Transactions of the Korean Nuclear Society Autumn Meeting
Changwon, Korea, October 30-31, 2025

Scaling Analysis and Sensitivity Calculation for PCCS Heat Exchanger in i-SMR Integral Effect Test Facility

Jin-Hwa Yang*, Byoung-Uhn Bae, Hwang Bae and Kyoung-Ho Kang
Korea Atomic Energy Research Institute
989-111 Daedeokdaero, Yuseong-gu, Daejeon, 305-353, Korea
**Corresponding author: f1yjh@kaeri.re.kr*

***Keywords :** scaling analysis, passive containment cooling system, integral effect test facility, i-SMR

1. Introduction

An innovative small modular reactor (i-SMR), one of the fully passive small modular reactors (SMRs), is being developed in Korea. There are three different passive safety systems: a passive emergency core cooling system (PECCS), a passive containment cooling system (PCCS), and a passive auxiliary feedwater system (PAFS), as shown in Fig. 1 [1].

In particular, the PCCS of the i-SMR removes heat in the steel containment vessel (CV) via condensation heat transfer through the PCCS heat exchanger (HX) when a loss-of-coolant accident (LOCA) occurs. The PCCS is composed of the PCCS HX, connecting pipes (feed and return), and an emergency cooling tank (ECT). The PCCS HX, consisting of tubes and a header, is located in the upper part of the CV. During normal operation, coolant continuously circulates inside the PCCS. In the event of an accident, steam inside the CV condenses on the outer wall of the PCCS HX tubes, while the water inside the tubes evaporates and flows out to the ECT through the return pipe. The PCCS continuously operates via natural circulation until the ECT is depleted. The fluid conditions in the CV are expected to be high-pressure and high-temperature, ranging from 1 to 4 MPa during the accident.

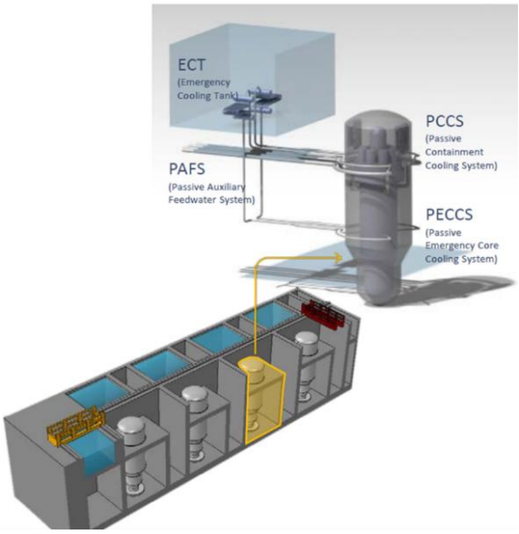
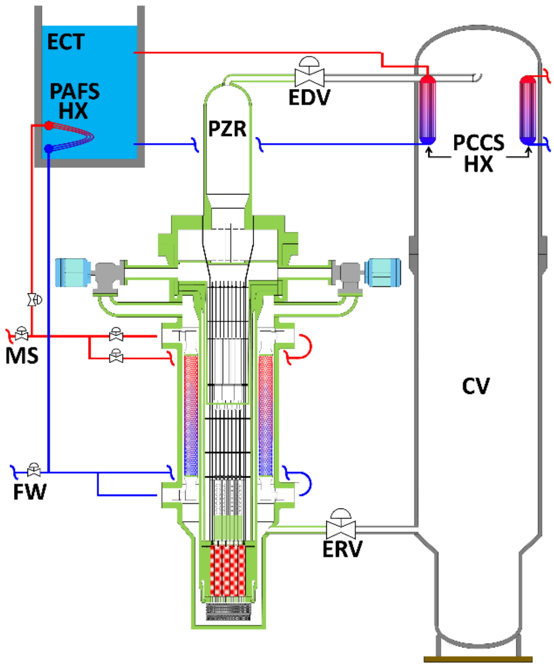
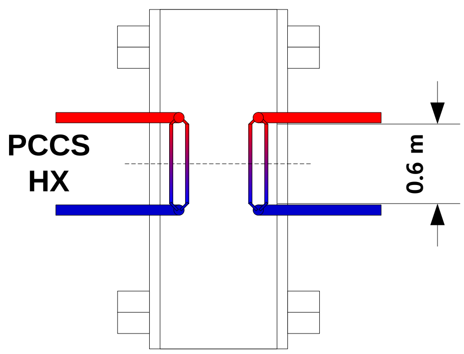


Fig. 1. Diagram of i-SMR with passive safety systems [1].

A new thermal-hydraulic experimental facility is being designed to validate design and safety of the i-SMR (Fig. 2(a)) [1]. A scaled-down PCCS is also being designed to simulate condensation heat transfer in the CV (Fig. 2(b)).



(a) i-SMR integral effect test facility [1]



(b) PCCS heat exchanger (HX)

Fig. 2. Schematics of i-SMR integral effect test facility.

2. Local Phenomena Scaling Analysis

2.1 Scaling of PCCS HX tubes

The three-level scaling method was applied to design an integral effect test facility [2]. To reflect the design characteristics of the i-SMR as closely as possible, the height, area, and volume scaling ratios were determined to be 1/2, 1/49, and 1/98 of the i-SMR, respectively.

In designing the PCCS in the integral effect test facility, the scaled-down energy dissipated by condensation through the PCCS HX must be considered as presented in Eq. (1).

$$Q_{PCCS} = \dot{m} c_p \Delta T \tag{1}$$

Assuming the temperature difference and physical properties are preserved, the ratio of condensation heat transfer should match the mass flow rate ratio as arranged in the Eq. (2).

$$(Q_{PCCS})_R = \dot{m}_{0,R} = a_{0R} l_{0R}^{1/2} \tag{2}$$

This is expressed by representing the heat transfer as the product of heat flux and heat transfer area as shown in Eq. (3).

$$(Q_{PCCS})_R = \left(q''_{PCCS}\right)_R (A_{PCCS})_R \tag{3}$$

Maintaining similar physical conditions, such as steam pressure and temperature, the heat transfer area ratio must follow the mass flow rate ratio in PCCS.

$$(A_{PCCS})_R = d_R l_R N_R = a_{0R} l_{0R}^{1/2} \tag{4}$$

Given the scale ratios of tube diameter (d_R) and length (l_R), the number of PCCS HX tube (N_R) can be determined (Table I).

2.2 Conflict between Global and Local Scaling

The PCCS is the most critical component of the PECCS, as the amount of condensate on the outer wall of the PCCS HX determines the water level in the CV and induces recirculation flow to the reactor coolant system (RCS) through the emergency recirculation valve (ERV). Therefore, preserving condensation heat transfer in the PCCS HX is a top priority. To determine the appropriate scaling ratio for the PCCS HX tube diameter, two candidate ratios were compared ($d_{PCCS,0R}$ = 1 vs. $d_{PCCS,0R} = l_{0R}^{1/2}$).

The global scaling with the Stanton number indicates how to scale effects between wall and axial convection (Eq. 5). According to the global scaling method, the tube diameter should be reduced as shown in Eq. 6.

$$St_{iR} \equiv \left(\frac{4hl_0}{\rho_f C_{pf} u_0 d}\right)_{iR} = \frac{l_{0,m}}{l_{0,p}} \left(\frac{u_{0,p}}{u_{0,m}}\right) \left(\frac{d_{PCCS,p}}{d_{PCCS,m}}\right) = l_{0R}\, u_{0R}^{-1}\, d_{PCCS,0R}^{-1} = 1 \tag{5}$$

$$d_{PCCS,0R} = l_{0R}\, u_{0R}^{-1} = l_{0R}^{1/2} \tag{6}$$

However, as shown in a study by Lee et al. [3], the effect of diameter reduction leads to distortion in condensation heat transfer affected by the correction factor for the curvature effect (η) as shown in the Eq. (7).

$$\overline{Nu}_D = \overline{Nu}_0 \cdot \eta \tag{7}$$

where

$$\overline{Nu}_0 = 890 Gr_L^{0.125} W_s^{*0.996} Ja^{-0.327}$$

$$\eta = D^*(1 - 1.21 lnD^*).$$

When tube diameter reduced following the global scaling with Stanton number as $1/\sqrt{2}$ of that of i-SMR, condensation heat transfer is distorted approximately 26%. To avoid this distortion, the tube diameter should be preserved as in the prototype.

3. Sensitivity Calculation

SPACE code [4] was used to perform sensitivity calculations for quantifying PCCS heat removal capacity using a simplified model, as illustrated in Fig. 3.

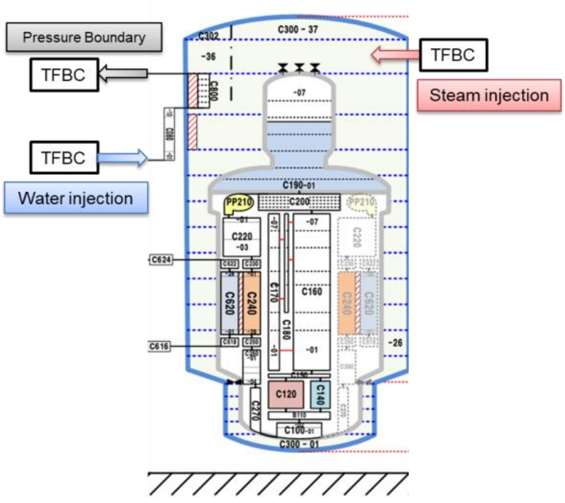


Fig. 3. Modelling of simplified PCCS in CV.

3.1 Calculation Modelling for PCCS Heat Removal

Scaling distortion between the i-SMR and the half-height test facility was assessed using a safety analysis code [5]. Two input models representing the geometry of the i-SMR and the test facility were developed for assessment of scaling distortion. However, previous models including the PAFS, complicating heat removal analysis by effect of PAFS operation. Additionally, natural circulation involving the ECT was not ideal for evaluating heat removal performance of PCCS tube due to change of boundary conditions.

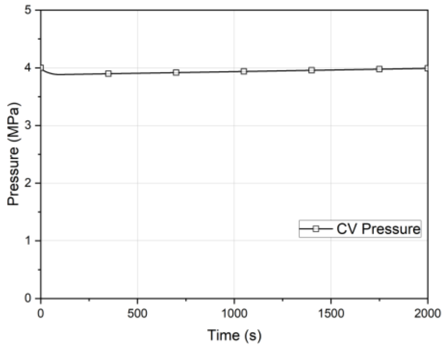
Thus, a simplified model was developed as shown in Fig. 3 to calculate PCCS heat removal capacity with different tube diameters for more effective way. For simplification, modelling of PAFS was eliminated and temporal face boundary conditions (TFBCs) were used for constant boundary conditions. Constant steam and water inlet flowrates were provided with TFBCs. Scaling ratios for geometric variables—tube diameter, length, thickness, and number—were determined by local phenomena scaling (Case 1) and global scaling (Case 2). Table I shows the cases with different scaled-down tube diameters, while keeping boundary conditions the same.

Table I: Scaling ratios of tube geometric variables

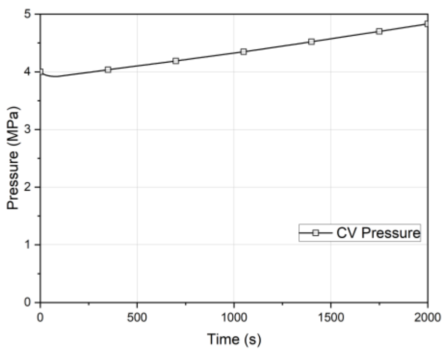
Case	Tube diameter	Tube length	Tube thickness	Number of tubes	PCCS water inlet flow rate / CV steam inlet flow rate
1	$d_{PCCS,\,0R}=1$	$l_{0R}=1/2$	$b_R=1$	$N_R=\frac{a_{0R}l_{0R}^{1/2}}{d_{PCCS,0R}l_{0R}}=\sqrt{2}/49$	Constant values were selected for same boundary conditions when CV pressure was stable as 4 MPa in Case 1.
2	$d_{PCCS,\,0R}=l_{0R}^{1/2}$	$l_{0R}=1/2$	$b_R=1$	$N_R=\frac{a_{0R}l_{0R}^{1/2}}{d_{PCCS,0R}l_{0R}}=2/49$	

3.2 Calculation Results

Boundary conditions were selected where CV pressure was stable around 4 MPa for about 2,000 seconds in Case 1 (Fig. 4(a)). In Case 2, the CV pressure increased over time as shown in Fig. 4(b).



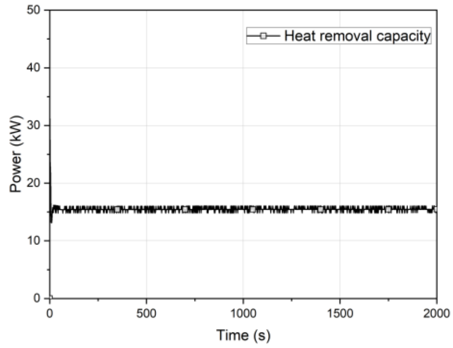
(a) Case 1



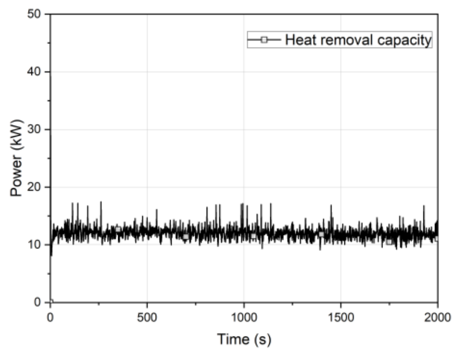
(b) Case 2

Fig. 4. CV pressure in sensitivity calculation.

The heat removal capacities with different tube sizes are presented in Fig. 5. The results showed slightly higher heat removal in Case 1 than in Case 2. This reduced heat removal in Case 2 caused greater pressure rise, indicating lower condensation heat transfer efficiency.



(a) Case 1



(b) Case 2

Fig. 5. Heat removal capacities for each case.

3. Conclusions

Scaling analysis and sensitivity calculations were performed to design the PCCS HX in the i-SMR integral effect test facility. A conflict between global scaling criteria and local phenomena preservation was identified. To select a suitable tube diameter scaling ratio, a sensitivity analysis was conducted using the SPACE code. Although exact transient behaviors could not be simulated, applying the same boundary conditions to cases with different tube diameters resulted in differing heat removal capacities. These findings indicate that the tube diameter of the PCCS HX should match that of the prototype to avoid scaling distortion.

ACKNOWLEDGMENTS

This work was supported by the Innovative Small Modular Reactor Development Agency grant funded by the Korea Government (MSIT R&D) (No. RS-2023-00257680).

REFERENCES

[1] J. H. Yang, B. U. Bae, H. Bae, K. H. Kang, "Scaling Analysis for Conceptual Design of Steel Containment Vessel in i-SMR Integral Effect Test Facility," Transactions of the Korean Nuclear Society Spring Meeting, Jeju, Korea, May 9-10, 2024.

[2] M. Ishii, et al., "The three-level scaling approach with application to the Purdue University Multi-Dimensional Integral Test Assembly (PUMA)", *Nuclear Engineering and Design*, 186, 177–211, 1983.

[3] Y. G. Lee, S. G. Lim, "Implementation of a new empirical model of steam condensation for the passive containment cooling system into MARS-KS code: Application to containment transient analysis," *Nuclear Engineering and Technology*, **Vol. 53**, pp. 3196-3206 (2021).

[4] SPACE Code Manual Vol. 2: User Manual, TP-KHNP-0032.

[5] J. H. Yang, B. U. Bae, H. Bae, K. H. Kang, "Scoping Analysis of Two-phase Flow in Condensate Pool for Scaling of Steel Containment Vessel of i-SMR Test Facility," NTHAS 13, Seoul, Korea, November 10-13, 2004.