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Preliminary Assessment of a PWR Steam Generator Analysis Code, CUPID-SG

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1. Mathematical Models

1.1. Governing equations for porous media

The porous media approach is a realistic choice to handle the U-tube bundle of the PWR steam generator. CUPID-SG code adopts the governing equation set for a porous media which can be obtained by FVM discretization with porosity (γ) and permeability (ε) as follows. The mass, momentum, and energy conservation equations for fluids and the conduction equation for a conductor are described in integral forms as follows:

$$\int \frac{\partial}{\partial t}(\alpha_k \rho_k) dV + \int \alpha_k \rho_k \vec{u}_k \cdot d\vec{S} = \int \Omega_k dV \,, \quad (1)$$

$$\begin{aligned} &\int \alpha_k \rho_k \frac{\partial \vec{u}_k}{\partial t} dV + \int (\alpha_k \rho_k \vec{u}_k \vec{u}_k) \cdot d\vec{S} - \vec{u}_k \int (\alpha_k \rho_k \vec{u}_k) \cdot d\vec{S} \\ &= -\int \alpha_k \nabla P dV + \int (\alpha_k \mu_k \nabla \vec{u}_k) \cdot d\vec{S} + \int \alpha_k \rho_k \vec{g} dV \\ &+ \int \vec{M}_{wk} dV + \int F_{ik}^{mass} + F_{ik}^{drag} + F_{ik}^{VM} dV \end{aligned} \quad ,(2)$$

where $\vec{M}_{wk} = -F_{wk}\vec{u}_k$,

$$F_{wk} = \left(\frac{2 f_k}{D_h} + \alpha_k \frac{K}{2L} \right) \rho_k \, | \vec{u}_k \, | ,$$

where f_k, K, D_h, L are fanning wall friction factor, form loss factor, hydraulic diameter, and length.

$$\begin{aligned} &\int \frac{\partial (\alpha_k \rho_k e_k)}{\partial t} dV + \int (\alpha_k \rho_k e_k \vec{u}_k) \cdot d\vec{S} = \int \alpha_k k_k \nabla T_k \cdot d\vec{S} \\ &+ \int E_k dV - \int P \frac{\partial \alpha_k}{\partial t} dV - P \int \alpha_k \vec{u}_k \cdot d\vec{S} \\ &+ \int q''_{f-s,k} d\vec{S} + q''_{f-p,k} A_{f-p,k} \end{aligned} \quad (3)$$

where, E_k is source terms of phase change, interfacial heat transfer, and volumetric heat, and $q''_{f-s,k}$ and $q''_{f-p,k}$ indicate the heat fluxes between fluid conductor in a open media and in a porous media, respectively.

$$E_g = Q_g + \left(\frac{h_f^*}{h_g^* - h_f^*} \right) H_{ig} [T_s - T_g] - \left(\frac{h_f^*}{h_g^* - h_f^*} \right) H_{if} [T_s - T_l] , \quad (4)$$

$$E_l = Q_l - \left(\frac{h_f^*}{h_g^* - h_f^*} \right) H_{ig} [T_s - T_g] + \left(\frac{h_f^*}{h_g^* - h_f^*} \right) H_{if} [T_s - T_l] , \quad (5)$$

$$q''_{f-s,k} = h_{f-s,k} (T_s - T_{f,k}) \,, \quad (6)$$

$$q''_{f-p,k} = h_{f-p,k} (T_p - T_{f,k}) , \quad (7)$$

where q''_{p-s} is the conductive heat flux between the conductors in a porous media and in a open media.

$$\begin{aligned} &\int \rho_p C_{P,p} \frac{\partial T_p}{\partial t} dV = \int \nabla \cdot k_p \nabla T_p dV + \int q'''_p dV \\ &+ \int q''_{p-s} dA - q''_{f-p} A_{f-p} \end{aligned} \quad , \quad (8)$$

1.2. Numerical Solution

The semi-implicit ICE scheme used in the RELAP5 code [1] was adopted as a basic numerical method, which uses a staggered grid and a donor-cell scheme. As for the conductor, a temperature matrix equation can be obtained by assembling discretized conduction equations for entire conductor cells. This matrix equation can be solved with a direct solver or an iterative solver.

2. Constitutive Relations

The constitutive models for interfacial transfers depend on a flow pattern map. The vertical flow regime map of the MARS code is adopted except for a stratified flow region as shown in Fig. 1. The flow regime is determined by mixture mass flux, void fraction, and geometry of a flow path.

The interfacial area model of MARS, which has separate interfacial area concentration correlations for bubbly, slug, and annular flow patterns, is used as-is to be consistent with the flow pattern map. The interfacial drag models based upon the resistance coefficient model are adopted for bubbly and slug, and the Churchill, Fore, and Asali models are alternatively chosen according to the Reynolds number and the flow direction for the annular-mist flow [2].

The interfacial heat transfer model for bubbly, slug, and annular-mist flow regimes, which are composed of the correlations at the interfaces of the superheated or subcooled liquid, and the superheated or subcooled gas, is migrated from MARS into CUPID-SG. The interfacial heat transfer model provides the heat transfer coefficients per unit volume in energy conservation equations, Eqs. (4) and (5). The interfacial heat transfer coefficients at the regime boundaries and in the churn flow regime are interpolated according to the vapor fraction.

The most importance models are the wall friction model and the wall heat partitioning model in the porous media. The wall friction model of ATHOS3 is adopted to calculate the pressure drop in the tube bundles for the axial and cross flows in the vertical and horizontal tube bundles, the concentrated resistance, and the cylindrical shell or shroud wall. The 2-phase pressure drop multiplier is considered in those friction models.

CUPID-SG assumes that the heating surface is evenly distributed in a cell with a given porosity. A single-phase heat transfer rate is evaluated by Dittus-Boelter correlation for a forced convection condition. For a natural convection, either Churchill-Chu or McAdams correlation is used by the flow direction [2].

Chen correlation [2] is used for a two-phase boiling heat transfer. Subcooled nucleate boiling is considered by applying an energy partitioning model with the modified Saha and Zuber correlation [3].

3. Calculations

As a variant code of CUPID code, the verification and validation efforts for CUPID-SG can be saved. In this work, the independent verification calculation for thermal conductor model and porous model are conducted as shown in Fig. 2 and Fig. 3. Benchmarking calculations against the FRIGG experiment [4] are introduced in Fig. 4. Figure 4 shows comparison of slab-averaged void fractions along the axial position. CUPID-SG predicts more accurate void fraction than ATHOS3 [5] did. The comparison shows that CUPID-SG predicts the slab-averaged void fraction far better than ATHOS3. The result shows that CUPID-SG makes a good prediction on the void fraction near the inlet where multi-dimensional effect exists and subcooled boiling occurs.

4. Conclusions

CUPID-SG has been developed to analyze the thermo-hydraulic performance of steam generators of PWR. In this work, the CUPID-SG was verified with conceptual problems of thermal conduction and porous media approach, and validated by comparing the prediction on FRIGG, which is one of the test cases of ATHOS3 code.

Acknowledgements

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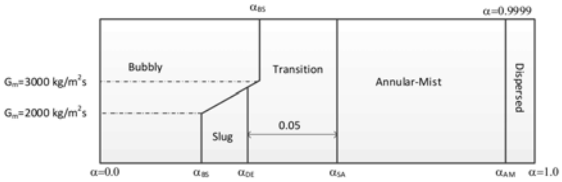

Fig.1. Flow regime map of CUPID-SG

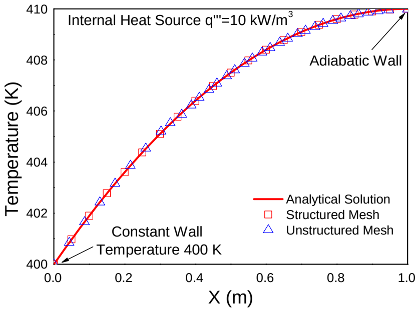

Fig. 2. Verification calculation of thermal conductor model.

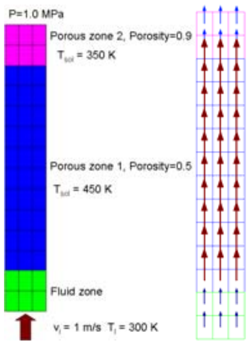

Fig. 3. Verification calculation of porous media model.

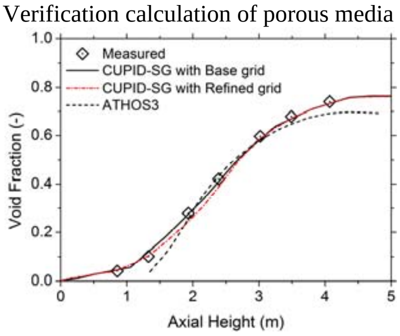

Fig. 4. Validation calculation of FRIGG test.