Neutronics Analysis of SMR with Natural Circulation using STREAM/RAST-K 2.0

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1. Introduction

Small Modular Reactors (SMRs) with their small size, reducing dependence on active control system and providing siting flexibility for locations unlike traditional larger reactors are receiving research interest from many countries.

The natural circulation in the reactor coolant system (RCS) primary loop is one of research topics in the SMR. It removes the reactor coolant pump (RCP) and passively provides the core mass flow rate by the buoyant force. Thus, it can prevent the design basis accident (DBA) such as FSAR 15.3.1 "Complete Loss of Flow" and FSAR 15.3.2 "Locked Rotor" events.

This paper investigates the neutronics aspects of the SMR design using the natural circulation (NC) compared to that using the forced circulation (FC). In this purpose, a scaling method is applied to approximate the mass flow rate in the NC condition. The numerical results show the core design parameters under both the FC and the NC conditions, calculated by the STREAM/RAST-K 2.0 (ST/R2) code system [1].

2. Mass Flow Rate for Natural Circulation

The single-phase loop momentum equation for steady flow [2] is

$$-g \oint \rho dz = \frac{1}{2} K_1 \frac{\dot{m}^2}{A^2 \rho_l}, \quad (1)$$

where $\dot{m}$ is the mass flow rate, A is the flow area, g is the acceleration by gravity, K_1 is the sum of the single-phase frictional and form losses around the loop, and ρ_l is the liquid density.

By integrating Eq. (1), the mass flow rate for the NC case condition can be expressed as:

$$\dot{m} = \left(\frac{2A^2 \beta g \rho_l^2 \Delta L \dot{Q}}{C_p K_1} \right)^{\frac{1}{3}}, \quad (2)$$

where $\dot{Q}$ is the thermal power of the reactor, ΔL is the height differences between the core and the steam generator, ρ_l is the liquid specific heat, and β is the liquid volumetric expansion coefficient.

When the mass flow rate in the NC condition is already known for the reference case, the mass flow rate in the arbitrary SMR can be approximated by a scaling method as:

$$\frac{\dot{m}_{arbitrary}}{\dot{m}_{reference}} \approx \left(\frac{A^2_{arbitrary} \dot{Q}_{arbitrary}}{A^2_{reference} \dot{Q}_{reference}} \right)^{\frac{1}{3}}, \quad (3)$$

where $\dot{m}$ is the mass flow rate, A is the flow area, $\dot{Q}$ is the thermal power, the subscription "arbitrary" indicates the quantity of the arbitrary SMR design of which the mass flow rate will be calculated by the scaling method, and the subscription "reference' indicates the quantity of the reference design, which is already known. In Eq. (3), it is assumed that the thermal-hydraulic characteristics such as β, $\rho_l, C_p, K_1, \Delta L$ of the reference design are same with those of the arbitrary SMR design. Table I shows the reference core design parameters used to determine the mass flow rate of the arbitrary SMR core with the NC condition.

Table I Reference core design parameters [3]

Parameter	Value
$\dot{Q}$ (MWt)	160
No. of FA	37
$\dot{m}$ (kg/s)	587.7
T_{in} (℃)	258
T_{out} (℃)	314
ΔT (℃)	56
T_{avg} (℃)	283.89

3. Numerical Results

3.1. Specification of Test Problem

To compare the neutronics aspects of the NC and the FC for the RCS circulation, the following test SMR core is considered. The core design parameters for the FC case is referred to Refs. [4] and [5]. Figure 1 shows the core loading pattern for the test SMR, while the fuel assembly types are given in Table II.

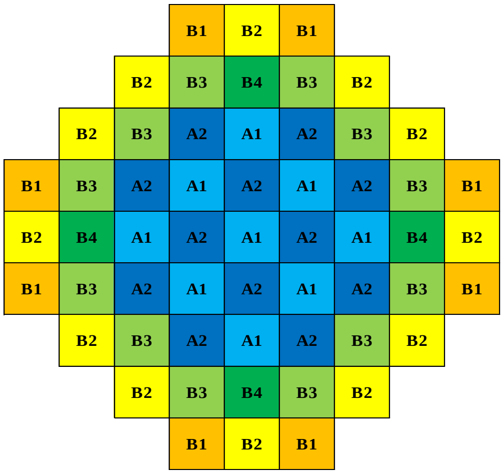

Figure 1. The Core Loading Pattern of the test SMR.

Table II Assembly type summary

Assembly type	No. of Assemblies	U^{235} Enrich. (w/o)	No. of Gd fuel rods	Gd Enrich. (w/o)
A1	9	2.82	8	8.0
A2	12		12	8.0
B1	8	4.95	4	8.0
B2	12		8	8.0
B3	12		20	8.0
B4	4		24	8.0

Table III shows the core design parameters for the FC and the NC cases, where the mass flow rate for the NC case is determined by Eq. (3), and the moderator inlet temperature is iteratively determined by:

$$T_{in}^{NC,(l+1)} = T_{out}^{FC} - (T_{out}^{NC,(l)} - T_{in}^{NC,(l)}), \quad (4)$$

where $T_{in}^{NC,(l)}$ is the moderator inlet temperature at the l-th iteration, $T_{out}^{NC,(l)}$ is the moderator outlet temperature calculated by the RAST-K, and T_{out}^{FC} is the moderator outlet temperature for the FC case, which is already given in Table III. It is noted that the outlet temperatures for the NC case is fixed to T_{out}^{FC} to prevent the coolant boiling.

Table III Test SMR core design parameters for FC and NC conditions

Parameter	FC	NC
$\dot{Q}$ (MWt)	330	330
No. of FA	57	57
$\dot{m}$ (kg/s)	2090	997.8
T_{in}(℃)	296	263
T_{out} (℃)	323	323
ΔT (℃)	27	60
T_{avg} (℃)	309.86	295.06

3.2. Comparisons of core analysis results

The ST/R2 simulations were performed for the NC and the FC conditions shown in Table III to compare the various neutronics parameters; the axial coolant temperature, the axial shape index (ASI), the axial power distribution, the power peaking factors (PPFs), the critical boron concentration (CBC), the moderator temperature coefficient (MTC), and the minimum departure from nucleate boiling ratio (MDNBR).

Figure 2 shows that the moderator temperature rise (ΔT) is larger and the average moderator temperature becomes lower in the NC case due to the smaller mass flow rate. Figure 3 shows that the CBC in the NC case becomes higher to compensate the positive reactivity caused by the lower moderator temperature. Figure 4 shows that the MTC for the NC case becomes less negative due to the lower moderator temperature and the higher CBC.

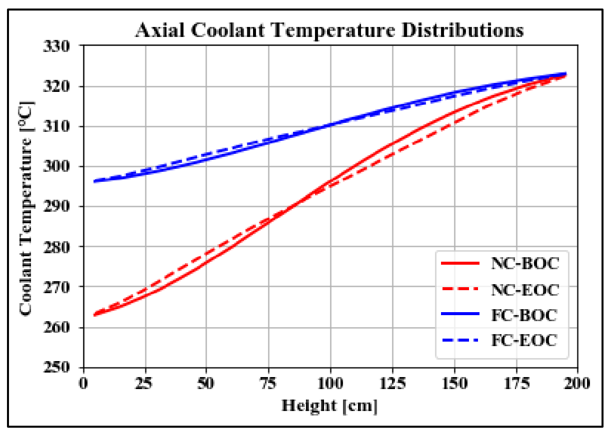

Figure 2. Coolant Temperature vs. Core Height at BOC and EOC.

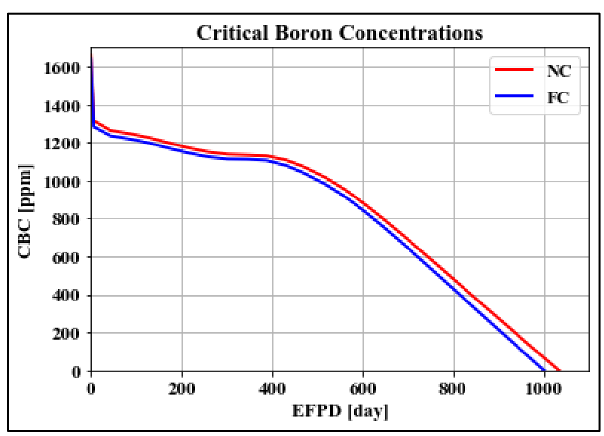

Figure 3. Critical Boron Concentration (CBC) vs. EFPD.

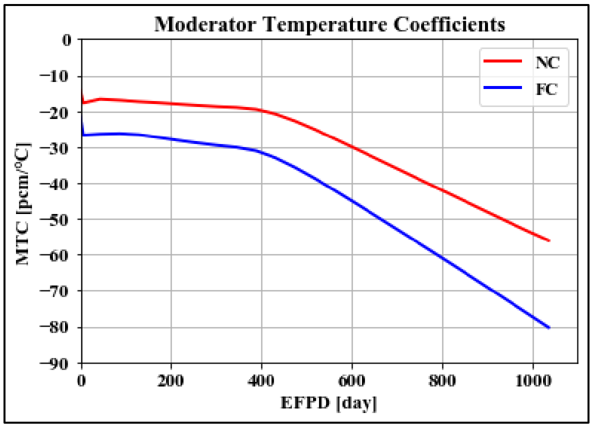

Figure 4. Moderator Temperature Coefficient (MTC) vs. EFPD.

Figure 5 shows that the ASI of the NC case is larger than that of the FC case at the BOC, while it becomes similar as the burnup proceeds. The larger ASI at the BOC indicates the bottom-skewed power distributions as shown in Figure 6. In the initial core at the BOC, where there is no fission product, the ASI is affected by the axial moderator temperature distributions. However, as the burnup proceeds, the fission products are built up in the higher power region, which leads to the flattened power distributions at the EOC for both the NC and the FC cases. Figure 7 shows that the PPFs (Fz, FdH, and Fq) of the NC and the FC cases are almost similar.

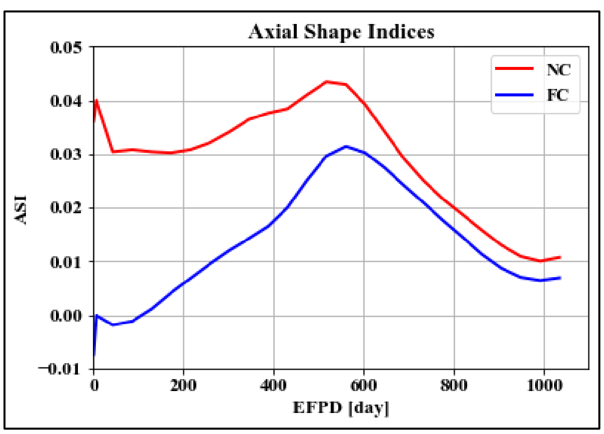

Figure 5. Axial Shape Index (ASI) vs. EFPD.

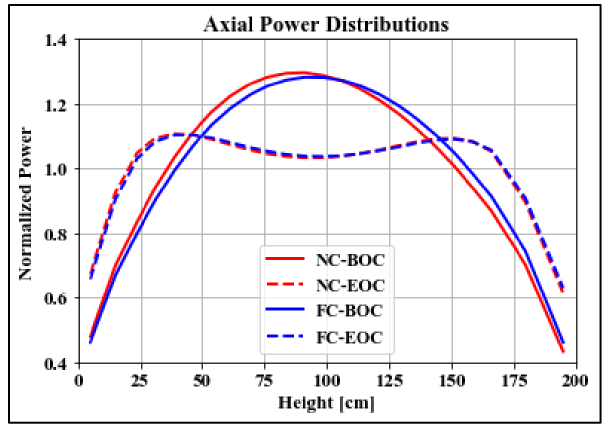

Figure 6. Normalized Power vs. Height at BOC and EOC.

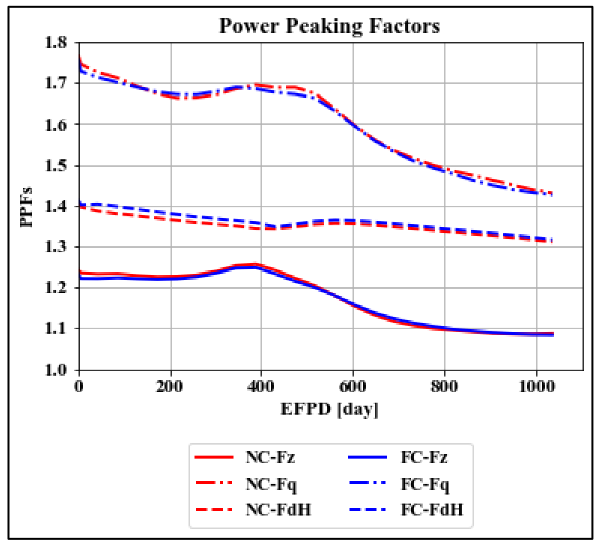

Figure 7. Power Peaking Factors (PPF) vs. EFPD.

Figure 8 shows that the DNBR is slightly reduced in the NC case, where the critical heat flux is calculated by the Bowring critical heat flux model which is valid in both the FC and the NC conditions [6]. The DNBR is affected by both the mass flow rate and the moderator temperature. In the NC case, the mass flow rate becomes a half of the FC case, which reduces the DNBR. In the meanwhile, the lower moderator temperature increases the DNBR. Since the effect of the lower mass flow rate is more dominant than that of the lower moderator temperature, the DNBR is reduced for the NC case.

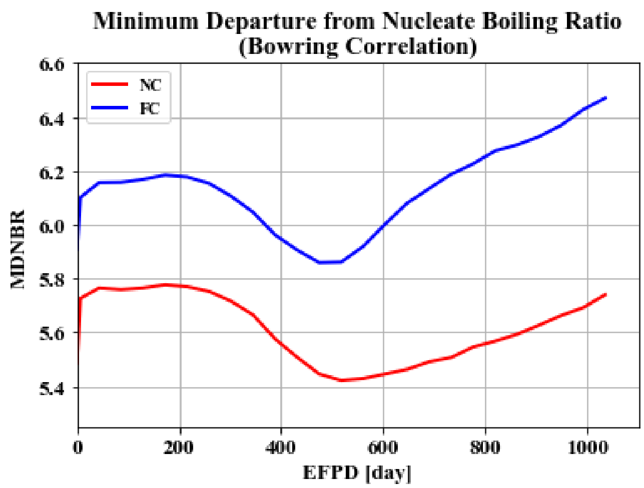

Figure 8. Minimum Departure from Nucleate Boiling Ratio (MDNBR) vs. EFPD.

4. Summary and Conclusions

Table IV summarizes the neutronics analysis results for the NC and the FC cases. It was concerned about the effects of the smaller mass flow rate of the NC case to the cycle length, the PPFs, and the MDNBR. The numerical results show that 1) the cycle length of the NC case becomes slightly enhanced due to the lower moderator temperature, 2) the PPFs of the NC and the FC cases are almost similar, and 3) the MDNBR becomes smaller in the NC case. However, compared to the DNBR safety limit (1.3), the DNBR margin of the NC case is still sufficient for the normal operation condition. Therefore, the concept of the NC can be applied to the SMR core design without big change in the core design parameter.

As a further study, it is worthwhile to investigate the transient analysis for the reactor startup and the power ascending procedure for the NC condition by considering the more accurate mass flow rate.

Table IV. Summary of neutronics analysis for NC and FC cases

RCS Circulation	NC	FC
Mass flow rate	Lower	Higher
T_{avg}	Lower	Higher
CBC	Higher	Lower
MTC	Less negative	More negative
ASI (at BOC)	Bottom-Skewed	Unskewed
PPFs	Similar	
MDNBR	Lower	Higher

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