Two-phase flow analysis performance improvement of CAP and plant application

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1. Introduction

The CAP (Containment Analysis Package) code is containment building analysis code for the containment integrity assessment, Emergency Core Cooling System (ECCS) performance assessment, and equipment qualification envelop analysis.[1] The code is also developed to be used for the analysis of average hydrogen concentration inside the containment building during the design basis accident. In this study, pipe component was implemented to CAP, and for the improvement of two-phase analysis in the pipe, interfacial heat and mass transfer model and interfacial drag model was also implemented. In addition to that, the film condensation model and boiling model were added to improve the wall heat transfer analysis performance. For the validation of wall condensation model, COPAIN experiment was analyzed.

2. Implementation of Pipe Component

CAP is designed to analyze the system by connecting lumped volumes to junctions. In this study, pipe component was implemented for the in-pipe analysis, and the flow regime map, interfacial heat and mass transfer model and interfacial drag model was added to analyze the various the-phase flows in the pipe. The interfacial heat and mass transfer model and interfacial drag model in the CAP is shown in Table 1 ~ 4.

Table 1. Interfacial area concentration model

Flow Regime		Interfacial area concentration
Bubbly		Hibiki [2]
Slug	Bubbles	Hibiki
	Taylor bubbles	Mishima [3]
Annular mist	Droplet	Azzorpadi [4]
	Film	Film thickness
Vertical Stratified		Hibiki

Table 2. Interfacial heat transfer model

Flow Regime	Gas-Interface HTC	Liquid-Interface HTC
Bubbly	$10^4 * dT_{sg} * F_{factor}$	Max (Lee-Ryley, Lucic) (Super-heated) [5,6] Unal [7] (Sub-cooled)
Slug	$10^4 * dT_{sg} * F_{factor}$ (Small bubble) Lee-Ryley (Taylor bubble)	Max (Lee-Ryley, Lucic) (Super-heated) Unal (Sub-cooled)
		Sieder-Tate (Taylor bubble)
Annular mist	Dittus-Boelter [8] (Super-heated) $10^4 * dT_{sg} * F_{factor}$ (Sub-cooled)	Brown [9] (Droplet)
		Dittus-Boelter (Film)
Horizontal stratified	Dittus-Boelter + $10^4 * dT_{sg} * F_{factor}$ (Super-heated) $10^4 * dT_{sg} * F_{factor}$ (Sub-cooled)	Dittus-Boelter + Conduction
Vertical Stratified	McAdams [10] * F_{factor} + 10^4 * a_{bubble}	McAdams * (1- F_{factor}) + Lee-Ryley (Super-heated) McAdams * (1- F_{factor}) + Unal (Sub-cooled)

Table 3. Interfacial drag model (Drag coefficient)

Interfacial Drag Coefficient (Drag coefficient)				
Flow Regime				Model
Bubbly	gas-liquid			Ishii & Chawla[11]
	gas-droplet			Ishii & Chawla
Slug	gas-liquid	Bubbles		Ishii & Chawla
		Taylor bubbles		Derived from Drift flux model
	gas-droplet			Ishii & Chawla
Annular mist	gas-liquid	Laminar		Churchill [12]
		Turbulent	Horizontal, Upward	Fore [13]
			etc.	Asali [14]
	gas-droplet			Ishii & Chawla
Horizontal stratified	gas-liquid			
	gas-droplet			Ishii & Chawla
Vertical stratified	gas-liquid			
	gas-droplet			Ishii & Chawla

Table 4. Drift flux model (Vertical Bubbly/Slug flow)

<table>
<tr><th></th><th>Bundle</th><th>Small pipe</th><th>Medium pipe</th><th>Large Pipe</th></tr>
<tr><td>Upward flow
(High mass flux)</td><td rowspan="5">EPRI, Bestion
[15, 16]</td><td>EPRI</td><td>EPRI</td><td rowspan="5">V_{gj} : EPRI
C_0: Kataoka-Hibiki [20]
j > 0.0 m/s
C_0: Goda
j < 0.0 m/s</td></tr>
<tr><td>Upward flow
(Medium mass flux)</td><td>Transition</td><td>Transition</td></tr>
<tr><td>Low mass flux
Counter-current flow</td><td>Zuber-Findlay [17]</td><td>Kataoka-Rouhani [19]</td></tr>
<tr><td>Downward flow
(Medium mass flux)</td><td>Transition</td><td>Transition</td></tr>
<tr><td>Downward flow
(High mass flux)</td><td>V_{gj} : EPRI
C_0: EPRI
j > 0.0 m/s
C_0: Goda [18]
j < 0.0 m/s</td><td>V_{gj} : EPRI
C_0: EPRI
J > 0.0 m/s
C_0: Goda
j < 0.0 m/s</td></tr>
</table>

3. Implementation of Wall Heat Transfer Model

Uchida and Tagami correlation was used in the CAP for the wall condensation analysis. However, in order to analyze the wall film condensation phenomena more reliable than those correlations, wall film condensation model is implemented in CAP. In addition, a new boiling model was implemented to analyze the wall boiling phenomenon.

3.1 Pure steam condensation model

Condensation heat flux at the wall is calculated as below.

$$q_t^{''} = h_c\left(T_w - T_{sppb}\right)$$

$q_t^{''}$: Total heat flux [*W/m*^{2}]
h_c: Condensation heat transfer coefficient [*W/m*^{2}*K*]
T_w: Wall temperature [*K*]
T_{sppb}: Saturation temperature at the bulk [*K*]

For the pure vapor condensation heat transfer coefficient, Nusselt correlation [21] and Shah correlation [22] are implemented in the CAP.

3.2 Wall condensation model with NC gases

For the wall condensation model with NC gases, Coluburn-Hougen [24] model is added in the CAP.

$$q_t^{''} = h_m h_{fgb}\rho_g \ln\left(\frac{1-\frac{P_{vi}}{P}}{1-\frac{P_{vb}}{P}}\right) = h_c\left(T_{vi} - T_w\right)$$

h_m : Mass transfer coefficient [*m/s*]
$T_{vi} = T_{sat}\left(P_{vi}\right)$ (Interface temperature [K])
$\rho_g = \rho_{sat}\left(P\right)$ [*kg/m*^{3}]
P : Total pressure [*Pa*]
P_{vi} : Steam partial pressure at the interface [*Pa*]
P_{vb} : Steam partial pressure at the bulk [*Pa*]
$h_{fgb} = h_{fg,sat}\left(P_{vb}\right)$ (Latent heat at the bulk [*J/kg*])

For the mass transfer coefficient, maximum value of Gilliand correlation [23] (forced convection), Rohsenow-Choi [23] (Laminar flow), and Churchill-Chu [12] (Natural convection) is used.

3.3 Nucleate boiling model

For the nucleate boiling model at the wall, Chen correlation [24] is implemented in CAP. Boiling heat flux of Chen correlation is calculated as below.

$$q'' = F \cdot h_l(T_w - T_l) + S \cdot h_{npb}(T_w - T_{spt})$$

F : Enhancement factor
h_l : Liquid convection heat transfer coefficient [*W/m*^{2}*K*]
S : Nucleate boiling suppression term
h_{npb} : Nucleate pool boiling heat transfer coefficient [*W/m*^{2}*K*]

3.3 Validation of Wall film condensation model

The COAPIN experiment calculation was performed to validate the wall film condensation model in CAP. The COPAIN experiment [25] was conducted at CEA to investigate the steam condensation on vertical walls in the presence of non-condensable gases. As shown in the Fig. 1, the test section of COPAIN experiment is a rectangular channel. The channel length is 3 m, and the condensation plate is 2 m in length, 0.6 m in width, and

Table 5. Test matrix of COPAIN experiment

Case	Pressure (bar)	Inlet Temp. (K)	Velocity (m/s)	Wall Temp. (K)	AMF (-)
P0441	1.02	353.2	3.0	307.4	0.767
P0443	1.02	352.3	1.0	300.1	0.772
P0444	1.02	351.5	0.5	299.7	0.773

0.5 m in depth. Wall condensation occurs at the aluminum plate wall, and the plate is cooled by water with a constant temperature on the wall.

COPAIN calculation results are shown in Fig. 2. Since CAP could not calculate the effect at the entrance region, calculation results has large discrepancy with experiment results, as shown in figure. However, in the forced convection case (P0441), the heat flux results at the fully developed region could be predicted close to the experiment results. In the case of natural convection calculations (P0443, P0444), heat flux results were still over-predicted at the fully developed region. Since CAP could not consider the liquid film at the wall, it is guessed that condensate drops rapidly in the form of droplet, and it enhance the mixing effect of steam-air mixture in the natural convection calculation. This discrepancy could be solved by allowing the condensation droplets to flow in the form of a liquid film or by assuming the condensation droplets as a loss of mass.

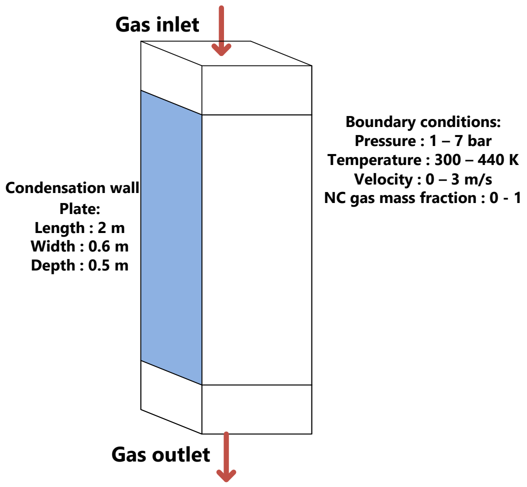

Fig. 1. Schematic of COPAIN experiment

4. Conclusions

In this study, pipe component and interfacial heat and mass transfer / drag models were implemented to CAP. In addition to that, the film condensation model and boiling model were added to improve the wall heat transfer analysis performance. COPAIN experiment was analyzed for the validation, and it shows that wall film condensation model is implemented into CAP appropriately. For the further work, more validation should be conducted for the two-phase flow validation.

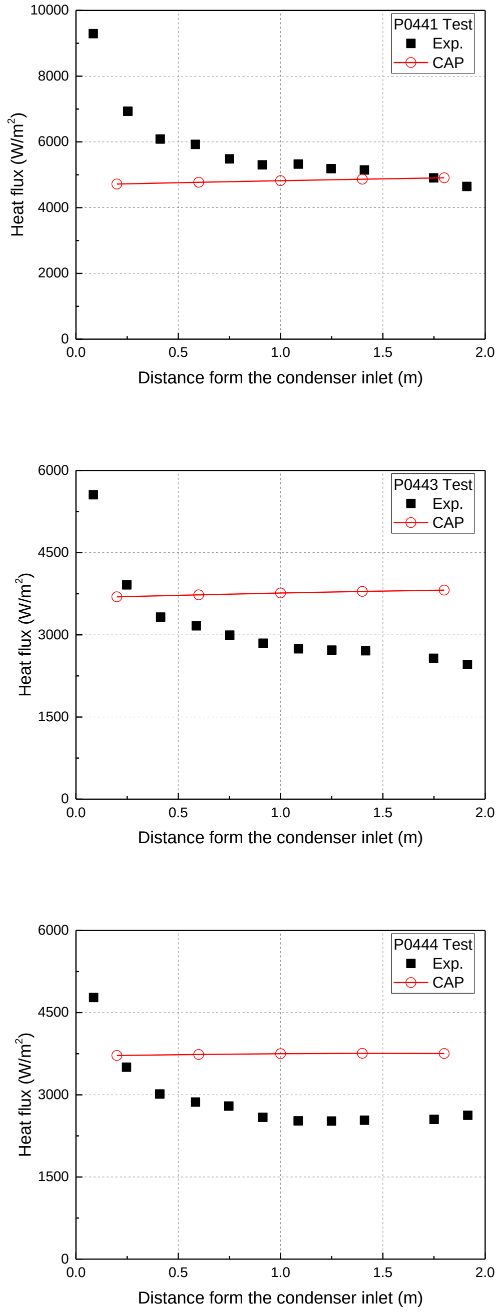

Fig. 2. COAPIN calculation results

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