

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

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Introduction

- ❖ 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.
- ❖ The conventional condensation analyses often neglect the condensate film or use the simplified Nusselt model. However, the assumptions of this model, including laminar flow, constant thermophysical properties, pure saturated steam, and negligible interfacial shear stress, limit its applicability to realistic containment conditions.
- ❖ In this study, a mechanistic liquid-film model based on Ghiaasiaan's momentum equation was developed to predict condensate film behavior with interfacial shear stress, and its performance was evaluated against the Nusselt model and CONAN (T30) condensation experiments.

Modeling

The solution of the liquid-film momentum equation

Momentum equation

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

Boundary condition:

$U_l = 0$ at the wall

$dU_l/dy = \tau_i/\mu_l$ at the film-vapor interface

Interfacial shear stress

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

Interfacial friction factor

$$f_{c,l} = 0.664 Re_i^{-0.5} \quad (\text{for laminar bulk mixture flow regime}) \quad (3)$$

$$f_{c,t} = 0.0592 Re_i^{-0.5} \quad (\text{for turbulent bulk mixture flow regime}) \quad (4)$$

Procedure for deriving the model solution

Nondimensionalization of the velocity distribution

$$U_l^*(y^*) = \int_0^{\delta_f^*} 1 - \frac{y^*}{\delta_f^*} + \tau_i^* dy^* \quad (5)$$

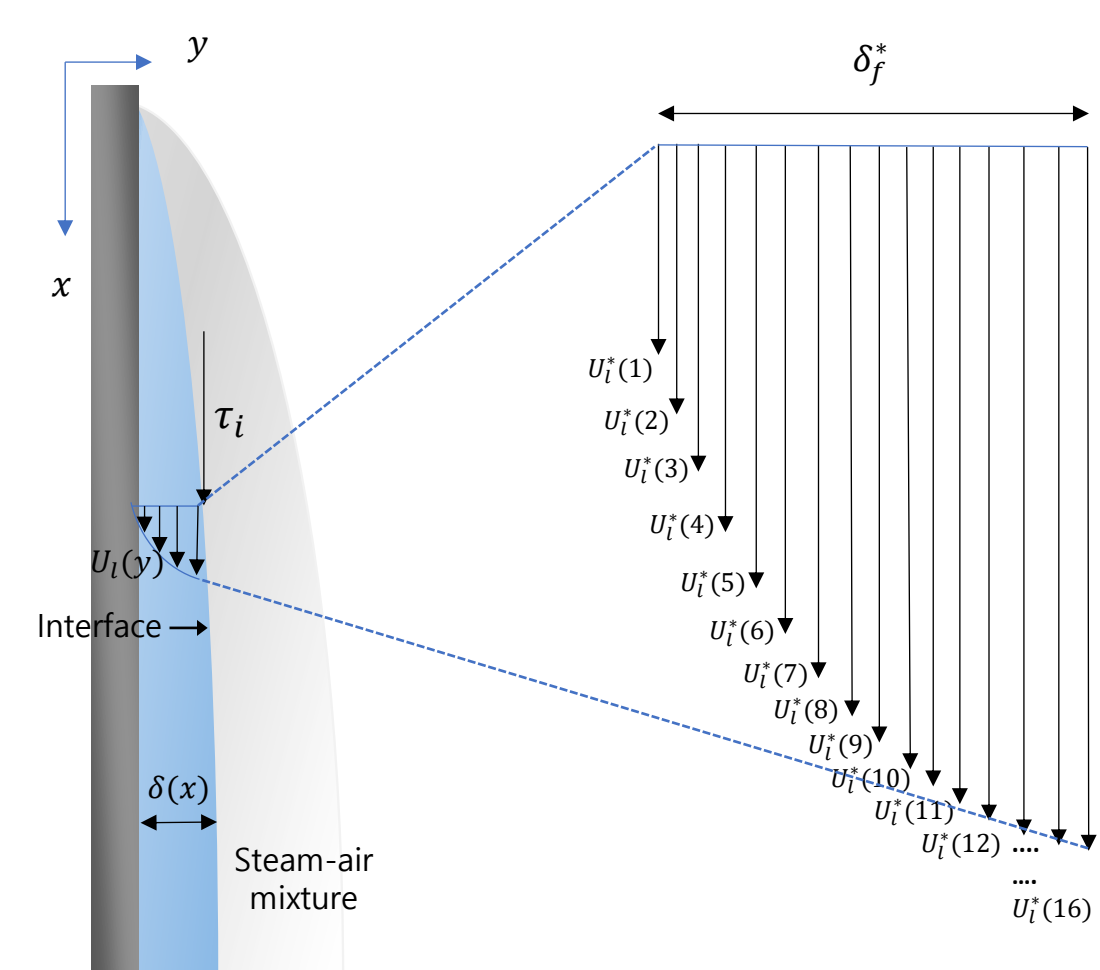
Definition of dimensionless variables

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

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

$$U_l^* = \frac{U_l}{\sqrt{\delta_f (1 - \frac{\rho_g}{\rho_l}) g \sin \theta}} \quad (8)$$

$$\tau_i^* = \frac{\tau_i}{\delta_f (\rho_l - \rho_g) g} \quad (9)$$



Mechanistic liquid film model

Fig. 1 Numerical integration of Simson 1/3 rule

Numerical solution and convergence criteria

Mass conservation condition

$$\frac{\Gamma_f}{\mu_l} = \int_0^{\delta_f^*} U_l^* dy^* \quad (10)$$

Newton-Raphson method

$$f(\delta_f^*) = \frac{\Gamma_f}{\mu_l} - \int_0^{\delta_f^*} U_l^* dy^* = 0 \quad (11)$$

$$\text{Update } \delta_f^*: \delta_{f, \text{new}}^* = \delta_f^* - \frac{f(\delta_f^*)}{f'(\delta_f^*)} \quad (12)$$

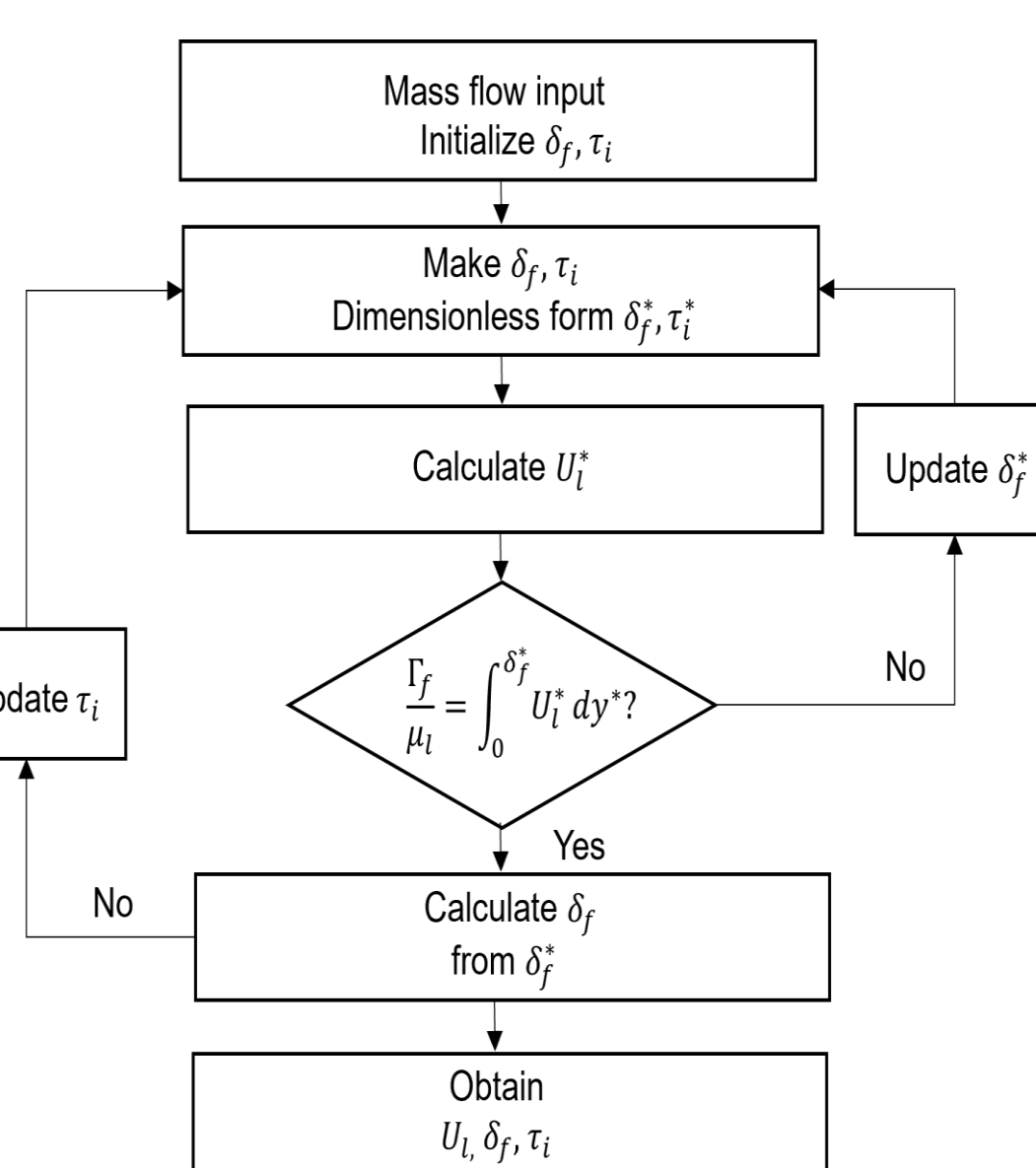


Fig. 2 Flow chart of mechanistic liquid-film model solution

convergence criteria

$$\text{Inner iteration tolerances: } |\delta_{f, \text{new}}^* - \delta_f^*| < 10^{-10} \quad (13)$$

$$\text{Outer iteration tolerances: } |\delta_{f, \text{new}} - \delta_f| < 10^{-10} \quad (14)$$

Simulation condition and Results

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

Table 1. Calculation condition

Condensing surface	Velocity (m/s)	Wall Temp (K)	Gas Temp (K)
vertical flat plate	2.63	315.45	345.45

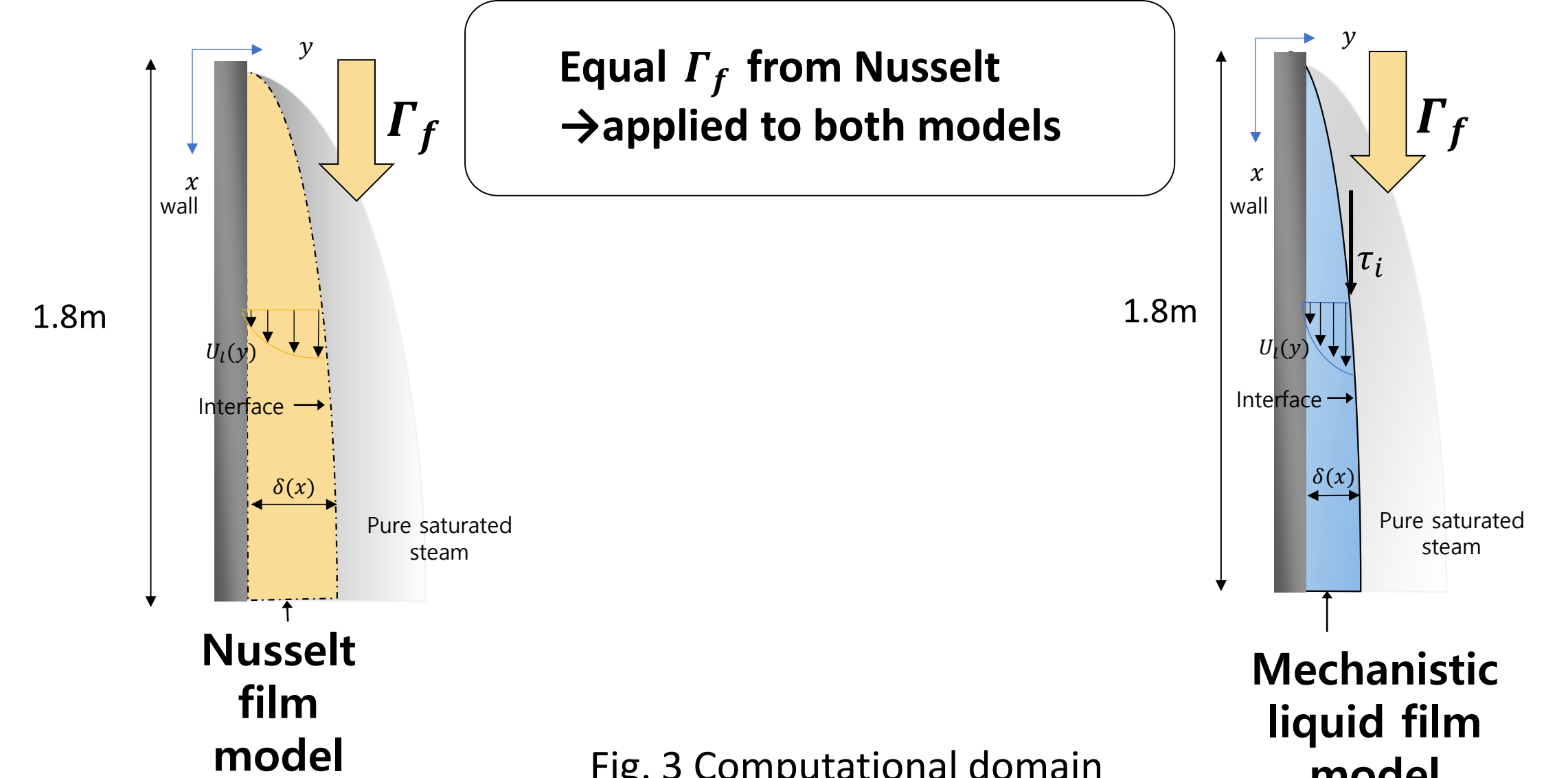


Fig. 3 Computational domain

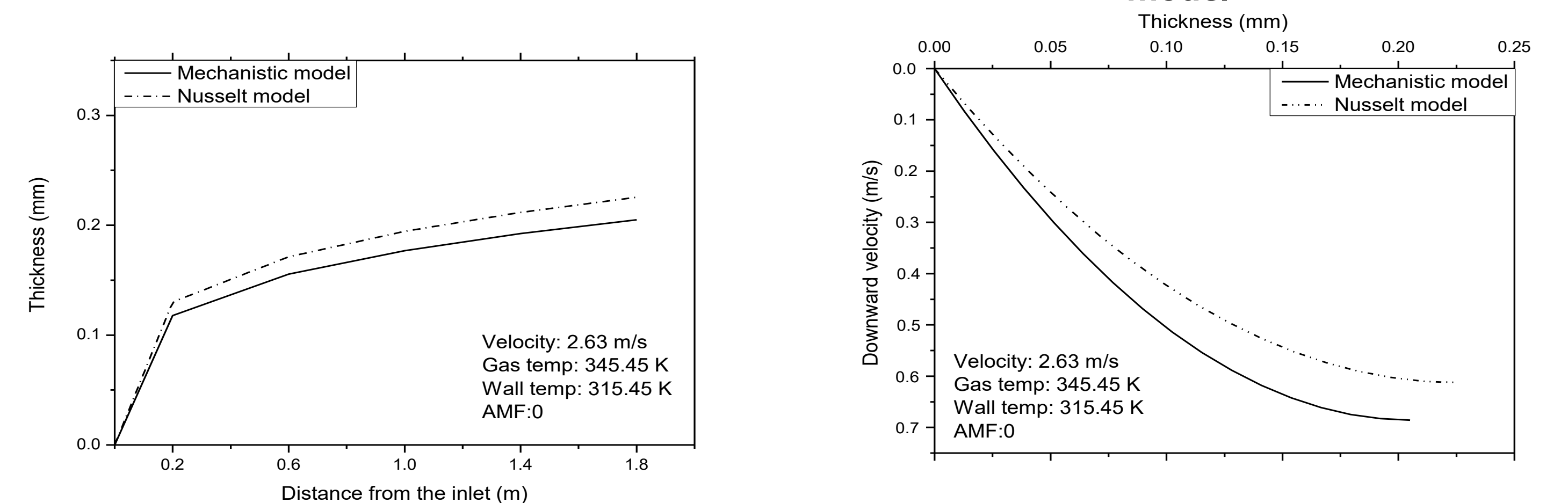


Fig. 4 Film thickness and Velocity profile of the liquid film at x = 1.8 m

Liquid film analysis in the CONAN (T30) experiments

Table 2. 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

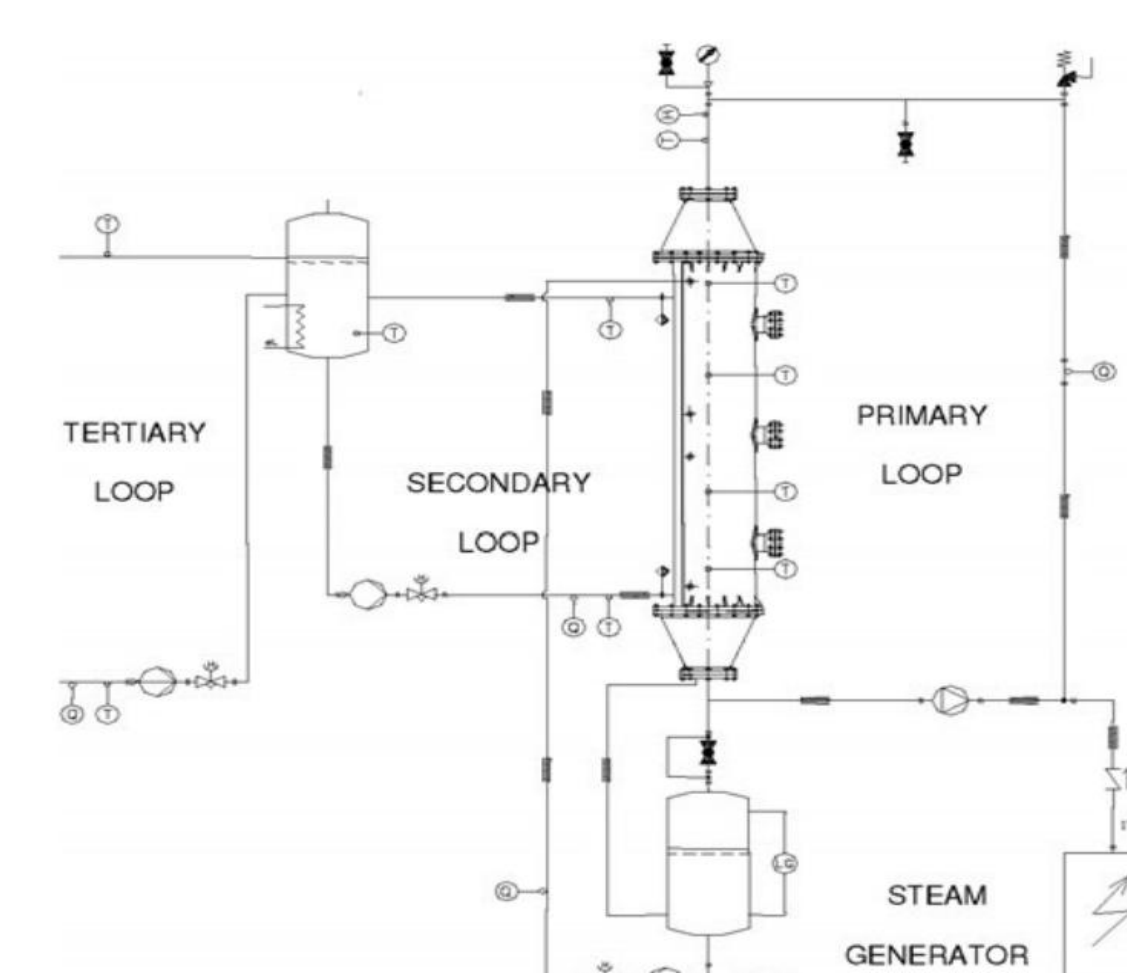


Fig. 5 CONAN test loop

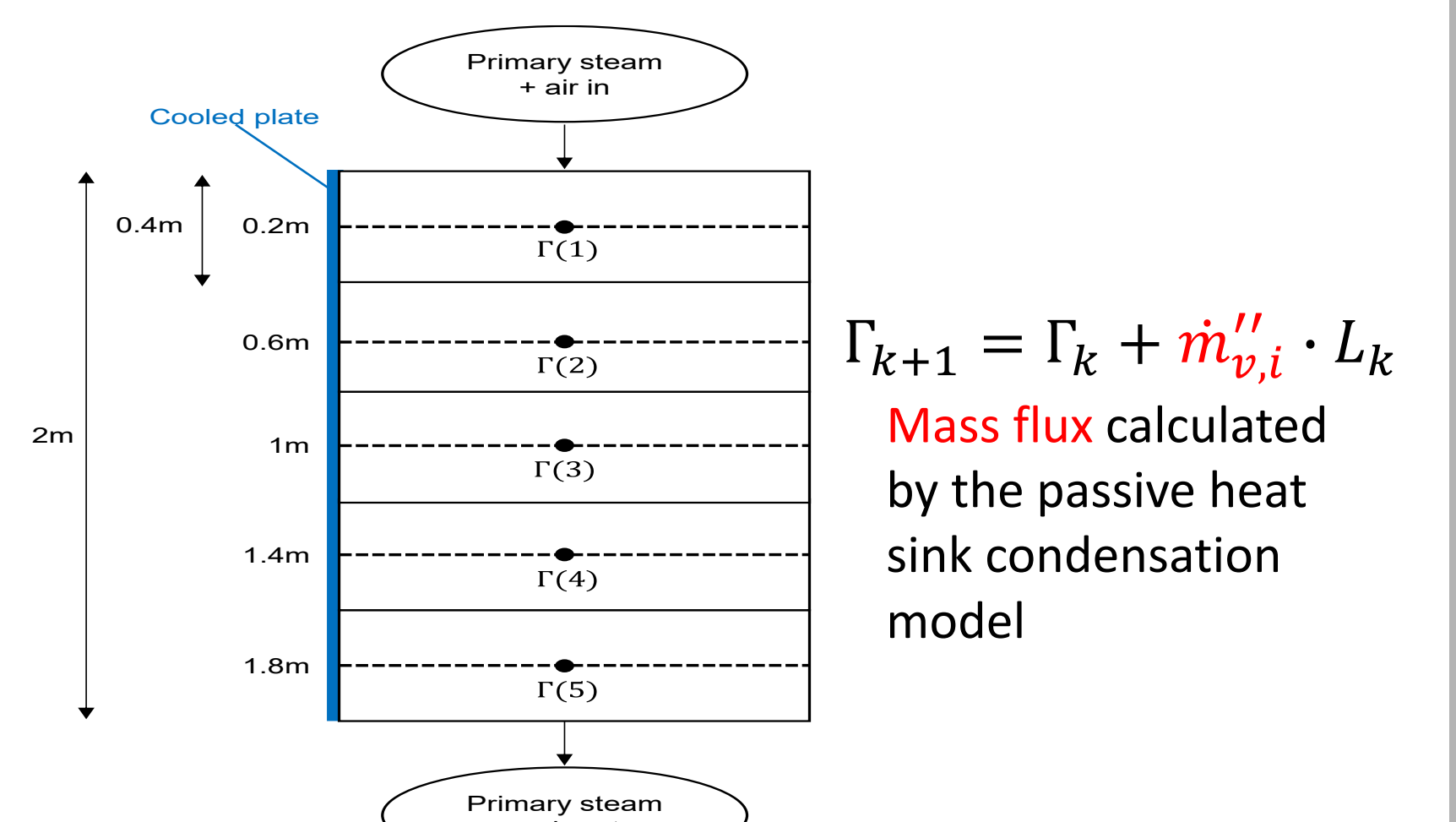


Fig. 6 Nodalization of the CONAN test section for simulation

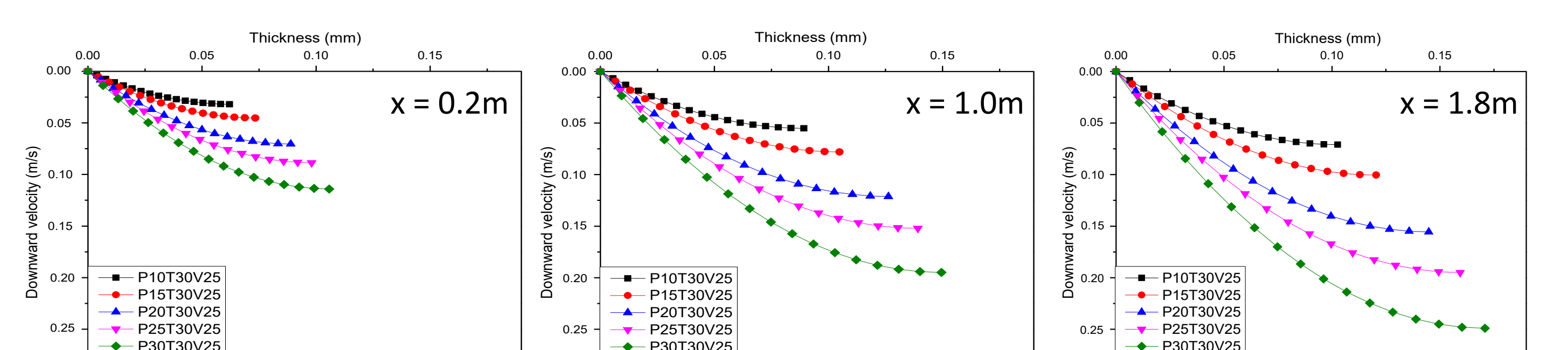


Fig. 7 Velocity profile of the liquid film at x = 0.2m, 1.0m, 1.8 m from the inlet in the CONAN (T30) experiments

Conclusions and Future work

- ❖ 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.
- ❖ 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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