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Circumferential distribution of local heat transfer coefficient during steam stratified flow condensation in vacuum horizontal tube

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ABSTRACT

An experimental system was built up to measure the wetted angle and circumferential distributions of local heat transfer coefficient during the steam stratified flow condensation in vacuum horizontal tube. The wetted angle is mainly affected by vapor quality. It decreases with vapor quality and steam mass flow rate, and increases with the steam saturation temperature. The Biberg's correlation and Rouhani's void fraction correlation are used together to predict the experimental value of wetted angle accurately. The tube wall is divided into filmwise condensation section and liquid accumulation section by the stratified interface. The local heat transfer coefficient in filmwise condensation section is significantly higher than that in liquid accumulation section. The local heat transfer coefficient increases with vapor quality and steam mass flow rate for all locations along the circumferential direction. The increase of temperature difference between steam and cooling water causes the decrease of local heat transfer coefficient in filmwise condensation section and has less effect on that in liquid accumulation section. With the change of steam saturation temperature, the heat transfer coefficients in two sections of the tube appear different variation tendencies. Based on the experimental values, new correlations for local heat transfer coefficient of steam condensation flow in stratified flow pattern are proposed.

1. Introduction

Condensation in horizontal tube is a common two-phase flow and phase change process, which is widely used in desalination, air conditioning, chemical engineering and other industrial equipment. When the mass flow rate is small, the gravity force makes the condensate gathered at the bottom of tube and the flow is in a stratified pattern. For the stratified flow condensation in horizontal tube, the heat transfer area could be divided into filmwise condensation section and liquid accumulation section, which located in the upper and bottom of the tube wall respectively. These two heat transfer sections are specified by the wetted angle or stratified angle. Fig. 1 shows the wetted angle or stratified angle and other geometrical parameters in stratified flow pattern.

Biberg [1] gave a simple explicit approximations of wetted angle for a given void fraction, written as Eq. (1). The maximum error is approximately 5×10^{-5} rad. The wetted angle could be calculated by using the Biberg's correlation and void fraction correlation together. For two phase flow in a horizontal tube, many correlations of void fraction based on experimental data have been put forward. These correlations are divided into four categories, which are homogeneous, slip ratio, based on Lockhart-Martinelli parameter and drift flux respectively. Six correlations from these four categories are summarized in Table 1.

$$\theta_{\mathrm{wet}} = \pi(1-\alpha) + \left(\frac{3\pi}{2}\right)^{1/3}\left[1-2(1-\alpha)+(1-\alpha)^{1/3}-\alpha^{1/3}\right] - \frac{1}{200}(1-\alpha)\alpha[1-2(1-\alpha)]\left[1+4\left((1-\alpha)^2+\alpha^2\right)\right] \quad (1)$$

The homogeneous model is assumed that the steam-liquid two phase flow is a homogeneous mixture with the same flow velocity, which is seriously inconsistent with the fact that the steam velocity is much greater than the condensate velocity in stratified flow. The Zivi [2] correlation and Smith [3] correlation belong to the slip ratio models. For these models, the slip ratio between the steam and liquid phase is considered. However, the two models are based on the experimental data of annular flow pattern. The Lockhart-Martinelli parameter X_{tt} reflects the steam-liquid two-phase flow vapor quality and fluid physical parameters, but this parameter cannot reflect the effect of steam mass flow rate. The drift flux models use the distribution parameter to represent the nonuniform of the void fraction distribution over the cross-section and the drift velocity to represent the difference between steam velocity and the two phase average velocity.

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Nomenclature

c_p	constant pressure specific heat, kJ/(kg·°C)
D	diameter, m
F	effective heat transfer area, m^2
G	mass flow rate, kg/(m^2·s)
g	acceleration of gravity, m/s^2
h	heat transfer coefficient, W/(m^2·K)
k	heat conductivity coefficient, W/(m·K)
L	length, m
m	mass flow rate, kg/s
Nu	Nusselt number
Pr	Prandtl number
Q	heat transfer rate, kW
Re	Reynolds number
r	latent heat, kJ/kg
T	temperature, °C
X_{tt}	Lockhart-Martinelli parameter
x	vapor quality

Greek symbols

Δ	difference
α	void fraction
θ	angle, °
μ	dynamic viscosity, Pa·s
ρ	density, kg/m^3
σ	surface tension, N/m

Subscripts

bot	bottom
c	cooling water
exp	experimental
i	number
in	inlet
l	liquid
out	outlet
pred	predicted
s	steam
so	steam only
up	upper
w	wall
wet	wetted
θ	angle

Ursenbacher et al. [4,5] developed a new non-intrusive image analysis and optical observation method to measure the stratified angle and void fraction in stratified flow pattern when R22 and R410A flow in a glass tube with an inner diameter of 13.6 mm and mass flow rate changing from 70 to 300 kg/(m^2·s). The experimental results match well with the results that calculated by Biberg [1] correlation and Rouhani [6] void fraction correlation, whose accuracy is about 5°. Wojtan et al. [7] measured the stratified angle of R22 in 8 and 13.6 mm diameter tubes experimentally. The results show that the film is thicker at the upper perimeter in 8 mm tube, which affects the measurement of stratified angle.

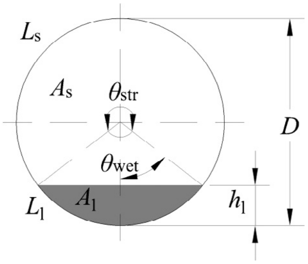

Fig. 1. Geometrical parameters in stratified flow pattern.

In previous studies, the local heat transfer coefficient of filmwise condensation at the upper of tube has received more attention than convective condensation at the bottom. Chato [8] considered that the height of condensate in the tube remains constant and the heat transfer at the bottom of tube could be neglected. The heat transfer mechanism at the upper of tube is essentially the same with the mechanism of film condensation on vertical plate analyzed by Nusselt [9]. But Chato's correlation does not reflect the effect of vapor quality and mass flow rate on heat transfer coefficient. Singh et al. [10] also put forward a correlation for filmwise condensation similar to Chato's correlation.

Jaster and Kosky[11] introduced the void fraction into Chato's [8] correlation to reflect the influence of vapor quality and mass flow rate. Zivi's [2] void fraction correlation is used in the correlation. Rosson [12] added Re_s to Chato's correlation taking into account the effects of steam velocity and vapor quality.

Shen et al.'s experiment [13] showed that the heat transfer coefficient at the bottom is small, but the heat transfer temperature difference is large, so the heat transfer rate at the bottom can't be neglected in the stratified flow pattern. Dobson and Chato

Table 1
Six correlations of void fraction.

Author	Category	Correlation
——	Homogeneous	$\alpha=\left[1+\left(\frac{1-x}{x}\right)\left(\frac{\rho_s}{\rho_l}\right)\right]^{-1}$
Zivi[2]	Slip ratio	$\alpha=\left[1+\left(\frac{1-x}{x}\right)\left(\frac{\rho_s}{\rho_l}\right)^{2/3}\right]^{-1}$
Smith[3]	Slip ratio	$\alpha=\left[1+\left(\frac{1-x}{x}\right)\left(\frac{\rho_s}{\rho_l}\right)K+(1-K)\left[\frac{\frac{1}{\rho_s/\rho_l}+K\left(\frac{1-x}{x}\right)}{1+K\left(\frac{1-x}{x}\right)}\right]^{1/2}\right]^{-1}$
Lockhart[23]	Based on Lockhart-Martinelli parameter	$\alpha=(1+0.28X_{tt}^{0.71})^{-1}$
Steiner[22]	Drift flux	$\alpha=\frac{x}{\rho_s}\left\{[1+0.12(1-x)]\left(\frac{x}{\rho_s}+\frac{1-x}{\rho_l}\right)+\frac{1.18(1-x)}{G}\left[\frac{g\sigma(\rho_l-\rho_s)}{\rho_l^2}\right]^{0.25}\right\}^{-1}$
Rouhani[6]	Drift flux	$\alpha=\frac{x}{\rho_s}\left\{[1+0.2(1-x)]\left(\frac{x}{\rho_s}+\frac{1-x}{\rho_l}\right)+\frac{1.18}{G}\left[\frac{g\sigma(\rho_l-\rho_s)}{\rho_l^2}\right]^{0.25}\right\}^{-1}$