Sensitivity Study of Film Condensation Model in CUPID

Moonhee Choi [a,b], Han Young Yoon[b], Hyun Sun Park [a]
[a] *Division of Advanced Nuclear Engineering, Pohang University of Science and Technology (POSTECH)*
77 Cheongam-ro, Nam-gu, Pohang, Gyungbuk, KOREA, 790-784
[b] *Korea Atomic Energy Research Institute, 1045 Daedeok-daero, Yuseong-gu, Daejeon, Korea, 305-353*
[*] *Corresponding author: hejsunny@postech.ac.kr*

1. Introduction

Condensation is important two-phase phenomena in various industrial fields and has been investigated widely for many years. The pioneering work of condensation analysis was done by Nusselt [1], who predicted heat transfer coefficient of pure vapor condensation on a vertical plate using condensate film thickness. In this paper, sensitivity study of film condensation model for pure vapor is conducted with a component scale thermal hydraulic analysis code, CUPID and compared with Nusselt's result.

2. Mathematical Model

CUPID [2] adopts three dimensional, two-fluid and three-field conservation equations with semi-implicit numerical scheme.

2.1 Governing Equations

CUPID adopts three dimensional, two-fluid and three-field conservation equations with semi-implicit numerical scheme. Separate conservation equations of mass, momentum, and energy are established for the three fields. The mass conservation equation for the k-filed is:

$$\frac{\partial}{\partial t}(\alpha_k \rho_k) + \nabla\cdot(\alpha_k \rho_k \vec{u}_k) = \Omega_k$$

where

$$\Omega_v = \Gamma_v$$
$$\Omega_l = (1-\eta)\Gamma_v - S_E + S_{DE}$$
$$\Omega_l = \eta\Gamma_v + S_E - S_{DE}$$
$$\eta = \alpha_d / (\alpha_l + \alpha_d)$$

The conservation equation of momentum for the k-field is:

$$\frac{\partial}{\partial t}(\alpha_k \rho_k \vec{u}_k) + \nabla\cdot(\alpha_k \rho_k \vec{u}_k \vec{u}_k) =$$
$$= -\alpha_k \nabla P + \nabla\cdot\left[\alpha_k(\mu_l + \mu_t)\nabla \vec{u}_k\right] + \alpha_k \rho_k \vec{g}$$
$$+ M_k^{mass} + M_k^{drag} + M_k^{ndrag} + M_k^{VM}$$

The conservation equation of energy for the k-field is:

$$\frac{\partial(\alpha_g \rho_g e_g)}{\partial t} + \nabla\cdot(\alpha_g \rho_g e_g \vec{u}_g) =$$
$$-P\frac{\partial \alpha_g}{\partial t} - P\nabla\cdot(\alpha_g \vec{u}_g) + \ddot{q}_g + \nabla(\alpha_g \vec{q}_g)$$
$$+\frac{P_s}{P} H_{ig}\left[T^s(P_s) - T_g\right] + \Gamma_v h_g^* - \left(\frac{P-P_s}{P}\right) H_{gf}(T_g - T_l)$$

$$\frac{\partial\{(\alpha_l + \alpha_d)\rho_l e_l\}}{\partial t} + \nabla\cdot(\alpha_l \rho_l e_l \vec{u}_l + \alpha_d \rho_d e_d \vec{u}_d) =$$
$$-P\frac{\partial(\alpha_l + \alpha_d)}{\partial t} - P\nabla\cdot(\alpha_l \vec{u}_l + \alpha_d \vec{u}_d) + \ddot{q}_l + \nabla\cdot(\alpha_l \vec{q}_l + \alpha_d \vec{q}_d)$$
$$+H_{if}\left[T^s(P_s) - T_l\right] - \Gamma_v h_f^* - \left(\frac{P-P_s}{P}\right) H_{gf}(T_g - T_l)$$

2.2 Initial and Boundary Conditions

In this study, condensation on a two-dimensional vertical wall is simulated and Fig. 1 shows a calculation condition. At the inlet, saturated steam is injected and constant pressure condition is assumed for the outlet. Initially, small fraction of liquid exists at the wall to simulate film condensation.

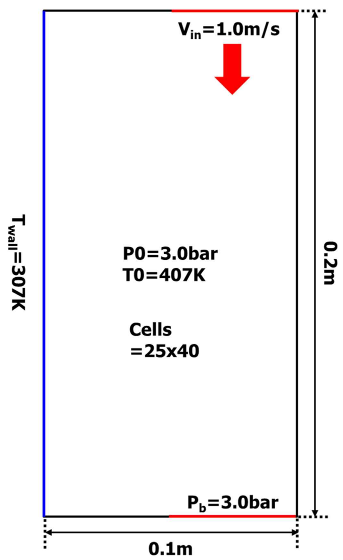

Fig. 1. Calculation condition

3. Sensitivity Test and Results

Currently, CUPID does not contain specific models for condensation and we postulated that the following five parameters are major factors of condensation modeling.

3.1 Interfacial Heat Transfer Coefficient

Initially, mist flow is distributed in the whole geometry and interfacial heat transfer coefficient of mist flow regime is used. In addition, only liquid phase is on the wall and there is no momentum and energy transfer between vapor phase and the wall to simulate film condensation. Therefore, the contacting surface between liquid and vapor on the wall is larger than mist flow and a constant multiplier is adopted for this case.

Compared with a default case, an interfacial heat transfer coefficient of liquid has higher effect than that of vapor.

Table I. Interfacial heat transfer coefficient effect

	Nusselt	Default	H_{if}	H_{ig}
Film Thickness(mm)	0.1527	0.0122	0.0240	0.0122

3.2 Wall Shear Stress

At the wall, momentum and energy transfer is decided by wall shear stress. Currently, a default model of CUPID assumes linear velocity profile and temperature profile on the wall based on void fraction and this should be modified. Also, there is a very thin liquid film on the wall and the real wall shear stress should be higher than the default model. If proper velocity and temperature profiles are developed, an accurate liquid film can be calculated.

Table II. Wall shear stress effect

	Nusselt	Default	τ_{wall}
Film Thickness(mm)	0.1527	0.0122	0.2515

3.3 Interfacial Drag

Since Nusselt assumed stationary vapor, interfacial drag for liquid phase at the wall is removed. However, the effect of interfacial drag is negligible.

Table III. Interfacial drag effect

	Nusselt	Default	C_{D_l}
Film Thickness(mm)	0.1527	0.0122	0.0122

3.4 Turbulence

In Nusselt's assumption, vapor flow is stagnant, however, constant liquid velocity is used for inlet condition in this calculation. This inlet condition makes vapor flow turbulent, thus, turbulence model for vapor phase is considered.

Table IV. Turbulence effect

	Nusselt	Default	Turbulence
Film Thickness(mm)	0.1527	0.0122	0.0432

3.5 Inlet Velocity

To verify effect of inlet velocity, two different inlet velocities were calculated. In this case, both wall shear stress and turbulence effects are considered for stability. Nusselt assumed a very theoretical situation which can hardly be simulated and should be investigated.

Table V. Inlet velocity effect

	Nusselt	Default	0.5m/s	1.5m/s
Film Thickness(mm)	0.1527	0.1015	0.1250	0.1021

4. Conclusion

In this study, total five parameters for condensation modeling are investigated and it was found that the interfacial heat transfer coefficient of liquid, wall shear stress, turbulence and inlet velocity have considerable effect on condensation on the vertical wall. Since Nusselt's theory has been developed in very ideal situation, further study is required for proper analysis. In addition, a physical process of condensation should be investigated for modeling of interfacial heat transfer and wall shear stress.

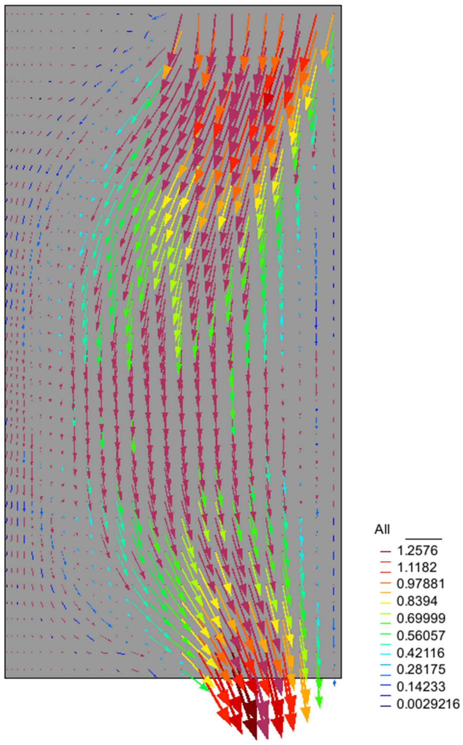

Fig. 2. Velocity result

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REFERENCES

[1] Nusselt, W., 1916. Die ober achenkondensation des wasserdampfes – the surface condensation of water. Zeitschrift Vereines Deutscher Ingenieure 27, 541–546.
[2] Han Young Yoon et al. 2011. CUPID Code Manual Volume I : Mathematical Models and Solution Methods, KAERI/TR-4403/2011.