Evaluation of Radiative Heat Transfer within Steel Containment Vessel of Small Modular Reactor

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1. Introduction

Small modular reactors (SMRs) can operate alongside renewable energy sources such as hydropower, wind, and solar power [1, 2]. They also function as independent low-carbon power sources and are increasingly recognized as a viable alternative to fossil fuel–based power plants. About 70 SMR designs are currently under development, mainly in advanced economies. NuScale's SMR received design certification (DC) from the U.S. Nuclear Regulatory Commission (NRC) in 2020 and is widely regarded as the most technologically mature design. In Korea, Korea Hydro & Nuclear Power (KHNP) leads "Team Korea" in the development of the Innovative SMR (i-SMR), as shown in Fig. 1 [3]. The program aims to secure a competitive position in the global SMR market in the 2030s.

Some small modular reactors (SMRs), such as NuScale and the i-SMR, adopt a steel containment vessel that surrounds the reactor vessel. This configuration enables a passive emergency core cooling system (ECCS) based on natural circulation of the coolant between the reactor vessel and the containment vessel under accident conditions. During normal operation, the annular space between the reactor vessel and the containment vessel is maintained under vacuum or near-vacuum conditions to minimize reactor heat loss. As a result, convective heat transfer is negligible, and radiative heat transfer becomes the dominant heat transfer mode governing thermal losses.

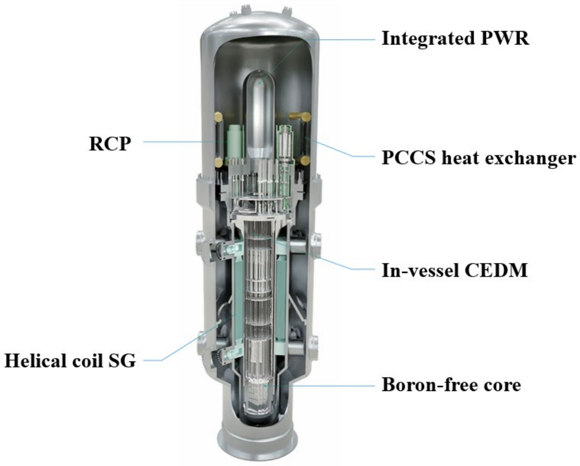

Fig. 1. Concept of i-SMR [3].

In this study, radiative heat transfer within a simplified domain representing the gap between the reactor vessel and the steel containment vessel of an SMR is analyzed. The results are intended to provide a technical basis for future SMR thermal and containment design.

2. Methods and Results

Radiative heat transfer within the space between the reactor vessel and the steel containment vessel was analyzed using a commercial CFD code. The computational domain was geometrically simplified such that the upper and lower regions of the reactor vessel were modeled as hemispherical sections, while the midsection was represented by a cylindrical domain.

A two-dimensional axisymmetric, steady-state analysis was performed. Convective heat transfer was neglected, and the Discrete Ordinates (DO) radiation model was applied. The surface emissivity was set to 0.9, and an effective absorption coefficient of 0.2 m^{-1} was assumed.

Fig. 2 illustrates the temperature distribution within the annular space between the reactor vessel and the containment vessel of a 170-MWe SMR. Figure 2 illustrates the temperature distribution within the annular space between the reactor vessel and the containment vessel of a 170-MWe SMR. Heat loss occurs through radiation from the outer wall of the containment vessel. Radiative heat transfer is significant in the upper region of the reactor due to the presence of the integrated pressurizer at the highest temperature. If reactor coolant pumps are positioned in the vicinity of the pressurizer, the adequacy of the cooling flow rate should be carefully evaluated.

In contrast, a substantial level of radiative heat transfer is also observed in the lower region of the reactor, where low-temperature coolant exiting the steam generators flows. In addition, the overall temperature of the containment vessel is evaluated to be significantly higher than that of conventional large-scale reactors. Consequently, if solenoid valves are installed around the containment vessel, appropriate cooling solutions should be considered to ensure their reliable operation.

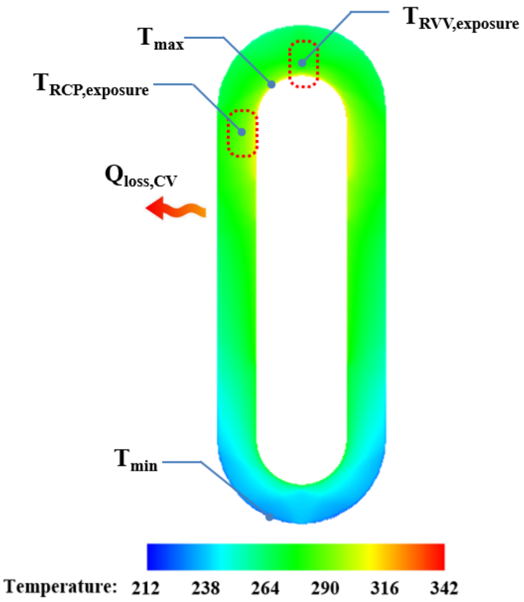

Fig. 2. Temperature distribution of 170-MWe SMR [3].

3. Conclusions

This study evaluated radiative heat transfer in the annular space between the reactor vessel and the steel containment vessel of a small modular reactor using a commercial CFD code. The results show substantial heat loss in the upper region of the reactor due to the presence of the integrated pressurizer, and indicate that the outer wall of the containment vessel is exposed to relatively harsher thermal conditions compared to those of conventional reactors. For SMR designs such as NuScale, in which solenoid valves are considered to enable compact ECCS valve configurations, appropriate valve cooling techniques are required to prevent thermal degradation and ensure reliable valve operation.

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