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Development of an analytical model for pure vapor downflow condensation in a vertical tube

Junli Gou, Baojing Wang, Jianqiang Shan *

School of Nuclear Science and Technology, State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University, Xi'an 710049, China

HIGHLIGHTS

- An analytical model for pure steam downflow condensation in a vertical tube is developed.
- An optimized transition criteria between the laminar and turbulent film flow is defined.
- Kay's turbulent eddy diffusivity model and his turbulent Prandtl number model are recommended.
- Good agreement between the new developed model and the experimental data are obtained.

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ABSTRACT

In-tube condensation of pure vapor are widely adopted by passive safety systems of advanced nuclear reactors to remove the decay heat. Accurate calculation of the in-tube condensation heat transfer coefficient is important for evaluating the heat removal ability. A better understanding of the mechanism of pure vapor condensation heat transfer and its modelling are essential for the design and assessment of those passive safety systems. An analytical model for pure vapor condensation in a vertical tube is developed based on mass, momentum and energy conservation equations. The total axial pressure drop is calculated through the momentum equation of the vapor core assuming a uniform radial pressure distribution. An optimized transition area between the laminar and turbulent film flow is defined to avoid discontinuity of heat transfer coefficients. Based on the sensitivity analyses, Kay's turbulent eddy diffusivity model and his turbulent Prandtl number model were recommended for the newly proposed model. The predicted results were compared with results of Shah (2016a,b), Chen et al. (1987) and Cavallini et al. (2002) correlations as well as Kuhn's and KAIST experimental data. It was found that the proposed model predicts the heat transfer coefficient well with a mean absolute deviation of 11.99% for Kuhn's data and 8.08% for KAIST's data.

1. Introduction

In-tube condensation has been widely used in heat exchangers of many power conversion systems. In the field of nuclear energy, it is applied by passive safety systems to remove decay heat, such as the Isolation Condenser of the SBWR (Khan and Rohatgi, 1992), the emergency condenser of the SWR1000 (Schaffrath et al., 1999), the Passive Containment Cooling System of the KNGR (Cho et al., 2000), and the Passive Residual Heat Removal System of the SMART reactor (Chung et al., 2006). Particularly among those applications, pure vapor downflow condensation in vertical tubes was adopted by the passive residual heat removal systems. A better understanding of the mechanism of pure vapor condensation heat transfer and its modelling are essential for the design and assessment of those passive safety systems.

In vertical tubes, pure vapor downflow condensation starts from the annular flow regime, where a thin liquid film flows attaching the tube wall, while the vapor flows in the core region. The thickness of the liquid film grows gradually, and the flow regime may change to slug flow, bubbly flow, etc. However, the annular flow is considered to be the most predominant flow regime, which contributes the most in condensation heat transfer process. When the liquid film is thin, the film flow is laminar and the heat transfer mechanism is dominated by heat conduction. With the increase of the film thickness, the film flow transits to turbulent flow, where the shear stress at the interface and the eddy in the film highly affect the condensation heat transfer. Due to the interfacial waves, the entrainment and deposition of droplets may

* Corresponding author.
E-mail address: jqshan@mail.xjtu.edu.cn (J. Shan).

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Nomenclature

A	flow area (m^2)
c_p	specific heat (J/(kg·K))
d	tube diameter (m)
D_{ep}	the droplets deposition rates (kg/(m^2·s))
E_n	droplet entrainment rate (kg/(m^2·s))
f	friction coefficient
g	gravitational acceleration (m/s^2)
G	mass flux rate (kg/(m^2·s))
h	heat transfer coefficient (kW/(m^2·K))
h_{fg}	latent heat (kJ/kg)
J_v	Dimensionless vapor velocity
k	thermal conductivity (W/(m·K))
Pr_t	turbulent Prandtl number
dP/dz	pressure gradient (Pa/m)
p	perimeter (m)
q	heat flux (kW/m^2)
r	tube radius (m)
Re	Reynolds number
S	heat source (J/s)
T	temperature (°C or °F)
u	velocity (m/s)
W	mass flow rate (m/s)
x	quality
y	distance from the tube wall (m)
z	axial location (m)

Greek symbols

α	void fraction
δ	film thickness (m)
ε_h	turbulent eddy thermal diffusivity (m^2/s)
ε_m	turbulent eddy diffusivity (m^2/s)
η	thermal diffusivity of water (m^2/s)
μ	dynamic viscosity (Pa·s)
ν	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)
τ	shear stress (N/m^2)
Γ	interfacial mass transfer rate (kg/(m·s))

Subscripts

cv	control volume
F	friction
v	vapor
G	gravity
i	interfacial
l	liquid
lo	lower bound
M	momentum
sat	saturation
up	upper bound
w	wall

Superscripts

+	dimensionless symbol

also play important roles on the condensation heat transfer (Kim and Mudawar, 2012).

In the past decades, a large amount of investigations on condensation heat transfer in vertical tubes have been conducted experimentally and theoretically. Based on the experimental databases, a lot of empirical and semi-empirical correlations have been developed. These correlations can be divided into three categories: two-phase multiplier based models, interfacial shear stress based models and boundary layer based models. The heat transfer coefficient (HTC) of the two-phase multiplier models can be calculated through multiplying that of the single-phase flow by a two-phase multiplier. Cavallini and Zecchin (1974) proposed a simple two-phase multiplier model, which was a semi-empirical correlation, for annular film flow condensation. Based on Chato (1960) model, Dobson and Chato (1998) presented a model which is applicable to stratified-wavy flow and annular flow. Shah (2009) proposed an improved version of his earlier model (Shah, 1979) and it could be used within a wider range of parameters. More recently, he (Shah, 2016a,b) developed a set of comprehensive correlations for condensation heat transfer in conventional as well as mini/micro channels in all orientations. A flow regime map for horizontal tubes was introduced, while the correlations for vertical tubes remained the same as those of Shah (2009). As for mini/micro channels, Shah classified three flow regimes and used Weber number and dimensionless vapor velocity as the transition criteria. Due to their simple forms, the two-phase multiplier based models are widely used in the thermal hydraulic codes such as RELAP5 and MARS (Chung et al., 2010; Ransom et al., 2001). The shear stress-based model assumes that the sub-layer of the laminar film acts as the dominant thermal resistance. Carpenter and Colburn model (Carpenter and Colburn, 1951), Soliman model (Soliman et al., 1968) and Chen model (Chen et al., 1987) belong to the shear stress based models. The boundary layer-based models consider the entire film as the dominant thermal resistance. They are similar to the analytical models that employ the momentum and heat transfer analogy. The representative models of this category are Kosky and Staub model (Kosky and Staub, 1971), Traviss model (Traviss et al., 1973), Moser model (Moser et al., 1998) and Cavallini model (Cavallini et al., 2002). Although there are a lot of correlations for predicting the heat transfer coefficient of in tube condensation, all correlations are limited by range of their correlating databases. In this paper, the results of the proposed model are compared with Shah (2016a,b), Chen et al. (1987) and Cavallini et al. (2002) correlations, which are chosen as the representatives of three categories of correlations.

Theoretical studies on pure vapor condensation in vertical tubes are usually carried out with analytical models based on the application of mass, momentum and energy conservation principles. The general calculation algorithm assumes an initial value of film thickness, and then calculates the heat transfer coefficient by energy conservation equation and the film velocity distributions by momentum conservation equation. Finally, it checks the convergence of the mass equation and obtains the film thickness by iteration. The main differences among the analytical models are how the effects of interfacial shear stress, pressure drop and turbulence are considered. Pure vapor in-tube condensation starts from laminar film flow and then transits to turbulent film flow as the condensate accumulates. For laminar film flow, most of the models apply the conservation principle only to the liquid film, neglecting the pressure drop and calculating the interfacial shear stress by correlations. Nusselt (1916) applied the boundary layer type equations for the liquid film on a vertical plate. The pressure drop and the interfacial shear stress were neglected so that the film velocity distribution and film thickness could be obtained by integration. However, the recent studies showed that these assumptions might cause significant inaccuracy (Oh and Revankar, 2005). Peterson