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A comprehensive numerical study on the subcooled falling film heat transfer on a horizontal smooth tube

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ABSTRACT

The effects of film flow rate, heat flux, inlet liquid temperature, tube diameter and liquid distributor height on subcooled falling film heat transfer outside a horizontal smooth tube are numerically studied, and a heat transfer correlation based on the current data is developed. Comparisons between the predicted results and the published experimental data in the literature are also conducted. The calculation ranges are: film flow rate from 0.025 to 0.284 kg m^{-1} s^{-1}, heat flux from 1.0 to 100 kW m^{-2}, inlet liquid temperature from 2 to 104 °C, tube diameter from 6.35 to 50.8 mm and liquid distributor height from 3.0 to 50.8 mm. The results indicate that: (1) the numerical results of the local heat transfer coefficient are in good agreement with the experimental data in the literature; (2) the surface tension plays an important role in the calculations of heat transfer in two stagnation zones, (3) the heat transfer coefficient shows four distinct zones along with peripheral angle: stagnation zone, impingement zone, thermal layer development zone and departure zone; (4) the heat transfer coefficient increases with increase in film flow rate, tube diameter or liquid distributor height, while keeps constant with increasing heat flux; (5) the correlation predicts 92% of the total 141 calculated data with deviations within ±10%, and predicts 78% of 284 data available in literature with deviations within ±30%.

1. Introduction

Heat transfer across a liquid film falling on a horizontal tube is widely encountered in various engineering applications, such as absorption, condensation/cooling, evaporation, and waste heat recovery. The heat transfer characteristics at the interface of the tube wall and the flowing film have attracted high technological interests. However, the interfacial heat transfer and film distribution are influenced by a multitude of factors: tube geometry, film flow rate, heat flux, liquid distributor and liquid properties, etc. [1–3]. So far, the falling film heat transfer mechanisms are not yet fully understood, despite tremendous experimental results have been reported. With development of the calculation approaches this problem has gained more and more attention with numerical simulations.

The following section reviews the studies on the effects of the aforementioned factors on the heat transfer of a subcooled liquid film falling over a horizontal tube.

Several investigations have focused on the heat transfer characteristics of the liquid film over a horizontal tube by analytical or numerical methods. The analytical model for laminar film condensation proposed by Nusselt [4] is the most widely used to predict the falling film heat transfer. The solution neglected the effects of the surface tension and inertial force [5], so its accuracy and universality are confined. Barba and Felice [6] built a heat transfer correlation of the falling film on a horizontal tube by an analysis approach based on an assumption of developed turbulent flow regime. Their predicted heat transfer coefficients are systematically lower than the experimental data due to neglecting the thermal developing region. Chyu and Bergles [7] proposed four heat transfer regions in the liquid film flowing on a horizontal tube with an analytical method: stagnation, jet impingement, thermal developing and fully developed regions. They also developed heat transfer correlations of the local or average coefficients in these regions. Rogers [8] and Fujita and Tsutsui [9] established heat transfer correlations of the local heat transfer coefficients in the developing and developed thermal boundary layers of a falling film on a horizontal tube, respectively. Sarma and Saibabu [10] correlated a heat transfer equation of a laminar liquid film falling on a horizontal tube with coupling the convective heat transfer in the liquid film and the thermal conduction in the tube wall. Louahlia-Gualous and Omari [11] obtained the local heat transfer coefficients of a falling film on a horizontal cylinder by inverse heat conduction analysis.

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Nomenclature

A	area, m^2
Ar	Archimedes number,
c_p	specific heat capacity, J kg^{-1} K^{-1}
D	diameter of tube, m
F	body force, N
g	gravity acceleration, ms^{-2}
H	liquid film distributor height, m
h	heat transfer coefficient, W m^{-2} K^{-1}
Nu	Nusselt number
Pr	Prandtl number,
P	pressure, Pa
q	heat flux, W m^{-2}
Re	film Reynolds number
T_i	inlet liquid temperature, °C
$\mathbf{v}$	velocity vector, ms^{-1}
We	modified Weber number

Greek

Γ	liquid film flow rate on one side of the tube per unit length, kg m^{-1} s^{-1}
t	time, s
θ	peripheral angle
α	volume fraction
λ	thermal conductivity, W m^{-1} K^{-1}
μ	dynamic viscosity, kg m^{-1} s^{-1}
ρ	density, kg m^{-3}

Subscript

ave	average variable
l	liquid refrigerant
w	wall

Besides, many experiments are conducted to investigate the falling film heat transfer performances. Parken [12] and Parken et al. [13] found that the local heat transfer coefficients are the highest at the top of the horizontal tube and then decreases along the periphery, and the average heat transfer performance increases with increase in inlet liquid temperature and film flow rate, while remains constant with change of heat flux, even decreases with increase in tube diameter, as noted by Liu and Zhu [14] and Rogers and Goindi [15]. As a continuation of Parken's work, Sernas [16] developed these correlations into dimensionless form. Chyu and Bergles [7] tested the falling film heat transfer performance of water on a horizontal cylinder and found that: the increasing film flow rate first promotes then weakens heat transfer; liquid distributor height has little effect on heat transfer at low film flow rate; and a higher heat flux slightly improves heat transfer performance. Mitrovic [17] pointed out that the heat transfer coefficient of the falling films of isopropylalcohol and water obviously increases as tube spacing increases especially under larger film flow rate. Rifert et al. [18] and Liu and Yi [19] tested the local and average heat transfer coefficients of water film evaporation on horizontal enhanced tubes and found that the longitudinally-profiled, low finned and roll-worked tubes provide higher heat transfer coefficients than the smooth tube. More recently, Narváez-Romo and Simões-Moreiraboth [20] tested the local and overall heat transfer behaviors and the film thickness of a liquid falling film over horizontal heated tubes and obtained an heat transfer correlation.

In recent decade, with the development of computational fluid dynamics (CFD), the fluid flow and heat transfer characteristics of the liquid film are studied by solving the governing equations. A finite volume method is employed to discretize the physical equations, and the Volume of Fluid (VOF) method is used to track free surface between the liquid and gas phases. Zhou et al. [21] simulated the heat transfer processes of inside and outside of a horizontal tube with a double phase model coupling internal condensation and external falling film evaporation. Luo et al. [22] and Qi et al. [23] numerically studied the falling film flow and heat transfer on several shaped tubes, such as drop-shaped and oval-shaped tubes [22] and elliptical tube [23]. Their results indicated that these shaped tubes can provide better heat transfer performances than the circular one. In previous simulations on the heat transfer behaviors of the liquid film heat transfer, the constant wall temperature is widely used in [24–27] and the constant heat flux is seems only adopted in [28]. Yang et al. [24] presented temperature profiles around the horizontal tube and believed that both conduction and convection contributes microscopic mechanisms to heat transfer in the falling film. Fiorentino and Starace [25] simulated the flow patterns and the film thickness around a tube with a 2-D model, in which the effects of the tube arrangement and film flow rate were also presented. Hosseinnia et al. [29] calculated the water vapor absorption in laminar falling film solution of water-LiBr in 3-D domain with aid of an in-house CFD code. More recently, Jin et al. [30] compared the numerical results of the falling film heat transfer coefficients with two distinct boundary conditions, and found that the constant heat flux provides around 12% higher heat transfer coefficients than the constant temperature.

The above review indicates that a number of studies on falling film heat transfer have been conducted, but further research is still needed in two aspects. Firstly, the comprehensive numerical simulations based on the boundary condition of constant heat flux are needed. Since in most practical applications, the constant heat flux condition is more likely to occur. Secondly, the existing heat transfer correlations generally considered one or two factors, which limit the applicability and mutual comparison. The objectives of this paper are to present the relationships of local and average heat transfer coefficients with the factors of film flow rate, heat flux, inlet liquid temperature, tube diameter and liquid distributor height, and to develop a universal heat transfer correlation of the subcooled falling film heat transfer on a horizontal smooth tube. For this purpose, a numerical study considering multi-factor to provide an overall comprehension of the falling film heat transfer characteristics is carried out with the commercial Ansys Fluent 15.0. The VOF model is used to capture the interface between the liquid and gas phases. And the forces of gravity, surface tension and wall adhesion are taken into account.

The rest sections are arranged as follows: the numerical method is introduced, in which the physical and mathematical model, data reduction, grid and time step independence verification are provided; then the results and discussion are presented, including the variations of the local and average heat transfer coefficients against the factors, the establishing of the heat transfer correlation based on the present numerical results; and finally, some conclusions are drawn.

2. Numerical simulation approach

2.1. Physical model

The studied tube is schematically shown in Fig. 1(a). The schematic diagram of the liquid film distribution is displayed in Fig. 1 (b). The tube diameter D ranges from 6.35 to 50.8 mm and distrib-