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Level-set based numerical simulation of film condensation in a vertical downward channel flow

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ABSTRACT

Numerical simulation of film condensation in a vertical downward channel flow is performed by employing the sharp-interface level-set method which can accurately implement the saturation temperature and phase-change mass flux conditions at the liquid-vapor interface. An analytical model for the internal film condensation is also developed by including the effect of vapor flow in the classical Nusselt model. The numerical results for film condensation in the laminar regime show good agreement with the analytical solutions. The level-set method is applied to investigate the effects of vapor velocity and wall temperature on the condensate film thickness and heat flux in the laminar and wavy regimes.

1. Introduction

Film condensation is a common phenomenon in two-phase heat exchangers for power generation, refrigeration and high-power device cooling. The process has three different regimes depending on the interface motion: laminar, wavy and turbulent regimes [1]. The condensate film is thin in the laminar regime and its interface is smooth and steady. As the film thickness increases due to condensation, the interface has an unsteady regular wavy motion and then the condensate flow becomes turbulent. Extensive studies have been conducted to develop a predictive model for the film condensation during the last century.

Nusselt [2] first proposed a theoretical model for laminar film condensation on a plate. Assuming that the liquid inertia is negligible and the vapor has no shear stress on the condensate film, he developed the explicit expressions for film thickness and heat transfer coefficient. Several researchers improved the Nusselt model by including the effects of liquid inertia and vapor shear stress, as reviewed in Refs. [3-5]. The theoretical model was extended by Lucas and Moser [6] for laminar film condensation in a vertical downward tube flow assuming that the vapor flow is fully developed at the inlet. Pan [7] developed a theoretical model for laminar and turbulent internal condensing flows by introducing a modification factor for the interfacial shear stress with mass transfer and the theoretical or empirical correlations for the friction factor.

As a more general analysis of film condensation, numerical simulations were performed in a number of studies, as reviewed in Ref. [8]. The volume-of-fluid (VOF) method, which was coupled to the Lee model [9] for evaluation of the mass flux due to phase change at the interface or the corresponding mass source for each phase, were widely used for computations of film condensation in various configurations including vertical (downward or upward) flows [10-12], horizontal flows [13,14] and microchannel flows [15]. The Lee model, where the mass source is evaluated from the temperature difference from the saturation temperature rather than the temperature gradient at the interface, is easy to implement for the VOF method in commercial CFD codes, such as FLUENT. However, the coefficient of the Lee model, which is called the mass transfer intensity factor, could not be determined in general so that its value varied by orders of magnitude depending on the problem, as indicated in Refs. [8,12,16].

In the earlier work of Zhang et al. [17], the VOF method was applied to convective condensation in horizontal miniature channels and the mass source due to phase change was determined by imposing the saturation temperature condition to the cells near the interface. Ganapathy et al. [18] performed numerical simulations of flow condensation in microchannels using the VOF method with the mass source evaluated from the heat flux jump at the interface. This phase-change model has advantages in that it does not require any artificial coefficient, unlike the Lee model. However, it is not easy to calculate the liquid-side and

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Nomenclature

c	specific heat
F	fraction function
g	gravity
h	grid spacing
h_{lv}	latent heat of vaporization
H	domain height
L	domain length
$\dot{m}$	mass flux across the interface
$\mathbf{n}$	unit normal vector
p	pressure
q	heat flux
Re_f	liquid film Reynolds number
t	time
t^*	artificial time
t_r	relative time
T	temperature
ΔT_w	wall subcooling, $T_w - T_{sat}$
$\mathbf{u}$	flow velocity vector, (u,v)
x, y	Cartesian coordinates

Greek symbols

α	step function
β	$\rho_v^{-1} - \rho_l^{-1}$
δ	liquid film thickness
κ	interface curvature
λ	thermal conductivity
μ	dynamic viscosity
ρ	density
σ	surface tension coefficient
τ	shear stress
ϕ	distance function from the liquid-vapor interface

Subscripts

f	fluid
i	inlet
l, v	liquid, vapor
s	liquid-vapor interface
sat	saturation
w	wall

Superscripts

-	area averaged
^	effective property

vapor-side heat fluxes at the interface separately while using the VOF method.

Miyara [19] presented another numerical method for film condensation, where the condensate film thickness is expressed as a function of time and the streamwise coordinate and thus the saturation temperature and phase-change mass flux conditions at the interface is straightforward to implement. The method was applied to investigate the interface motion and heat transfer in wavy film condensation on a vertical plate. Narain et al. [20] improved the film thickness based method for internal condensing flows with wavy interfacial oscillations by using a characteristic scheme for solving the interface tracking equation and adaptive grids. The method was successfully applied to wavy film condensation on a vertical plate and various internal condensing flows [21-23]. However, the Lagrangian method generally is not easy to extend to the interface configurations with large distortion or change in topology, unlike the Eulerian interface capturing methods such as the VOF method.

As another Eulerian method, a level-set (LS) method was developed for various boiling and evaporation problems [24-29], but it was not applied to film condensation. One of the major difficulties in computation of film condensation is the handling of a very thin condensate film, which requires a very nonuniform grid. If the LS method is based on diffuse-interface modeling, in which the interface is treated as a transition region smoothed over several grid spacings, it is not so efficient to extend to film condensation using a nonuniform grid where the thickness of interface region can be larger than the film thickness. The LS method can be improved by employing the ghost fluid method (GFM) [30-34] as a numerical technique for sharply enforcing the interface conditions without being smeared-out over several grid spacings.

In this work, the sharp-interface LS method is applied to film condensation in a vertical downward channel flow. The method has advantages in accurately imposing the saturation temperature and phase-change mass flux conditions at the interface compared with the VOF method. An analytical model for the internal film condensation is also developed to validate the present numerical

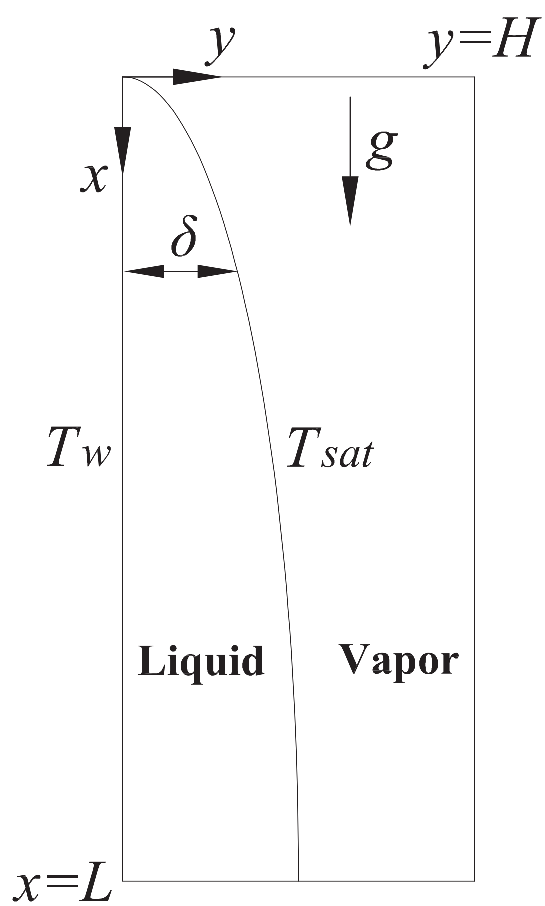

Fig. 1. Configuration of liquid and vapor layers in computation of film condensation.