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A Mechanistic Approach for Heat Transfer Estimation in Horizontal and Vertical Non-Boiling Two-Phase Pipe Flow

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A mechanistic model is proposed to estimate heat transfer coefficient for non-boiling two-phase flow in horizontal and vertical pipes using analogy between friction factor and heat transfer. The proposed mechanistic correlation is validated by using experimentally measured heat transfer data. Evaluation of the mechanistic correlation with the measured heat transfer data indicated that the analogy between friction factor and heat transfer can be used with reasonable accuracy for heat transfer prediction in non-boiling two-phase pipe flow. Comparison with experimental results showed that the bulk of the data points were predicted within ±30% by the mechanistic model.

1. Introduction

In industrial applications such as the flow of oil and natural gas in flow lines and wellbores, the knowledge of non-boiling two-phase, two-component (liquid and permanent gas) heat transfer is required. During the production of two-phase hydrocarbon fluids from an oil reservoir to the surface, temperature of the hydrocarbon fluids changes due to the difference in temperatures of the oil reservoir and the surface. The change in temperature results in heat transfer between the hydrocarbon fluids and the earth surrounding the oil well, and the ability to estimate the flowing temperature profile is necessary to address several design problems in petroleum production engineering (Shiu and Beggs, 1980).

The hydrodynamic and thermal conditions of non-boiling two-phase flow are dependent upon the interaction between the two phases. Due to the complex nature of the two-phase gas-liquid flow, the accessible heat transfer data and applicable correlations for non-boiling two-phase flow are extremely limited in the literature. In most situations encountered by practicing engineers, direct heat transfer measurements for two-phase flow are extremely difficult to perform. It is in such respect that mechanistic models for heat transfer estimation using, for example, analogy between friction factor and heat transfer can have appealing prospect.

The concept of developing two-phase heat transfer correlation based on the analogy of momentum and heat transfer has been explored by a few researchers (Fried, 1954; Vijay et al., 1982; Kaminsky, 1999). However, there are still many unanswered questions concerning the viability and robustness of a two-phase heat transfer correlation developed based on the analogy of momentum and heat transfer. It is the goal of this study to explore the plausibility of using the Reynolds analogy to develop a mechanistic correlation to predict heat transfer coefficients for non-boiling two-phase flow in pipes.

2. Development of Correlation

The development of a correlation to analogize momentum and heat transfer in non-boiling two-phase pipe flow begins with the Reynolds analogy. The Reynolds analogy relates important parameters of momentum and thermal boundary layers in a simplistic form in terms of friction coefficient (c_f), Nusselt number (Nu), Prandtl number (Pr), and Reynolds number (Re):

$$c_f/2 = \mathrm{Nu}\,\mathrm{Re}^{-1}\,\mathrm{Pr}^{-1} \tag{1}$$

For flow inside pipes, the frictional pressure gradient is given as

$$\left(-\frac{dp}{dz}\right)_f = \frac{4\tau_0}{D} = \frac{2c_f}{D\rho}\left(\frac{\dot{m}}{A}\right)^2 \tag{2}$$

Combining both Eq. (1) and Eq. (2) yields the expression relating the heat transfer coefficient with the frictional pressure gradient:

$$\mathrm{Nu} = \frac{D\rho A^2}{4\dot{m}^2}\left(-\frac{dp}{dz}\right)_f \mathrm{Re}\,\mathrm{Pr} \tag{3}$$

Using the definitions for Nusselt number (Nu), Prandtl number (Pr), and Reynolds number (Re), Eq. (3) can be expressed in terms of the heat transfer coefficient (h) with the following expression:

$$h = \frac{\rho c}{\dot{m}}\left(-\frac{dp}{dz}\right)_f \frac{A^2}{\pi D} \tag{4}$$

Adopting Eq. (4) for the use in non-boiling two-phase pipe flow, the ratio of the heat transfer coefficient for the two-phase flow (h_{TP}) to the heat transfer coefficient for liquid single-phase flow (h_L) becomes

$$\frac{h_{TP}}{h_L} = \frac{c_{TP}}{c_L}\frac{\dot{m}_L}{\dot{m}}\frac{\rho_{TP}}{\rho_L}\frac{(dp/dz)_{f,TP}}{(dp/dz)_{f,L}} = \frac{c_{TP}}{c_L}\frac{\dot{m}_L}{\dot{m}}\frac{\rho_{TP}}{\rho_L}\phi_L^2 \tag{5}$$

Note that the frictional pressure gradient ratio for the two-phase flow to the liquid single-phase flow is recognized as the pressure drop multiplier (ϕ_L^2) defined by Lockhart & Martinelli (1949). In this study, the values for the two-phase frictional pressure gradient, $(dp/dz)_{f,TP}$, are determined via experimental measurements, while the single-phase liquid frictional pressure gradients, $(dp/dz)_{f,L}$, are calculated using Eq. (2) with $c_f = 16/Re_{SL}$ for $Re_{SL} < 2000$, and the Blasius equation, $c_f = 0.079/Re_{SL}^{0.25}$, for $Re_{SL} > 2000$. Introducing a constant as a leading coefficient (C) for the ratio of two-phase to single-phase specific heats (c_{TP}/c_L), and exponents (m, n, and p) into Eq. (5), the mechanistic heat transfer correlation takes on the following expression:

$$\frac{h_{TP}}{h_L} = C\left(\frac{\dot{m}_L}{\dot{m}}\right)^m \left(\frac{\rho_{TP}}{\rho_L}\right)^n \phi_L^p \tag{6}$$

The mass flow rate ($\dot{m}$) in Eq. (6) is the sum of the gas phase ($\dot{m}_G$) and liquid phase ($\dot{m}_L$) mass flow rates. The two-phase density (ρ_{TP}) is defined as the mass of two-phase fluids per unit volume of the pipe and can be determined using

$$\rho_{TP} = \alpha\rho_G + (1-\alpha)\rho_L \tag{7}$$

The void fraction (α) needed to calculate the two-phase density in Eq. (7) is measured experimentally or estimated using void correlations recommended by Woldesemayat and Ghajar (2007). The single-phase liquid heat transfer coefficient (h_L) is calculated using the Sieder and Tate (1936) correlation.

3. Experimental Setup

The test section, with air and distilled water as working fluids, is a 27.9 mm I.D. straight stainless steel pipe with length to diameter ratio of 95. A schematic of the overall experimental setup is shown in Figure 1. The uniform wall heat flux boundary condition is maintained by a Lincoln SA-750 welder for $Re_{SL} > 2000$ and a Miller Maxtron 450 DC welder for $Re_{SL} < 2000$. The water and air flow rates are measured by Micro Motion Coriolis flow meters, models CMF100 and CMF025, respectively. T-type thermocouple wires were cemented with Omegabond 101 on the outside wall of the stainless steel test section. The inlet and exit temperatures are measured by Omega TMQSS-125U-6 thermocouple probes. Calibration of thermocouples and thermocouple probes showed accuracies within ±0.5°C. Validyne model DP15 pressure transducer with a series of interchangeable diaphragms (full scale accuracy of ±0.25%) is used to measure pressure drop. Careful attention is given to ensure that the range of the diaphragm used is conducive to the pressure being measured. The peripheral heat transfer coefficient (local average) was calculated using a data reduction program developed by Ghajar and Kim (2006). The reliability of the experimental setup and procedures was checked and validated by making several single-phase validation runs with distilled water (Kim and Ghajar, 2002). The uncertainty analysis of the overall experimental procedures using the method of Kline and McClintock (1953) showed that there is a maximum of 11.5% uncertainty for heat transfer coefficient and 3.5% for pressure drop. Detail discussions on non-boiling two-phase heat transfer experimental data measured from this experimental setup are documented by Ghajar and Tang (2007).

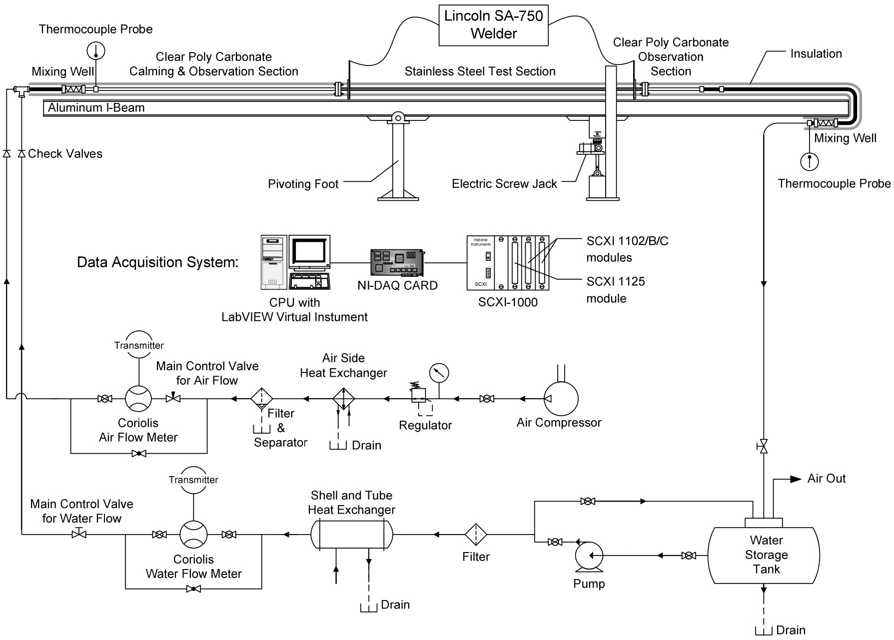

Figure 1. Schematic of experimental setup

4. Validation of Correlation with Experimental Data

Heat transfer experimental data for non-boiling two-phase flow in horizontal and vertical pipes were used for comparison with the correlation. Experimental data points for horizontal pipe were measured from the experimental setup described in previous section, and data points for vertical pipe were measured by Sujumnong (1998). Table 1 summarizes the experimental data points used in the validation of the mechanistic correlation, Eq. (6). The experimental database consists of 233 data points with different gas-liquid combinations and wide ranges of superficial gas and liquid Reynolds numbers, and liquid Prandlt number. When compared with the experimental data points, the predictions by the correlation, Eq. (6), are satisfactory. Overall, the correlation successfully predicted 85% of the 233 experimental data points within ±30% agreement.

Table 1. Summary of experimental data used in the validation of the correlation

Data set	No. of data points	Pipe orientation	Re_{SL}	Re_{SG}	Pr_L
Air-water	98	Horizontal	1900 to 26000	600 to 47000	6.3 to 7.7
Air-water†	63	Vertical	1500 to 107000	20 to 150000	6.0 to 7.4
Air-glycerin(59%) /water (41%)†	49	Vertical	70 to 8300	40 to 59000	72 to 96
Air-glycerin(82%) /water(18%)†	23	Vertical	50 to 600	40 to 23000	800 to 920

† Sujumnong (1998)

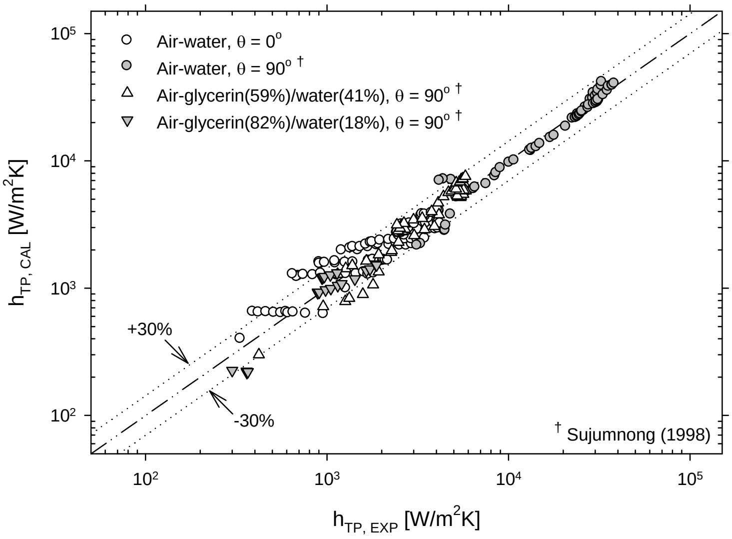

Figure 2. Comparison of predictions by Eq. (6) and experimental two-phase heat transfer coefficients

The predicted data points have an average error range of −15% to 29%, and an average absolute error of 22%. The leading coefficient and exponents used in Eq. (6) for this validation are C = m =1, n = −0.1, and p = 0.2. Figure 2 shows the comparison of the calculated h_{TP} values from the mechanistic correlation, Eq. (6), with experimental data for non-boiling two-phase flow in horizontal and vertical pipes. The results illustrated in Figure 2 show that the mechanistic correlation, Eq. (6), performed quite satisfactory, thus prompting further investigations are necessary to determine the viability and robustness of the two-phase mechanistic heat transfer correlation, Eq. (6).

5. Conclusions

A mechanistic correlation for non-boiling two-phase flow in horizontal and vertical pipes was developed based on Reynolds analogy. The mechanistic correlation is validated with experimental data. The comparison of the experimental data and predictions of the mechanistic correlation is quite satisfactory. The results from this study prompt the need for further investigations on whether the mechanistic correlation has the robustness for application in various gas-liquid combinations, pipe diameters, system pressures, and pipe inclinations.

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Nomenclature

A	cross section area, m^2
C	constant value leading coefficient
c	specific heat, J/(kg K)
c_f	Fanning friction coefficient
D	pipe diameter, m
dp/dz	pressure gradient, Pa/m
h	heat transfer coefficient, $W/(m^2\,K)$
k	thermal conductivity, W/(m K)
$\dot{m}$	mass flow rate, kg/s
Nu	Nusselt number, hD/k
Pr	Prandtl number, $\mu c/k$
Re	Reynolds number, $4\dot{m}/(\pi D\mu)$

Greek symbols

α	void fraction
ϕ	pressure drop multiplier
θ	pipe inclination angle, deg.
μ	dynamic viscosity, kg/(m s)
ρ	density, kg/m^3
τ_0	wall shear stress, N/m^2

Subscripts and superscripts

CAL	calculated
EXP	experimental
f	frictional
G	gas phase
L	liquid phase
SG	superficial gas
SL	superficial liquid
TP	two-phase
m, n, p	constant value exponents