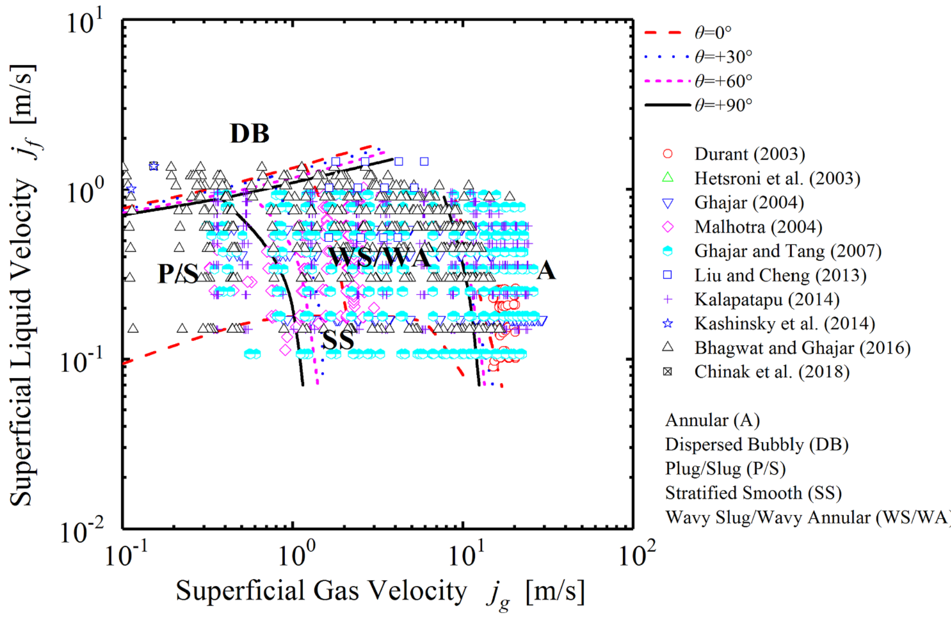

Fig. 1. Flow conditions of collected database in Bhagwat and Ghajar flow-regime map [20].

significantly. Based on the experimental analysis, Groothuis and Hendal [22] proposed two different heat transfer coefficient correlations in the same functional form as Sieder-Tate [23] correlation for air-water flow and gas-oil flow.

Kudirka et al. [24] investigated flow and heat transfer characteristics of upward air-water and air-ethylene glycol mixtures in a vertical pipe. The experimental results indicated that the dependence of two-phase heat transfer coefficient on mass flow rate and gas-liquid ratio was small. Besides, Kudirka et al. [24] found that the introduction of air could effectively enhance the two-phase heat transfer coefficient.

Table 2
Summary of existing two-phase heat transfer coefficient correlations for no-phase-change two-phase flow.

Sources	Two-phase correlations	Single-phase correlations
Knott et al. (1959) [10] (V)	$\frac{h_{2\Phi}}{h_{1\Phi}} = (1 + \frac{j_g}{j_f})^{1/3}$,	$Nu_{1\Phi} = 1.86(Re_f Pr_f \frac{D}{L})^{1/3}(\frac{\mu_B}{\mu_W})^{0.14}$ (L) $Nu_{1\Phi} = 0.027Re_f^{0.8} Pr_f^{0.33}(\frac{\mu_B}{\mu_W})^{0.14}$ (T)
Groothuis and Hendal (1959) [22] (V)	$Nu_{2\Phi} = 0.029Re_{tp}^{0.87} Pr_f^{1/3}(\frac{\mu_B}{\mu_W})^{0.14}$(A/W) $Nu_{2\Phi} = 2.6Re_{tp}^{0.39} Pr_f^{1/3}(\frac{\mu_B}{\mu_W})^{0.14}$ (A/G)	
Kudirka et al. (1965) [24] (V)	$Nu_{2\Phi} = 125(\frac{j_g}{j_f})^{0.125}(\frac{\mu_g}{\mu_f})^{0.6} Re_f^{0.25} Pr_f^{1/3} \times (\frac{\mu_B}{\mu_W})^{0.14}$	
Ueda and Hanaoka (1967) [25] (V)	$Nu_{2\Phi} = 0.075Re_m^{0.60} \frac{Pr}{1 + 0.35(Pr - 1)}$ $Re_m = \frac{\rho j_m D}{\mu_f}$	
Aggour (1978) [9] (V)	$\frac{h_{2\Phi}}{h_{1\Phi}} = (1 - \alpha)^{-1/3}$, $\frac{h_{2\Phi}}{h_{1\Phi}} = (1 - \alpha)^{-0.83}$,	(L) $Nu_{1\Phi} = 0.0155Re_f^{0.83} Pr_f^{0.5}(\frac{\mu_B}{\mu_W})^{0.33}$ (T)
Vijay et al. (1982) [27] (V)	$\frac{h_{2\Phi}}{h_{1\Phi}} = \Phi_f^{0.489}$,	(L) $Nu_{1\Phi} = 1.615(Re_f Pr_f \frac{D}{L})^{1/3}(\frac{\mu_B}{\mu_W})^{0.14}$ (T)
Rezkallah and Sims (1989) [8] (V)	$\frac{h_{2\Phi}}{h_{1\Phi}} = (1 - \alpha)^{-0.8}$,	$Nu_{1\Phi} = 0.023Re_f^{0.8} Pr_f^{0.33}(\frac{\mu_B}{\mu_W})^{0.14}$
Kalapatapu (2014) [18] (V)	$\frac{h_{2\Phi}}{h_{1\Phi}} = (\Phi_f^2)^{0.39}$,	$Nu_{1\Phi} = 1.86(Re_f Pr_f \frac{D}{L})^{1/3}(\frac{\mu_B}{\mu_W})^{0.14}$(L) $Nu_{1\Phi} = 0.027Re_f^{0.83} Pr_f^{0.5}(\frac{\mu_B}{\mu_W})^{0.33}$ (T)
King (1952) [8] (H)	$\frac{h_{2\Phi}}{h_{1\Phi}} = \frac{(1 - \alpha)^{-0.52}}{1 + 0.025Re_f}(\Phi_f^2)^{0.32}$,	$Nu_{1\Phi} = 0.023Re_f^{0.8} Pr_f^{0.4}$
Fedotkin and Zarudnev (1970) [29] (H)	$Nu_{2\Phi} = 0.0182Re_m^{0.882} Pr_f^{0.43}(\frac{Pr_{f,B}}{Pr_{f,W}})^{0.25}$ $Re_m = \frac{\rho_f j_f D}{\mu_f} + \frac{\rho_g j_g D}{\mu_g}$	
Kago et al. (1986) [30] (H)	$Nu_{2\Phi} = (0.021Re_m^{0.8} + 4.5)Pr_f^{1/3}(\frac{\mu_B}{\mu_W})^{0.14} \times \{1 + 0.3\exp[-0.5(Fr_f - 2)^2]\}$	
Ghajar and Tang (2010) [31] (I)	$\frac{h_{2\Phi}}{h_{1\Phi}} = F_p[1 + 0.82(\frac{x}{1 - x})^{0.08}(\frac{1 - F_p}{F_p})^{0.39}(\frac{Pr_g}{Pr_f})^{0.03}(\frac{\mu_f}{\mu_g})^{0.01}(I^*)^{0.40}]$	

Notes: 1. L and T represent laminar flow ($Re_f \leqslant 2300$) and turbulent flow ($Re_f > 2300$), respectively.
2. A/W represents air and water mixture and A/G represents air and gas-oil mixture.
3. V, H and I represent vertical, horizontal and inclined pipes, respectively.

Based on the experimental analysis, a two-phase heat transfer coefficient correlation was developed with correction factors such as (μ_f/μ_g) and (j_f/j_g), where μ_f and μ_g are the liquid and gas dynamic viscosities, respectively.

Ueda and Hanaoka [25] carried out both experimental and theoretical analysis on upward two-phase annular flow in vertical pipes with a wide range of liquid flow rates, void fraction and liquid Prandtl number. The eddy diffusivity for momentum in liquid film was assumed to be equal to that for heat. Finally, Ueda and Hanaoka [25] proposed a heat transfer coefficient correlation which was a function of the liquid Prandtl number and Reynolds number based on the equivalent mean velocity of the liquid phase.

Aggour [9] investigated flow and heat transfer characteristics of upward co-current no-phase-change two-phase flow in vertical pipes. Three gases, namely, air, helium and Freon 12 were used in the experiment to analyse the effect of gas densities on local and mean heat transfer coefficient. Aggour [9] claimed that the introduction of gas only acted to increase the flow velocities of liquid and the heat was taken away by liquid only. The actual velocity of liquid could be calculated using void fraction and superficial liquid velocity. Based on such hypotheses, Aggour [9] developed a simple two-phase heat transfer coefficient correlation which was similar to Dorresteign correlation [26]. Only void fraction was considered in Aggour [9] correlation.

Vijay et al. [27] investigated flow and heat transfer performance of upward no-phase-change two-phase flow in vertical pipes and analysed the relationship between forced convective heat transfer coefficient and frictional pressure drop. Then, a heat transfer coefficient correlation was developed as a function of two-phase multiplier.

Rezkallah and Sim [8] conducted experimental study on hydrodynamics and heat transfer characteristics of upward no-phase-change air-liquid two-phase flow in vertical pipes. The liquids used in their experiments were water, glycerine-water (58–42% by weight) and silicone liquid (Dow Corning 200, 5cS viscosity grade). They analysed the effect of surface tension on heat transfer and flow characteristics. Rezkallah and Sim [8] proposed a two-phase heat transfer coefficient correlation based on liquid-acceleration model. The comparison between the experimental heat transfer coefficient and the calculated results indicated that the overall algebraic deviation and the root-mean-square deviations were −8.8% and 20.4%, respectively.

Kalapatapu [18] inferred that the two-phase heat transfer was related to pressure drop based on which a modified heat transfer coefficient correlation was developed in the same form as Vijay et al. [27] correlation. Comparing Kalapatapu [18] correlation with the experimental results obtained from inclined pipes with different inclination angles showed that 97% of the data fell within ± 30% range.

2.2.2. Horizontal flow correlation

King [28] investigated flow and heat transfer characteristics of an air-water mixture in an 18.7 mm I.D. horizontal pipe and developed a correlation to predict the heat transfer coefficient of two-phase flow based on the experimental results. In King [28] correlation, void fraction and two-phase multiplier were considered.

Kago et al. [30] studied heat transfer and flow characteristics of two-phase gas-liquid and gas-slurry flow in horizontal pipes and analysed the effect of liquid viscosities on two-phase heat transfer coefficient. Kago et al. [30] proposed a correlation based on Sieder and Tate [23] correlation to estimate the two-phase heat transfer coefficient. To consider the effect of mixing length on two-phase heat transfer coefficient, a correction function was introduced in Kago et al. [30] correlation.

2.2.3. Inclined upward flow correlation

Ghajar and Tang [31] investigated the heat transfer performance of upward air-water two-phase flow in horizontal and slightly inclined pipes (θ = 2°, 5° and 7°) and developed a two-phase heat transfer coefficient correlation based on the assumption that the total heat transfer coefficient was the sum of individual heat transfer coefficient of liquid and gas. Besides, flow regime factor, F_p, and inclination factor, I^*, were introduced in Ghajar and Tang [31] correlation to account for the effect of flow regimes and pipe inclinations on two-phase heat transfer coefficient. The flow regime factor and inclination factor were defined as:

$$F_p = (1-\alpha) + \alpha\left[\frac{2}{\pi}\tan^{-1}\left\{\sqrt{\frac{\rho_g(v_g - v_f)}{\Delta\rho g D}}\right\}\right]^2 \quad (1)$$

$$I^* = 1 + Eo\ |\sin\theta| \quad (2)$$

where v_g, v_f, $\Delta\rho$, and D are the void fraction averaged mean gas velocity, liquid fraction averaged mean liquid velocity, density difference between gas and liquid, and pipe diameter, respectively. Eo is Eötvös number defined by:

$$Eo = \frac{\Delta\rho g D^2}{\sigma} \quad (3)$$

where σ is the surface tension.

Several heat transfer coefficient correlations in various forms for no-phase-change two-phase flow in horizontal pipes, vertical pipes and inclined pipes are collected. However, only one heat transfer coefficient correlation, Ghajar and Tang [31] correlation, was developed for slightly inclined two-phase flow. A simple inclination factor was used in the correlation to account for the effect of pipe inclination on heat transfer coefficient without considering the physical fundamental behind the two-phase heat transfer process. The applicability of the existing correlations for vertical, horizontal and inclined pipes to the collected database is conducted in the next section.

2.3. Performance evaluation of existing heat transfer coefficient correlations with collected database

In this section, the comparisons between experimental results from the collected database and the calculated results by the existing correlations are conducted for the performance evaluation of the existing two-phase heat transfer coefficient correlations. The ratio of two-phase heat transfer coefficient (or two-phase Nusselt number) to single-phase heat transfer coefficient (or single-phase Nusselt number) is selected as the objective parameter. The ratio is defined as "two-phase heat transfer multiplier" by:

$$\Phi_h = \frac{h_{2\Phi}}{h_{1\Phi}} = \frac{Nu_{2\Phi}}{Nu_{1\Phi}} \quad (4)$$

where $h_{2\Phi}$ (or $Nu_{2\Phi}$) is the two-phase heat transfer coefficient (or two-phase Nusselt number) and $h_{1\Phi}$ (or $Nu_{1\Phi}$) is the single-phase heat transfer coefficient (or single-phase Nusselt number) flowing at the same superficial liquid velocity.

To evaluate the prediction accuracy quantitatively, four statistical indices, namely, mean error, m_d, standard deviation, s_d, mean relative deviation, m_{rel}, and mean absolute relative deviation, $m_{rel,\ ab}$, are introduced [32]. The mean error, m_d, represents the average bias of the correlation and the standard deviation (bias), s_d, means the scatter of the experimental results around the calculated results (random uncertainty or random error). The mean relative deviation, m_{rel}, represents the relative difference of the correlation and the mean absolute relative deviation, $m_{rel,\ ab}$, is usually selected as a prediction error. The definitions of these statistical indices are as follows.

$$m_d = \frac{1}{N}\sum_{i=1}^{N}[\Phi_{h,\ cal}(i) - \Phi_{h,\ exp}(i)] \quad (5)$$

$$s_d = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}\left[\Phi_{h,\,cal}(i) - \Phi_{h,\,exp}(i) - m_d\right]^2} \tag{6}$$

$$m_{rel} = \frac{1}{N}\sum_{i=1}^{N}\frac{\Phi_{h,\,cal}(i) - \Phi_{h,\,exp}(i)}{\Phi_{h,\,exp}(i)} \tag{7}$$

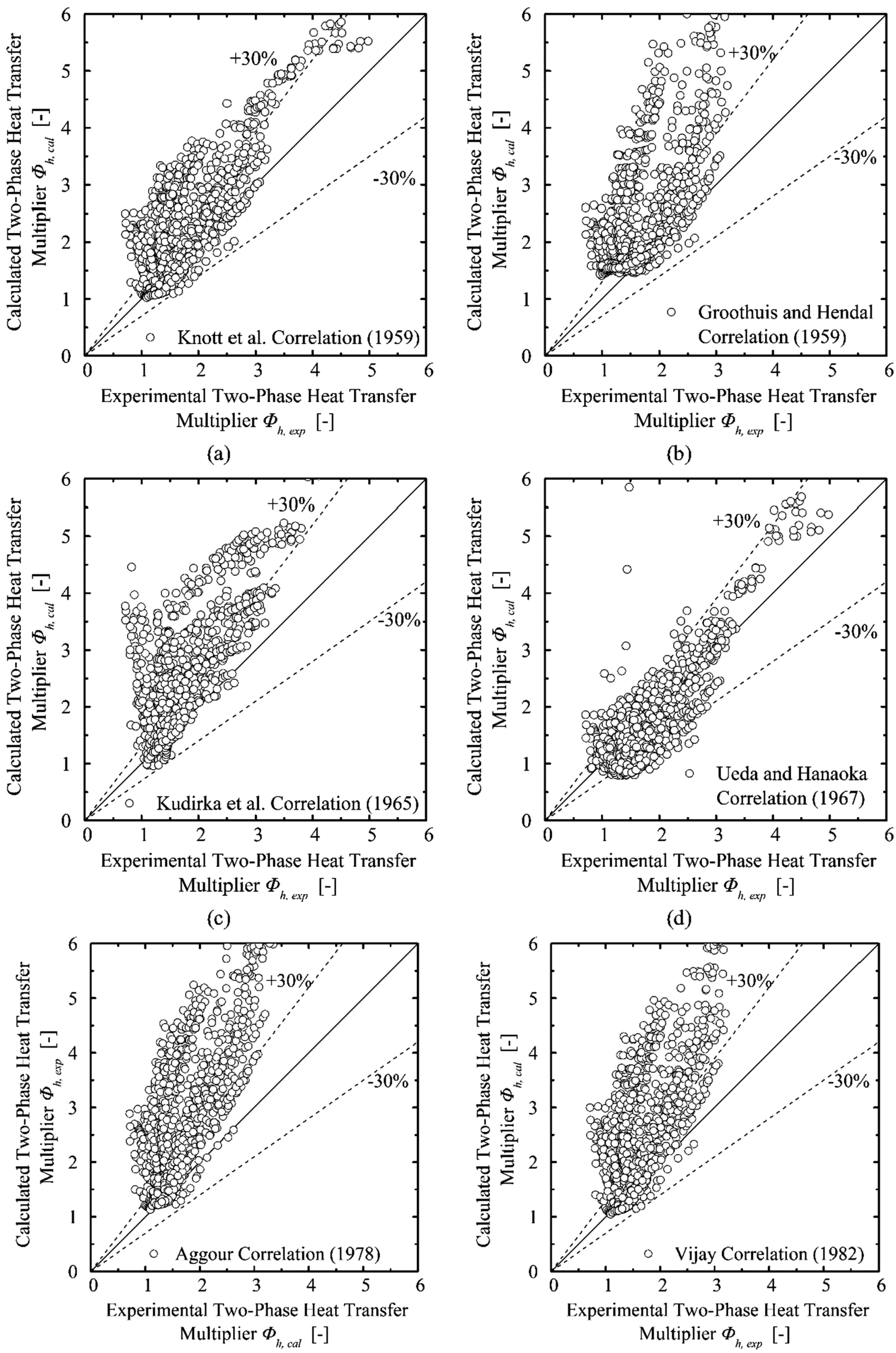

Fig. 2. Comparison of existing correlations with collected database for upward no-phase-change two-phase flow in inclined pipes.

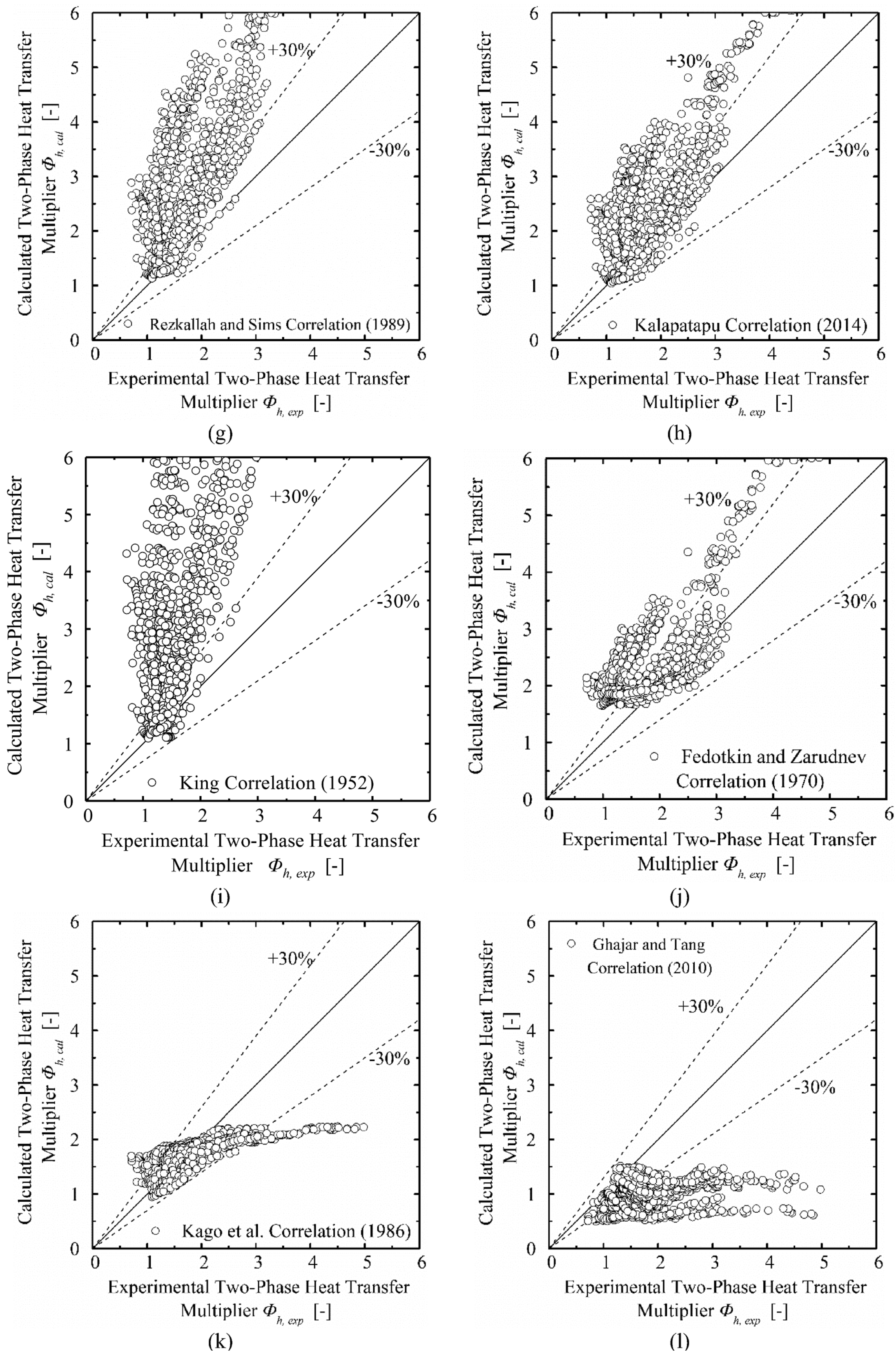

Fig. 2. (*continued*)

$$m_{rel,ab} = \frac{1}{N}\sum_{i=1}^{N}\frac{|\Phi_{h,\,cal}(i) - \Phi_{h,\,exp}(i)|}{\Phi_{h,\,exp}(i)} \tag{8}$$

where N, $\Phi_{h,\,cal}(i)$, and $\Phi_{h,\,exp}(i)$ represent the number of samples, calculated and experimental two-phase heat transfer multipliers, respectively.

Fig. 2 presents the comparison of existing correlations with the collected database for upward no-phase-change two-phase flow in inclined pipes. The abscissa and ordinate in Fig. 2 represent the experimental and calculated two-phase heat transfer multipliers, respectively. As discussed above, the pipe inclination plays an important role in two-phase heat transfer coefficient. However, most of the existing correlations were developed for only horizontal or vertical pipes without considering the effect of pipe inclination on two-phase heat transfer coefficient. Therefore, none of the existing correlations could predict the whole collected database with acceptable accuracy, as shown in Fig. 2.

Fig. 2 (a), (b), (c), (e), (f), (g), (h), (i) and (j) show that correlations such as Knott et al. [10] correlation, Groothuis and Hendal [22] correlation, Kudirka et al. [24] correlation, Aggour [9] correlation, Vijay et al. [27] correlation, Rezkallah and Sims [8] correlation, Kalapatapu [18] correlation, King [28] correlation and Fedotkin and Zarudnev [29] correlation tend to overestimate the two-phase heat transfer multiplier, especially at high two-phase heat transfer multiplier. To the contrary, Fig. 2 (k) and (l) indicate that Kago et al. [30] correlation and Ghajar and Tang [31] correlation tend to underestimate the two-phase heat transfer multiplier, especially when the two-phase heat transfer multiplier is high. Fig. 2 (d) demonstrates that Ueda and Hanaoka [25] correlation may calculate the two-phase heat transfer multiplier evenly around the experimental values with relatively high degree of scattering.

Table 3 tabulates the performance evaluation of the existing heat transfer coefficient correlations by the collected database of upward two-phase flow in inclined pipes. The mean relative deviation, m_{rel}, ranges from -82.3% in Ghajar and Tang [31] correlation to 49.3% in King [28] correlation. The mean absolute relative deviation, $m_{rel,\ ab}$, ranges from 23.9% in Knott [10] correlation and 82.9% in Ghajar and Tang [31] correlation. Although Table 3 demonstrates that Knott et al. [10] correlation could achieve the lowest mean absolute relative deviation, Knott et al. [10] correlation tends to overestimate the two-phase heat transfer multiplier, especially when the heat transfer multiplier is high. Therefore, Knott et al. [10] correlation is not suitable for predicting the upward two-phase heat transfer coefficient in inclined pipes.

As demonstrated above, none of the existing correlation including Ghajar and Tang [31] correlation could accurately predict the two-phase heat transfer coefficient of the whole database in inclined pipes. In view of these, it is important to develop a new theoretically-supported heat transfer coefficient correlation for upward no-phase-change two-phase flow in inclined pipes with a wide range of applicability. The effect of pipe inclination on the two-phase heat transfer multiplier should be incorporated in the new correlation.

Table 3
Performance evaluation of exiting correlations for collected upward no-phase-change two-phase flow database in inclined pipes.

Statistical parameters	m_d [−]	s_d [−]	m_{rel} [%]	$m_{rel,\ ab}$ [%]
Knott et al. [10] correlation (V)	0.553	0.583	20.1	23.9
Groothuis and Hendal [22] correlation (V)	1.06	1.31	31.4	31.8
Kudirka et al. [24] correlation (V)	0.834	0.710	28.8	29.9
Ueda and Hanaoka [25] correlation (V)	0.106	0.814	−10.7	26.1
Aggour [9] correlation (V)	1.34	1.06	38.6	38.9
Vijay [27] correlation (V)	1.04	1.04	30.9	32.4
Rezkallah and Sims [8] correlation (V)	1.14	0.883	35.3	36.1
Kalapatapu [18] correlation (V)	0.834	0.710	28.8	29.9
King [28] correlation (H)	2.59	2.70	49.3	49.5
Fedotkin and Zarudnev [29] correlation (H)	0.670	0.506	27.9	28.9
Kago et al. [30] correlation (H)	−0.0284	0.483	10.1	21.3
Ghajar and Tang [31] correlation (I)	−0.713	0.647	−82.3	82.9

3. Development of heat transfer multiplier correlation for upward two-phase flow in inclined pipes

3.1. Model development based on extended Chilton-Colburn analogy

In this section, a two-phase heat transfer multiplier correlation of upward no-phase-change two-phase flow in inclined pipes is developed based on "extended" Chilton-Colburn analogy [33,34]. In order to derive dominant non-dimensional parameters, simplified boundary layer equations for 2-dimensional laminar flow with neglected gravitational force and viscous dissipation are considered as follows.

$$v_z\frac{\partial v_z}{\partial z} + v_y\frac{\partial v_z}{\partial y} = -\frac{1}{\rho}\frac{dp}{dz} + \upsilon\frac{\partial^2 v_z}{\partial y^2} \tag{9}$$

$$v_z\frac{\partial T}{\partial z} + v_y\frac{\partial T}{\partial y} = \alpha_{\mathrm{td}}\frac{\partial^2 T}{\partial y^2} \tag{10}$$

where v_z, v_y, ρ, υ, $T$and α_{td} are the axial velocity (or z-directional velocity), velocity perpendicular to a wall (or y-directional velocity), density, kinematic viscosity, temperature and thermal diffusivity, respectively. Eqs. (9) and (10) are non-dimensionalized by the characteristics length, velocity and temperature scales as:

$$v_z^*\frac{\partial v_z^*}{\partial z^*} + v_y^*\frac{\partial v_z^*}{\partial y^*} = -\frac{dp^*}{dz^*} + \frac{1}{\mathrm{Re}}\frac{\partial^2 v_z^*}{\partial y^{*2}} \tag{11}$$

$$v_z^*\frac{\partial T^*}{\partial z^*} + v_y^*\frac{\partial T^*}{\partial y^*} = \frac{1}{\mathrm{Re\,Pr}}\frac{\partial^2 T^*}{\partial y^{*2}} \tag{12}$$

The temperature and velocity profiles at the surface can be described by friction factor, Nusselt number and Reynolds number as follows.

$$\left.\frac{\partial v_z^*}{\partial y^*}\right|_{y^*=0} = \frac{C_f Re}{2} \tag{13}$$

$$\left.\frac{\partial T^*}{\partial y^*}\right|_{y^*=0} = Nu \tag{14}$$

According to Reynolds analogy, the heat transfer is related to the momentum transfer. Therefore, the non-dimensionalized temperature profile at the wall surface should be the same as the non-dimensionalized velocity profile when $dp^*/dz^* = 0$ and $Pr = 1$.

$$\left.\frac{\partial v_z^*}{\partial y^*}\right|_{y^*=0} = \left.\frac{\partial T^*}{\partial y^*}\right|_{y^*=0} \tag{15}$$

Therefore,

$$\frac{C_f Re}{2} = Nu \tag{16}$$

The friction factor, C_f, is equal to the Fanning friction factor, f_F [33,34]. According to Chilton-Colburn analogy, Eq. (16) can be further extended to a wide range of Pr as:

$$\frac{f_F Re}{2} = NuPr^{-1/3} \quad (0.6 \leqslant Pr \leqslant 60) \tag{17}$$

or

$$\frac{f_{F,1\Phi} Re_{1\Phi}}{2} = Nu_{1\Phi}Pr^{-1/3} \quad (0.6 \leqslant Pr \leqslant 60) \tag{18}$$

Due to the insignificant sensitivity of pressure gradients on Chilton-Colburn analogy, Eq. (17) can be extended to turbulent flow [35].

The Chilton-Colburn analogy is further extended to two-phase flow as:

$$\frac{f_{\mathrm{F},1\Phi}\Phi_f^2 Re_{2\Phi}}{2} = Nu_{2\Phi}Pr^{-1/3} \tag{19}$$

where the subscript, 1Φ and 2Φ represent single-phase and two-phase flows, respectively.

Diving Eq. (19) by Eq. (18) yields:

$$\frac{Nu_{2\Phi}}{Nu_{1\Phi}} = \Phi_f^2 \frac{Re_{2\Phi}}{Re_{1\Phi}} \quad (20)$$

where the single-phase Reynolds number, $Re_{1\Phi}$, and two-phase Reynolds number, $Re_{2\Phi}$, are expressed as follows.

$$Re_{1\Phi} = \frac{GD}{\mu_f} \quad (21)$$

$$Re_{2\Phi} = \frac{GD}{\mu_m} \quad (22)$$

where μ_f and μ_m are the single-phase liquid viscosity and two-phase mixture viscosity. The relationship between μ_f and μ_m is expressed as follows [2].

$$\frac{\mu_m}{\mu_f} = (1-\alpha)^{-n} \quad (23)$$

where the exponent, n, is determined by specific flow regimes.

The two-phase heat transfer multiplier is expressed by substituting Eqs. (21) and (22) into Eq. (20) as:

$$\Phi_h = (1-\alpha)^n \Phi_f^2 \quad (24)$$

Two-phase multiplier, Φ_f^2, represents the ratio of two-phase frictional pressure drop to single-phase frictional pressure drop defined as follows.

$$\Phi_f^2 = \frac{(dp/dz)_{F,2\Phi}}{(dp/dz)_{F,1\Phi}} \quad (25)$$

Chisholm's [36] correlation is often used to calculate the two-phase multiplier, Φ_f^2 as:

$$\Phi_f^2 = 1 + \frac{C}{X} + \frac{1}{X^2} \quad (26)$$

where C is the Chisholm's parameter depending on gas and liquid Reynolds number. X is Martinelli parameter defined by:

$$X = \left[\frac{(dp/dz)_{F,f}}{(dp/dz)_{F,g}}\right]^{0.5} \quad (27)$$

Substituting Eq. (26) into Eq. (24) yields:

$$\Phi_h = (1-\alpha)^n \left(1 + \frac{C}{X} + \frac{1}{X^2}\right) \quad (28)$$

where the Chisholm's coefficient, C, is dependent on whether a flow is laminar or turbulent. To reduce the complexity and ensure the sufficient flexibility of the new correlation, Eq. (28) is further approximated as follows [37].

$$\Phi_h = (1-\alpha)^a \left(1 + \frac{A}{X^b}\right) \quad (29)$$

where a, b and A are empirical parameters to be determined by the experimental data.

3.2. Similarity analysis of the developed correlation with existing two-phase heat transfer coefficient correlations

As summarized in Table 2, several existing heat transfer coefficient correlations are developed using void fraction, α, or two-phase multiplier, Φ_f^2. According to Chisholm [36], two-phase multiplier, Φ_f^2 can be expressed as follows.

$$\Phi_f^2 = \frac{1}{(1-\alpha)^m} \quad (30)$$

The exponent, m, usually ranges from 1.75 to 2.00 [36].

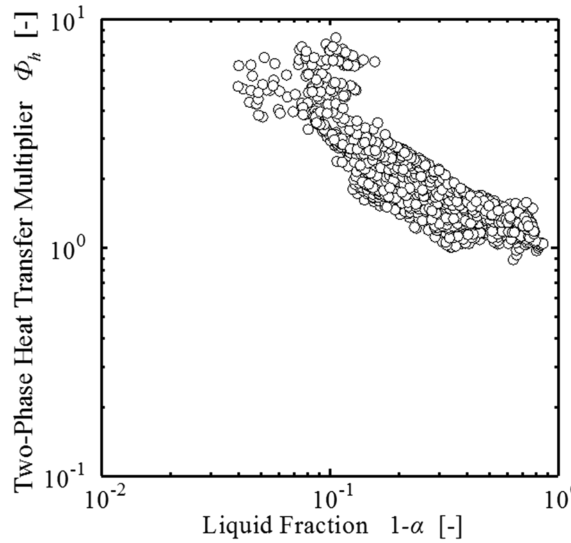

Fig. 3. Variation of two-phase heat transfer multiplier with liquid fraction in inclined pipes.

Substituting Eq. (30) into Eq. (24) yields:

$$\frac{Nu_{2\Phi}}{Nu_{1\Phi}}\left(=\frac{h_{2\Phi}}{h_{1\Phi}}\right) = (1-\alpha)^{n-m} \quad (31)$$

or

$$\frac{Nu_{2\Phi}}{Nu_{1\Phi}}\left(=\frac{h_{2\Phi}}{h_{1\Phi}}\right) = \Phi_f^{2(1-\frac{n}{m})} \quad (32)$$

Eq. (31) is the exactly same functional form of Aggour [9] correlation and Rezkallah and Sims [8] correlation, while Eq. (32) is the exactly same functional form of Vijay [27] correlation and Kalapatapu [18] correlation, validating the theoretical analysis used in developing the new correlation in this section.

Figs. 3 and 4 present the variations of upward two-phase heat transfer multiplier in inclined pipes with liquid fraction, $1-\alpha$, and two-phase multiplier, Φ_f^2, respectively. Systematic relationships between the two-phase heat transfer multiplier and liquid fraction and between the two-phase heat transfer multiplier and two-phase multiplier are found, which experimentally validates the intrinsic theoretical

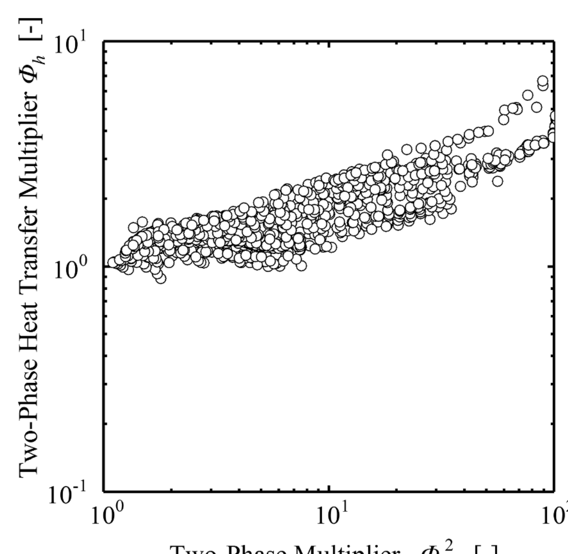

Fig. 4. Variation of two-phase heat transfer multiplier with two-phase multiplier in inclined pipes.

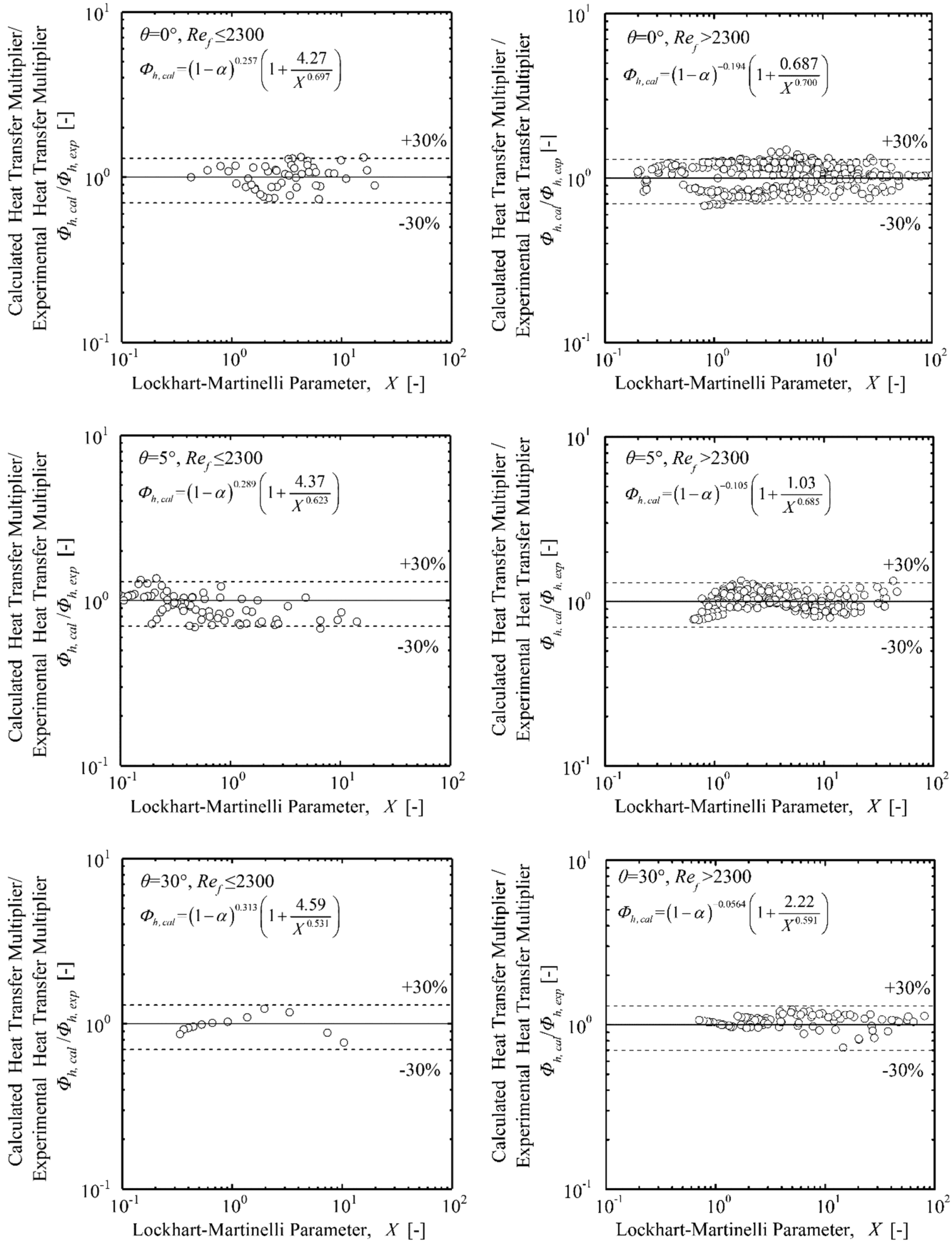

Fig. 5. Comparison between the experimental and calculated two-phase heat transfer multipliers by the newly-developed correlations in inclined pipes.

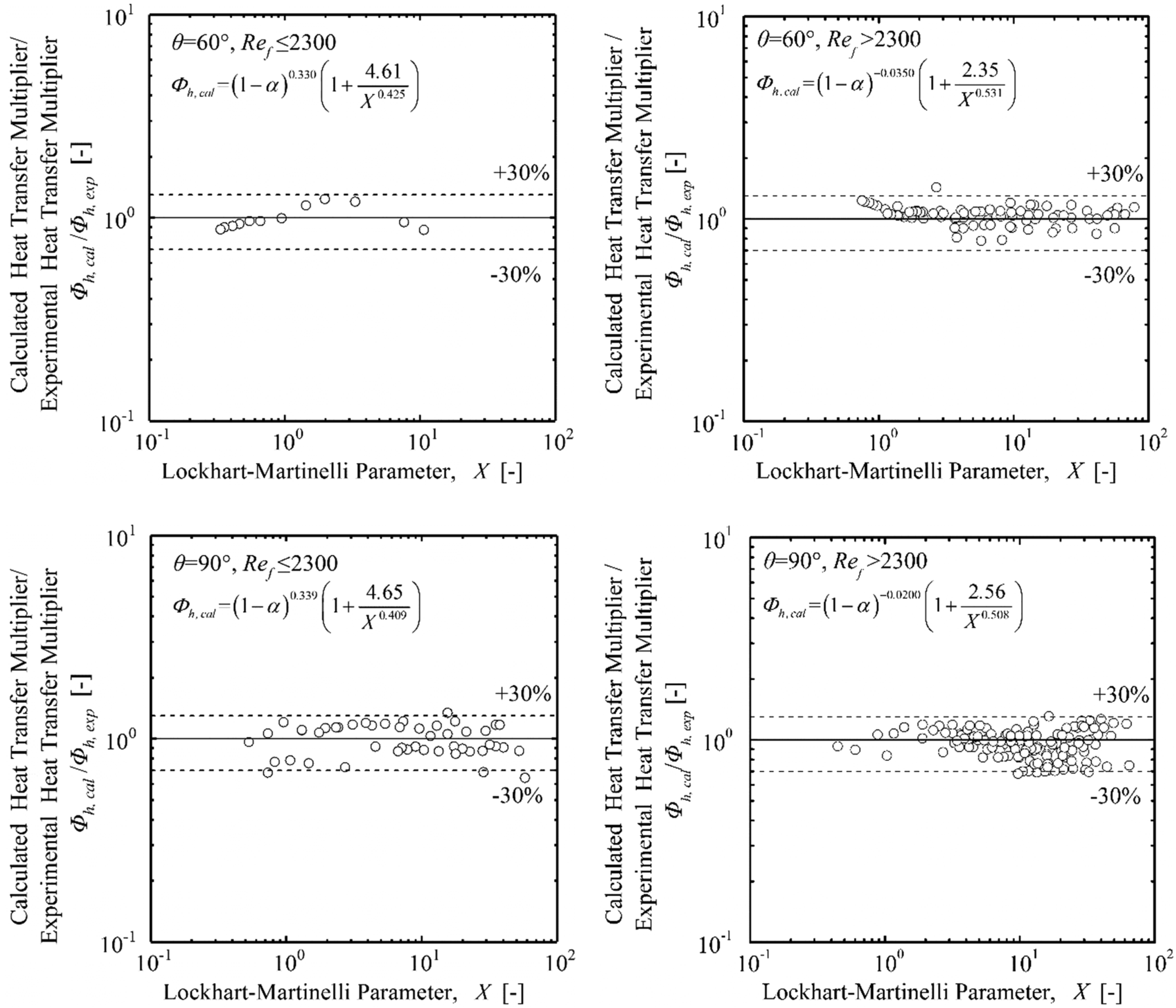

Fig. 5. (*continued*)

base of the model development.

3.3. Development of two-phase heat transfer multiplier correlation for upward two-phase flow in inclined pipes

In the authors' previous investigation, Dong and Hibiki [33,34] have developed the two-phase heat transfer multiplier correlations for no-phase-change two-phase flows in horizontal and vertical pipes based on theoretical analysis and a large experimental database. The correlations are summarized as follows.

Horizontal pipes:

$$\Phi_h = (1-\alpha)^{-0.194}\left(1+\frac{0.687}{\mathrm{X}^{0.700}}\right) \quad \text{for turbulent flow} \tag{33}$$

$$\Phi_h = (1-\alpha)^{0.257}\left(1+\frac{4.27}{\mathrm{X}^{0.697}}\right) \quad \text{for laminar flow} \tag{34}$$

Vertical pipes:

$$\Phi_h = (1-\alpha)^{-0.0200}\left(1+\frac{2.56}{\mathrm{X}^{0.508}}\right) \quad \textit{for turbulent flow} \tag{35}$$

$$\Phi_h = (1-\alpha)^{0.339}\left(1+\frac{4.65}{X^{0.400}}\right) \quad \textit{for laminar flow} \tag{36}$$

As indicated in Eq. (29), three parameters, a, b and A, need to be identified to develop a new two-phase heat transfer multiplier correlation for upward two-phase flow in inclined pipes, and the effect of pipe orientation on these parameters should be examined. The values of a, b and A are identified based on the experimental two-phase heat transfer multiplier of upward two-phase flow in inclined pipes. According to the authors' previous research [33,34,38], Gnielinski [39] correlation ($Re_f > 2300$) and Sieder-Tate [40] correlation ($Re_f \leqslant 2300$), are adopted to calculate the single-phase heat transfer coefficient for turbulent and laminar flows, respectively, and are also used in this study. The effect on thermal entrance region on the averaged heat transfer performance is considered by the introduction of D/L in the correlations.

For laminar flow ($Re_f \leqslant 2300$)

$$Nu_{1\Phi} = 1.86\left(Re_f Pr_f \frac{D}{L}\right)^{1/3}\left(\frac{\mu_B}{\mu_W}\right)^{0.14} \tag{37}$$

For Turbulent flow ($Re_f > 2300$)

$$Nu_{1\Phi} = \frac{(f_D/8)(Re_f-1000)Pr_f}{1+12.7\sqrt{f_D/8}\,(Pr_f^{2/3}-1)}\left[1+\left(\frac{D}{L}\right)^{2/3}\right] \tag{38}$$

where f_D is Darcy friction factor, calculated by Eq. (39). Darcy friction factor, f_D, is four times of Fanning friction factor, f_F, namely, $f_D = 4f_F$ [41].

$$f_D = (1.82\log_{10} Re_f - 1.64)^{-2} \tag{39}$$

Fig. 5 presents the comparison between the calculated and experimental heat transfer multipliers in pipes with different inclination angles. The pipe inclination changes from 0° in horizontal orientation to 90° in upward vertical orientation. Each figure in Fig. 5 includes a tentative correlation with three parameters determined by the data taken at the specific inclination angle. The comparison between the calculated and experimental heat transfer multipliers indicate that most of the predicted values fell within ± 30% of the experimental values. The values of the parameters, a, b and A in Eq. (29) for upward two-phase flow in inclined pipes have been experimentally identified based on the collected database. In the next step, functional forms are to be identified to correlate the parameters, a, b and A with the inclination angle.

As the pipe inclination angles increase from 0° to 90°, the parameter of a increases from 0.257 to 0.339 for laminar flow and from −0.194 to −0.02 for turbulent flow, while the parameter of b decreases from 0.697 to 0.406 for laminar flow and from 0.700 to 0.508 for turbulent flow. The parameter of a is relatively small, and the change on the inclination angle is insignificant. The change of the parameter, b, on $\sin\theta$ is approximately linear. To simplify the development process of the new correlation, linear assumptions of the parameter of a and b on $\sin\theta$ are adopted. The linear functions are determined so that the values of the parameters, a and b, agree with the values for horizontal and vertical flows at$\theta = 0°$ and 90°, respectively. The parameter of A is determined by the collected experimental data and the calculated values of a and b in different inclined pipes. Any modeling errors of a and b are compensated in determining the parameter of A. Fig. 6 presents the dependence of A on the pipe inclination angles. It is clearly observed that the parameter of A increases monotonously with the pipe inclination angles. However, the increasing gradient is different and the turning points occurs at $\theta = 20^o$ ($\sin\theta = 0.34$). Two linear correlations of A are developed based on the collected database. The expressions of the new correlations are given as follows.

For laminar flow ($Re_f \leqslant 2300$)

$$a = 0.257 + 0.0820\sin\theta \tag{39}$$

$$b = 0.697 - 0.288\sin\theta \tag{40}$$

$$A = 4.27 + 0.757\sin\theta \quad (\theta < 20^o) \tag{41}$$

$$A = 4.46 + 0.186\sin\theta \quad (\theta \geqslant 20^o) \tag{42}$$

For turbulent flow ($Re_f > 2300$)

$$a = -0.194 + 0.174\sin\theta \tag{43}$$

$$b = 0.700 - 0.192\sin\theta \tag{44}$$

$$A = 0.687 + 3.34\sin\theta \quad (\theta < 20^o) \tag{45}$$

$$A = 1.45 + 1.11\sin\theta \quad (\theta \geqslant 20^o) \tag{46}$$

Finally, the explicit form of the two-phase heat transfer multiplier correlation for upward gas-liquid two-phase flow in inclined pipes is given as follows.

For laminar flow ($Re_f \leqslant 2300$)

$\theta < 20^o$

$$\Phi_h = (1-\alpha)^{0.257+0.0820\sin\theta}\left(1 + \frac{4.27 + 0.757\sin\theta}{X^{0.697-0.288\sin\theta}}\right) \tag{47}$$

$\theta \geqslant 20^o$

$$\Phi_h = (1-\alpha)^{0.257+0.082\sin\theta}\left(1 + \frac{4.46 + 0.186\sin\theta}{X^{0.697-0.288\sin\theta}}\right) \tag{48}$$

For Turbulent flow ($Re_f > 2300$)

$\theta < 20^o$

$$\Phi_h = (1-\alpha)^{-0.194+0.174 sin\theta}\left(1 + \frac{0.687 + 3.34\sin\theta}{X^{0.700-0.192 sin\theta}}\right) \tag{49}$$

$\theta \geqslant 20^o$

$$\Phi_h = (1-\alpha)^{-0.194+0.174 sin\theta}\left(1 + \frac{1.45 + 1.11\sin\theta}{X^{0.700-0.192 sin\theta}}\right) \tag{50}$$

where void fraction of upward no-phase-change two-phase flow for inclined pipes can be calculated by Dong-Hibiki [42] correlation. The Dong-Hibiki [42] correlation is explained in Appendix. Beggs and Brill [43] and Bhagwat and Ghajar [20] found that the void fraction of upward two-phase flow in inclined pipes between 0° and 20° decreased with the pipe inclinations while it varied little in inclined pipes between 20° and 90°, further validating the newly-developed two-phase heat transfer multiplier correlation, in which the turning point of A occurred at 20°.

Simple linear correlations for the exponents of a, b and A are used in the new correlation to express the effect of pipe inclination on upward no-phase-change two-phase heat transfer coefficients. When $\theta = 0^o$ (horizontal flow), Eqs. (47) and (49) are reduced to Dong and Hibiki [33] correlation for horizontal flow, while when $\theta = 90^o$ (vertical flow), Eqs. (48) and (50) are reduced to Dong and Hibiki [34] correlation for vertical flow. Therefore, the newly-developed two-phase heat transfer multiplier correlation achieves built-in accordance with the previous correlations.

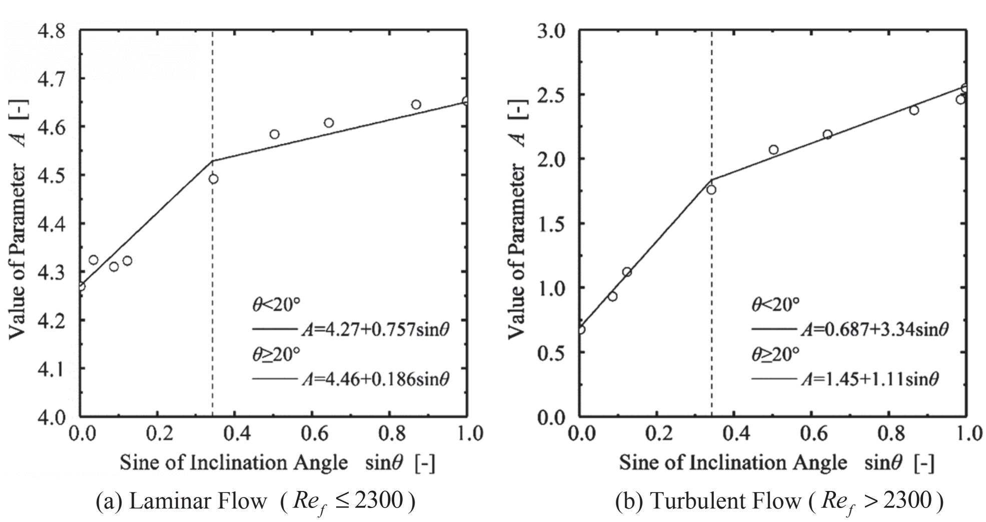

Fig. 6. Dependence of parameter, A, on pipe inclination angles.

4. Performance evaluation of the newly-developed two-phase heat transfer coefficient correlation for upward two-phase flow in inclined pipes

As discussed above, the two-phase heat transfer multiplier correlation for upward no-phase-change two-phase flow in inclined pipes has been developed. This section assesses the predictive capability of the newly-developed correlation. Fig. 7 presents the comparison between the experimental and calculated two-phase heat transfer multipliers. The left and right figures in Fig. 7 represent the comparisons for laminar flow ($Re_f \leqslant 2300$) and turbulent flow ($Re_f > 2300$) conditions, respectively. The comparison results indicate that the newly-developed correlations demonstrate excellent agreement with the collected database. The calculated two-phase heat transfer multipliers fall evenly around the experimental values.

Table 4 tabulates the quantitative performance evaluation of the newly-developed multiplier correlations for upward no-phase-change two-phase heat transfer in inclined pipes. The comparison results indicate that more than 95% of the two-phase heat transfer multiplier are predicted within ± 30% of the experimental values with the mean relative deviation, m_{rel}, of -0.206% and the mean absolute relative deviation, $m_{rel,\ ab}$, of 12.9%. Besides, the newly-developed correlations do not show any systematic deviations within the collected data.

In the transition region between laminar and turbulent flows (tentatively set as $2000 \leqslant Re_f \leqslant 2300$), the following interpolation function is tentatively proposed.

$$\Phi_h = \Phi_{h,\ laminar}(1-\omega) + \Phi_{h,\ turbulent}\,\omega \tag{51}$$

where the weighting function, ω, is given by

$$\omega \equiv \frac{\log_{10} Re_f - \log_{10} 2000}{\log_{10} 2300 - \log_{10} 2000} \tag{52}$$

Fig. 8 presents the comparison between the newly-developed upward no-phase-change two-phase heat transfer multiplier correlation with experimental data in a pipe with different inclination. In this comparison, the experimental data by Bhagwat and Ghajar [20] were used. The superficial liquid velocity, j_f, is 0.45 m/s and the superficial gas velocity, j_g, is 7.3 m/s. The pipe inclination angles range from 0° to 90°. The open symbols represent the experimental two-phase heat transfer multipliers, while the solid line represents the calculated two-phase heat transfer multiplier. The two-phase heat transfer multiplier increases with the increased inclination angle. The comparison results indicate that the newly-developed correlation agrees with the experimental data well.

In summary, the newly-developed correlation demonstrates superior predictive performance in upward no-phase-change two-phase heat transfer multiplier to existing correlations. The newly-developed correlation is validated by air-water flow, and its applicablerange is $3.07\times10^2 \leqslant Re_f \leqslant 8.90\times10^4$, $2.50\times10^1 \leqslant Re_g \leqslant 6.40\times10^4$, $12.5\ \text{mm} \leqslant D \leqslant 49.2\ \text{mm}$. When $\theta = 0^o$ (horizontal flow), the newly-developed correlation is reduced to Dong and Hibiki [33] correlation for horizontal flow, while when $\theta = 90^o$ (vertical flow), the newly-developed correlation is reduced to Dong and Hibiki [34] correlation for vertical flow. Dong and Hibiki [33] correlation for horizontal flow was validated by air-water and air-oil flow, and its applicable range is $2.00\times10^2 \leqslant Re_f \leqslant 1.8\times10^5$, $2.70\times10^2 \leqslant Re_g \leqslant 9.10\times10^4$ and$8.0\ \text{mm} \leqslant D \leqslant 51.5\ \text{mm}$. Dong and Hibiki [34] correlation for vertical flow was validated by air-water, air-oil, air-glycerine, Freon-water and helium-water flow, and its applicable range is

Table 4
Performance evaluation of newly-developed two-phase heat transfer multiplier correlations for upward two-phase flow in inclined pipes.

Statistical parameters	m_d [–]	s_d [–]	m_{rel} [%]	$m_{rel,\ ab}$ [%]
$Re_f \leqslant 2300$	−0.154	0.693	−5.01	15.8
$Re_f > 2300$	0.0331	0.273	1.22	12.1
Overall	−0.00965	0.416	−0.206	12.9

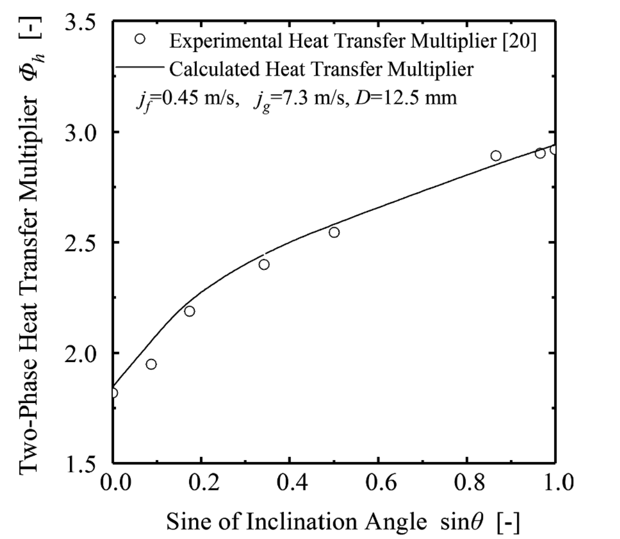

Fig. 8. Comparison between the calculated two-phase heat transfer multiplier by the newly-developed correlation and the experimental data taken by Bhagwat and Ghajar [20].

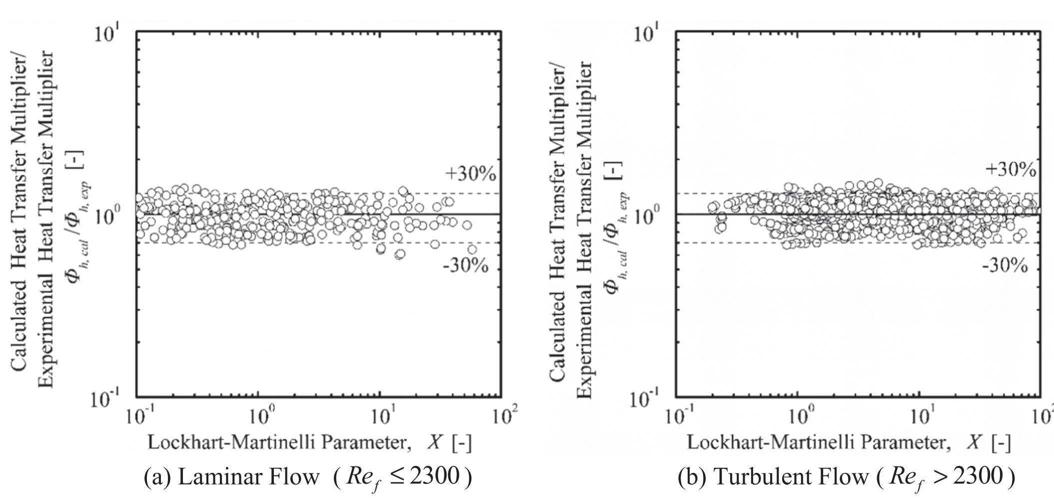

Fig. 7. Predictive capability of the newly-developed two-phase heat transfer multiplier correlation for upward two-phase flow in inclined pipes.

$2.56 \times 10^2 \leqslant Re_f \leqslant 9.05 \times 10^4$, $6.30 \times 10^1 \leqslant Re_g \leqslant 3.90 \times 10^4$, $11.7\ mm \leqslant D \leqslant 70.0\ mm$. The applicable ranges of the correlations for vertical and horizontal flows are wider than the applicable range of the newly-developed correlation. As the newly-developed heat transfer multiplier correlation may be viewed as the interpolation of Dong and Hibiki [33,34] correlations for horizontal and vertical flows, the newly-developed correlation may be extendedly used under the applicable conditions of horizontal and vertical correlations, but further validation work is necessary.

5. Conclusions

In this study, a robust and theoretically-supported two-phase heat transfer multiplier correlation for upward no-phase-change two-phase flow in inclined pipes is developed based on extended Chilton-Colburn analogy. The newly-developed two-phase heat transfer multiplier correlation would be useful to accurately predict the heat transfer coefficient of the no-phase-change two-phase heat transfer systems with inclined pipes, such as petroleum pipelines and nuclear power plants. The major achievements in this study are summarized as follows.

1. An extensive literature survey identified more than 1800 experimental data of heat transfer coefficient for upward two-phase flow in various flow regimes in inclined pipes and 12 heat transfer coefficient correlations including 3 correlations from horizontal pipes, 8 correlations from vertical pipes and 1 correlation from inclined pipes.
2. The comparison between the experimental and calculated two-phase heat transfer multipliers indicated that none of the existing correlations could predict the whole database with acceptable accuracy.
3. A concept of "two-phase heat transfer multiplier" defined by the ratio of two-phase Nusselt number to single-phase Nusselt number was proposed to describe the two-phase heat transfer characteristics. The dependence of two-phase heat transfer multiplier on void fraction and two-phase multiplier was analytically deduced from extended Chilton-Colburn analogy to two-phase flow. A new two-phase heat transfer multiplier correlation for upward no-phase-change two-phase flow in inclined pipes was developed based on the analytical formula and 1800 collected two-phase heat transfer data.
4. The newly-developed upward no-phase-change two-phase heat transfer multiplier correlation could predict more than 95% of the two-phase heat transfer multiplier within ± 30% of the experimental values with the mean relative deviation, m_{rel}, of -0.206% and the mean absolute relative deviation, $m_{rel,\ ab}$, of 12.9%. Its applicable range is $3.07 \times 10^2 \leqslant Re_f \leqslant 8.90 \times 10^4$, $2.50 \times 10^1 \leqslant Re_g \leqslant 6.40 \times 10^4$, $12.5\ mm \leqslant D \leqslant 49.2\ mm$.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

As void fraction plays an important role in predicting two-phase heat transfer multiplier, the accurate prediction of void fraction is critical to the determination of two-phase heat transfer multiplier. Dong and Hibiki [42] have developed a drift-flux correlation for upward two-phase flow in inclined pipes. The effect of inclination angle on drift-flux parameters, C_0 and V_{gj}, is formulated in Dong and Hibiki [42] correlation. According to Zuber and Findley [44], the expression of the one-dimensional drift-flux model is given as follows.

$$\alpha = \frac{j_g}{C_0(j_g + j_f) + V_{gj}} \tag{A1}$$

where C_0 is the distribution parameter characterizing the phase distribution. V_{gj} is the drift velocity characterizing the relative motion between two phases. The drift-flux correlation for upward two-phase flow in inclined pipes is given as follows [42].

For $0 \leqslant j_g^+/j^+ < 0.9$

$$C_\infty = (0.400 \sin\theta + 0.800)\exp\left[\log_e\left(\frac{1.80 - 0.700\sin\theta}{0.400\sin\theta + 0.800}\right)\left(\frac{j_g^+/j^+}{0.900}\right)^{1.5}\right] \tag{A2}$$

For $0.9 \leqslant j_g^+/j^+ \leqslant 1$

$$C_\infty = (-8.00 + 7.00\sin\theta)\frac{j_g^+}{j^+} + 9.0 - 7.00\sin\theta \tag{A3}$$

where C_∞ is the asymptotic value of the distribution parameter at the density ratio of zero. The distribution parameter is given as follows.

$$C_0 = C_\infty - (C_\infty - 1)\sqrt{\frac{\rho_g}{\rho_f}} \tag{A4}$$

The drift velocity, V_{gj}, for upward two-phase flow in inclined pipes is given as follows.

For $0 \leqslant j_g^+/j^+ < 0.9$

$$v_{gj} = \sqrt{2}\left(\frac{\Delta\rho g \sin\theta\sigma}{\rho_f^2}\right)^{1/4} \tag{A5}$$

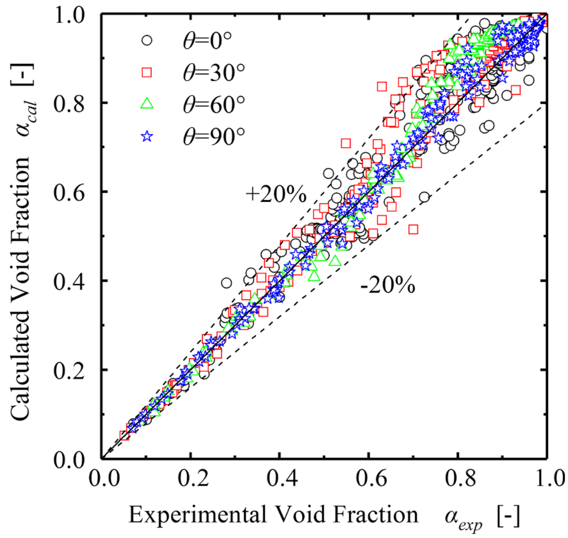

Fig. A1. Comparison between the experimental and calculated void fraction by Dong and Hibiki [40] correlation.

For $0.9 \leqslant j_g^+/j^+ \leqslant 1$

$$v_{gj} = \sqrt{2}\left(\frac{\Delta\rho g \sin\theta\sigma}{\rho_f^2}\right)^{1/4}\left(\frac{1-j_g^+/j^+}{0.1}\right) \tag{A6}$$

Fig. A1 presents the comparison between experimental and calculated void fractions by Dong and Hibiki [42] correlation for upward two-phase flow in inclined pipes. The comparison results indicate that more than 95% of the experimental void fraction could be predicted within ± 20% error. The mean relative deviation, m_{rel}, is 3.52% and the mean absolute relative deviation, $m_{rel,\ ab}$, is 5.62%. Dong and Hibiki [42] correlation is adopted in this study to predict the void fraction of upward two-phase flow in inclined pipes.

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