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# Analysis of Wall film Condensation with CUPID in the Presence of Non-Condensable Gases

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## 1. Introduction

In the nuclear reactor safety, the film condensation in the presence of non-condensable gases is highly safety relevance since it is closely associated with the performance of components installed for the containment cooling in accident conditions, such as passive containment cooling systems. However, when non-condensable gases are present during condensation, the heat transfer can be degraded significantly by the accumulation of non-condensable gases near the interface between the liquid film and the gas mixture [1]. Therefore, a large number of experiments and analytical studies have been performed to investigate these phenomena and obtain accurate knowledge about condensation rates and heat transfer rates.

In this study, the wall film condensation model with a non-condensable gas was implemented into the CUPID code and a conceptual problem for condensation in a large system was analyzed. This paper introduces the implemented non-condensable gas mass diffusion model for CUPID and wall film condensation model. Then presents the simulation results using CUPID with the model for a conceptual condensation problem of Dehbi [2].

## 2. Implementation of mass diffusion model into CUPID

CUPID includes the mass conservation equation of the non-condensable gas so that the gas mixture simulation of steam and a non-condensable gas can be calculated. Nevertheless, it neglects the mass and energy transfer due to a species diffusion induced by the spatial gradient of their mass fractions. For this reason, CUPID limits its gas mixture simulation capability to a highly convective flow where the effect of the mass diffusion can be ignored. However, in the wall film condensation simulation, the mass diffusion of non-condensable gas plays an important role when code estimates the non-condensable gas mass fraction in a computational cells. If a condensation occurs, the non-condensable gas accumulates near the interface between the gas mixture and the liquid film. At the same time, the accumulated non-condensable gas can be diluted by the species mass diffusion. Therefore, the non-condensable gas mass fraction can be over-predicted without considering the mass diffusion because of the overestimated accumulation. This certainly results in the underestimation of the film condensation rate. For this reason, the mass diffusion of the gas species and subsequent energy transfer with the species transport were implemented in the CUPID code to extend its capability to the film condensation. The modified species mass conservation equation and the energy transport equation are given by below equations.

$$\frac{\partial}{\partial t}(\alpha_g \rho_g m_n) + \nabla \cdot (\alpha_g \rho_g m_n \vec{U}_g) = \underline{\nabla \cdot \left(\alpha_g \rho_g D \nabla m_n\right)} \tag{1}$$

$$\begin{aligned} \frac{\partial\left(\alpha_g \rho_g e_g\right)}{\partial t} + \nabla \cdot \left(\alpha_g \rho_g e_g \vec{U}_g\right) &= -P\frac{\partial \alpha_g}{\partial t} - P\nabla \cdot \left(\alpha_g \vec{U}_g\right) + \dddot{q}_g \\ &+\nabla\left(\alpha_g \vec{q}_g\right) + \frac{P_s}{P} H_{ig}\left[T_s\left(P_s\right) - T_g\right] + \Gamma_v h_g^* - \left(\frac{P-P_s}{P}\right) H_{fg}\left(T_g - T_l\right) \\ &+\underline{\nabla \cdot \left[\alpha_g \rho_g D(h_n - h_v)\nabla m_n\right]} \end{aligned} \tag{2}$$

where $m_n$ is the non-condensable gas mass fraction, $h_n$ is the non-condensable gas enthalpy, $h_v$ is the vapor enthalpy, and $D$ is the effective diffusivity which is the sum of the molecular diffusivity [3] and turbulent diffusivity [4]. The two terms underlined were added for the film condensation simulation in the present work.

For the verification of the implemented mass diffusion model, a conceptual problem was simulated and the calculation result was compared with STAR-CCM+ result. Fig. 1 gives the problem description and indicates the computational domains, initial and boundary conditions. The two-dimensional channel has 10 m width and 24 m height as in Dehbi's conceptual problem [2]. Initially, the channel was filled with a steam-air mixture with 50 % steam by mass. Then, a steam-air mixture was injected from the inlet with air mass fractions of 80% and 50% for the central region and the other regions, respectively. The inlet fluid velocity and temperature were 0.3 m/s and 405 K. Fig. 2 showed compared results with the STAR-CCM+ calculation and they showed a good agreement with each other. Supported by these simulations of a conceptual problem, it was verified that the mass diffusion model had been implemented into CUPID appropriately.

## 3. Implementation of film Condensation model into CUPID

In the film condensation process, a thin liquid film is created on the condensate wall and it flows down along the wall. Generally, the thickness of the liquid film is too thin to resolve so that a sub-grid liquid film model was implemented into CUPID in order to capture its behavior. [5]

CUPID gives the liquid film mass flow rate ($\Gamma_f$), the pressure drop and the gas velocity in the wall adjacent cells to the liquid film model, then solves a momentum equation for the liquid film with the given mass flow rate and evaluates the wall and interfacial shear stresses. The evaluated stresses are transferred to CUPID and employed in the momentum equations of the two-fluid model.

A wall film condensation model was implemented into CUPID after the implementation of the liquid film model. For the analysis of wall film condensation in the large system like containment wall, the wall film condensation model proposed by Ghiaasiaan [6] and Naylor and Friedman [7] was applied in CUPID. [8]

The followings are the equations for the condensation model.

- The interface temperature

$$T_i = T_s\left(X_{v,i}P\right) \tag{3}$$

where $T_i$ represents interface temperature, $X_{v,i}$ is vapor mole fraction at the interface.

- Mass fraction at the interface

$$m_{v,i} = \frac{X_{v,i}M_v}{X_{v,i}M_v + (1-X_{v,i})M_n} \tag{4}$$

where $M_v$ and $M_n$ represent molecular weights of vapor and non-condensable gas, respectively.

- Condensation mass flux

$$m'' = -K_{g,i}\ln\left(\frac{1-m_{v,b}}{1-m_{v,i}}\right) \tag{5}$$

where $K_{g,i}$ is the mass transfer coefficient. The mass transfer coefficient is obtained from wall function approach introduced in Martın-Valdepenas et al. [9] based on the heat and mass transfer analogy.

$$K_{g,i} = H_{g,i}\left(\frac{\rho_g D_g}{k_g}\right)\left(\frac{Sc}{\Pr}\right)^{1/3} \tag{6}$$

In this equation, the condensation, mass transfer coefficient ($K_{g,i}$) is evaluated from the convection heat transfer coefficient ($H_{g,i}$), calculated using the wall law.

- Heat balance equation

$$H_{g,i}(T_g - T_i) - \frac{k_f}{\delta_f}\left(T_i - T_w\right) + m''h_{fg} = 0 \tag{7}$$

where $\delta$ is the liquid film thickness from the liquid film model and the liquid-side heat transfer rate is obtained with the assumption that temperature profile of liquid film is linear.

A solution procedure is shown in Fig. 3. For the calculation, the mole fraction is assumed at first, and interface temperature and mass fraction of vapor are calculated using given mole fraction. Thereafter, the condensation mass flux at the gas/liquid interface was calculated using mass fraction, then total mass flow rate of a liquid film could be obtained from the condensation mass flux and the convective mass flow rate from the upstream cell. When the total mass flow rate is determined, the film thickness could be calculated from liquid film model. With the calculated film thickness, the interfacial heat transfer coefficient, and the condensation mass flux, the satisfaction of the heat balance equation at the interface, Eq. (7), is evaluated. By an iterative solution method, the solutions of Eqs. (3)~(7) can be obtained and the calculation proceeds to next cell.

## 4. Verification of the implemented model for a large system

The wall film condensation model was implemented into CUPID and a conceptual problem of Dehbi[2] as shown in Fig. 4 was simulated. Dehbi’s conceptual problem simulates the flow over a hypothetical vertical wall condenser which is 20 m long with 360 K temperature. A steam-air mixture with 50% steam by mass is assumed to enter the channel from the top with a low velocity of 0.3 m/s. The fluid entrance temperature was set to 405 K and the domain was held at 4 bar pressure.

Figs. 5-8 show the CUPID simulation results conducted with wall film condensation model. As the gas mixture meets the cold wall and the condensation starts, the void fraction near the condensate wall decreases as shown in Fig. 5-(a). At the same time, the air mass fraction in the wall adjacent cells increases sharply near the condenser top due to the reduction of the steam mass by the condensation as indicated in Fig. 5-(b) and Fig. 6. Proceeding downward from the condenser top, due to the increasing density of gas mixture with the air mass fraction, the gas velocity is accelerated as seen in Fig. 7. It results in the increase of the turbulent viscosity and accordingly, turbulent diffusivity. It should be noted that the air mass fraction along the condensate wall is determined by the sum between its accumulation due to the wall condensation and the dilution due to the mass diffusion. In the present simulation result of Fig. 6, the air mass fraction increases rapidly as the condensation starts, but it makes a turnaround and then decreases slowly as the turbulent mass diffusion effect becomes significant. Due to increasing velocity along the condenser wall and the decreasing non-condensable gas mass fraction below a certain elevation, the wall heat flux and the condensation mass flux increase gradually as shown in Fig. 8.

However, as shown in Fig. 8, the inclination of the heat flux curves were lower in the CUPID simulation and therefore, the heat flux in the upper part of the condensate wall (distance from the condenser top < 5 m) was over-predicted, while that in the lower part was under-predicted when compared with the single-phase approach. This discrepancy can be explained by the relative velocity between the gas and the interface. In the single-phase approach, the wall boundary for the gas is the no-slip wall since the liquid film is neglected. However, in the two-phase approach, the wall boundary for gas is the downward liquid film interface. The momentum, heat and mass transfers are significantly influenced by the relative velocity and its decrease may cause the deceleration of the increasing trend of the wall heat flux. However, in the single phase approach, the decreasing trend of the relative velocity cannot be considered and the evaluated wall heat flux increases more steeply than in the CUPID result. This difference in the interface velocity treatment can be attributed to the reason of the different inclination of the heat flux, and the effect of the decreasing relative velocity is deemed important when the condensate wall is long so that the liquid film is accelerated sufficiently.

Different from the single-phase flow approaches, this model is able to consider the thermal resistance of the liquid film and the influence of the liquid velocity on the gas velocity. This implies that this two-phase flow approach can be applied for more general applications where the liquid film cannot be ignored.

## 5. Conclusions

In the present study, a two-fluid model CMFD code, CUPID was modified and improved for modeling a wall film condensation in the presence of non-condensable gases. This implemented model was verified by solving the Dehbi's conceptual problem and comparing the results with single-phase approaches. A fairly good agreement was obtained between the present approach and the other even though a discrepancy in the inclination of the condensation heat flux was observed due to the difference in the treatment of the interface velocity.

In the future, more validation will be performed with this film condensation model for the two-fluid model against various experimental databases, not only for the vertical flat plate but also for tube geometry in order to extend its capability to a passive containment cooling system where a film condensation occurs on a tube bundle.

## Acknowledgement

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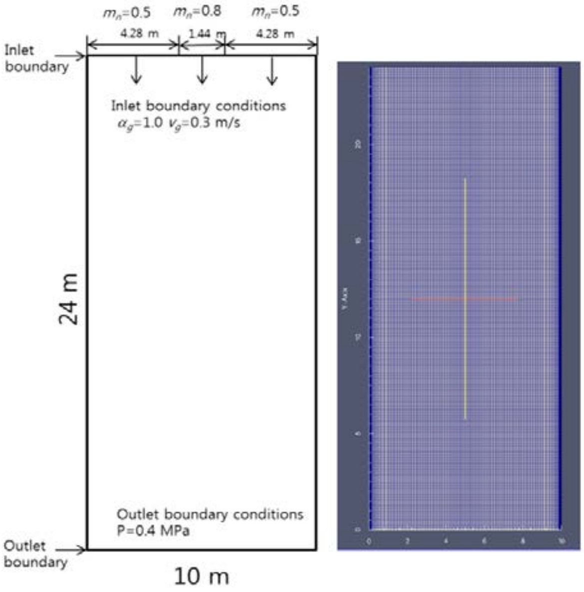


Fig. 1. Conceptual problem for mass diffusion of non-condensable gas

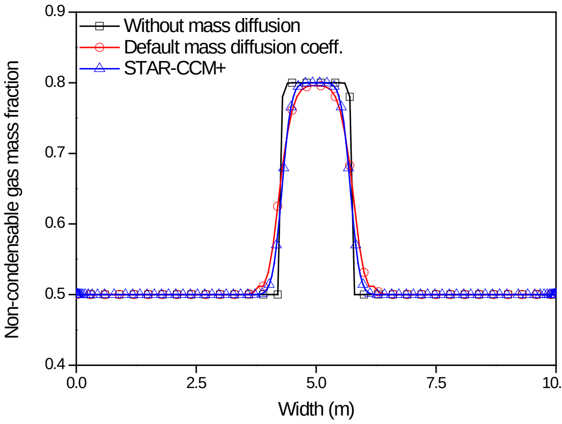


Fig. 2. Code-to-code verification result: CUPID vs. STAR-CCM+

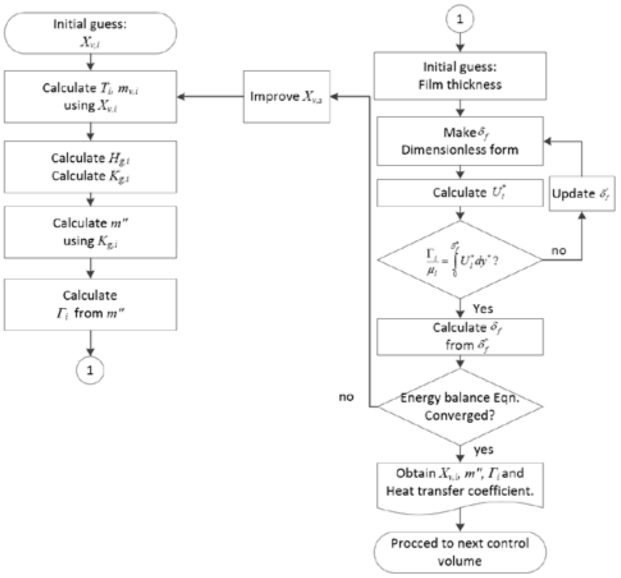


Fig. 3. Flowchart of the wall condensation model

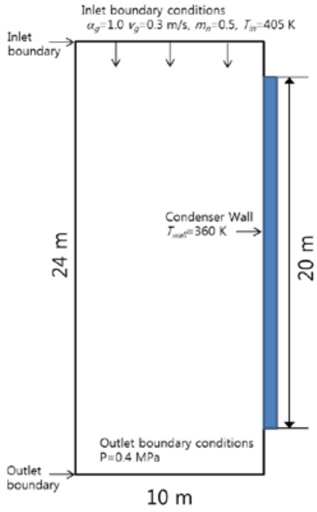
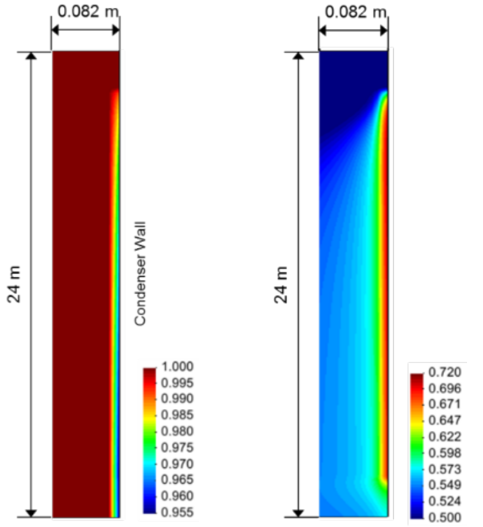


Fig. 4. Dehbi condensation problem condition



(a) Void fraction (b) Air mass fraction

Fig. 5. Calculation result: void fraction

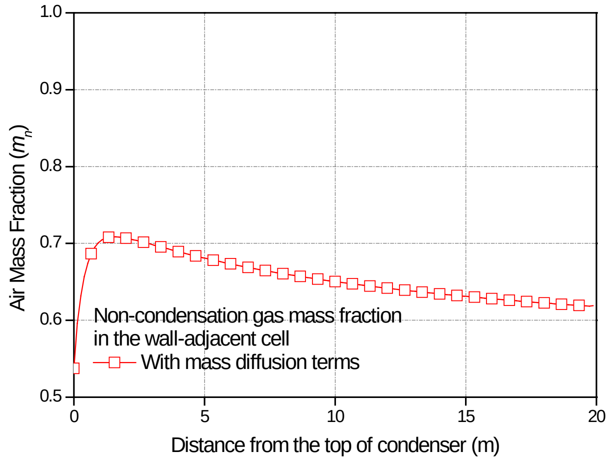


Fig. 6. Calculation result: air mass fraction

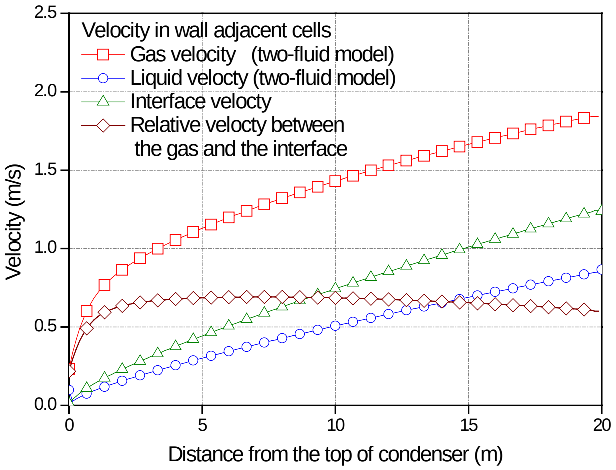


Fig. 7. Calculation result: gas/liquid velocity

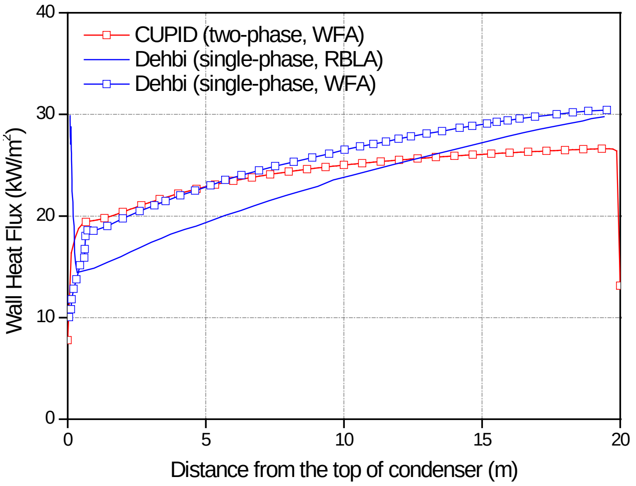


Fig. 8. Comparison between CUPID and Dehbi's calculation results