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Research Paper

Heat transfer correlation for two-component two-phase slug flow in horizontal pipes

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HIGHLIGHTS

- Heat transfer correlations and database for horizontal flows were reviewed extensively.
- None of existing correlations predicted all horizontal flow databases satisfactorily.
- The dependence of heat transfer coefficient on pressure drop was derived analytically.
- A semi-theoretical heat transfer correlation for horizontal flow was developed.

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Heat transfer coefficient
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ABSTRACT

Two-component gas-liquid two-phase slug flow in horizontal pipes occurs frequently in many industrial applications. The flow and heat transfer characteristics are complicated due to the intermittent flow structures. In view of the importance of predicting the heat transfer characteristics of the slug flow, this present study aims at developing a semi-theoretical heat transfer correlation for two-component two-phase slug flow based on the concept of Reynolds and Chilton-Colburn analogies. Firstly, an extensive literature review on existing databases and correlations of heat transfer coefficient for two-component two-phase slug flow was conducted. More than 500 experimental data and 8 heat transfer correlations were collected. The comparison between collected database and correlations indicated that none of the correlations could estimate the whole database satisfactorily. The relationship between heat transfer and pressure drop was investigated theoretically and an improved semi-theoretical heat transfer correlation was developed based on Reynolds and Chilton-Colburn analogies and the collected experimental results from 16 sources. The comparison analysis demonstrated that the newly-developed correlation achieved an excellent predictive capability with a wide range of test conditions. The newly developed correlation demonstrated that 91.5% of the data was predicted within ± 30% error with the mean absolute relative deviation of 14.0%. In addition, the extension of the new correlation to other horizontal two-phase flow regimes was discussed. The newly-developed semi-theoretical correlation would be useful for predicting heat transfer coefficient of two-component two-phase flow in horizontal pipes.

1. Introduction

Gas-liquid two-phase slug flow in horizontal pipes commonly occurs in many industrial applications such as nuclear power plants, petroleum pipelines, and chemical reactors, etc. The flow characteristics of two-phase slug flow are complicated due to the intermittent passage of elongated bubbles and liquid slug bodies [1] as depicted in Fig. 1. The heat transfer of two-phase slug flow in horizontal pipes is crucial, especially in offshore petroleum pipelines. The mixture of oil and gas from the reservoir could be as hot as 75 °C, while the surrounding seawater at the seabed could be as cold as 4 °C [2]. The huge temperature difference could cause a large amount of heat loss from the hot fluids to the surroundings. Consequently, gas hydrate or wax deposition may be formed inside the pipe due to the temperature decrease of oil and gas mixtures, which could reduce the effective flow area and even lead to blockage of petroleum pipelines [3,4]. Therefore, it is indispensable to investigate the heat transfer characteristics of two-component two-phase slug flow in horizontal pipes and to develop a reliable correlation to predict the heat transfer coefficient accurately.

Studies on heat transfer of two-component two-phase slug flow have continued for decades and several empirical heat transfer correlations were proposed based on experimental results. Fried [5] studied the flow

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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	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 difference [–]
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 [–]
s_d	standard deviation [–]
T	temperature [K]
v	velocity m/s
x	quality [–]
X	Lockhart-Martinelli parameter [–]
y	direction perpendicular to a wall [–]
z	axial direction [–]

Greek symbols

α	void fraction [–]
μ	dynamic viscosity [Pa·s]
ρ	density [kg/m^3]
τ	shear stress [Pa]
Φ_f^2	two-phase multiplier [–]

Subscripts

B	bulk [–]
cal	calculated [–]
exp	experimental [–]
f,1ϕ	liquid [–]
F	friction [–]
g	gas [–]
m	gas-liquid mixture [–]
2ϕ	gas-liquid two-phase [–]
W, w	wall [–]

Superscript

*	non-dimensional [–]

and heat transfer characteristics of air-oil two-phase flow in a horizontal pipe and plot the relationship between heat transfer enhancement ratio and pressure drop multiplier. Johnson [6] conducted an experimental study on air-oil two-phase flow, and the experimental results indicated that the heat transfer coefficient decreased as the pressure increased. Johnson [6] claimed that the trend was attributed to the higher liquid holdup and lower liquid velocity under high system pressure. Hetsroni et al. [7] measured local temperature field of two-phase slug flow in a horizontal pipe and analyzed the effect of Taylor bubble length and frequency on local heat transfer coefficient. Wang [8] carried out both experimental and theoretical study on heat transfer and hydrodynamic characteristics of air-water and air-oil two-phase flow in horizontal pipes. Ghajar and Tang [9] experimentally studied non-boiling two-phase heat transfer mechanism in horizontal and slightly inclined pipes and analyzed the effect of inclined angles on heat transfer coefficient. Wang et al. [10] performed a comprehensive investigation of air-water and air-oil two-phase slug flow in horizontal pipes and analyzed the effect of flow parameters such as flow rates, slug frequency and Taylor bubble length on heat transfer coefficient. Gao et al. [11] designed an experimental study on heat transfer of two-phase gas-oil flow and the experimental results indicated that the heat transfer coefficients of slug flow fluctuated largely and decreased as the gas volume fraction increased.

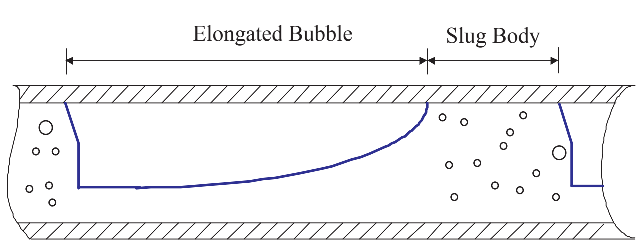

Fig. 1. Schematic of slug flow in a horizontal pipe.

The heat transfer enhancement mechanism of two-phase slug flow was explained by several theories. Martin and Sims [12] and Shah [13] claimed that the heat transfer enhancement was attributed to the increase of mean mixture velocity defined as the sum of single-phase liquid and gas velocities based on separated flow model. Based on this hypothesis, they proposed the ratio of superficial gas velocity to superficial liquid velocity as a key parameter in two-phase heat transfer correlations. Hughmark [14] argued that the introduction of gas into liquid accelerated liquid phase and the heat transfer coefficient of two-phase flow was assumed to be equal to that of the single-liquid flow at the actual velocity. Based on this assumption, the liquid holdup was introduced in the correlation to account for the actual velocity. In addition, Fried [5] and Kalapatapu [15] developed correlations of two-phase heat transfer enhancement ratio using pressure drop multiplier, Φ_f^2. The numerical models for heat transfer of two-phase slug flow were also studied by several researchers. Niu and Dukler [16] developed an algorithm to predict the temperature distribution along the pipe rim. Zhang et al. [17] developed a unified model of the convective heat transfer coefficient for gas-liquid two-phase flow. Bassani et al. [18] proposed a mechanistic model to estimate the scooping phenomenon for the heat transfer of slug flow. However, most of the heat transfer correlations were developed based on the researchers' own data and the applicability of these correlations is limited. In view of this, it is desirable to develop a new heat transfer correlation of two-component two-phase slug flow with a wide range of test conditions.

The purpose of this study is to develop an improved heat transfer correlation of two-component two-phase slug flow in horizontal pipes with a wide range of test conditions. Firstly, more than 500 experimental data of two-component two-phase slug flow in horizontal pipes with different fluids, pipe diameters, heating/cooling methods and flowing conditions were collected from 16 sources. Secondly, the existing two-phase heat transfer correlations for horizontal pipes were collected. Thirdly, the comprehensive comparison of the existing correlations and collected data was conducted. Lastly, the relationship