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CUPID-MARS Coupled Simulation for APR+ Passive Auxiliary Feedwater System

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1. Introduction

R&D and introduction of passive safety system which can improve the safety by maintaining the cooling performance of the reactor even when the power supply in the power plant is completely lost have been actively conducted. The domestic nuclear industry has introduced a Passive Auxiliary Feedwater System (PAFS) to the next-generation reactor APR+ [1], which consists of PCHX (Passive Condensation Heat Exchanger) and PCCT (Passive Condensation Cooling Tank). It can supply auxiliary feedwater to the steam generator for more than 8 hours in case of an emergency, even after the power supply is lost [2].

In order to analyze the thermal-hydraulic phenomena in PAFS realistically, multi-dimensional analysis methods need to be applied in PCCT where the two-phase natural circulation occurs and long transient time up to 8 hours needs to be covered. As the existing computational tools have limitations for long transient and multi-dimensional phenomena simulation in the whole reactor system, an advanced numerical method is necessary. In the present study, a multi-scale thermal hydraulic analysis technique by coupling the system analysis code MARS [3] and component analysis code CUPID [4] was established and applied for the APR+ accident analysis. The result showed the applicability of the coupled CUPID-MARS code to practical accident analyses when multi-dimensional effect is significant and needs to be investigated.

2. Heat Structure Coupling Method

In the present multi-scale simulation, the whole reactor system except the PCCT was simulated by MARS as its prediction capability has been validated for long time. The PCCT was simulated by CUPID because the multi-dimensional natural circulation is dominant in it. The heat transfer between the PCHX and the PCCT is considered by exchanging the heat structure outer surface and the second outmost heat structure temperature at every time step. MARS transfers the latter to CUPID and it calculates the wall heat flux and surface temperature using the transferred value. Then, the calculated wall temperature is transferred to MARS and it solves the heat conduction equation for the heat structure using the transferred value as the wall temperature boundary condition.

For the coupling, the DLL (Dynamic-Linked Library) version of MARS was used and CUPID was the driver of the DLL. The data transfer was established between two codes using the interactive control function of MARS. Fig. 1 shows the computational domain of the PAFS simulation and data exchange procedure.

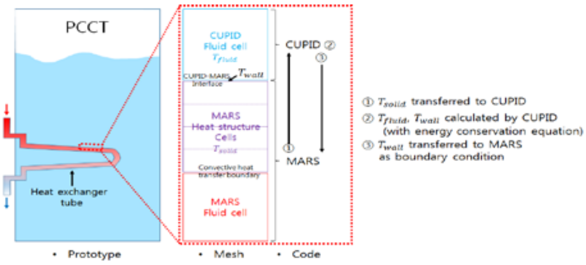

Fig. 1. Explicit coupling method with DLL [5]

3. Validation of the Coupled Code against the PASCAL experiment

Prior to the application of the code to an accident analysis, the coupled code and the models for the passive cooling system need to be validated. For this purpose, the PASCAL test facility was simulated using the coupled code. For the condensation model in the PCHX, Ahn et al.'s [6] model was applied by implementing the model into MARS. For the boiling heat transfer model on the PCHX outer surface, Jeon et al.'s [7, 8] was implemented into CUPID. Both models were validated against the PASCAL [9] test facility from independent validation simulation using MARS.

Fig. 2 shows the nodalization for the PASCAL simulation using the coupled code. The steam generator system was modeled using MARS and the PCCT was simulated using CUPID. The PCCT was modelled in two-dimension by having a single mesh in the depth direction because the PCCT of PASCAL has a slab geometry with 0.11 m depth. The number of meshes for the PCCT was 1815 (33×55).

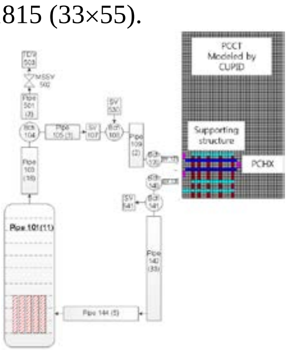

Fig. 2. CUPID-MARS nodalization for PASCAL

Figure 3 shows water level transient calculation result. When the PAFS starts to operate, water level increases due to heat up and swelling. As heat up is subsequently continues, the water temperature near the free surface starts to exceed the saturation temperature and then, flash occurs making the free surface deviate from the horizon. The water level is decreased by boil-off until the operation finishes.

Figure 4 shows the comparison result between the calculation and experiment of the local PCCT water temperature. It was confirmed that the CUPID-MARS code could predict water temperature rise and plateau quantitatively well.

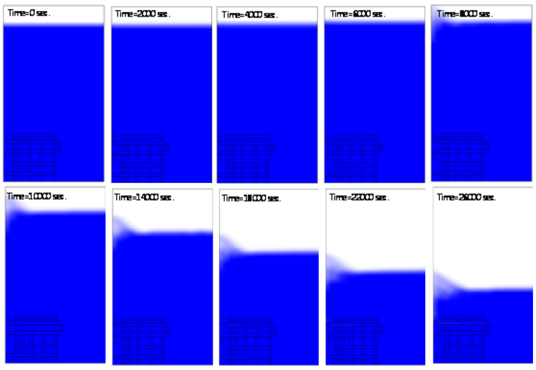

Fig. 3. Calculation result: water level transient

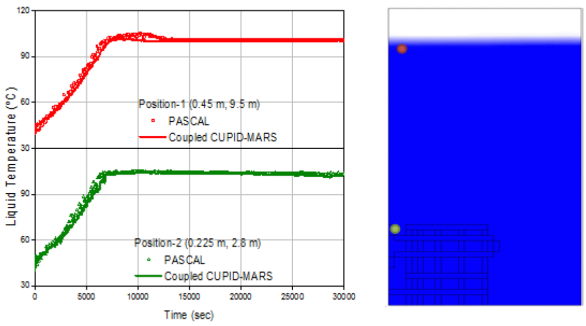

Fig. 4. Calculation result assessment: liquid temperature transient

Figure 5 shows the results of PCHX internal pressure calculation and experimental data. The results are compared with those obtained by two other cases; one with the original condensation model of MARS [3] and the RPI boiling model [10] of CUPID and the other with Ahn et al.'s condensation model and the RPI boiling model. As shown in the figure, the MARS original model over-predicts the pressure inside the PCHX as it under-predicts the condensation heat transfer coefficient. The application of the Ahn et al.'s condensation model improves the prediction capability but discrepancy is remained if the boiling heat transfer model is not improved. When Jeon et al.'s model was applied, good agreement between the calculation and experiment was obtained and from these results, it could be confirmed that the coupled CUPID-MARS can accurately predict the overall heat transfer coefficient if the heat transfer models are improved.

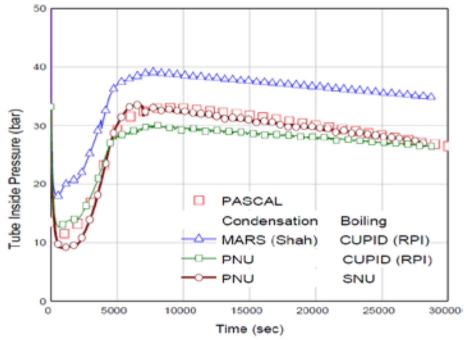

Fig. 5. Pressure transient in PCHX

4. Application of the coupled code for APR+ feedline break accident analysis

After the validation of the code, the coupled code was applied for a practical safety analysis. In order to produce a demonstration result for the multi-scale TH analysis, the APR + FLB (Feedwater Line Break) accident was simulated using the coupled code and the results were compared with the one-dimensional MARS simulation. Fig. 6 shows the computational model for the APR+; whole reactor system except the PCCT was modelled using MARS and the PCCT was modelled using CUPID in three-dimension. The PCCT was modelled with 38,340 cells and porous model was applied for the heat exchanger bundle.

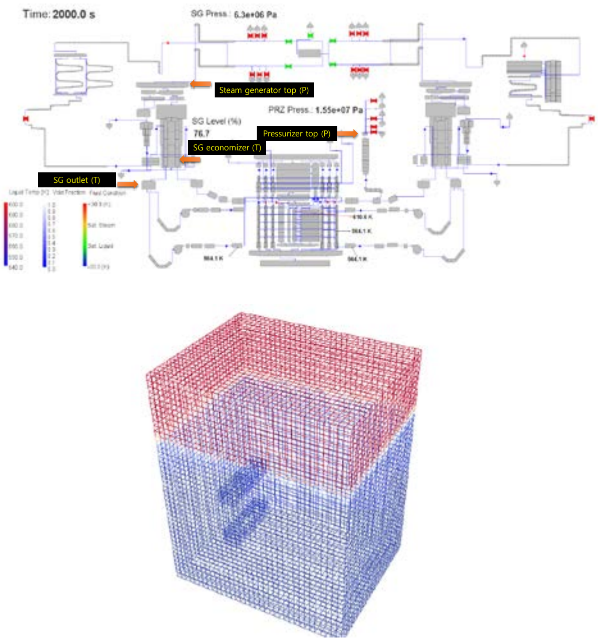

Fig. 6. Nodalization and mesh of APR+ analysis

The total calculation time was 28,800 seconds after the break of a main feedwater line.

Figures 7 and 8 show the result of void fraction and temperature calculation in a water tank. If PAFS is activated, the heat exchanger is heated first. Then, the heat is transferred to the water near the heat exchanger and the natural circulation is activated. As the heat is transferred continuously, the water swells and the liquid level increase. Around 4,600 sec. after the PAFS activation, the flashing near the free surface is started and the water level decreases (Fig. 7). The natural circulation behavior in the PCCT was qualitatively well reproduced in the present simulation.

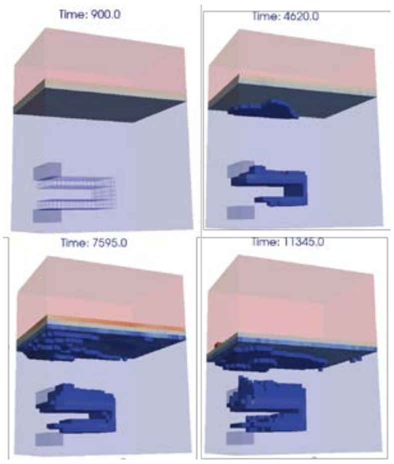

Fig. 7. Void fraction transient

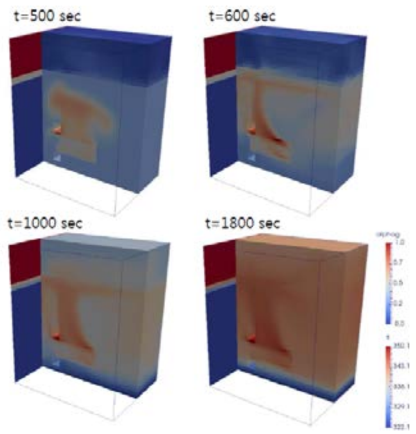

Fig. 8. CUPID-MARS void fraction simulation result

Figures 9 and 10 shows the pressure and liquid temperature transient in the primary and secondary side of the plant modelled by MARS. After the activation of PAFS, the pressure and temperature were decreased as the residual heat is transferred to the PCCT. Compared with the original MARS calculation results, the cooling rate is faster in the coupled simulation with the effect of the model improvement and multi-dimensional modelling. This result confirms that the sufficient cooling performance of the PAFS under the FLB condition and the overcooling criterion needs to be carefully checked in the future simulation.

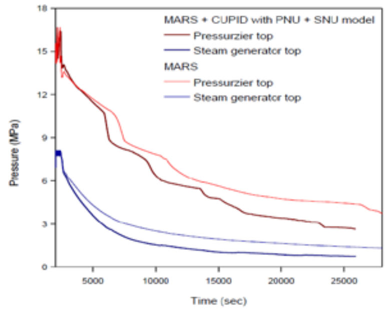

Fig. 9. Pressure simulation result

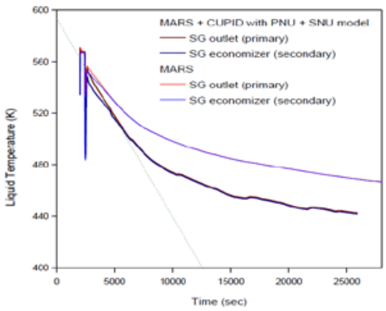

Fig. 10. Liquid temperature simulation result

5. Conclusions

In this study, a multi-dimensional thermal hydraulic analysis code CUPID and a one-dimensional systematic thermal hydraulic analysis code MARS were coupled in order to more precisely analyze the thermal hydraulic phenomena that can occur in the APR + PAFS. The CUPID code was used for the multi-dimensional PCCT analysis and MARS for the whole reactor system including PCHX. By overcoming the disadvantages of conventional analysis methods, it was possible to simulate the whole system more realistically. In this analysis, it was confirmed that the behavior of water in the water tank and the internal pressure behavior of PCHX can be predicted accurately.

From the present work, the feasibility of the multi-scale analysis by coupling 1D and 3D codes was successfully demonstrated and it can be utilized effectively in the future to resolve issues on multi-dimensional TH phenomena.

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