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Numerical study on modeling of liquid film flow under countercurrent flow limitation in volume of fluid method

Taro Watanabe [a,*], Takashi Takata [b], Akira Yamaguchi [c]

[a] Graduate School of Engineering, Osaka University, 2-1, Yamadaoka, Suita-shi, Osaka 565-7895, Japan
[b] Japan Atomic Energy Agency, 4002 Narita-chou, Oarai-machi, Higashi-Ibaraki-gun, Ibaraki 331-1393, Japan
[c] Graduate School of Engineering, The University of Tokyo, 2-22 Shirakata-Shirane, Tokai-mura, Naka-gun, Ibaraki 319-1188, Japan

HIGHLIGHTS

- Thin liquid film flow under CCFL was modeled and coupled with the VOF method.
- The difference of the liquid flow rate in experiments of CCFL was evaluated.
- The proposed VOF method can quantitatively predict CCFL with low computational cost.

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ABSTRACT

Countercurrent flow limitation (CCFL) in a heat transfer tube at a steam generator (SG) of pressurized water reactor (PWR) is one of the important issues on the core cooling under a loss of coolant accident (LOCA). In order to improve the prediction accuracy of the CCFL characteristics in numerical simulations using the volume of fluid (VOF) method with less computational cost, a thin liquid film flow in a countercurrent flow is modeled independently and is coupled with the VOF method. The CCFL characteristics is evaluated analytically in condition of a maximizing down-flow rate as a function of a void fraction or a liquid film thickness considering a critical thickness. Then, we have carried out numerical simulations of a countercurrent flow in a vertical tube so as to investigate the CCFL characteristics and compare them with the previous experimental results. As a result, it has been concluded that the effect of liquid film entrainment by upward gas flux will cause the difference in the experiments.

1. Introduction

A heat removal by reflux condensation of vapor at a steam generator (SG) is considered as one of possible core cooling measures under a loss of coolant accident (LOCA) especially in a pressurized water reactor (PWR). In the reflux condensation, a countercurrent flow is formed in a heat transfer tube at the SG. In the heat transfer tube, the vapor generated in the core flows upward in the center, whereas condensed water flows downward along the peripheral. When the upward velocity of the vapor phase increases, the downward water flow rate will be suppressed and vanish finally. This process is designated as a countercurrent flow limitation (CCFL). The CCFL affects the cooling performance in the reactor, therefore it is important to estimate the CCFL characteristics. In particular, the CCFL condition in which downward water flow rate becomes zero or no liquid film exists in the tube, is quite important because of the criteria of operating limit of reflux condensation by the SG.

A flooding, in which a disturbance of gas-liquid interface occurs and thus a liquid flow rate becomes unstable, takes place under the CCLF condition. Generally, CCFL characteristics is expressed by using the Wallis correlation or Wallis parameters (Wallis, 1969) which are respectively defined as follows:

$$\sqrt{J_G^*} + m\sqrt{J_L^*} = C, \tag{1}$$

$$J_k^* = J_k\sqrt{\frac{\rho_k}{g \cdot D_w(\rho_L - \rho_G)}}, \quad (k = G, L), \tag{2}$$

where J [m/s] is the volumetric flux, J^* is the non-dimensional volumetric flux, m and C are the empirical constants, D_w [m] is the characteristic length, g [m/s^2] is the gravity acceleration, and

* Corresponding author.
E-mail addresses: watanabe_t@qe.see.eng.osaka-u.ac.jp (T. Watanabe), takata.takashi@jaea.go.jp (T. Takata), yamaguchi@n.t.u-tokyo.ac.jp (A. Yamaguchi).

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Nomenclature

A	constant [−]
B	constant [−]
B_o	non-dimensional number [−]
C	constant [−]
D	diameter or flow channel width [m]
D_e	hydraulic diameter [m]
D_w	characteristic length in Wallis parameter [m]
f	VOF function [−]
f_k	friction coefficient [−]
g	gravity acceleration [m/s^2]
G_{in}	inflow rate of mass in virtual liquid film flow model [kg/s]
G_{out}	outflow rate of mass in virtual liquid film flow model [kg/s]
G_{VOF}	exchange mass flow rate in virtual liquid film flow model with VOF simulation [kg/s]
J	volumetric flux [m/s]
J^*	non-dimensional volumetric flux [−]
$J_{k,VOF}$	volumetric flux of VOF simulation [m/s]
J_{max}	volumetric flux calculated from liquid film flow model [m/s]
m	constant [−]
n	constant [−]
p	pressure [Pa]
Re	Reynolds number [−]
u	bulk velocity [m/s]
V_{cell}	volume of control volume [m^3]
Δy	mesh size adjacent to wall [m]

Greek letters

α	void fraction [−]
δ	liquid film thickness [m]
δ_{max}	liquid film thickness calculated from liquid film flow model [m]
δ_{min}	critical thickness of liquid film [m]
ν	dynamic viscosity [m^2/s]
ρ	density [kg/m^3]
σ	surface tension [N/m]
τ	shear stress [Pa]

Subscripts

G	gas phase
L	liquid phase
i	interface
w	wall

ρ [kg/m^3] is the density. The subscripts G and L denote the gas and liquid phases, respectively.

In the CCFL characteristics, it has been reported that a geometrical factor, such as a horizontal pipe length to diameter ratio and an inclination angle, affect the characteristic. (Vallée et al., 2011; Prayitno, 2012). Consequently, a numerical simulation based on CFD will be an alternative way to investigate the CCFL characteristic in detail (Kinoshita, 2010; Murase et al., 2012). A volume of fluid (VOF) method has an advantage to investigate a gas-liquid interaction directly and thus a quantitative investigation has been carried out in case of a horizontal pipe (Murase et al., 2012).

The geometrical factors also affect the CCFL characteristics in a vertical pipe (Bankoff and Lee, 1983; Jeong and No, 1994). In a vertical pipe, a thin liquid film will appears inside the pipe. Therefore, numerical investigation becomes more difficult in case of a vertical pipe comparing with that in a horizontal pipe. For instance, Kusunoki et al. (2014) carried out numerical simulations using the VOF method to investigate the influence of the fluid properties on the CCFL characteristics at a lower end of the vertical tube. In the simulations, water was injected through an inner wall of tube to achieve the flooding at the lower end. However, it was reported that computations with turbulent models (the standard k-ε and the k-ω SST models) were unstable for pressures lower than 1.0 MPa. Computations with laminar model were stable but overestimated falling water flow rates.

In the present paper, a thin liquid film flow is modeled independently and is coupled with the VOF method in order to enhance a prediction accuracy of the CCFL characteristics with a low computational cost. Firstly, the CCFL characteristics of a flow rate and a film thickness are evaluated analytically by using one-dimensional liquid film flow model when a spatial resolution in the VOF computation is insufficient to depict the phenomenon. Then, the conservations of mass and the VOF function are updated in the VOF method if necessary. We also have carried out preliminary computations of a countercurrent flow in a vertical tube so as to investigate an applicability of the present model and the CCFL characteristics.

2. Liquid film flow model under countercurrent flow

In the liquid film flow model, an annular flow is assumed with non-condensable gas-liquid (air-water). One-dimensional governing equations under the steady state flow are derived from the momentum balance at the cylindrical coordinate. In our previous study (Watanabe, 2014), we have demonstrated that the prediction accuracy of the CCFL characteristics with the governing equations based on a bulk momentum balance have superiority rather than those on a boundary layer approximation by comparing with the experimental result (Richter, 1981). Hence the model based on the bulk momentum balance is used in the present study. Furthermore, a concept of the critical film thickness is introduced so as not to evaluate unrealistic film thickness.

2.1. Governing equations

Fig. 1 shows a steady state countercurrent annular flow in a vertical tube. In this model, local velocity distributions of gas and liquid phases are not taken into consideration. Instead, the bulk velocities of gas (u_G) and liquid (u_L) are used. This one-dimensional model is originally proposed by Sudo (1994) and Monde (1995). δ is a liquid film thickness. τ_i and τ_w are the interface and wall shear stresses, respectively. Even though the liquid film thickness fluctuates under the CCFL, the time averaged δ and the velocity of a liquid film (u_L) are assumed to be constant when gas flow rate is constant in the steady state flow.

Control volume I consists of an overall flow in a cross-section, and Control volume II consists of only a gas phase. α in Fig. 1 is the void fraction and is calculated as $\alpha = (1 - 2\delta/D)^2$. The momentum balance of Control volume I is:

$$-\frac{\partial p}{\partial z}\frac{\pi D^2}{4} + \tau_W \pi D - [\rho_G \alpha + \rho_L (1-\alpha)] g \frac{\pi D^2}{4} = 0. \tag{3}$$

Then, the momentum balance of Control volume II is:

$$-\frac{\partial p}{\partial z}\frac{\pi D^2}{4}\alpha - \tau_i \pi D \sqrt{\alpha} - \rho_G \alpha g \frac{\pi D^2}{4} = 0. \tag{4}$$