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Frictional pressure drop during steam stratified condensation flow in vacuum horizontal tube

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ABSTRACT

The frictional pressure drop of steam condensation flow in vacuum horizontal tube was studied experimentally. The steam saturation temperature changes from 50 to 70 °C, the steam mass flux varies from 2 to 10 kg/(m^2·s), vapor quality range are from 0 to 1 and the temperature difference between steam and cooling water are 3, 5 and 8 °C respectively. 205 experimental data were obtained in the experiment and compared with 25 existing frictional pressure drop models in three different kinds. All the experimental conditions are stratified flow and the flow states are turbulent and laminar flow in steam and liquid phase respectively. The frictional pressure drop increases with mass flux and vapor quality. It decreases with saturation temperature and has less relationship with temperature difference. Five models with the highest prediction accuracy are Quibén's model, Chisholm's model, Zhang's model, Sun's model, Lee's model.

1. Introduction

Steam condensation flow in horizontal tube is widely used in various industrial fields, such as chemical industry, air conditioning and desalination. A review of refrigerants condensation flow inside and outside tube was proposed by Cavallini et al. [1]. Later, Miyara [2], and Dalkilic [3] also gave comprehensive reviews of condensation flow, including the heat transfer, flow pattern, void fraction and pressure drop. Wang et al. [4] investigated the heat transfer characteristics of steam condensation flow in vacuum horizontal tube with inner diameter of 18 mm experimentally. Condensation heat transfer of vapor and noncondensable gas mixtures in horizontal tube with inner diameter of 27.5 mm when the inlet pressure is 0.2 MPa is shown in Wu and Vierow's study [5]. Similar experiment with inner diameter of 16 mm at the pressure 0.1 MPa was conducted by Ren et al. [6]. Thome [7] proposed a new condensation model for horizontal tube including two types of heat transfer mechanisms in the tube: film condensation at the top of tube and convective condensation at the bottom.

Two-phase flow is a very complex thermodynamic process. The frictional pressure drop of two-phase flow plays an important role in design and optimization of heat exchanger, especially for multi-effect evaporation desalination plant. The steam condenses in vacuum horizontal tube in multi-effect evaporation desalination plant, and the pressure drop of this process has a great influence on the thermal performance of desalination system [8]. Kouhikamali et al. [9] investigated the pressure drop in the heat exchangers of multi-effect evaporation with thermal vapor compression system and showed that condensation pressure drop in the tube has most influence on the system performance among all different kinds of pressure losses. Considering condensation pressure drop in tube increases the specific heat transfer surface area by about 7% than neglecting it.

The frictional pressure drop of refrigerant condensation flow at high or atmospheric pressure has been studied extensively, but there are few studies about the frictional pressure drop of steam condensation flow under vacuum conditions.

The main factors influencing the frictional pressure drop are steam mass flux, vapor quality and saturation temperature. Many experiments [10–13] showed that the frictional pressure drop increased with the mass flux and vapor quality. Col et al. [14] investigated propane condensation flow in minichannel and found that the pressure drop increases with vapor quality and the increment increases with mass flux. Zhuang et al. [15] measured R170 condensation flow in a 4 mm diameter horizontal tube. The frictional pressure drop increases with mass flux and the effect of mass flux weakens as the saturation temperature increases. Quibén and Thome [16] measured the pressure drop of R134a, R22 and R410A experimentally. They found that the frictional pressure drop increased to the maximum firstly and then decreased with the increasing vapor quality. The mechanism of this phenomenon is the transitions of flow patterns. Charnay et al. [17] got the same experimental results with Quibén and Thome [16]. Zhang et al.

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Nomenclature

A	area
B	coefficient
C	coefficient
Co	confinement number
c_p	specific heat at constant pressure, kJ/(kg·°C)
D	diameter, m
f	friction factor
Fr	Froude number
G	mass flux, kg/(m²·s)
g	gravity, m/s²
j^*	dimensionless velocity
L	length, m
m	mass flow rate, kg/s
n	number
p	pressure, Pa
Q	heat transfer rate, kW
Re	Reynolds number
r	latent heat, kJ/kg
T	temperature, °C
We	Webb number
X	Lockhart-Martinelli parameter
x	vapor quality
Y	Chisholm parameter

Greek symbols

Δ	difference
α	void fraction
δ	film thickness, m
μ	dynamic viscosity, Pa·s
θ	angle, °
ρ	density, kg/m³
σ	surface tension, N/m
ϕ^2	two phase friction multiplier

Subscripts

annular	annular
c	cooling water
d	dimensionless
exp	experimental
frict	frictional
i	ordinal number
in	inlet
l	liquid
lo	liquid only
mom	momentum
out	outlet
pred	predicted
s	steam
strat	stratified
static	static
tp	two-phase
tt	turbulent-turbulent
v	vapor
vo	vapor only

[18] investigated pressure drop of R22, R410A and R407C in horizontal tube with two different diameters. The experimental results showed that vapor quality had less relationship with frictional pressure drop when the vapor quality was higher than 0.8. A large number of experimental studies [10,12,13,17–20] showed that the frictional pressure drop decreased with the saturation temperature. The increase of saturation temperature leads to the increase of vapor density. So the vapor velocity decreases at the same mass flux, and the friction between vapor and condensate and tube wall is weakened. Steam condensation flow pressure drop at very low mass flux was reported by Guo et al. [21], the flow pattern observed in the experiment is stratified flow. The effects of tube length and inclination were studied experimentally, but the effects of mass flux, vapor quality and saturation temperature were not mentioned.

Charmay et al. [17] compared their experimental data with different existing models. They approved that the homogeneous models proposed by Cicchitti et al. [22], Awad and Muzychka [23], the separated models proposed by Müller-Steinhagen and Heck [24], Zhang and Webb [25] and Friedel [26] are more accurate. Xu et al. [27] collected 3480 data of in-tube two-phase flow from existing literatures, in which the tube diameter varied from 0.0695 mm to 14 mm and the mass flux changed from 8 to 6000 kg/(m²·s), and then assessed and analyzed 28 models. The results showed that the homogeneous models proposed by Beattie and Whalley [28] and McAdams et al. [29], the separated models proposed by Müller-Steinhagen and Heck [24] and Sun and Mishima [30] made the most accurate prediction. Ould Didi et al. [31] measured the frictional pressure drop of 5 different refrigerants in horizontal tube and obtained 788 data, which matched well with models proposed by Müller-Steinhagen and Heck [24] and Grönnerud [32]. The model proposed by Müller-Steinhagen and Heck [24] is the most suitable for annular flow, while the model proposed by Grönnerud [32] is the most suitable for intermittent flow and stratified wavy flow. The experiment of Wang et al. [20] showed that Müller-Steinhagen and Heck [24] model gave the most accurate prediction of frictional pressure drop. Col et al.'s experiments [14] showed that the pressure drop calculated by Friedel [26] model is in good agreement with the measured values. Guo et al.'s data [21] showed that the existing correlations were not valid for condensation at very low mass flux.

2. Two-phase frictional pressure drop prediction models

The empirical models are widely used to calculate the two-phase frictional pressure drop, due to the complexity of the two-phase flow. The models have the advantages of easy calculation and high accuracy. But they can only be applied to certain experimental conditions, on which the models based. These models usually can be divided into two categories, homogeneous models and separated models. In recent years, the phenomenological model based on flow pattern has been proposed.

2.1. Homogeneous model

Homogeneous model is the simplest model to analyze multiphase flow. The vapor and liquid flow are assumed to be at the same velocity, so in this case the two-phase flow is considered as idealized single-phase fluid flow. The frictional pressure drop of two-phase flow can be calculated as a single-phase flow by using the mixture fluid properties, shown in Eq. (1):

$$\left(\frac{\Delta p}{\Delta L}\right)_{\rm frict} = \frac{G^2}{2D\rho_{\rm tp}} f_{\rm tp} \tag{1}$$