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Analysis of Heat Loss in Dual Vessel Design of Low Temperature SMR

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1. Introduction

As part of an effort to achieve carbon neutrality, there are movements in many countries around the world to replace thermal power generation, which is a major energy source but has high carbon emissions, with new renewable energy and nuclear power generation.

However, the large nuclear power plants currently in use have a disadvantage that acts as a major issue, it is difficult to maintain safety in the event of power loss. This has also been revealed in accidents such as the Fukushima nuclear power plant accident, and accordingly, several innovative reactor designs that increase passive safety have been proposed.

New Small Modular Reactors (SMRs) with innovative passive safety concepts are being proposed and designed around the world. Among them, a pool type design such as NuScale of the United States is emerging as a representative design form [1]. The pool type integrated SMR design removes primary side heat by using natural circulation using the height difference between the core and the steam generator. It has high resistance to SBO (station blackout) accidents because it does not use a pump in the primary system, and it can avoid small break LOCA accidents because there is no pipe in primary system.

In addition to this all-in-one design, the SMR design of the LDR-50 (Low-temperature District Heating and Desalination Reactor) idea introduced by VTT in Finland is emerging [2,3]. SMR not only produces electricity but also can add various options such as hydrogen production and process heat utilization. The design idea of the LDR-50 uses the energy from the reactor to heat liquid water without producing steam in the secondary system. The hot water is then used for district heating in the form of process heat.

The LDR-50 uses the idea of an accident safety system using a dual containment vessel. The dual containment vessel is filled with water to some extent, and when the temperature of the primary system coolant rises in the event of an accident, the water in the intermediate containment vessel boils. And it cooled again through an external water tank to finally cool the primary system coolant. However, this design requires that the intermediate containment be filled with water in normal conditions, which results in some heat loss.

In this paper, a simple nuclear reactor system adopting the safety system concept of LDR-50 is modeled, and the amount of heat lost in the steady state is measured.

2. Numerical Method

2.1 Reactor Modeling

For the analysis, Modelica in the form of open source and TRANSFORM library developed inside Modelica were used. Modelica is a system code capable of modeling not only large nuclear power plants but also various SMRs such as NuScale [4,5]. Analysis was performed using the TRANSFORM library, which contains correlations for various components used in nuclear reactors, among internal library in Modelica.

The nuclear reactor used in the analysis was modeled to have an output of 50 MW_{th} and it was set to operate at low pressure and low temperature compared to existing SMRs or large nuclear power plants. The total height of the reactor was set at 9.7m to remove heat by natural circulation, the steam generator was 5m and the core was set at 1m. The natural circulation flow rate of the primary system was modeled to be 341 kg/s, and accordingly, the inlet and outlet temperature difference was maintained at 35℃. The operating pressure was set at 5 bar.

Since it is an SMR that operates at low temperature and low pressure, no steam is generated in the secondary system, and it is designed in such a way that the high-temperature water that receives heat from the heat exchanger transfers heat directly to another place. Accordingly, the feed water inlet flow rate and temperature were set to 20℃, 239.12 kg/s, and the pressure was set to 1 bar.

The intermediate containment gap was modeled so that the inner and outer walls had a thickness of 3 cm, respectively, and a between gap is 5cm. It was modeled to be filled with 2m high water to remove heat through boiling in case of an accident. It was set that there was a large water tank where the temperature of 20℃ was maintained at the outermost part, and the reactor was modeled so that it was completely submerged in the water tank. Considering the design idea of LDR-50 where boiling occurs at a lower temperature, both the intermediate containment wall and the outer water bath are modeled to operate at 1 bar.

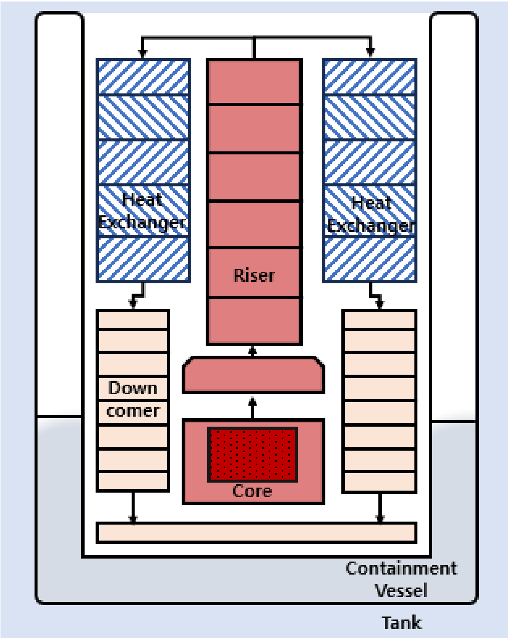

Fig. 1. Nodalization of simple system reflecting the idea of LDR-50 in Modelica

2.2 Analysis cases

In order to compare the heat loss in the dual containment vessel at different operating temperatures, the inlet temperature of 65℃ and 85℃ were calculated respectively. The case where heat does not escape from the primary system was first calculated, and the case where heat escaped by cold water in the primary system was compared. The water level of the intermediate containment vessel was assumed to be 2 m in steady state.

3. Numerical Results

Before calculating the amount of heat loss through the intermediate containment vessel, the case where no heat is lost was first calculated for modeling check and comparison. When the inlet temperature was 65℃ and 85℃, it was confirmed that the outlet temperature was 100℃ and 120℃, satisfying the temperature difference of 35℃. And it was confirmed that the modeling of a height of 9.7m for the natural circulation flow rate was appropriate for the calculation.

Table I: Analysis results with no heat loss cases

	Case 1	Case 2
Core inlet temperature	65.2℃	84.3℃
Core outlet temperature	100.2℃	119.3℃
Mass flow rate	341.26 kg/s	341.1 kg/s
Power	50.13 MW_{th}	50.38 MW_{th}

Next, the case where heat loss through the dual containment vessel was calculated. The core inlet and outlet temperatures decreased by about 1℃ in both cases 1 and 2, but the temperature difference was maintained. The flow rate also showed the same value as the case without heat loss. Excluding the heat loss, it was confirmed that the heat was well transferred to the heat exchanger and had a steady state. In the case of the containment water temperature, it was confirmed that the two walls had the same thickness and material as 3 cm, and thus had a value close to the median value of the core inlet temperature and the tank water. The heat loss to the external water tank through the intermediate containment vessel was 0.31 MW_{th} (0.6%) in Case 1 and 0.44 MW_{th} (0.9%) in Case 2. Considering the improvement of safety, it was confirmed that the passive safety system using the dual containment vessel design can be used in practice due to low heat loss.

Table II: Analysis results with heat losses cases

	Case 1	Case 2
Core inlet temperature	64.8℃	83.5℃
Core outlet temperature	99.9℃	118.8℃
Mass flow rate	341.3 kg/s	340.3 kg/s
Power	50.19 MW_{th}	50.36 MW_{th}
Containment water temp.	38.8	46.7
Containment pressure	1bar	1bar
Heat loss	0.31 MW_{th}	0.44 MW_{th}

4. Conclusions

To test the degree of steady-state heat loss of the long-term cooling system using the dual containment vessel proposed by LDR-50, a 50 MW_{th} pool type reactor was modeled through Modelica. It was confirmed that the modeled simple system design had sufficient heat center height difference and natural circulation flow rate, and it was confirmed that the inlet and outlet temperature difference could be well simulated. In both cases of low-temperature SMR, it was confirmed that the heat loss did not exceed 0.9%. In the event of an accident in the future, the amount of heat removed through boiling was confirmed, and the basis for performing accident analysis for several accidents such as SBO was prepared.

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