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Hydrodynamic behaviors of the falling film flow on a horizontal tube and construction of new film thickness correlation

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ABSTRACT

The laminar liquid film falling on a horizontal smooth tube is studied numerically. The instantaneous hydrodynamic characteristics of falling film flow, the importance of surface tension in calculation and the effects of film flow rate, tube diameter, liquid distributor height and inlet liquid temperature on the flow field and film thickness are elucidated. The results indicate that: (1) The surface tension is important in the calculations of falling film flow on a horizontal tube; (2) The film falling on a circular tube has obvious instantaneous behaviors; (3) The film thickness increases with increase of film flow rate, while decreases with increase of the tube diameter, liquid distributor height and liquid temperature, respectively; (4) The film distribution along the peripheral angle is unsymmetrical, and the minimum thickness appears in 110–150° of peripheral angle depending on the working conditions. Furthermore, new correlations of falling film thickness on a horizontal tube based on the present data are established, which fit 97% of 84 data in $\theta = 2–15°$ within ±20%, 90% of 632 data in $\theta = 15–165°$ within ±20%, and 73% of 112 data in $\theta = 165–178°$ within ±30%.

1. Introduction

The falling liquid film outside the horizontal tubes is widely encountered in the evaporation [1], condensation [2,3] and cooling [4,5] processes of desalination [6], refrigeration and petrochemical industries, mainly owing to the advantages in better heat/mass transfer performance while lower liquid charge [7–9]. However, the database regarding hydrodynamic characteristics of the liquid film falling on the horizontal tube is insufficient.

The falling liquid film flowing over a single horizontal tube is influenced by various factors such as film flow rate, liquid temperature, liquid distributor type/height and tube geometries. These factors adjust the applications of gravity, viscous shearing, surface tension and wall adhesion, then change the film flow patterns and film distributions, and eventually affect the heat and mass transfer performances. When the liquid film falls on a horizontal tube, the heat is transferred from the tube wall, across the thin liquid layer, and then to the liquid gas interface, during which the film flow field and film thickness play important roles in the thermal resistance. In previous investigations, the film thickness evolution on the horizontal tube has been studied with analytical [10–13], numerical [14–18] and experimental methods [19–25].

The published analytical and numerical studies concerning the liquid film thickness on the horizontal tube are most often based on many hypotheses. To the authors' knowledge the study of Nusselt [10] is the pioneering work on the prediction of falling film thickness. He obtained an analytical solution of the condensing film thickness on a vertical plate with neglecting the surface tension and inertial force. By replacing the vertical plate with an inclined one, the local film thickness can be predicted by the following equation for various inclination angles

$$\delta = \left(3\mu_l\Gamma/\rho_l^2 g\sin(\pi\beta/180)\right)^{1/3} \tag{1}$$

where β (°) is the inclination angle of the plate. Thus, the film thickness of the liquid film falling on a horizontal tube can be calculated by Eq. (1) with replacement of the inclination angle β by the peripheral angle θ (°). Based on Nusselt's solution, Rogers [11] and Chyu and Bergles [12] correlated the film thickness on a horizontal tube, as expressed

$$\delta = \left(\frac{3\mu_l\Gamma}{\rho_l(\rho_l - \rho_v)g\sin(\pi\theta/180)}\right)^{1/3} \tag{2}$$

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Nomenclature

Ar	Archimedes number, $Ar = \rho_l^2 g D^3/\mu_l^2$
D	diameter of tube, mm
F	source term in momentum equation
g	gravity acceleration, m s^{-2}
H	liquid distributor height, m
p	pressure, Pa
Re	film Reynolds number, $Re = \frac{4\Gamma}{\mu}$
s	tube spacing, m
t	time, s
T	temperature, °C
u, v	component of velocity, m s^{-1}
x, y	coordinates, m
We	modified Webber number, $We = \frac{\Gamma^2}{\pi^2 \rho_l D \sigma}$
Greek	
α	volume fraction
Γ	liquid film flow rate on one side of the tube per unit length, kg m^{-1} s^{-1}
δ	film thickness, m
θ	peripheral angle from the upper stagnation point, °(degree)
μ	dynamic viscosity, kg m^{-1} s^{-1}
ρ	density, kg m^{-3}
σ	surface tension coefficient, N m^{-1}

The thickness of the liquid film falling on a horizontal tube has also been measured in several studies with intrusive or non-intrusive techniques. Rogers and Goindi [19] measured the film thickness of laminar water film on a circular tube with large diameter (132 mm) using three dial point gauges, and built a film thickness correlation

$$\delta/d = 1.186 Re^{1/3} (Ar \sin(\pi\theta/180))^{-1/3} \tag{3}$$

Xu et al. [20] measured the falling film thickness on a horizontal tube with micro-measuring instrument and observed that the film thickness increases with the film flow rate and the average film thickness almost remains constant when tube diameter varies from 20 to 40 mm. By using an optical method, Gstoehl et al. [21] measured the falling film thickness of water, reagent grade ethylene glycol, and a water–glycol mixture (50%–50% by mass) on a horizontal tube with different film flow rates and liquid distributor heights. Mohamed [22] investigated the effect of fluted surface on the film thickness, and found that the fluted structure facilitates the thinning of liquid film especially for smaller flute pitch. Hou et al. [23] found that the tube diameter has little influence on film thickness, and that the tube spacing, s, should be considered for the lower part of the tube ($\theta > 90°$). They also developed a piecewise correlation based on Nusselt's solution [10] with considering the effect of s/D, as follows

$$\delta = C\left(\frac{3\mu_l \Gamma}{\rho_l(\rho_l - \rho_v) g \sin(\pi\theta/180)}\right)^{1/3} (s/D)^n \tag{4}$$

where $C = 0.9754$, $n = -0.1667$ for $0° < \theta \leq 90°$, and $C = 0.84978$, $n = -0.16479$ for $90° < \theta < 180°$.

Recently, Narváez-Romo and Simões-Moreira [26] evaluated the intrusive methods of film thickness measuring techniques. They inferred that the deviations between their intrusive measurement and the Nusselt film thickness model [10] were related to two reasons: (1) Nusselt expression was developed for a liquid film flow over a vertical flat plate without interfacial waves; (2) the probe or needle tip of the measuring instrument gave rise to waves and crest at the liquid surface. They also modified the Nusselt's film thickness correlation based on their data, as follows

$$\delta = \left(\left(\frac{3\mu_l \Gamma}{\rho_l(\rho_l - \rho_v) g \sin(\pi\theta/180)}\right)^{1/3}\right)^{1.041} \tag{5}$$

In recent years, with the development of computer, the falling film flow behaviors are studied by numerical simulations, which is generally based on a few assumptions while can avoid the interference of measuring elements on the film surface. Min and Choi [14] used marker and cell (MAC) method to track the phase interface during the absorption of the LiBr solution on a horizontal tube with self-developed Navier–Stokes procedure. Besides, the VOF method is widely employed to capture the free surface of the liquid film on a horizontal tube [15–17,27–30]. Fiorentino and Starace [5] simulated the flow patterns and the film thickness on the triangular tube bundle with a 2-D model. And found that both tube arrangement and film flow rate have effects on the flow patterns. More recently, Ji et al. [31] calculated the falling film flow of LiBr solution over a hydrophilic horizontal tube and modified the Nusselt equation with considering the asymmetric feature, as follows

$$\delta = \left(\frac{3\mu_l \Gamma}{\rho_l(\rho_l - \rho_v) g \sin(0.75(\pi\theta/180))}\right)^{1/3} \tag{6}$$

The falling film thickness can be obtained by above analytical, numerical and experimental methods. In general, the accurate measurement of film thickness is very difficult due to the free surface waviness and the small order of film thickness. For that reason, the reliable numerical simulations are required to help us understand the hydrodynamic characteristics of the thin liquid film flow. However, the previous studies always introduced oversimplifications of transport phenomena in falling films, such as neglecting inertial force and surface tension. Additionally, there is no universal correlation of falling film thickness over a horizontal tube to consider these forces and the aforementioned factors. In this paper, the instantaneous hydrodynamic characteristics of the falling film flow and the effects of aforementioned factors are taken into account, and new falling film thickness correlations are also constructed.

The rest sections are arranged as follows: firstly the numerical method and procedure are introduced; then the results and discussion are presented, including the role of surface tension in calculation, instantaneous film flow characteristics, and the effects of five factors on the film flow field and film thickness, as well as the construction of the falling film thickness correlations, and finally some conclusions are drawn.

2. Numerical simulation approach

2.1. Physical model

This study focuses on a horizontal smooth tube in a square-pitch tube bundle, as shown in Fig. 1(a), where D is the tube diameter, s the tube spacing, and H the liquid distributor height. Fig. 1(b) illustrates the schematic liquid film distribution on the horizontal tube. One half of the tube and inter-tube space is served as the calculation domain due to symmetry. The scopes of parameters in the calculations are listed in Table 1.