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Assessment of MARS-KS Heat Transfer Model for the PAFS Heat Exchanger in the LAPLACE Test Facility

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1. Introduction

The passive auxiliary feedwater system (PAFS) is one of the advanced safety systems adopted in the APR1000 and APR+ nuclear power plants to completely replace the conventional active auxiliary feedwater system [1]. The key component of the PAFS is a passive condensation heat exchanger (PCHX), which cools down the secondary system of the steam generator by condensation heat transfer. The steam generated in the steam generator is condensed in the inside of the PCHX tubes submerged in the water pool of the passive condensation cooling tank (PCCT).

In order to validate of cooling and operational performance of PAFS using a bundle of prototypic passive condensation heat exchanger, a large-scale test facility, LAPLACE (Large Scale PAFS Loop for Assessment of Condensation Effectiveness) has been constructed with the volume scale of 1/12 for APR1000 PAFS (1/16 for APR+ PAFS) as shown in Fig. 1 [2]. This study focused on the assessment of a thermal hydraulic system analysis code, MARS, for validating the quasi-steady state tests of the LAPLACE test facility. The calculation result can be used to evaluate the prediction capability of the MARS-KS code for the heat removal capability of the PAFS. Also, the sensitivity study has been performed with adopting the advanced models for the condensation and boiling heat transfer of the PCHX.

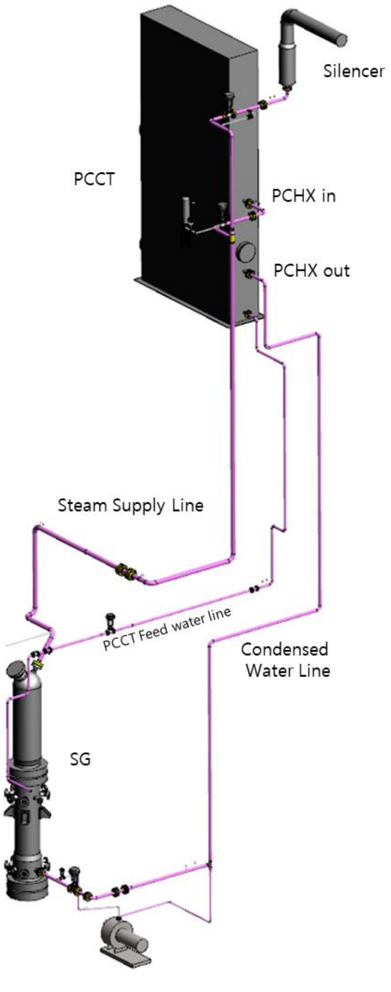

Fig. 1. LAPLACE test facility

2. MARS-KS Calculation Condition

The LAPLACE test facility was assessed with a thermal hydraulic analysis code, MARS-KS, to investigate the condensation heat transfer at the heat exchanger and the natural convection in the loop. The nodalization of the LAPLACE test facility for the MARS-KS calculation was shown in Fig. 2. The steam generator (SG), the natural circulation flow pipelines, and the PCHX were modeled with the one-dimensional hydraulic components such as the PIPE, BRANCH, and JUNCTION. The nodalization of the SG included the riser section, recirculation pipes, separator and dryer. Fifteen tubes of the PCHX in the LAPLACE test facility was modeled with a single channel pipe, of which hydraulic diameter was equivalent to the prototypic tube diameter to conserve the wall friction inside the tube. The PCHX tube was divided into 24 nodes. The pool side of the PCCT was modeled with the three-dimensional rectangular geometry of the MULTID component to simulate a multi-dimensional effect of the natural convection flow. It had three nodes in a lateral direction, where the center volumes were connected through the PCHX heat structure. 12 nodes and 18 nodes were adopted in a longitudinal and a height direction, respectively.

The heat removal capability of the PAFS is highly dependent of the condensation heat transfer on the inner wall and the boiling heat transfer of the outer wall of the PCHX. The sensitivity calculation of the MARS-KS code was conducted including following cases for the heat transfer coefficient.

- Case 0 : Default heat transfer option on inner and outer walls
- Case 1 : PAFS condensation model with Option 98
- Case 2 : Bundle heat transfer model on the outer wall (Heat transfer mode 134 and heated equivalent diameter 50.8 mm)
- Case 3 : Application of both models in Case 1 and 2

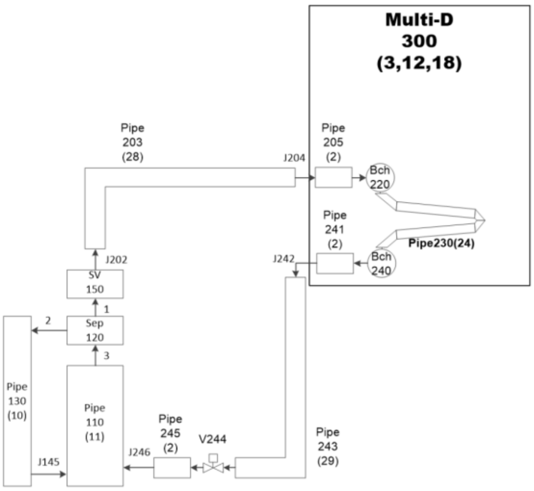

Fig. 2. MARS-KS nodalization for LAPLACE test facility

3. Result and Discussion

To maintain a confidentiality of the test data, all of the test results were divided by the design condition value of the APR+ PAFS and plotted on a non-dimensional axis. Figures 3 and 4 showed the MARS-KS calculation results for the steam pressure and the steam temperature, respectively, during the simulation of the nominal power condition in the LAPLACE SS-01 test. As the thermal power was being constantly supplied to the SG heaters, the steam pressure and temperature were increased until the thermal balance through the heat transfer of the PCHX was achieved. The converged steam pressure and the temperature in the Case 0 with the default heat transfer model were smaller than the design condition of the PAFS at the maximum heat removal. It means that the current constitutive model in the MARS-KS code has the sufficient margin in predicting the heat removal capability of the PAFS. However, the calculation result for the steam pressure or temperature was larger than the LAPLACE SS-01 test result of P*=0.45 and T*=0.91 [3], which pointed out that the heat transfer models had too much conservatism when compared to the actual test. This conservatism was reduced and the conversed steam condition became closer to the test result, as the improved heat transfer models were adopted in Case 1 and Case 2. When both models for the PAFS condensation and the bundle heat transfer were applied in Case 3, the most effective improvement was observed in predicting the converged steam pressure and temperature.

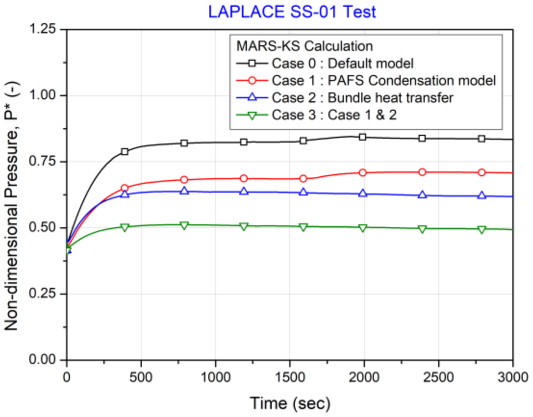

Fig. 3. Steam pressure of MARS-KS calculation for SS-01 test

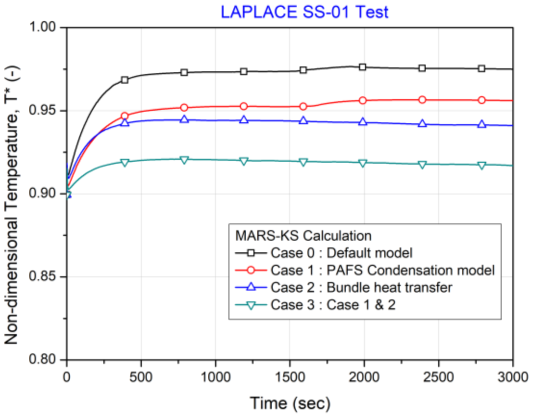

Fig. 4. Steam temperature of MARS-KS calculation for SS-01 test

Figure 5 compared the steam pressure in simulating all quasi-steady state condition (SS) tests with varying the thermal power supply. As observed in the SS-01 calculation results, the Case 3 presented the most accurate result for the conserved steam pressure. In the calculation for the SS-01 test with the highest thermal power, the adoption of the bundle heat transfer model in the Case 2 showed a better prediction than the Case 1 with the improved PAFS condensation model. However, as the thermal power was reduced, the PAFS condensation model in the MARS-KS code showed the more effective in improving the result when compared to the default model. This pointed out that the enhancement of the boiling heat transfer was more dominant in a higher heat flux region due to the increase of the nucleate heat transfer coefficient and turbulent bubble agitation on the tube surface.

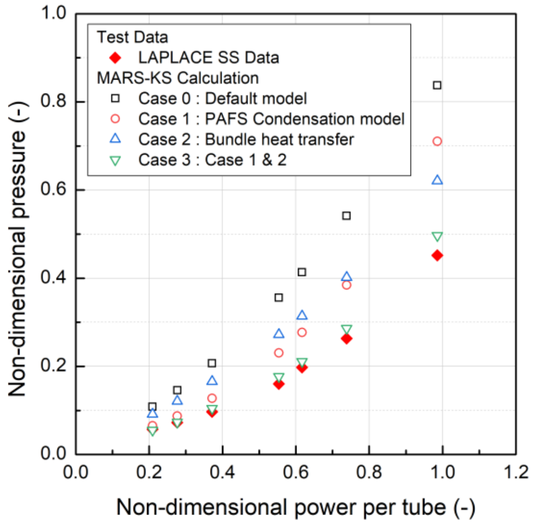

Fig. 5. Steam pressure of MARS-KS calculation in SS tests

4. Conclusion

A large-scale experimental facility named as LAPLACE (Large Scale PAFS Loop for Assessment of Condensation Effectiveness) for the PAFS has been constructed in order to investigate the effect of full-length tube bundle on the operational performance of the PAFS. This study performed the post-test calculation of the quasi-steady state tests in the LAPLACE test facility using the MARS-KS code. The calculation result proved that the current heat transfer model of the code had a sufficient margin in predicting the heat removal rate of the PAFS. The prediction capability for the heat transfer could be enhanced by adopting more proper heat transfer models for the condensation and boiling phenomena in the PCHX. As a future work, the transient test case in the LAPLACE test will be evaluated with the MARS-KS code analysis.

ACKNOWLEDGEMENT

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