Preliminary Assessment of Parallel-Tube Modeling for a PCCS Heat Exchanger Using MARS-KS

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Keywords: i-SMR, PCCS, natural circulation, condensation, MARS-KS

1. Introduction

The innovative Small Modular Reactor (i-SMR), currently under development in Korea, incorporates advanced passive safety features to improve overall safety and reliability under a wide range of abnormal and accident conditions. One of these systems is the Passive Containment Cooling System (PCCS).

During accident conditions, high-temperature steam released into the Containment Vessel (CV) is condensed on the outer surfaces of the Passive Containment Cooling Heat Exchanger (PCCHX) tubes. The heat transferred through the tube walls is removed by cooling water circulating between the PCCHX and the Emergency Cooling Tank (ECT). The resulting heat removal reduces pressure and temperature within the CV and therefore contributes to accident mitigation.

The PCCHX consists of numerous tubes connected between common headers and arranged in several layers to provide the required heat-removal capability. Individual tubes may have different lengths, heat-transfer areas, and hydraulic resistances depending on their location and geometrical configuration. In system-level safety analyses, these characteristics are usually represented using an equivalent one-dimensional PIPE component with averaged parameters. Although this approach is suitable for evaluating the overall PCCS response, a detailed tube representation can be useful to examine the effects of tube-specific characteristics.

In this study, a preliminary assessment of a detailed PCCHX tube representation was performed using MARS-KS. The conventional equivalent PCCHX model was replaced by a detailed parallel-tube model in which representative tubes were modeled separately according to their geometrical characteristics. The overall PCCS response predicted by the detailed model was first compared to the original model using a single equivalent PIPE with averaged parameters. The detailed model was then used to examine the effects of representative tube location and length on the tube-side thermal-hydraulic behavior during the transient.

2. Passive Containment Cooling System

The PCCS in i-SMR is a two-train open-loop system consisting of PCCHXs, ECTs, and associated piping and equipment. The ECT contains a large inventory of water, serves as the heat sink, and is open to the atmosphere.

The PCCHXs are located in the upper region of the CV and remove heat by condensing steam released during accident conditions. As each PCCHX is located at a lower elevation than the ECT, natural circulation is established by the elevation difference and the density difference between the relatively cold water supplied from the ECT and the heated water leaving the PCCHX. This enables passive containment heat removal without continuous electrical power or operator action.

The overall PCCS performance is influenced by various parameters, including the system pressure, heat transfer at the PCCHX, the elevation difference between the PCCHX and ECT, coolant inventory, flow-path geometry, hydraulic resistance, and inlet subcooling. Therefore, appropriate representation of the PCCHX hydraulic and thermal characteristics is important for system-level assessment of PCCS performance.

For this study, a prototypical i-SMR model developed by Jeon et al. using MARS-KS was used. This model includes the major systems and components, such as the Reactor Vessel (RV), Containment Vessel (CV), and passive safety systems including the Passive Auxiliary Feedwater System (PAFS) and PCCS with ECT.

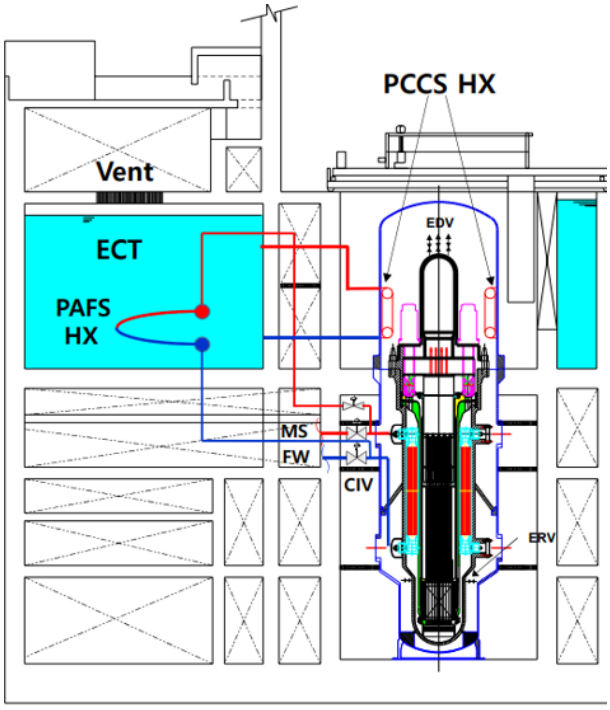

Figure 1. Schematic of i-SMR with PCCS and ECT

3. Methodology

In the original i-SMR model, the PCCHX tube bundle was represented by a single equivalent PIPE component with averaged parameters. For the present study, this component was replaced by a detailed parallel-tube model, while keeping the overall hydraulic and heat-transfer properties consistent with the original model.

The actual PCCHX tubes are divided into four layers. Therefore, a simplified MARS-KS model consisting of eight representative tubes was developed to investigate the effects of tube location and geometry on the thermal-hydraulic behavior. The developed model represents half of the actual PCCHX configuration, considering the symmetrical geometry of the heat exchanger.

These eight tubes represent four tube layers in two regions of the PCCHX. One group of tubes represents the center region, while the other represents the side region. This allows direct comparison of corresponding tubes between the two regions. Within each region, the tubes also have different lengths according to the PCCHX geometry. The PCCHX configuration and MARS-KS nodalization are shown in Figure 2.

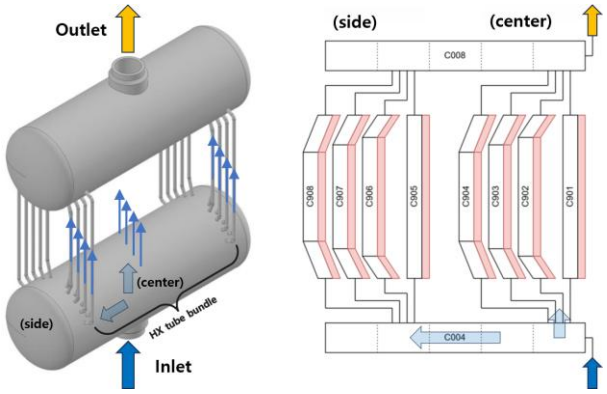

Figure 2. PCCS HX and MARS-KS nodalization

As a representative accident scenario, an inadvertent opening of one Emergency Depressurization Valve (IOEDV) was selected. To confirm consistency with the original i-SMR model, the overall system responses calculated using the original PCCHX PIPE model and the detailed parallel-tube model were compared. The RV and CV pressure responses, total PCCHX heat-transfer rate, and PCCS natural-circulation behavior showed similar trends between the two models. Therefore, the detailed tube representation did not significantly affect the overall PCCS response during the analyzed scenario.

The detailed model was then used to examine the effect of tube location. Corresponding tubes located in the center and side regions were compared in terms of mass flow rate, heat-transfer rate, and outlet liquid temperature. The simulation results showed relatively small differences between the two regions. This indicates that, under the conditions considered in the present MARS-KS analysis, the regional location of the tubes within the PCCHX tube bundle has a limited effect on tube-side thermal-hydraulic behavior.

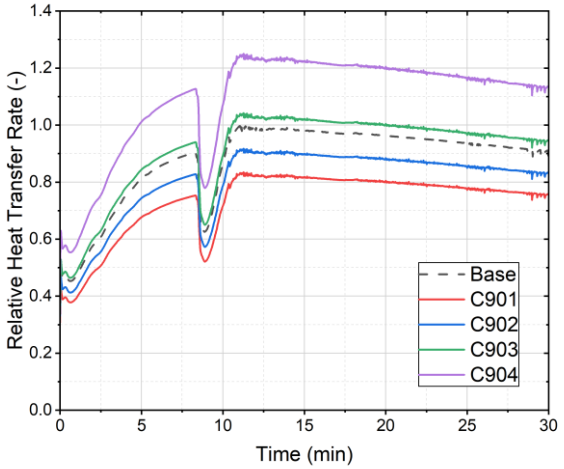

Figure 3. Heat transfer rate in PCCHX tubes

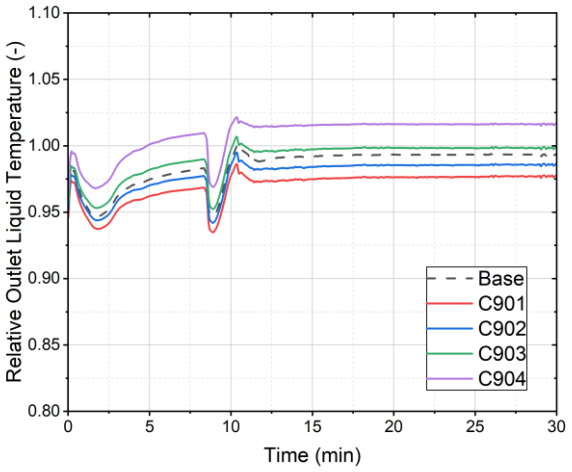

Figure 4. Outlet temperature in PCCHX tubes

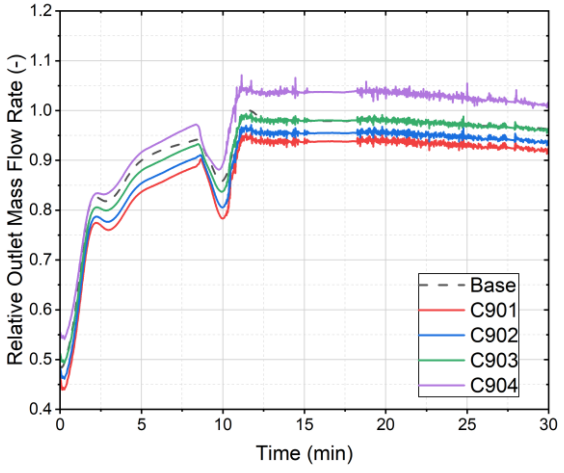

Figure 5. Outlet mass flow rate in PCCHX tubes

The effect of the tube length was also examined by comparing representative tubes having different lengths, as shown in Figures 3–5. The quantities shown in these figures are normalized, with the Base line representing the result from the original equivalent PIPE model. For

the heat-transfer rate, the Base result was scaled to an equivalent single-tube basis to allow direct comparison with the individual-tube results. Individual-tube flow rate, heat-transfer rate, and outlet temperature showed larger differences among tubes having different lengths than between corresponding tubes in the center and side regions. Such differences are expected because tube length directly affects hydraulic resistance, heat-transfer area, and coolant heating along the tube.

In particular, the differences in the heat-transfer rate between individual tubes do not directly indicate differences in condensation heat-transfer characteristics. Tubes having different lengths also have different heat-transfer areas, which contribute to differences in the total heat removed by each tube. Therefore, the observed tube-level differences mainly represent redistribution of flow and heat removal among the parallel tubes, while the overall PCCHX response remains similar to that of the original PIPE model with averaged parameters.

The tube-side thermal conditions were also evaluated based on the coolant temperature. Although some differences in outlet temperature were observed among the representative tubes, the coolant remained subcooled during the simulated period due to the hydrostatic pressure within the PCCS loop. No tube-side boiling was predicted under the simulated IOEDV scenario.

It is worth noting that the present detailed model is based on a one-dimensional representation using MARS-KS. Therefore, multidimensional steam flow distribution and detailed local condensation behavior around the PCCHX cannot be directly evaluated using the current model. Such local condensation behavior may be further investigated using a multidimensional model of the CV region around the PCCHX.

4. Conclusions

In this study, a detailed parallel-tube model of the PCCHX for i-SMR was developed using MARS-KS to evaluate the influence of individual tube representation during the IOEDV scenario. The original PCCHX PIPE model was replaced by a parallel-tube model with representative tubes having different locations within the tube bundle and different geometrical characteristics to represent the PCCHX configuration in more detail.

The detailed model showed overall PCCS behavior similar to that of the original equivalent model, including total PCCHX heat removal, natural-circulation flow, and RV and CV pressure responses. Corresponding tubes in the center and side regions showed relatively small differences for the analyzed conditions. More noticeable differences were observed among tubes having different lengths due to differences in hydraulic resistance, heat-transfer area, and coolant heating along each tube.

These tube-level differences were mainly associated with redistribution of flow and heat removal among the parallel tubes and did not significantly affect the overall PCCS response. Therefore, the equivalent PIPE model can be reasonably used for preliminary system-level analysis of the overall PCCHX behavior, while the detailed parallel-tube PCCHX model provides additional information on individual tube behavior. Future work may couple the detailed parallel-tube PCCHX model with a multidimensional model of the CV region around the PCCHX to further investigate steam flow distribution and local condensation behavior.

ACKNOWLEDGEMENT

This work was supported by the Innovative Small Modular Reactor Development Agency grant funded by the Korean Government (Ministry of Climate, Energy and Environment, MCEE) (No. RS-2024-00404240).

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