

Assessment of Thermal-Hydraulic Similarity between the i-SMR and Ideally Scaled-Down Model under an IOEDV Transient

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1. Introduction

In Korea, the i-SMR is being developed as a small modular reactor that enhances safety by employing Passive Safety Systems (PSSs) as the main design feature. The i-SMR is an integral Pressurized Water Reactor (PWR), in which the reactor core, pressurizer (PZR), Reactor Coolant Pumps (RCPs), and once-through helical-coil Steam Generators (SGs) are integrated within a single Reactor Vessel (RV). In addition, the i-SMR employs the Passive Auxiliary Feedwater System (PAFS), Passive Containment Cooling System (PCCS), and Passive Emergency Core Cooling System (PECCS), which are designed to mitigate accidents without electrical power or operator actions by relying on natural driving forces such as natural circulation, gravity, and pressure differences (see Fig. 1). These passive safety systems do not operate independently, but are thermally and hydraulically coupled through the RV, Containment Vessel (CV), and Emergency Cooling Tank (ECT) to provide core cooling and residual heat removal under accident conditions [1].

The Korea Atomic Energy Research Institute (KAERI) is developing an Integral Effect Test (IET) facility to experimentally evaluate the major thermal-hydraulic phenomena and PSS behavior of the i-SMR under accident conditions. The IET facility is being scaled down from the original i-SMR design based on Ishii's three-level scaling approach [2–4]. Because the passive safety systems of the i-SMR rely primarily on natural circulation, it is important to adequately preserve the major thermal-hydraulic characteristics affecting natural circulation, including height, flow rate, and heat transfer, in the scaled-down model. Accordingly, in the present study, an ideally scaled-down Half-Height (HH) model of the i-SMR was developed based on the global scaling ratios applied to the IET design, and its thermal-hydraulic behavior was compared with that of the prototype.

To assess the adequacy of the scaling methodology applied to the scaled-down model, it is necessary to determine whether the major thermal-hydraulic behavior of the prototype under accident transient conditions is reproduced similarly in the scaled-down model. For this purpose, an Inadvertent Opening of an Emergency Depressurization Valve (IOEDV) was selected as the representative transient in this study. The IOEDV causes Reactor Coolant System (RCS) depressurization and CV

pressurization due to reactor coolant discharge through the Emergency Depressurization Valve (EDV), followed by the coupled operation of the PAFS, PCCS, and PECCS; therefore, it provides a suitable basis for comparing the thermal-hydraulic behavior of the prototype and the scaled-down model [1]. In the present study, IOEDV transient analyses were performed for the i-SMR prototype and HH model using the SPACE code, and the normalized results of the major thermal-hydraulic variables were compared. Based on this comparison, the ability of the HH model to reproduce the major thermal-hydraulic behavior of the prototype under the IOEDV transient was examined, and the adequacy of the applied scaling methodology was assessed.

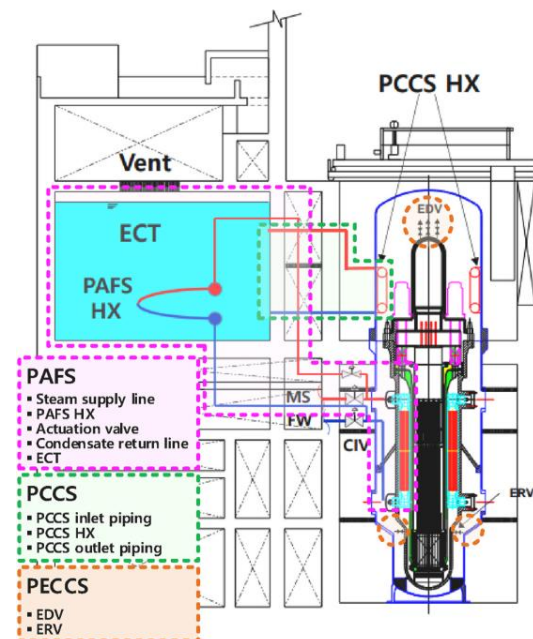


Fig. 1. passive safety systems in i-SMR (PAFS, PCCS, PECCS) [1]

2. Methods and Results

2.1 Ideally Scaled-down Model

In this study, IOEDV transient analyses were performed using the SPACE code for the i-SMR Prototype (OR) model and an ideally scaled-down HH nodalization model developed according to Ishii's

scaling methodology (see Table I and Fig. 2). The vertical height of the HH model was set to 1/2 of the OR model, and the corresponding scaling ratios were applied to each variable to preserve the major thermal-hydraulic phenomena of the prototype system.

Because the OR and HH models have different scales, the analysis results were normalized using the scaling ratio for each variable to compare the thermal-hydraulic behavior of the two models on the same basis.

Table I: Global scaling ratio for HH. [2]

Parameter	Symbol	Scale Ratios	
Length, height, elevation	l_{OR}	l_{OR}	1/2
Diameter	d_{OR}	d_{OR}	1/7
Area	a_{OR}	d_{OR}^2	1/49
Volume	v_{OR}	$l_{OR}a_{OR}$	1/98
Heat transfer rate	$d_R^2 l_R^{1/2}$	$d_R^2 l_R^{1/2}$	$1/49\sqrt{2}$

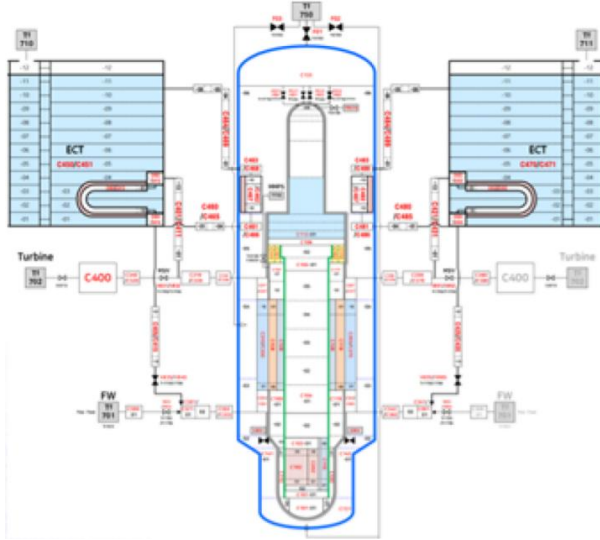


Fig. 2. SPACE nodalization of i-SMR(HH)

2.2 Primary System and Containment Results

Fig. 3 shows the normalized pressures of the RV, SG, and CV. Immediately after the IOEDV, the RV pressure decreases sharply due to coolant discharge, whereas the CV pressure increases due to the inflow of coolant discharged from the RV. Thereafter, as the pressure difference between the RV and CV decreases, the pressures of the systems gradually decrease. Except for some differences during the early phase of the transient, the OR and HH models exhibit similar pressure trends in the RV, SG, and CV, and the results become nearly identical as the transient progresses. These results indicate that the primary-system depressurization and CV pressurization associated with the IOEDV are appropriately reproduced in the HH model.

Fig. 4 shows the normalized water levels of the RV and CV. Following the IOEDV, the RV water level decreases and the CV water level rises as reactor coolant is discharged from the RV into the CV. Thereafter, the changes in water level become less pronounced as the

pressure difference between the RV and CV decreases, and the water levels in both regions reach nearly constant levels. The OR and HH models show generally similar trends in the initial water-level response and subsequent stabilization. Therefore, the RV and CV pressure and water-level responses associated with the IOEDV are considered to be reproduced in the HH model with trends similar to those of the OR model.

2.3 Passive Safety System Results

Fig. 5 shows the normalized core thermal power and heat removal rates of the PAFS, PCCS, and CV. Following the IOEDV, the heat removal rates of the PAFS and PCCS initially increase and then gradually decrease as the transient progresses. The OR and HH models show similar overall trends, although some quantitative differences are observed in the heat removal rates. The reasons for these differences have not yet been fully identified and are currently under investigation. Further refinement of the model and analysis conditions will be carried out to improve the similarity between the two models.

Fig. 6 shows the normalized PAFS natural circulation flow rate. Immediately after the IOEDV, the PAFS flow is rapidly established and then gradually decreases as the transient progresses. The OR and HH models show similar average flow-rate trends.

Fig. 7 shows the normalized PCCS natural circulation flow rate. After the IOEDV occurs, the PCCS flow rate increases rapidly as the CV pressure and temperature increase. The flow rate then gradually decreases as the accident progresses. The OR and HH models show similar overall flow-rate trends, indicating that the PCCS natural circulation behavior is similarly reproduced in the HH model.

Fig. 8 shows the normalized mass flow rates through the EDVs and ERVs of the PECCS. During the early phase of the accident, EDV flow occurs due to the large pressure difference between the RV and CV and rapidly approaches zero as the pressure difference decreases. The ERV initially exhibits flow in the direction opposite to the EDV flow and then gradually decreases. Although some differences in flow magnitude and oscillations are observed during the early phase, the overall behavior, in which the flow through each path rapidly decreases after being established, is similar in the OR and HH models.

3. Conclusions

In this study, an IOEDV transient analysis was performed using the SPACE code for the i-SMR prototype and an ideally scaled-down Half-Height (HH) model developed according to Ishii's scaling methodology, and the normalized results of the major thermal-hydraulic variables were compared. Following the IOEDV, the prototype and HH models showed generally similar transient behavior in the EDV discharge flow rate, system pressure, and RV and CV water levels. The PAFS, PCCS, and PECCS also showed

similar trends in their major flow and heat removal characteristics. Although some quantitative differences and local oscillations were observed in the natural circulation flow rates and heat removal rates, the major thermal-hydraulic phenomena and overall trends during the transient remained similar to those of the prototype. These results confirm that the applied scaling methodology appropriately preserves the major thermal-hydraulic characteristics of the i-SMR prototype in the HH model under the IOEDV transient condition.

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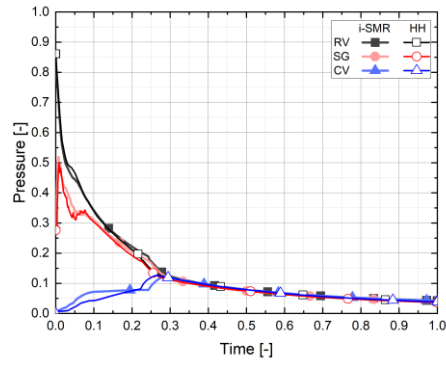


Fig. 3. Normalized Pressure

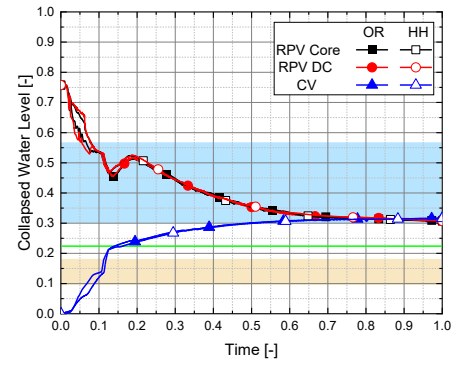


Fig. 4. Normalized RV and CV water level

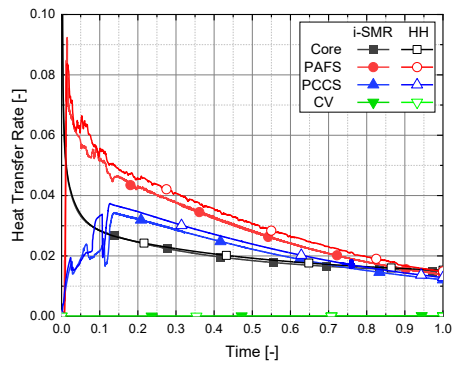


Fig. 5. Normalized heat transfer rate

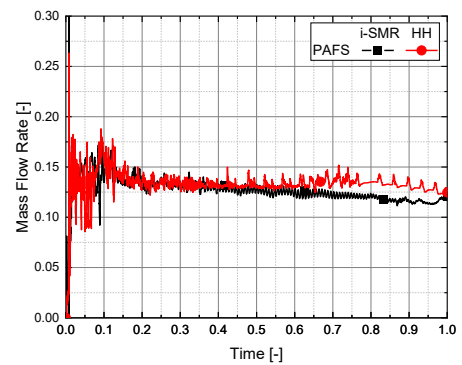


Fig. 6. Normalized PAFS mass flow rate

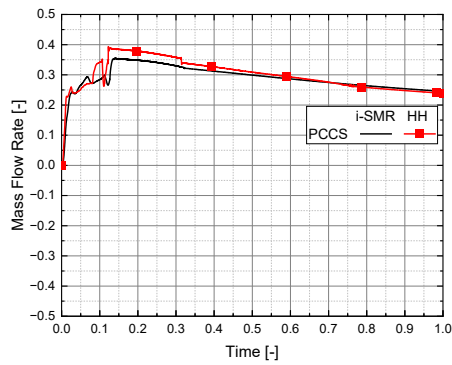


Fig. 7. Normalized PCCS mass flow rate

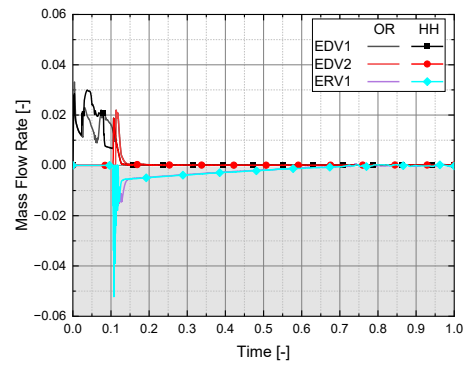


Fig. 8. Normalized PECCS mass flow rate