Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 9-10, 2024

An Experimental Study on the Effect of Thermal Radiation Shielding within a Metal Containment Vessel of Small Modular Reactors

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***Keywords :** SMR, MCV, thermal radiation shielding, emissivity, insulation performance

1. Introduction

Small modular reactors (SMRs), a representative technological advancement in the nuclear industry, generate an electricity power capacity of up to 300 MW(e) per module [1]. These reactors are gathering attention for enhanced safety features, lower capital cost, and modular design based on their smaller size and power compared to conventional reactors. As a part of the innovative safety components being explored, the concrete containment building has been substituted with a metal containment vessel (MCV) in numerous advanced SMRs.

In accident situations, the MCV helps remove residual heat within the reactor core due to its superior thermal conductivity to concrete containment building. However, this thermal property may cause potential side effects, such as relatively significant heat losses under normal operation. In addition, a non-insulating reactor, adopted to prevent the sump-screen blockage issue during recirculating coolant, makes the inevitable heat loss more significant.

Exploring ways to minimize heat loss through the MCV is imperative to improve reactor efficiency. One of the notable strategies for mitigating heat loss is maintaining a weak vacuum between the reactor pressure vessel (RPV) and MCV, as NuScale exemplified [2]. In the vacuum condition, conductive and convective heat transfer can be effectively suppressed due to the absence of heat transfer media. However, thermal radiation can be transferred depending on the temperature of the RPV outer wall [3].

Lee et al. (2024) demonstrated that radiative heat loss dominates in the Korean innovative-SMR (i-SMR) with MCV in a weak vacuum condition [4]. Figure 1 shows the comparison of the heat loss with and without thermal radiation shielding (TRS). They suggested that the heat loss via MCV could be reduced using TRS with low emissivity, especially in a vacuum. However, the study does not include experimental verification and validation of the numerical results.

Therefore, the objective of this study is to evaluate the contribution of radiative heat loss on the MCV structure and experimentally verify the effect of TRS. This study confirms the effects of design parameters of TRS on the heat transfer mechanism within the MCV by a scaling experiment of the Korean i-SMR at internal pressure below 0.08 bar. The design parameters of TRS were selected based on the research of Mohammad et al. [5], considering both diameter and material. Based on the results, this study validated the results of the previous numerical analysis [4] and proposed a design direction for a more efficient Korean i-SMR.

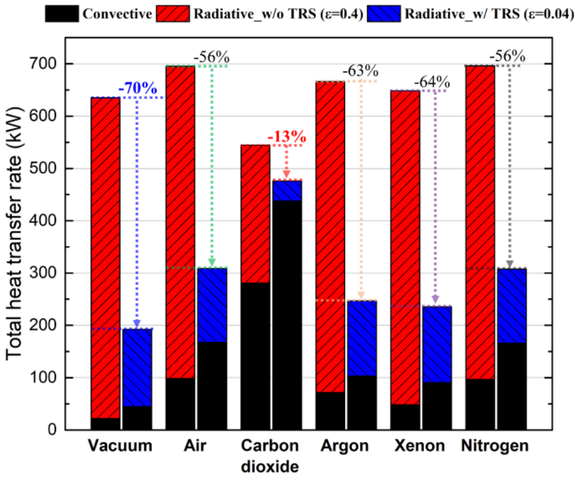

Fig. 1. Comparison of the heat loss with and without thermal radiation shielding (TRS) [4].

2. Description of Experimental Setup

Schematic of the experimental setup is illustrated in Figure 2, which consists of the cartridge heater with an aluminum conductor, a stainless-steel chamber, temperature sensors (thermocouples and resistance temperature detectors), a vacuum pump, a pressure gauge, a power supply, and a data acquisition system.

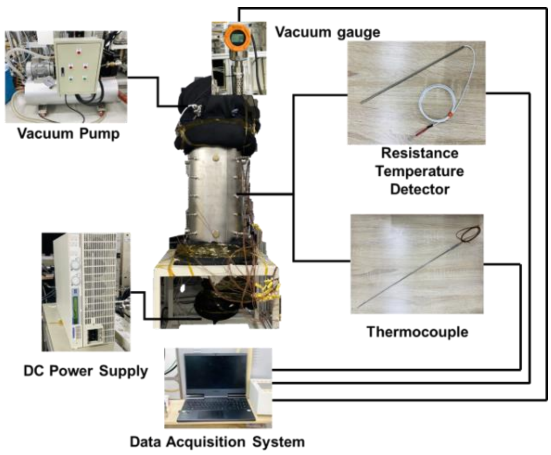

Fig. 2. Schematic of experimental setup

Figure 3 shows a schematic of the experimental apparatus consisting of a 6T and 400D(Inner) stainless-steel chamber (i.e., SS304) and a 1-inch cartridge heater with 101.6D(outer) aluminum conductor, representing the MCV and RPV, respectively. The experimental apparatus was designed to evaluate the radiative heat loss of the Korean i-SMR. Thus, during the design process of the experimental apparatus, the view factor of the target reactor was considered as a significant parameter. The view factor, an important parameter in radiative heat transfer, was determined by only geometric features such as the ratio of related surface areas. In the Korean i-SMR, the view factor of an interested region (i.e., pressurizer region) is 0.273, while that of this apparatus is 0.254 with an error of 7 %. The top and bottom flanges were chosen to seal the chamber tightly. Insulators, such as ceramic fiber and carbon fiber, were installed to minimize the heat loss through the flanges.

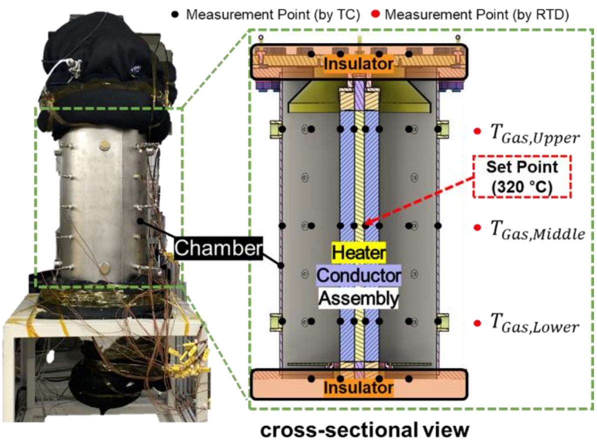

Fig. 3. The experimental apparatus and measurement points.

The power input was adjusted using the DC power supply to maintain a target heater temperature of 320 °C, the coolant temperature of the pressurizer region in the Korean i-SMR. The temperature of the heater-al conductor assembly, bulk, chamber wall, and flanges can be measured with K-type thermocouples (TCs), and the ambient temperature can be measured with resistance temperature detectors (RTDs). It has been stated that the TCs provide an accuracy of about 2 °C, and the RTDs provide an accuracy of about 0.3 °C. The measured temperatures were used to determine the steady state of the experiments.

The experiments are summarized in Table I. The chamber was set to a low vacuum of 0.08 bar for all experimental cases. The Background conduction case was performed by filling a chamber with ceramic fiber. The Background conduction case is aimed to determine the heat loss caused by conduction in the experimental apparatus, which occurs in all cases. As the Base case, experiments were conducted without TRS. The cases labeled as 'Al-200', 'Al-400', and 'SS304-400' were conducted by varying the diameter and material of the TRS. Diameter and emissivity were selected as design parameters for TRS due to their influence on radiative heat transfer rates, as described in equation (1), where P, ε, σ, and T represent the radiated power, surface emissivity, Stefan-Boltzmann constant, and temperature, respectively. Diameters of 200 mm and 400 mm were chosen, representing 1/3 and 3/3 of the distance between the chamber and the Al conductor, as shown in Figure 4. The materials selected to vary the emissivity were aluminum (Al) and stainless steel (SS304), with assumed emissivity values of 0.04 and 0.3, respectively [6].

Table I: Test matrixes for assessment of insulation performance of the MCV

Experimental Cases	**Filling condition (pressure)**	**TRS parameters**		
		Material	**Diameter (mm)**	**emissivity**
Background conduction case (w/o TRS)	Ceramic Fiber Insulator (0.08 bar)	-	-	-
Base case (w/o TRS)	Vacuum (0.08 bar)	-	-	-
Al-200	Vacuum (0.08 bar)	Aluminum	200	0.04
Al-400	Vacuum (0.08 bar)	Aluminum	400	0.04
SS304-400	Vacuum (0.08 bar)	SS304	400	0.3

(1) $P = \varepsilon\sigma A({T_1}^4 - {T_2}^4)$ where A is surface area

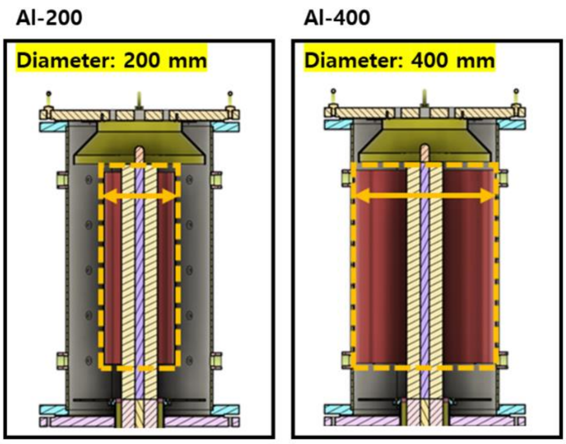

Fig. 4. Schematics for the installation of the thermal radiation shielding.

Figure 5 shows the temperature variation of the measurement points by the experimental time. Steady state was defined as a difference of less than 0.5 °C between the maximum and minimum temperatures over 3600 seconds. The experiments were conducted indoors with an ambient temperature of 18 °C. The experiments were repeatably conducted three times for each case.

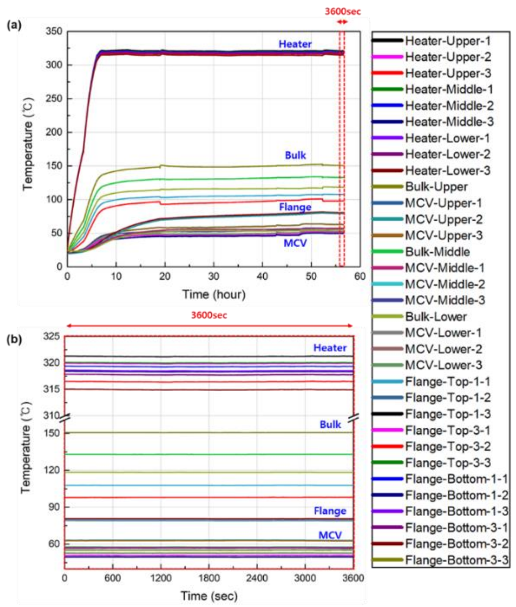

Fig. 5. Temperature variations by experimental time: (a) Full time and (b) under steady state.

3. Results and Discussion

3.1 Experiments for the Base case and Background conduction case

The primary assumption of this study is that the effect of convective heat transfer was negligible because the experiments were conducted in a vacuum chamber. The Base case was conducted to evaluate the combined heat loss by conduction and radiation. To obtain reference data, the Background conduction case, which assumes that heat loss occurs only by conduction, was performed to analyze the heat transfer mechanism of the experimental apparatus by comparing it with other cases. Figure 6 shows the radial temperature distribution from center to MCV of two experimental cases. The two experimental cases were compared to determine the contribution of radiative heat transfer to the total heat losses. Figure 7 shows the experimental apparatus's background conduction and the proportion of radiative heat loss in the total heat loss. The results imply that radiative heat loss accounts for about 60% of the total heat loss. The results of the preliminary experiments are shown in Table II. The background conduction value was assumed to be constant for subsequent experimental results.

Table II: The results of the preliminary experiments

Experimental Case	Heater Temp. (°C)	Chamber Pressure (bar)	Ambient Temp. (°C)	Heater Input (W)
Background conduction case	320.40	0.08	18.08	144.34
Base case	319.97	0.05	18.52	338.53

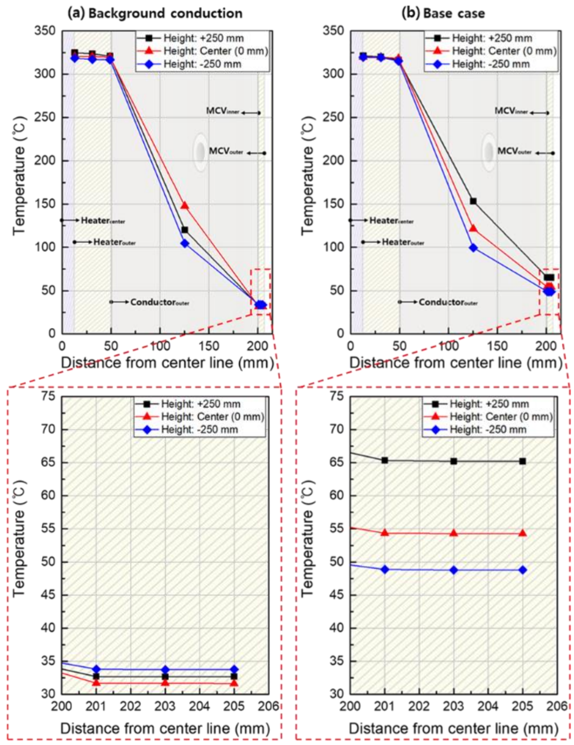

Fig. 6. Radial temperature distributions from center to MCV of (a) Background conduction case and (b) Base case.

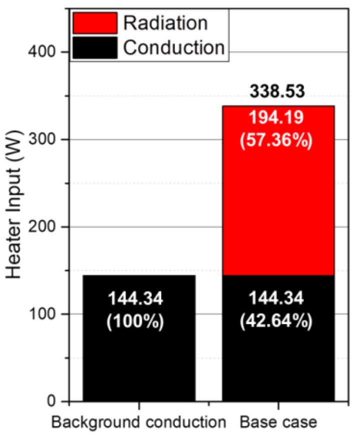

Fig. 7. Heat loss of Background conduction and Base case.

3.2 The effect of the thermal radiation shielding

The experiments were conducted with and without TRS to verify the effect of the TRS. Figure 8 shows the radial temperature distribution of the Base case and Al-400 case. In the case of TRS, the TRS is made of aluminum and has a diameter of 400 mm. Table III and Figure 9 show the results of experiments conducted with and without TRS. Heat loss was approximately 12% lower without TRS than with TRS. This difference in heat loss is probably due to the emissivity difference between the inner wall of the chamber and the TRS, as well as the effect of the increased wall thickness due to the TRS. A reduction of about 12% in heat loss is considered significant. To identify more effective ways to apply TRS, various variables of TRS were evaluated.

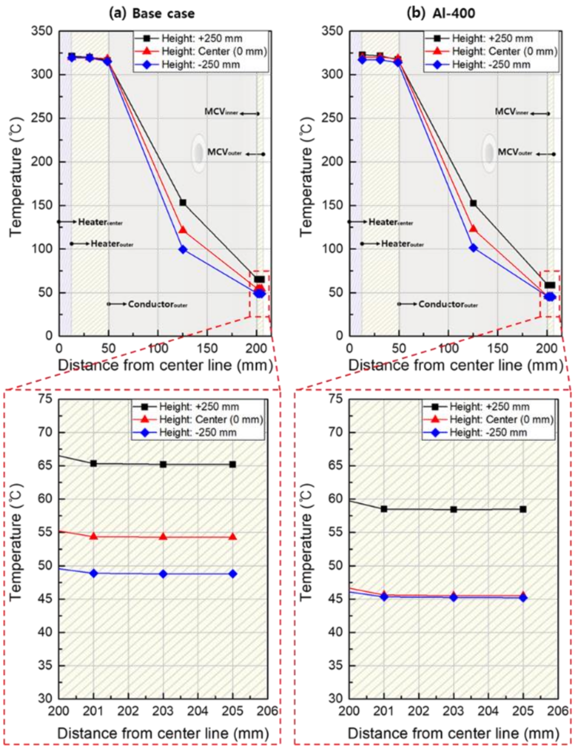

Fig. 8. Radial temperature distributions from center to MCV of (a) Base case and (b) Al-400 case.

Table III: The results of the TRS effect experiments

Experimental Case	Heater Temp. (°C)	Chamber Pressure (bar)	Ambient Temp. (°C)	Heater Input (W)
Base case	319.97	0.05	18.52	338.53
Al-400	320.13	0.06	17.60	297.03

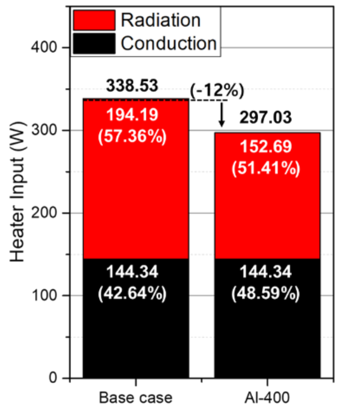

Fig. 9. Heat loss of Base case and Al-400 case.

3.3 The effect of the thermal radiation shielding parameters

Experiments were conducted with different diameters and materials to find the optimal TRS. Figure 10 shows the radial temperature distribution of TRS cases. Table IV and Figure 11 show the results of the experiments depending on the diameter and material of the TRS. In experiments with varying TRS diameters, the heat loss of the 200 mm TRS was about 3% lower than that of the 400 mm TRS. The result seems to be due to the additional conductive heat transfer from the 400 mm TRS to the chamber. In experiments with varying the TRS material, the Al TRS's` heat loss was found to be about 10% lower than that of the SS304 TRS. The experimental results suggest that an emissivity of 0.04 provides better insulation than an emissivity of 0.3.

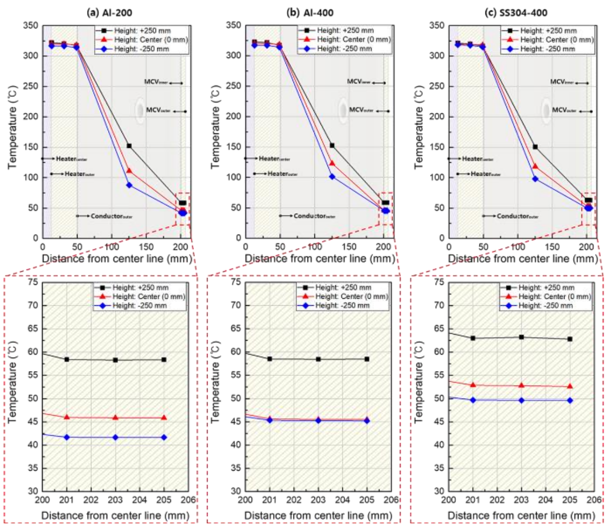

Fig. 10. Radial temperature distributions from center to MCV of (a) Al-200 case, (b) Al-400 case, and (c) SS304-400 case.

Table IV: The results of the thermal radiation shielding parameters experiment

Experimental Case	Heater Temp. (°C)	Chamber Pressure (bar)	Ambient Temp. (°C)	Heater Input (W)
Al-200	319.87	0.06	17.86	289.11
Al-400	320.13	0.06	17.60	297.03
SS304-400	320.04	0.06	18.31	327.38

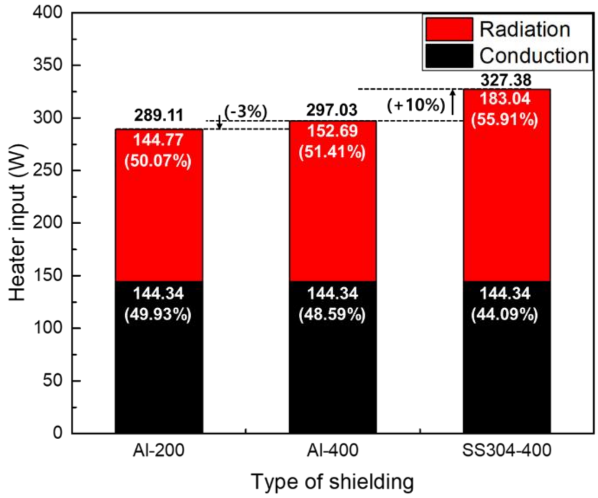

Fig. 11. Conjugate heat losses according to the thermal radiation shielding type.

4. Conclusions

This study experimentally analyzed the contribution of radiation heat transfer to the total heat loss and evaluated the reducing heat loss performance depending on the TRS feature in the vacuum chamber. As the TRS features, the material and the diameter were selected. The results indicated that installing TRS can reduce heat loss by approximately 12%. Furthermore, the heat loss decreases when the emissivity and diameter are lower.

Although Lee et al.'s computational results showed a 70% reduction in heat loss with TRS, this experimental study showed only 12%. This difference may be due to the low emissivity of the aluminum conductor used in the experimental apparatus, which may have underestimated the radiation source. Lee et al. set the RPV material as carbon steel (i.e., SA508), so the emissivity was set to 0.7. However, in this experiment, the RPV material was aluminum, which has an emissivity of 0.04, so much less radiant heat would have been emitted. Also, the heat loss to the top and bottom was not evaluated, so the amount that reaches the wall surface needs further analysis. Also, TRS temperature measurements need to be added for a more definitive analysis. This study will be precisely demonstrated using more advanced scaling experiments.

However, reducing the heat loss by 12% means reducing the heat loss of the i-SMR by 75 kW. This reduction in heat loss can lower the reactor's average temperature, affecting its efficiency. TRS can be applied to improve efficiency. In particular, TRS is more effective at low emissivity and small diameter and needs to be reflected in the design to reduce the heat loss of SMR.

Acknowledgments

This study was sponsored by the Korea Hydro & Nuclear Power Co.’s affiliated Central Research Institute (KHNP-CRI).

This work was supported by the Innovative Small Modular Reactor Development Agency grant funded by the Korea Government (MSIT) (No. RS-2023-00259516) and the National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIT) (No. NRF-2022M2D2A1A02061334)

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