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Correlations of void fraction for two-phase refrigerant flow in pipes

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HIGHLIGHTS

- Correlations of void fraction for two-phase flow are reviewed.
- Survey of experimental data of void fraction for two-phase refrigerant flow is conducted.
- Applicability of the existing void fraction correlations to two-phase refrigerant flow is assessed.
- A new void fraction correlation for two-phase refrigerant flow in pipes is proposed.

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ABSTRACT

The calculation of void fraction for two-phase refrigerant flow in pipes is required in many fields. Although numerous void fraction correlations have been proposed and lots of related assessments have been conducted for the past six decades, almost all of them were on the basis of data gained from two-phase flow experiments on air–water or steam–water, whose applicability to two-phase refrigerant flow needs to be evaluated. In this paper, a state-of-the-art survey of correlations and experimental investigations is conducted. There are 41 correlations reviewed, and 1574 experimental data points of 5 refrigerants are compiled, with hydraulic diameters ranging from 0.5 to 10 mm and mass fluxes ranging from 40 to 1000 kg m^{-2} s^{-1}. Based on the collected data, a comprehensive evaluation of the reviewed correlations is made, and a new correlation which can give fairly good predictions for both macro- and mini-channels is proposed.

1. Introduction

Void fraction is defined as the ratio of the cross-sectional area occupied by the vapor to the total cross-sectional area of the flow channel. It is an important dimensionless parameter for the determination of pressure drop, heat transfer coefficient, refrigerant charge, and flow pattern transition in various two-phase flow applications, including refrigeration and air condition systems, pipeline network systems, nuclear power systems, chemical process systems, and aircraft and spacecraft environmental control and life-support systems. Therefore, the correct calculation of void fraction is meaningful.

In the past six decades, extensive theoretical and experimental investigations pertaining to void fraction have been conducted. Because the underlying mechanisms have still been unclear, many empirical and semi-empirical correlations have been developed instead, varying with the databases, assumptions, and parameters. Nowadays, greater emphasis is placed on the understanding of evaporation and condensation processes for refrigerants [1]. However, the stern reality is that most correlations of void fraction are limited to air–water or steam–water flow in pipes, and the correlations specifically established for refrigerants are relatively scarce. The significant property differences between air–water and refrigerants result in the necessity of a comprehensive evaluation for the applicability of the existing correlations from air–water studies to refrigerants. Lots of assessments of void fraction correlations focusing on air–water and steam–water have been conducted [2–9], while only few evaluations related to refrigerants have been made.

Rice [10] compared the homogeneous correlation and other 9 correlations [11–19] to verify the effect of their calculations on refrigerant charge inventory predictions. Four correlations [14,16–18] were found to give the closest agreement to the measured total system charge. Similarly, Farzad and O'Neal [20] evaluated 8 of the 10 correlations tested by Rice [10] except those of Smith [13] and Rigot [19] to check this effect. The results indicated that the Hughmark [18] correlation appeared to provide the best agreement with the measured data over the range of charging conditions involved. Moreover, according to the Hughmark [18] correlation, Porto et al. [21] developed an alternative method for estimating the refrigeration inventory, which showed better predictions.

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Nomenclature

C_0	distribution parameter
D	hydraulic diameter (m)
e_A	mean absolute relative deviation (%)
e_R	mean relative deviation (%)
Fr	Froude number
Ft	Froude rate
G	mass flux (kg m^{-2} s^{-1})
g	gravity (m s^{-2})
p	pressure (Pa)
q	heat flux (W m^{-2})
R^2	coefficient of determination
Re	Reynolds number
RMSE	root mean squared error
S	slip ratio
U	velocity (m s^{-1})
U_{gm}	drift velocity (m s^{-1})
U_m	two-phase mixture velocity (m s^{-1})
U_{sg}	superficial gas velocity (m s^{-1})
U_{sl}	superficial liquid velocity (m s^{-1})
We	Weber number
X	Lockhart–Martinelli parameter
x	vapor quality

Greek symbols

α	void fraction
μ	dynamic viscosity (Pa s)
ρ	density (kg m^{-3})
σ	surface extension (N m^{-1})

Subscripts

cr	critical
exp	experimental
g	gas
go	gas-only
h	homogeneous
l	liquid
lo	liquid-only
pred	predicted
tp	two-phase
tt	turbulent liquid and turbulent gas

Dalkilic et al. [22] compared 35 void fraction correlations to examine the effect of various correlations on the two-phase friction factor predictions based on the experimental data of R134a condensation in vertical downward flow. They found that although there was only a small difference in void fraction, a clear difference was seen in the momentum pressure drop which would be used to calculate the frictional pressure drop and then to determine the two-phase friction factor. One year later, Dalkilic et al. [23] compared the same 35 correlations to verify the effect of various correlations on the film thickness predictions in the same way and found that the film thickness values obtained from the void fraction correlations of Spedding and Chen [24] and Chisholm [25] were very close to the experimental data due to their low deviation with the annular flow model of Whalley [26]. These 35 correlations were evaluated again by Dalkilic and Wongwises [27] when they proposed a new experimental approach on determining the condensation heat transfer coefficient. Based on the evaluation, 8 correlations [14,15,25,28–32] were chosen because of good agreements between the predicted and experimental results.

Koyama et al. [33] investigated the void fraction of R134a flowing adiabatically in a smooth tube with an inner diameter (ID) of 7.52 mm, mass fluxes from 125 to 250 kg m^{-2} s^{-1}, and vapor qualities from 0.01 to 0.96. They assessed the homogeneous correlation and other 4 correlations [12,13,16,17] with their experimental data and found that the best correlations were those by Smith [13] and Baroczy [16].

Wojtan et al. [34] compared the homogeneous correlation and other 3 correlations [12,35,36] against the data of R22 and R410A flowing in tubes with IDs of 13.6 and 8 mm. It was found that the Steiner [35] correlation for horizontal flows was the best and accurately predicted the stratified flow void fraction data.

Jassim and Newell [37] developed a new void fraction model using probabilistic flow regime map for R134a, R410A, and air–water in 6-port channels, which could accurately predict the void fraction for the entire quality range and for all these three fluids. Similarly, Jassim et al. [38] developed a new model for single tubes. They compared the new and the homogeneous correlations as well as other 11 correlations [12–14,17,28,35,39–43] with 427 data points of R11, R12, R134a, R22, and R410A flowing in tubes with IDs from 4.26 to 9.58 mm and mass fluxes from 70 to 900 kg m^{-2} s^{-1} under condensation, adiabatic, and evaporation conditions. It was found that the new correlation was the best, followed by those of Yashar et al. [42], Premoli et al. [14], Steiner [35] and Smith [13].

Winkler et al. [44] investigated experimentally the void fraction of R134a condensing flow in channels with hydraulic diameters from 2 to 4.91 mm. With the 140 measured data points in the intermittent, wavy, and intermittent–wavy overlap flow regimes, they proposed a new correlation. A comparison between the new and the homogeneous correlations as well as other 17 correlations [11–18,28,30,40,42,45–49] with the experimental data were made. It was found that the new correlation could give satisfactory predictions for each flow regime, while none of the other correlations could give suitable predictions for the intermittent and the intermittent–wavy flow. Besides, the correlations of Lockhart and Martinelli [15], Yashar et al. [42], and Bankoff [47] could give relatively good predictions for the wavy flow.

The above evaluations indicate that either the number of correlations covered or the number of data used was limited, resulting in inconsistent conclusions. In this paper, a comprehensive literature search of the commonly used and often cited void fraction correlations is conducted, and an up-to-date survey of experimental investigations associated with the void fraction of refrigerants is performed. On the basis of the experimental data, an all-round evaluation of the existing correlations is carried out, and a new correlation is developed.

2. Review of void fraction correlations

The correlations of void fraction proposed so far can be classified into five categories, viz. homogeneous correlation, slip ratio correlations, $K\alpha_h$ correlations, drift flux correlations, and miscellaneous correlations [6,8].

2.1. Homogeneous correlation

This correlation is derived by treating the gas and liquid phases as a homogeneous mixture flowing with the same velocity. It is of the form