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Reactor Power and Thermal Safety Margin in a Natural Circulation Small Modular Reactor Adopting TOP Lattice Core Design

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1. Introduction

For achieving carbon neutrality, rapid transition of the energy sources from fossil fuel to sustainable energy sources such as solar, wind, and nuclear energy. In particular, small modular reactor (SMR) is being highlighted thanks to low carbon emission, low initial cost, and enhanced safety. Among them, several design concepts propose replacement of the reactor coolant pumps (RCPs) with natural circulation even during normal operation as shown in Fig. 1. The RCP-induced events and cost are eliminated and the primary system can be more simplified. However, the natural circulation SMR (NC-SMR) is disadvantageous in improving reactor power which is major factor of economic feasibility.

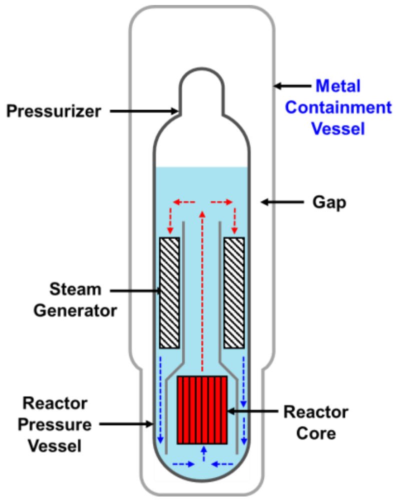

Figure 1. Conceptual drawing of NC-SMR.

To increase reactor power, truly optimized PWR (TOP) lattice can be adopted. The TOP lattice core design can reduce the pressure drop thanks to its larger pitch to diameter of fuel rods and flow area in the core region [1]. In the previous study, the analytic calculations were carried out and effective reactor power increase without large geometric change was confirmed [2, 3]. However, to verify the results, an additional investigation using well-validated system code such as MARS-KS is required.

Thus, in this study, the reactor power and thermal safety margin were investigated by using MARS-KS code. To develop the MARS-KS input model of the NC-SMR, the updated steady-state analysis (ST-ST analysis) from the previous study was carried out [3]. In addition, several major parameters such as active core length and power distributions were modified. MARS-KS results of conventional and TOP core designs were compared. As the major variables, the reactor power and departure from nucleate boiling ratio (DNBR) which is thermal safety margin were mainly compared.

2. Numerical methodology

As shown in Fig. 2, the calculation was iterated to satisfy pressure balance between buoyancy and total pressure drop in the primary system and heat balance between heat generation from the reactor core and transferred heat through the helical steam generators (helical SGs). The core inlet and outlet temperatures were set as iterating variables. As the PWR type was adopted, the saturation temperature in the primary system was set as maximum temperature of the iteration. The SG design parameters were recalculated when the core temperature conditions satisfying pressure and heat balance is non-existent. The pressure in the primary system was set as 15.5 MPa. The differences of the conventional and TOP core designs are summarized in Table 1.

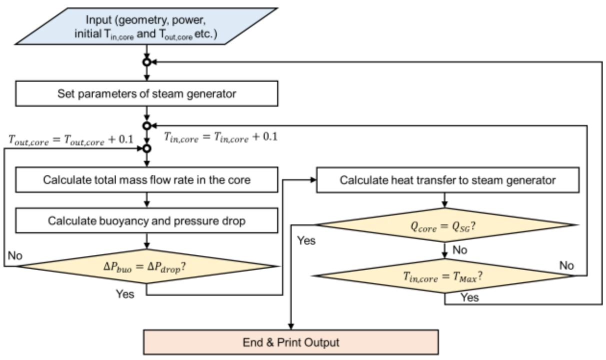

Figure 2. Flow chart of steady-state analysis.

Table 1. Major design parameters of NC-SMR.

Parameter	Reference core	TOP lattice
Thermal power	330 MWt	Calculated
FA type, total number of FA	17×17, 69	17×17, 69

Core height	2.0 m	2.0 m
Diameter of pellet, cladding, control rod	8.1916 mm, 9.5800 mm, 12.3266 mm	7.6000 mm, 8.9284 mm, 12.3266 mm
Pin pitch	12.6230 mm	12.6230 mm
Core channel hydraulic diameter	**11.5973 mm**	**13.7944 mm**
Total height of reactor vessel	23.7 m	23.7 m
Total diameter of reactor vessel	3.0 m	3.0 m,
Feedwater inlet temperature	150 °C	150 °C

By using the design parameters computed from the ST-ST analysis, the MARS-KS input model of the NC-SMR was developed as shown in Fig. 3. In this study, the metal containment was excluded from the modelling. The details of the core and SG regions were displayed in Figs. 3(a) and 3(b). The axial nodes for the core and SG tubes were 20 and 30 volumes, respectively.

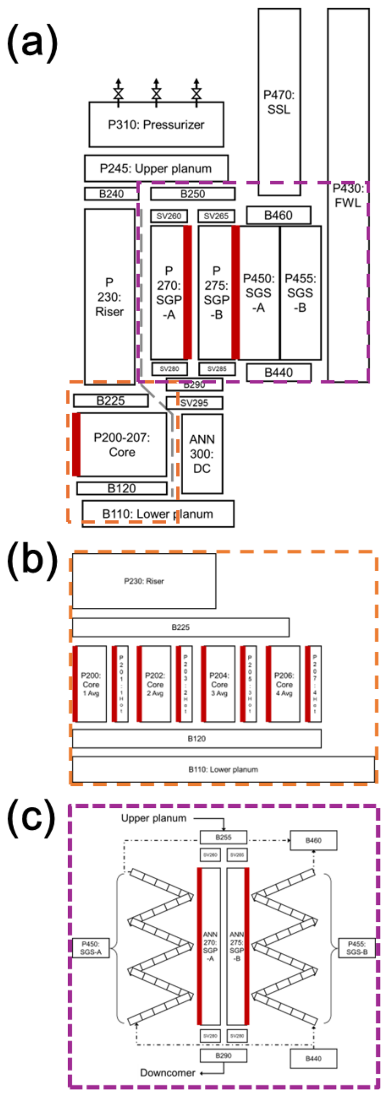

Figure 3. MARS-KS input model nodalization (a) total system, (b) core region, (c) SG region.

3. Results and discussions

The MARS-KS results showed good agreements with the ST-ST analysis results as shown in Tables 2 and 3. The maximum difference of the major parameters was 3.0 %. The core temperature differences were evaluated larger in the MARS-KS calculations. According to relation between temperature difference and mass flow rate under same thermal power, the mass flow rates were also evaluated lower in the MARS-KS.

Table 2. ST-ST analysis and MARS-KS results of NC-SMR adopting conventional core design.

Parameters	ST-ST	MARS-KS	Difference
Reactor power	330.0 MWt	330.0 MWt	0.0 %
Core temperature difference	72.3 °C	74.0 °C	2.3 %
Coolant mass flow rate	857.6 kg/s	849.6 kg/s	0.9 %
Feedwater mass flow rate	143.4 kg/s	141.6 kg/s	1.2 %

Table 3. ST-ST analysis and MARS-KS results of NC-SMR adopting TOP lattice core design.

Parameters	ST-ST	MARS-KS	Difference
Reactor power	340.5 MWt	340.5 MWt	0.0 %
Core temperature difference	72.3 °C	74.5 °C	3.0 %
Coolant mass flow rate	884.9 kg/s	870.44 kg/s	1.6 %
Feedwater mass flow rate	148.0 kg/s	146.1 kg/s	1.3 %

The stable natural circulation was formed and the reactor power, total mass flow rate, and core temperatures in the primary system maintained steady values for 72 hours as shown in Fig. 4. As shown in Fig. 4(a), by adopting the TOP lattice, the reactor power could be enhanced by 3.2 %. Owing to reduced fuel rod diameter, increased flow area, and pitch to diameter, the pressure drop decreased in the core region. Accordingly, the mass flow rate increased as shown in Fig. 4(b). However, the increase in the mass flow rate was smaller than the increase in the reactor power in the MARS-KS results because adoption of the TOP lattice in the MARS-KS calculation caused the change in the core temperature difference which showed same values in the ST-ST analysis.

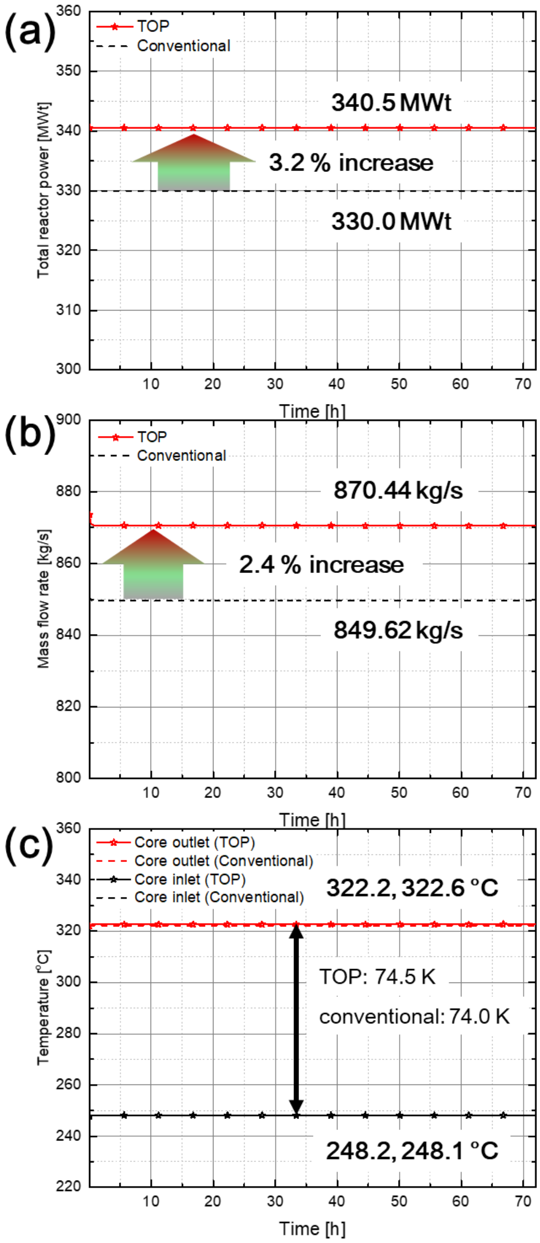

Figure 4. Comparison between MARS-KS results of conventional and TOP lattice core designs.

As the minimum DNBR values were observed at the same channel, 3rd ring hot channel shown in Fig 3(b), the values were selected to depict Fig. 5. The large pitch to diameter and mass flow rates were expected to be advantageous for enhancing CHF. However, the heat transfer area in core region decreased by 6.8 % as the fuel rod diameter decreased. In other words, the heat flux increased which is the denominator of the DNBR. Consequently, the minimum DNBR decreased from 4.75 to 4.52 as shown in Fig. 5. Nonetheless, the minimum value is larger than 1.3 which is often proposed value of the thermal safety margin limit. However, decreasing rate in the DNBR differs depending on the reactor model. Thus, careful assessment is required to adopt the TOP lattice in each reactor design.

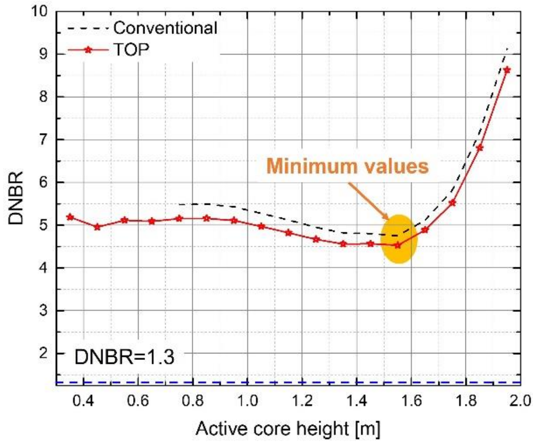

Figure 5. Minimum DNBR of NC-SMR.

4. Conclusion

In this study, the effects of the TOP lattice core design was investigated by using MARS-KS. The diameter of fuel rods and directly related geometric parameters were changed by adopting the TOP lattice core design. Adoption of the TOP lattice is expected to reduce the pressure drop in the core region and increase reactor power without change of the reactor vessel size. In addition, although the DNBR value decreased by 4.7 %, the minimum DNBR was 4.52 which is sufficiently acceptable. Thus, the TOP lattice is attractive option for the power enhancement of the NC-SMR without increase in the reactor vessel size.

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