Application of a Mechanistic Liquid Film Model to Advance Condensation Heat Transfer Analysis in Passive Heat Sinks of Containment

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1. Introduction

Since the Fukushima accident, the importance of passive heat sinks for heat removal and severe accident mitigation has been increasingly emphasized.

Since passive heat sinks, such as liner plates and concrete walls, are the primary means of removing heat from the containment building when the spray system fails in multiple failure accidents, a precise analysis of condensation behavior is essential.

In typical condensation analyses, the condensate film is either neglected or simplified using the Nusselt liquid-film model [1]. The Nusselt model is based on several simplifying assumptions—laminar flow, constant thermophysical properties, pure saturated steam, and negligible interfacial shear stress—which limit its applicability to the complex thermo-fluid phenomena inside large-scale containments. Moreover, because the Nusselt model determines film thickness first from the wall and subsequently calculates the film mass flow rate and velocity profile, it becomes difficult to consistently reflect changes in condensation conditions.

In this study, the mechanistic liquid-film model is implemented based on the momentum equation for film flow proposed by Ghiaasiaan [2], enabling quantitative prediction of the downward-flowing condensate film along a condensation surface while explicitly accounting for interfacial shear stress. In this model, dimensionless film thickness, downward velocity, and interfacial shear stress are defined, and the velocity distribution within the film is obtained from the momentum equation. Based on the mass conservation, the condensation rate is directly transferred to the film mass flow rate, thickness, downward velocity profile, and interfacial shear stress.

To predict the influence of interfacial shear stress on liquid film behavior, the mechanistic liquid-film model was evaluated under the same film mass flow rate as calculated by the Nusselt model, and the results were compared with those of the Nusselt model.

In addition, the mechanistic liquid-film model was applied to simulate steam condensation in the presence of non-condensable gases, utilizing data from CONAN vertical plate condensation experiment.

2. Modeling

2.1 The solution of the liquid-film momentum equation

The liquid film model is presented by Ghiaasiaan with the assumption of a liquid film in a stagnant gas. The momentum equation of a liquid film is:

$$\frac{d}{dy}\left[(\nu_l + E)\frac{dU_l}{dy}\right] - \frac{1}{\rho_l}\frac{dP}{dz} + g\sin\theta = 0 \qquad (1)$$

where E is the eddy diffusivity in the liquid film. The boundary conditions were specified as $U_l = 0$ at the wall and $dU_l/dy = \tau_i/\mu_l$ at the film–vapor interface. The interfacial shear stress is given by:

$$\tau_i = \frac{1}{2} f_c \rho_b (u_b - u_i)^2 \qquad (2)$$

where ρ_b is the density of the mixture bulk, u_b is the velocity at the mixture bulk, u_i is the velocity at the film–vapor interface. f_c is the interfacial friction factor, which quantifies the momentum exchange between the bulk steam flow and the liquid film at the interface. It is expressed as a function of the interfacial Reynold number, Re_i, and the equations for both the laminar (Eq. (3)) and turbulent (Eq. (4)) flow regions—where the distinction is determined based on the Reynolds number of the mixture bulk flow—are derived as:

$$f_{c,l} = 0.664 {Re_i}^{-0.5} \qquad (3)$$

$$f_{c,t} = 0.0592 {Re_i}^{-0.2} \qquad (4)$$

2.2 Procedure for deriving the model solution

The nondimensional form of Eq. (1) can be integrated numerically when the mass flow rate (Γ_f) is specified and an initial estimate of the liquid film thickness (δ_f) is provided. In this study, the mass flow rate (Γ_f) was obtained from the condensation mass flux ($\dot{m}''_{v,i}$) by Yu's model [3]. Using this estimated thickness, the velocity profile within the film is computed. In the numerical procedure, the film thickness is discretized into 16 computational nodes.

The nondimensional form of Eq. (1) defined as:

$$\Gamma_f/\mu_l = \int_0^{\delta_f^*} U_l^*\, dy^* \tag{5}$$

U_l^* is the dimensionless velocity:

$$U_l^* = \frac{U_l}{\sqrt{\delta_f(1-\frac{\rho_g}{\rho_l})\mathrm{g}\sin\theta}} \tag{6}$$

δ_f^* is the dimensionless film thickness:

$$\delta_f^* = \frac{\delta_f}{\nu_l}\sqrt{\delta_f(1-\frac{\rho_g}{\rho_l})\mathrm{g}\sin\theta} \tag{7}$$

y^* is the dimensionless distance from the wall:

$$y^* = \frac{y}{\nu_l}\sqrt{\delta_f(1-\frac{\rho_g}{\rho_l})\mathrm{g}\sin\theta} \tag{8}$$

The resulting velocity profile is then integrated to verify compliance with Eq. (5). If the criterion is not satisfied, the assumed film thickness is iteratively adjusted until convergence is obtained, as shown in Fig. 1.

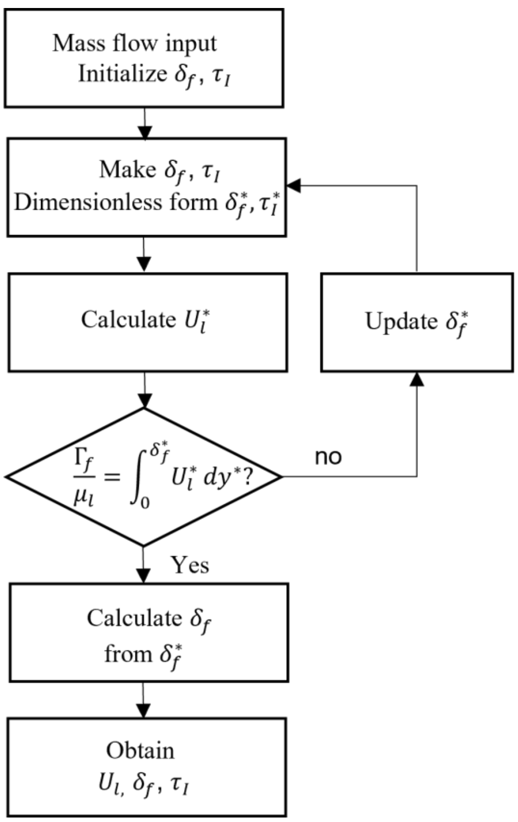

Fig. 1. Flow chart of the liquid-film model solution

3. Results

3.1 Comparative analysis of the mechanistic and Nusselt models under equal mass flow distribution

In this study, a vertical flat plate 1.8 m in height is considered, where pure steam condenses on the surface and a condensate film subsequently flows downward under gravity. The bulk steam flow velocity was 2.63 m/s, its temperature was 345.45 K, and the wall temperature was set to 315.45 K. When the mechanistic liquid-film model is applied with the mass flow rate (Γ_f) as calculated from the Nusselt model, the comparison of film thickness and interfacial velocity reveals clear differences. As shown in Fig. 3, the mechanistic model predicts a higher film velocity due to the interfacial shear stress exerted by the vapor. Consequently, as illustrated in Fig. 2, the film thickness becomes thinner compared to that predicted by the Nusselt model.

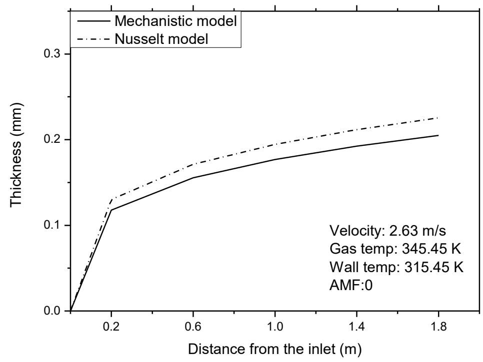

Fig. 2. Comparison of liquid-film thickness between the mechanistic model and the Nusselt model

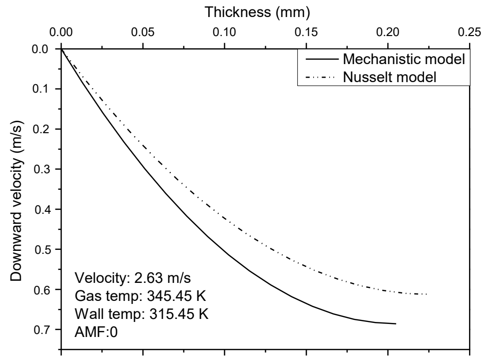

Fig. 3. Velocity profile of the liquid film at x = 1.8 m from the inlet

3.2 Liquid-film analysis in the CONAN (T30) experiments

To assess the model performance under forced convection with non-condensable gases, simulations were carried out based on the CONAN experiments [4] conducted at the University of Pisa, which studied the effect of non-condensable gases inside containment structures during hypothetical accidents.

In the analysis of CONAN experiments, it is necessary to consider the local air mass fraction that varies with the location of the condensation surface and the resulting changes in the thermodynamic properties of the mixture bulk. In this study, Yu's model [3] was utilized to update the bulk mixture properties at each location based on the calculated local air mass fraction and to calculate the condensation mass flux ($\dot{m}''_{v,i}$). In this way, the variation of non-condensable gas fraction with position and the associated changes in thermodynamic properties were incorporated into the analysis of the condensation. Table I shows the test conditions for each case.

As shown in Figs. 4–6, the end point of each curve corresponds to the film thickness up to the liquid–gas interface. Condensation mass flux ($\dot{m}''_{v,i}$) provides the mass flow rate (Γ_f), which varies depending on the air mass fraction. The mass flow rate (Γ_f) is then used as the input to the mechanistic liquid-film model, thereby determining the resulting film thickness and velocity profile. As a result, under higher air mass fraction conditions, the reduced mass flow rate (Γ_f) leads the model to predict a smaller film thickness and interfacial velocity, whereas under lower air mass fraction conditions, a larger mass flow rate (Γ_f) results in greater thickness and velocity. These results demonstrate that the model qualitatively reflects the influence of different air contents on steam condensation.

Table I: Specifications of the CONAN (T30) experiment cases.

Case	Velocity (m/s)	Wall Temp (K)	Gas Temp (K)	AMF
P10T30V25	2.57	303.55	348.75	0.716
P15T30V25	2.6	302.75	356.65	0.581
P20T30V25	2.59	303.85	364.65	0.37
P25T30V25	2.6	304.25	366.95	0.29
P30T30V25	2.62	307.95	370.15	0.155

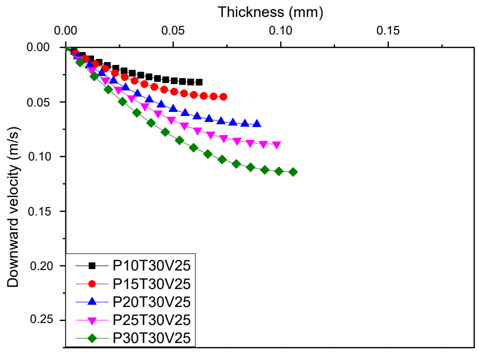

Fig. 4. Velocity profile of the liquid film at x = 0.2 m from the inlet in the CONAN (T30) experiments

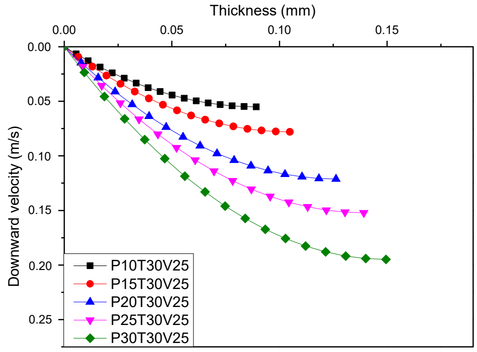

Fig. 5. Velocity profile of the liquid film at x = 1.0 m from the inlet in the CONAN (T30) experiments

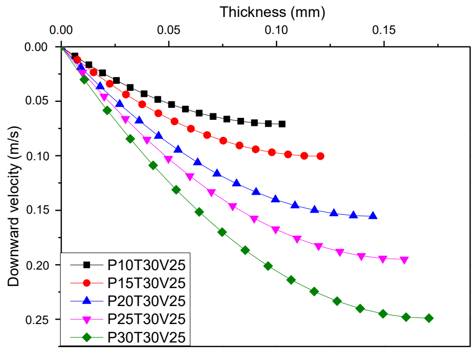

Fig. 6. Velocity profile of the liquid film at x = 1.8 m from the inlet in the CONAN (T30) experiments

4. Conclusions and Future Works

In this study, the mechanistic liquid-film model for steam condensation on passive heat sinks was implemented, which allows a more precise analysis of condensation behavior by accounting for interfacial shear stress. The model was applied to simulate the CONAN experiment in order to predict changes in liquid-film thickness and downward velocity with varying air mass fractions. A comparative validation was performed against the Nusselt model under the assumption of identical liquid-film mass flow distribution, demonstrating the distinct influence of interfacial shear. Furthermore, the model is planned to be extended by incorporating the re-evaporation phenomenon observed in recent studies on superheated-steam condensation, in order to enhance its applicability to realistic containment conditions.

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