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A new correlation of two-phase frictional pressure drop for condensing flow in pipes

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HIGHLIGHTS

- Survey of two-phase frictional pressure drop (THFPD) experimental data of condensing flow is conducted.
- Applicability of the existing THFPD correlations to condensing flow is assessed.
- A new THFPD correlation for condensing flow in pipes is proposed.

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ABSTRACT

The calculation of two-phase frictional pressure drop for condensing flow in pipes is essential in many areas. Although numerous studies concerning this issue have been conducted, an accurate correlation is still required. In this paper, an overall survey of correlations and experimental investigations of two-phase frictional pressure drop is carried out. There 525 experimental data points of 9 refrigerants are gathered from literature, with hydraulic diameter from 0.1 to 10.07 mm, mass flux from 20 to 800 kg/m^2 s, and heat flux from 2 to 55.3 kW/m^2. The 29 existing correlations are evaluated against the experimental database, among which the best one has a mean absolute relative deviation (MARD) of 25.2%. Based on all the experimental data, a new correlation which has an MARD of 19.4% is proposed, improving significantly the prediction of two-phase frictional pressure drop for pipe condensing flow.

1. Introduction

Two-phase frictional pressure drop of condensing flow in pipes has been a research subject for several decades. It is a significant design parameter in numerous engineering applications, such as refrigeration, air conditioning, nuclear industry, and spacecraft thermal control systems.

Many theoretical and experimental studies have been carried out for calculating two-phase frictional pressure drop. Since the mechanisms occurring in two-phase flow have not been thoroughly comprehended, plenty of empirical correlations have been developed instead. To estimate which correlations could give more accurate predictions for two-phase frictional pressure drop, a number of researchers have evaluated certain correlations against various experimental data sources (Tribbe and Muller-Steinhagen, 2000; Choi et al., 2008; Sun and Mishima, 2009; Zhang et al., 2010; Li and Wu, 2010; Fang et al., 2012).

Zhang et al. (2010) divided the flow in pipes into four categories: adiabatic liquid–gas flow, adiabatic liquid–vapor flow, evaporating flow, and condensing flow. They found it was better to use different correlations for each of the four flow types. Cavallini et al. (2002) proposed a specialized correlation to capture the frictional pressure drop for condensing flow in smooth tubes when operating with pure or blended halogenated refrigerants. Kim and Mudawar (2012) found out that the micro-channel condensing flow indicated closer features in flow structure to adiabatic two-phase flow than to boiling flow. Thus, a separate analysis of the characteristics of two-phase frictional pressure drop for condensing flow is necessary.

Although many studies relating to condensing flow have been conducted, specialized evaluations of two-phase frictional pressure drop correlations for condensing flow are few, among which some conclusions are inconsistent and even controversial. Some research indicates the above dilemma of the existing evaluations of two-phase frictional pressure drop for condensing flow in pipes.

Dalkilic et al. (2010) evaluated 12 two-phase frictional pressure drop models (Lockhart and Martinelli, 1949; Chisholm, 1973; Friedel, 1979; Chen et al., 2001; Cavallini et al., 2002; Garimella et al., 2005; Mishima and Hibiki, 1996; Wang et al., 1997; Wilson et al., 2003; Souza and Pimenta, 1995; Tran et al., 2000; Lee and Lee, 2001) against the experimental frictional pressure drop of condensing flow of R600a and R134a. The experiment of R600a was

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Nomenclature

C	Chisholm parameter
D	hydraulic diameter (m)
f	Darcy–Weisbach friction factor
Fr	Froude number
g	gravity (m/s^2)
G	mass flux ($kg/m^2 s$)
La	Laplace constant
L	channel length (m)
q	heat flux (W/m^2)
Re	Reynolds number
We	Weber number
x	vapor quality
X	Lockhart–Martinelli parameter
$\Delta p/\Delta L$	pressure gradient (Pa/m)

Greek symbols

μ	dynamic viscosity (Pa s)
ρ	density (kg/m^3)
σ	surface extension (N/m)
ϕ^2	two-phase friction multiplier

Subscripts

g	gas
go	gas only
l	liquid
lo	liquid only
tp	two-phase

conducted in a horizontal tube of 4 mm ID with mass flux from 75 to 115 kg/m^2 s and vapor quality from 0.45 to 0.9, while the experiment of R134a was conducted in a vertical tube of 8.1 mm ID with mass flux from 300 to 400 kg/m^2 s and vapor quality from 0.7 to 0.95. They found that the correlations of Chisholm (1973), Chen et al. (2001) and Mishima and Hibiki (1996) could predict most of the experimental frictional pressure drop within ±30% for R600a, and that the correlations of Cavallini et al. (2002) and Chen et al. (2001) could predict all the experimental data within ±20% for R134a.

Bohdal et al. (2011) compared 4 correlations (Friedel, 1979; Chen et al., 2001; Garimella et al., 2005; Cavallini et al., 2002) with the experimental data of R134a and R404A condensing flow in 0.31–3.3 mm ID pipes. It was found that the methods of Friedel (1979) and Garimella et al. (2005) could provide satisfactory predictions. Based on their experimental data, they proposed a new correlation for calculating the frictional pressure drop of annular and annular–stratified flow, and the new correlation could predict the experimental data within ±20%.

Patil and Sapali (2011) investigated the frictional pressure drop of R134a and R404A condensing in a U-tube of 8.56 mm ID with mass flux from 90 to 800 kg/m^2 s and saturation temperature from 35 °C to 60 °C. They assessed 4 correlations (Friedel, 1979; Chisholm, 1973; Muller-Steinhagen and Heck, 1986; Gronnerud, 1979) with the experimental data, and found that the Friedel (1979) correlation performed best, capturing 75% data of R134a and 64.92% data of R404A within ±30%. The correlation of Muller-Steinhagen and Heck (1986) placed second, capturing 57.57% of R134a data and 46% of R404A data within ±30%.

Charun (2012) studied the pressure drop of R404A condensing flow in 1.4–3.3 mm ID pipes. They compared 5 correlations (Friedel, 1979; Chen et al., 2001; Garimella et al., 2005; Cavallini et al., 2002; Zhang and Webb, 2001) with the experimental data. The results indicated that the correlations of Friedel (1979) and Garimella et al. (2005) could give the best predictions.

Son and Oh (2012) verified the same 12 correlations as Dalkilic et al. (2010) and (2) additional correlations (Zhang and Webb, 2001; Yan and Lin, 1999) using the experimental data of R22, R134a, and R410A condensing in a horizontal tube of 1.77 mm ID with mass flux from 450 to 1050 kg/m^2 s and saturation temperature of 40 °C. They found that the correlation of Chen et al. (2001) showed the best prediction for all fluids, the correlations of Friedel (1979), Cavallini et al. (2002), Mishima and Hibiki (1996), Zhang and Webb (2001), Garimella et al. (2005), Lee and Lee (2001) and Souza and Pimenta (1995) predicted the experimental data within 20–40%. In addition, they also found that all correlations proposed for large diameter tubes displayed large deviations with the experimental data.

The above literature review states clearly that the correlation of two-phase frictional pressure drop for condensing flow is still an issue to be solved. This paper intends to develop a more accurate correlation for calculating the two-phase frictional pressure drop for condensing flow, for which an all-sided survey of the experimental data of the two-phase frictional pressure drop for condensing flow and the existing correlations for two-phase frictional pressure drop is conducted. On the strength of the available experimental data, an evaluation of the existing correlations is carried out and a new correlation for two-phase frictional pressure drop of condensing flow is proposed.

2. The available experimental data of two-phase frictional pressure drop for condensing flow

The collected experimental data sources of two-phase frictional pressure drop for condensing flow from a comprehensive literature survey are listed in Table 1, which contains 525 data points of 9 refrigerants flowing in a wide scope of test geometries and operation conditions.

For the scale of channels, Kandlikar (2002), Kew and Cornwell (1997), and Mehendale et al. (2000) proposed 3 judging criteria, among which the Kandlikar (2002) classification is the most popular one. Since the extensive experiments conducted by Chawla (1967) could provide a clue for the diameter ranges, the smallest diameter used in his experiments was 3 mm, and few experimental results were reported for pipes smaller than 3 mm by other researchers, Kandlikar (2002) took 3 mm as the threshold of macro-scale and micro-scale channels. In this work, the Kandlikar classification is used.

For flow regimes, Lockhart and Martinelli (1949) defined turbulent liquid-turbulent gas (*tt*), turbulent liquid-viscous gas (*tv*), viscous liquid-turbulent gas (*vt*), viscous liquid-viscous gas (*vv*), and transitional regimes by considering the flow of $Re > 2000$, $Re < 1000$, and $1000 < Re < 2000$ to be turbulent, viscous, and transitional, respectively.

For flow patterns, Wojtan et al. (2005) proposed the most recent version of flow pattern map based on Kattan et al. (1998) for diabatic two-phase flow, which was examined by Moreno Quiben (2005) and Mauro et al. (2007) with their evaporating experimental data of flow patterns and was consistent with them.

The statistical results of the 525 experimental data points are as the following:

(1) The hydraulic diameter ranges from 0.1 to 10.07 mm, 344 data points are from macro-channels, and the rest 181 data points are from micro-channels.
(2) The mass flux ranges from 20 to 800 kg/m^2 s, and heat flux from 2 to 55.3 kW/m^2. Most of the data have qualities between 0.2 and 0.8. Only 95 data points are in the quality range from 0.8 to 1.0 and 61 those from 0 to 0.2.