

Rough Calculation of Heat Loss in Scaled-Down Test Facility for SMR

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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 (see Fig. 1). To verify the safety of the i-SMR and to establish an experimental database for licensing, KAERI is constructing a thermal-hydraulic integral effect test (IET) facility (see Fig. 2).

An IET facility provides reliable data when the thermal-hydraulic phenomena of a nuclear power plant (NPP) are accurately reproduced in a scaled-down facility. For this purpose, scaling parameters such as elevation and volume are defined, and the geometric similarity of PSSs is primarily considered. However, heat loss to the environment is inevitable due to the temperature difference from the surroundings. This heat loss can cause significant distortion in the thermal-hydraulic behavior and performance of PSSs, whose driving forces are relatively weak.

Since PSSs rely on natural circulation driven by density and hydrostatic head differences instead of pump power, an increase in system heat loss can reduce the fluid temperature, decrease the density difference, and eventually degrade the driving force. If scaling distortion occurs in an IET facility, increased heat loss changes the density difference of the fluid, which can cause the driving force of PSSs to deviate from the design intent.

Thus, in this study defines a conceptual reactor, referred to as the Conceptual SMR (C-SMR), by assuming the geometry of the reactor vessel (RV) and CV of the i-SMR, and qualitatively evaluates the heat loss through the outer walls of the RV and CV. Then, an ideal scaled-down facility (IS-C-SMR) is considered. This facility is designed to preserve the key thermal-hydraulic phenomena of the reference C-SMR by applying an ideal scaling analysis. The IS-C-SMR is compared with the Actual Scaled-down C-SMR (AS-C-SMR), which is a test facility designed by considering the actual plant layout.

For the C-SMR, IS-C-SMR, and AS-C-SMR, the heat loss from the RV and CV is roughly calculated to examine the scaling distortion. These results are expected to provide insights for minimizing heat loss in the i-SMR thermal-hydraulic IET facility.

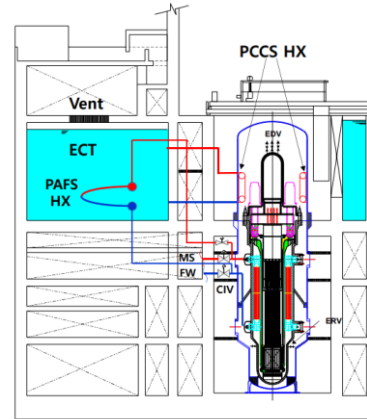


Fig. 1. Schematic of i-SMR [1]

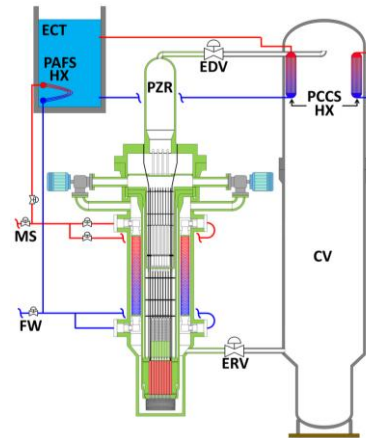


Fig. 2. Schematic of i-SMR integral effect test facility [2]

Table I: Global scaling ratios for IET. [2]

Parameters	Scaling Ratios for IET
Length	1/2
Diameter	1/7
Cross-sectional Area	1/49
Volume	1/98
Heat transfer rate	$1/49\sqrt{2}$

2. Calculation Method

2.1 Heat Loss Coefficient

To calculate the heat loss, we used the heat loss coefficient in Fig. 3. This author has the experience to

determine the heat loss in the pipes and the vessel in the ATLAS [3]. Based on the heat loss quantification results for ATLAS, this author obtained the graph below by averaging the heat loss in all components. At this time, the pipe and the vessel were separated to derive a value. Heat loss (Q) can be simply calculated using the heat loss coefficient (h_{loss}), the outer surface area of the equipment and piping (A), and the difference between the fluid temperature (T_{fluid}) and the ambient temperature (T_{amb}) as follows:

$$Q = 1.5h_{loss} \cdot A \cdot (T_{fluid} - T_{amb}) \quad (1)$$

For reference, the heat loss coefficients in Fig. 3 were derived on the assumption that all components in ATLAS are covered with insulation. In this study, since the RV and CV of C-SMR is assumed to have no insulation, a factor of 1.5 was arbitrarily applied to the coefficients in Fig. 3 [3].

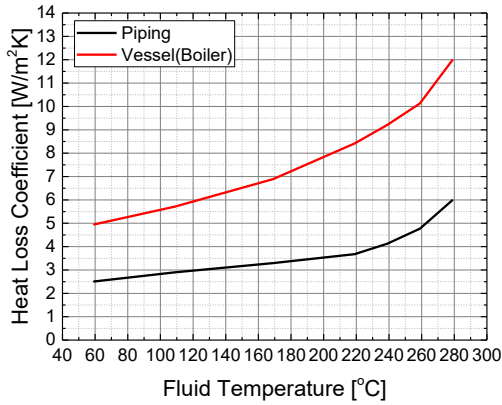


Fig. 3. Heat loss coefficient (h_{loss}) for rough calculation [3]

2.2 Geometry and Temperature

The geometry of the C-SMR was assumed as shown in Fig. 4, and the diameters and elevations of the IS-C-SMR were calculated according to the scaling ratios in Table I. Based on these geometric data, the surface areas were calculated. The heat loss of AS-C-SMR was calculated by classifying it into two distinct options. For AS-C-SMR#1, the RV and CV were modeled as separate components with identical dimensions. In the case of AS-C-SMR#2, the surface area was determined based on a calculated diameter that ensures the CV volume is equivalent to that of the IS-C-SMR.

To calculate the heat loss of the C-SMR, IS-C-SMR, and AS-C-SMR, the RV and CV fluid temperatures were assumed to 300°C and 150°C, respectively. For the AS-C-SMR, the temperature of the connecting pipes between the RV and CV was set to 200°C. and the ambient temperature was assumed to be 20°C.

3. Rough Calculation of Heat Loss

The rough heat loss for the C-SMR, IS-C-SMR and AS-C-SMR, was calculated using the heat loss

coefficients presented in Fig. 3 and the geometric parameters shown in Fig. 4.

For the C-SMR, the RV and CV heat losses were calculated as 2.3 MW and 1.37 MW, corresponding to about 0.46% and 0.27% of the total 500 MW thermal power, respectively. Thus, in the full-scale nuclear power plant, heat loss to the environment is relatively small compared with the core power.

When the system was scaled down ideally to the IS-C-SMR with 8 MW core power, the RV and CV heat losses became 0.15 MW and 0.08 MW, i.e., 1.89% and 1.02% of the total power. Although the absolute values decreased, the relative fractions increased by roughly a factor of four compared with the C-SMR, indicating that heat-loss effects are amplified by scaling even when the RV is still located inside the CV.

In the AS-C-SMR, the RV and CV are structurally separated because of layout constraints, and additional piping between them is exposed to the ambient. In this configuration, the RV, CV, and piping heat losses were 0.28 MW, 0.08 MW, and 0.003MW, corresponding to 3.54%, 1.02%, and 0.034% of the 8 MW power. The total fraction of power lost to the environment increases from 0.27% in the C-SMR to 1.02% in the IS-C-SMR and to about 4.3% in the AS-C-SMR. This trend shows that structural separation and additional surface area can significantly distort heat loss in a scaled-down facility, potentially reducing the natural-circulation driving forces of the passive safety systems.

Table II: Heat Loss Comparison by C-SMR

	Heat Loss [MW]	Heat Loss Rate [%]
Q_{RV} [MW]	2.30	0.46
Q_{CV} [MW]	1.37	0.27
Q_{total} [MW]	1.37	0.27

Table III: Heat Loss Comparison by IS-C-SMR

	Heat Loss [MW]	Heat Loss Rate [%]
Q_{RV} [MW]	0.15	1.89
Q_{CV} [MW]	0.08	1.02
Q_{total} [MW]	0.08	1.02

Table IV: Heat Loss Comparison by AS-C-SMR#1

	Heat Loss [MW]	Heat Loss Rate [%]
Q_{RV} [MW]	0.28	3.54
Q_{CV} [MW]	0.08	1.02
Q_{pipe} [MW]	0.003	0.034
Q_{total} [MW]	0.37	4.6

Table V: Heat Loss Comparison by AS-C-SMR#2

	Heat Loss [MW]	Heat Loss Rate [%]
Q_{RV} [MW]	0.28	3.54
Q_{CV} [MW]	0.06	0.72
Q_{pipe} [MW]	0.003	0.034
Q_{total} [MW]	0.34	4.3

4. Conclusions

A rough heat-loss evaluation performed for a C-SMR, IS-C-SMR and AS-C-SMR. In the C-SMR, RV and CV heat losses are small (0.46% and 0.27% of core power), whereas the IS-C-SMR shows substantially increased fractions (1.89% and 1.02%). In the AS-C-SMR, the combined heat loss from the RV, CV, and piping reaches about 4.3% of the core power, due to the structural separation of the RV and CV and the exposed piping.

These results indicate that heat-loss distortion is non-negligible in scaled-down SMR test facilities and can weaken the natural-circulation driving forces of passive safety systems. Therefore, to accurately reproduce the thermal-hydraulic phenomena of PSSs, it is necessary to install insulation and tracing heaters to minimize heat loss in the design of the i-SMR IET facility.

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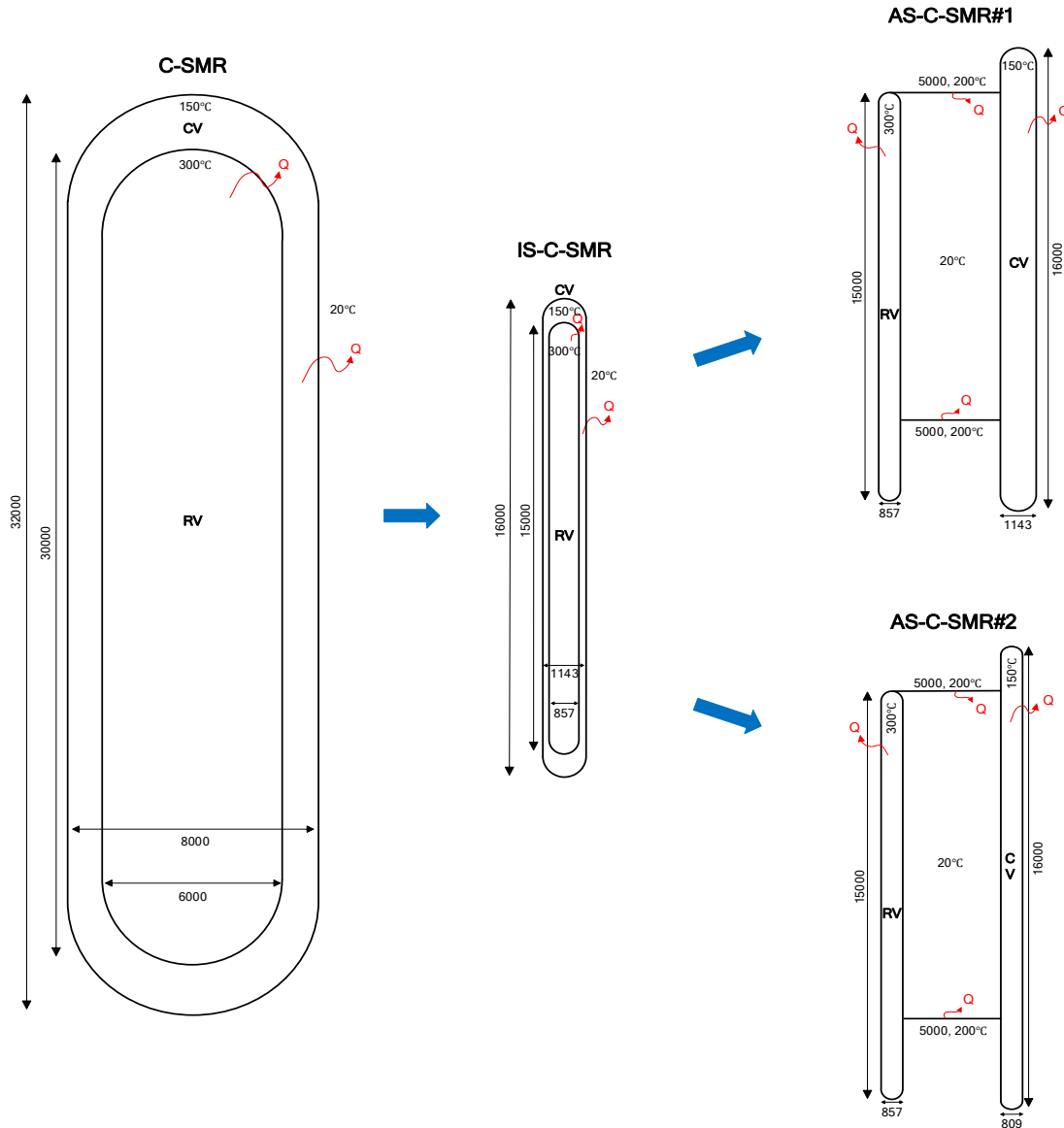


Fig. 4. Schematic of C-SMR and scaled-down facility (length unit: mm)