Development of CUPID-SG, a Component Code for a PWR Steam Generator

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1. Introduction

CUPID-SG is derived from CUPID for exclusive use in analyzing thermo-hydraulics in typical steam generators of PWRs. CUPID-SG is aimed at being a design code for steam generators and providing more insight into boiling flows over tube bundles. To treat the complex thermo-hydraulic phenomena on the shell side of a steam generator, CUPID-SG has a set of constitutive models for a two-phase flow map, interfacial heat and mass transfer, interfacial drag, wall friction, wall heating, and heat partitioning in flows over tube bundles. CUPID-SG supports unstructured meshes to treat the complex geometry of PWR steam generators. As a feasibility study, constitutive models available in the literature [1,2,3] were compiled and integrated into CUPID-SG. The calculations by CUPID-SG were validated by the data from FRIGG experiments. The benchmark cases are the test cases used in validating ATHOS3[4]. This paper describes the conservation equations and constitutive correlations in CUPID-SG, and presents the benchmark results against the FRIGG experiments.

2. Mathematical Models

The CUPID-SG code adopts a transient two-fluid, three-field model to describe the thermo-hydraulics in PWRs. The two-fluid means liquid and vapor. The three-field refers to gas, continuous liquid, and droplets. A computing cell including tube bundles is modeled as porous media with a proper porosity and permeability to simulate flow channels with tube bundles.

The continuity equations for the vapor, liquid, and liquid droplets are given by

$$\frac{\partial}{\partial t}(\alpha_k \rho_k) + \nabla \cdot (\alpha_k \rho_k \underline{u}_k) = \Omega_k \qquad (1)$$

The continuity equation for the total non-condensable component is given as

$$\frac{\partial}{\partial t}(\alpha_g \rho_g X_n) + \nabla \cdot (\alpha_g \rho_g X_n \underline{u}_g) = 0 \qquad (2)$$

The momentum equations for total gas, liquid, and liquid droplets are given by

$$\begin{aligned} &\frac{\partial}{\partial t}(\alpha_k \rho_k \underline{u}_k) + \nabla \cdot (\alpha_k \rho_k \underline{u}_k \underline{u}_k) = -\alpha_k \nabla P \\ &+ \nabla \cdot [\alpha_k \tau_k] + \alpha_k \rho_k \underline{g} + P \nabla \alpha_k + F_{ik}^{mass} + F_{ik}^{drag} + F_{ik}^{VM} \end{aligned} \qquad (3)$$

A thermal-equilibrium between continuous liquid and droplets is assumed and the temperature and density of the continuous liquid and droplets are equal to each other. Thus, only two energy equations are required for the gas field and combined liquid field.

$$\begin{aligned} &\frac{\partial}{\partial t}\left[\alpha_g \rho_g e_g\right] + \nabla \cdot (\alpha_g \rho_g e_g \underline{u}_g) = -P \frac{\partial}{\partial t}\alpha_g \\ &- P \nabla \cdot (\alpha_g \underline{u}_g) + \nabla \cdot \left(\alpha_g \underline{q}_g\right) + Q_{ig} - Q_{gl} \end{aligned} , \qquad (4)$$

$$\begin{aligned} &\frac{\partial}{\partial t}\left[(\alpha_d + \alpha_l)\rho_l e_l\right] + \nabla \cdot \left[(\alpha_l \underline{u}_l + \alpha_d \underline{u}_d)\rho_l e_l\right] = \\ &- P \frac{\partial}{\partial t}(\alpha_d + \alpha_l) - P \nabla \cdot (\alpha_d \underline{u}_d + \alpha_l \underline{u}_l) \\ &+ \nabla \cdot \left(\alpha_d \underline{q}_d + \alpha_l \underline{q}_l\right) + Q_{il} + Q_{gl} \end{aligned} \qquad (5)$$

For a mathematical closure, the undefined terms and coefficients in the right-hand side of the governing equations should be established. Equations of the states are also needed. Interfacial area concentration, interfacial drag force, and interfacial heat transfer coefficient models are defined for conventional flow regime map. The thermal structure model is indispensable for CUPID-SG code, in which the structure model takes a role of the solid conductor of porous media. The governing equation of thermal structure model of CUPID-SG is as follows:

$$\rho_s C_{p,s} \frac{\partial T_s}{\partial_t} = \nabla \cdot k_s \nabla T_s + Q_s + q''_{f-s} \qquad (6)$$

where Q_s and q''_{f-s} are volumetric heat source and the heat flux between fluid-conductor.

3. Constitutive Relations

The constitutive models for interfacial transfer depend on a flow pattern map and the topology of the interface. CUPID-SG uses the vertical flow regime map of the MARS code. The flow regime map for the porous media model of CUPID-SG is shown in Fig. 1. The flow regime is determined by mixture mass flux, void fraction, and geometry of a flow path.

The interfacial area concentration is dependent on the topology of the phasic interface. The interfacial area model of MARS is used as-is to be consistent with the flow pattern map.

The interfacial heat transfer models for bubbly, slug, and annular-mist flow regimes are 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.

As each flow direction is defined to have an independent pressure loss, flow resistances by vertical tubes are calculated independently. The vertical velocity component is used to calculate the axial pressure drop owing to axial flows over vertical tubes. The total pressure drop per unit volume is calculated from the local flow and geometric parameters as

$$F_z = f_a A_{SV} \rho |v_z| v_z \Phi \quad (7)$$

For the friction of the cross flows around vertical tubes, below empirical correlation is applied

$$F_x = f_c C_A C_V A_{SV} \rho |v_x| v_x \Phi \quad (8)$$

$$F_y = f_c C_A C_V A_{SV} \rho |v_y| v_y \Phi \quad (9)$$

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 [2] for a forced convection condition. For a natural convection, either Churchill-Chu [2] or McAdams[2] correlation is used by the flow direction.

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].

4. Calculations

The experimental version of CUPID-SG is benchmarked against the FRIGG experiment. The test cases which were used in validating ATHOS3 [4] are chosen for the benchmark. The selected cases are simulated with CUPID-SG and the results are compared with those of ATHOS3 and the measured data.

Figure 3 shows comparison of slab-averaged void fractions along the axial position. CUPID-SG predicts a higher void fraction than ATHOS3 did. The comparison shows that CUPID-SG predicts the slab-averaged void fraction far better than ATHOS3. Figure 3 also shows the calculation result with the refined grid shown in Fig. 2. 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. Little difference is observed in the results from the base and the refined grid. That is the base grid in Fig. 2 has sufficient axial resolution.

5. Conclusions

CUPID-SG is being developed to analyze the thermo-hydraulic performance of steam generators of PWR. The CUPID-SG is validated by comparing the prediction on FRIGG, which is one of the test cases of ATHOS3 code. The result confirms that the CUPID-SG integrated with the constitutive models can analyze a boiling flow over tube bundles, which is typical in PWR steam generators.

Acknowledgements

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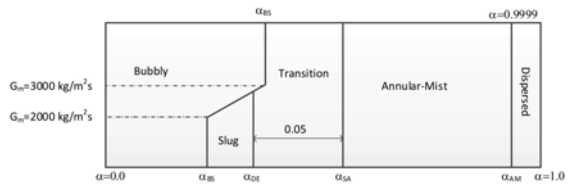

Fig.1. Flow regime map of CUPID-SG

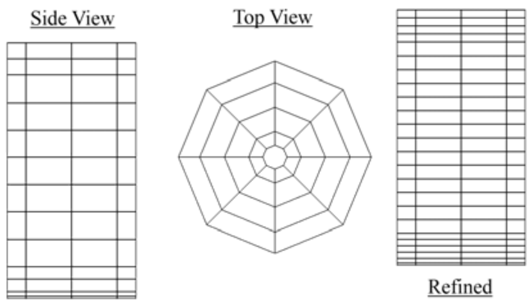

Fig. 2 Grids for FRIGG Calculation.

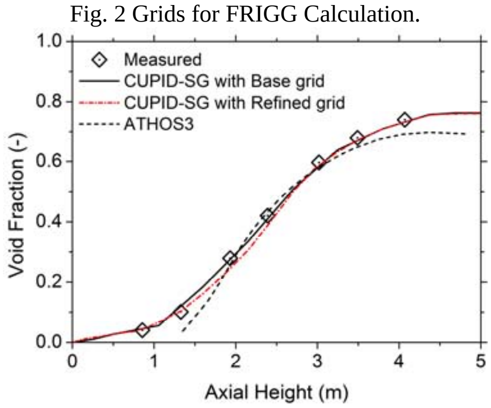

Fig. 3 Comparison of vapor fraction profiles.