Heat Structure Coupling of CUPID and MARS for the Passive Auxiliary Feedwater System Analysis

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1. Introduction

In the present study, the CUPID code was coupled with a system analysis code MARS and the coupled code was applied for the simulation of the PASCAL test facility [1], which is constructed to validate the cooling performance of the Passive Auxiliary Feedwater System (PAFS). The two-phase phenomena in the steam supply system including the condensation in the Passive Condensate Heat Exchanger (PCHX) were calculated by MARS and those in the Passive Condensate Cooling Tank (PCCT) including the natural circulation and the boil-off were modeled by CUPID. This paper presents the coupling method and the simulation results using the coupled codes.

2. Heat Structure Coupling of CUPID and MARS

The PASCAL test facility consists of two separated systems; the primary system is the steam supply system and the secondary one is the PCCT. The interface between two systems is the PCHX tube submerged in the PCCT and there is no flow interaction but only heat transfer. In the case of the primary system, the one-dimensional model of MARS is expected to predict the phenomena in the PCHX appropriately but the secondary side needs to be modeled by a multi-dimensional model in order to reproduce the natural circulation phenomena in a large water pool. For this reason, the CUPID code was applied in the present simulation coupled with MARS by a dynamic linked library (DLL) coupling method. The two-phase phenomena inside the PCHX including the condensation and the phase stratification were calculated by MARS and those in the PCCT including the natural circulation and the boil-off were modeled by CUPID as shown in Fig. 1. The coupling interface between two codes is the PCHX tube outer wall as also indicated in the figure and the conduction equation for the PCHX tube was included in the MARS simulation.

At first, the second outmost temperature of the heat structure (T_{solid}) was transferred from MARS to CUPID. With this solid temperature and the fluid temperature (T_{fluid}) in the secondary side, the following energy conservation equation was solved to obtain the wall temperature (T_{wall}) by CUPID;

$$q_{conduction} = \frac{k_s (T_{solid} - T_{wall})}{r_{out} \cdot \ln(r_{out} / r_{in})} = q_{conv} + q_{quench} + q_{evap} , \qquad (1)$$

$$q_{conv} = h_{conv} A_{1f} \left(T_{wall} - T_{fluid} \right),$$

$$q_{quench} = \left(\frac{2}{\sqrt{\pi}} \sqrt{t_w k_l \rho_l C_{pl}} \, f \right) A_{2f} \left(T_{wall} - T_{fluid} \right),$$

$$q_{evap} = N'' f \left(\frac{\pi}{6} D_{b,depart}^3 \right) \rho_g h_{fg} ,$$

where, A_{1f} : single-phase heat transfer area ratio, A_{2f} : two-phase heat transfer area ratio, t_w : bubble waiting time, f : bubble frequency, N'' : active nucleation site density, and $D_{b,depart}$: bubble departure diameter. This heat partitioning model was employed in order to simulate the subcooled boiling on the PCHX tube wall and the details of the correlations were summarized in our previous paper [2]. After that, the calculated wall temperature was transferred to MARS for the boundary condition of the heat conduction equation. MARS solved the conduction equation together with the convective boundary condition imposed on the inner tube wall and the temperature distribution through the tube was obtained. And then, the second outmost temperature was delivered again to CUPID for new time step calculation. This procedure was repeated in all porous cells of CUPID which include the PCHX tube for every time step.

3. Simulation of the PASCAL test facility

Fig. 2 shows the nodalization of the coupled MARS-CUPID calculation for the PASCAL test facility. The PCCT was modeled with the porous media model of CUPID. Thus, the complicated geometry of the PCHX and its supporting structure were considered using porosity, permeability, heat transfer area, etc. A total of 1815 (33×55) meshes were used for the present simulation as shown in Fig. 2. At the right top of the PCCT, a constant pressure boundary condition was imposed for the flow outlet.

Fig. 3 shows the calculated void fractions inside and outside the PCHX, the wall boiling rate on it, and the liquid temperature distribution at 1000 secs. The void fraction inside the PCHX was calculated by MARS. At the inlet, almost pure steam (α_g=0.999) was delivered from the steam generator. As it flowed through the PCHX, it condensed to the water due to the heat release to the PCCT and then, the void fraction decreased gradually along the tube. At the outlet, the calculated void fraction was 0.919 and 99.4 % of the steam inflow was condensed. Because of a high heat flux of the condensation heat transfer, the PCHX outer wall temperature exceeded the saturation temperature and then, a subcooled boiling occurred on the PCHX as shown in Fig 3-(b) and (c). But the water maintained a subcooled state at this moment, the generated bubble condensed immediately and the void fraction remained very close to zero. Subsequently, the boiling heat transfer increased the liquid temperature near the PCHX. Then, due to the buoyancy, the heated water rose up and the natural circulation was activated in clockwise direction as shown in Fig 3-(d).

Fig. 4 shows the behaviors of the void fraction distribution until a flashing was initiated. As the water temperature increased, the water level was elevated from 9.8 m to 10.4 m owing to a swelling (Fig 4-(a)~(c)). For initial 7000 seconds, the single phase natural circulation was continued because the liquid subcooling had been maintained, but after that, a two-phase region appeared near the free surface as presented in Fig. 4-(d). The start of the two-phase natural circulation caused the acceleration of the liquid by bubbles and the deviation of the free surface from the horizon as shown in Fig. 4-(d). These are well correspondent with the experimental observation result qualitatively.

4. Conclusion

In the present study, the multi-scale thermal-hydraulic analysis method using the coupled MARS-CUPID code was applied for the simulation of the passive condensation cooling phenomena. The primary side of the PASCAL test facility including the PCHX was simulated by MARS and the secondary side, the PCCT, was modeled by the CUPID. It was found that the overall two-phase behaviors inside the water pool and the condensation heat transfer inside the heat exchanger were qualitatively well reproduced with the coupled code. Comparison of various parameters between the test and the simulation will be performed in the future for a quantitative analysis.

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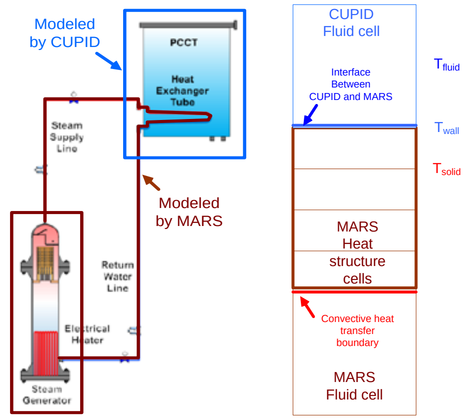

Fig. 1. Coupling approach

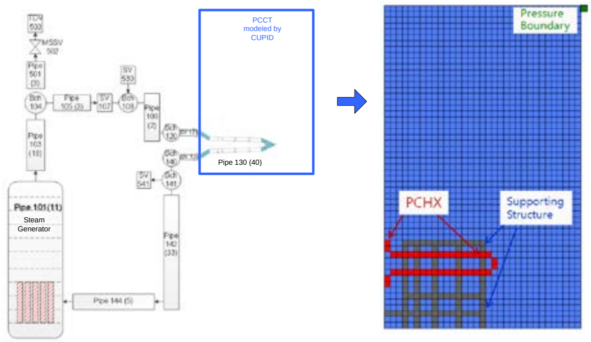

Fig. 2. Nodalization for the PASCAL test facility

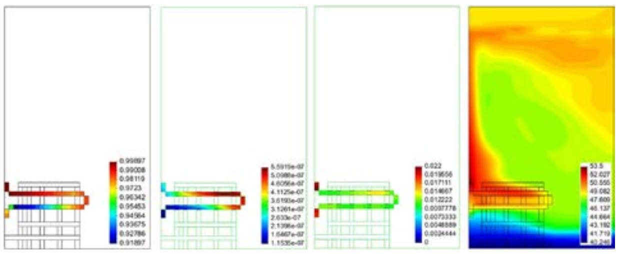

Fig. 3. Calculation results at t=1000 sec. ((a) Void fraction inside the PCHX (°C); (b) void fraction outside the PCHX; (c) wall boiling rate outside the PCHX (kg/s·m^3); (d) liquid temperature (°C))

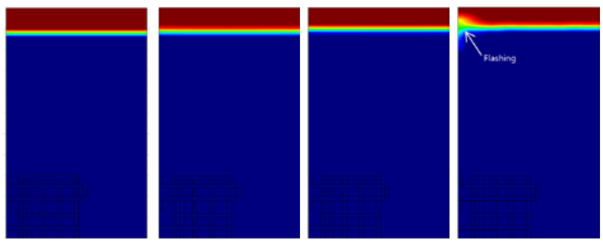

Fig. 4. Calculation results: void fraction ((a) 0 sec.; (b) 2500 sec.; (c) 5000 sec.; (d) 7500 sec.)