Sensitivity Analysis of Initial Flow Rate for Startup of Inactive Reactor Coolant Pumps in SMR with Natural Circulation

Jaejin Lee*, Doyoung Shin, Joonsoo Park, Chi-Jin Choi
Korea Atomic Energy Research Institute, 111 Daedeok-daero 989beon-gil, Yuseong-gu, Daejeon, 34057, Republic of Korea
**Corresponding author: jaejinlee@kaeri.re.kr*

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1. Introduction

In conventional commercial reactors, the startup of reactor coolant pumps (RCPs) from an inactive state is typically analyzed only with specific operational modes such as hot shutdown, cold shutdown, or refueling, but not the power operation mode. This is because, in the power operation mode, the RCPs are designed to be continuously operational to maintain the necessary coolant flow. Consequently, safety analyses for the event primarily assess whether the integrity of the reactor coolant system pressure is maintained and if there is a loss of shutdown margin due to reduced coolant temperatures.

Recently, various cooling designs for the reactor coolant system (RCS) have been proposed for small modular reactors (SMRs). NuScale operates entirely with passive cooling system without pumps [1], while others like SMART100 employ forced circulation through active pumps [2]. However, some reactors are designed to incorporate both forced and natural circulation in the power operation mode to accommodate more complex conditions for power production. For these reactors, unlike commercial reactors, the startup of inactive RCPs during natural circulation power operation should be considered as a design basis event. Because the core is already critical, immediately after the event, the core power rapidly increases due to the negative moderator temperature feedback. Therefore, the objective of accident analysis for the event should differ from that of commercial reactors, which primarily evaluates shutdown margin reduction and system integrity due to pressure. Instead, it requires a conservative evaluation of safety parameter related to fuel integrity, such as the minimum departure from nucleate boiling ratio (MDNBR).

This paper is prepared to demonstrate the preliminary accident analysis results of inactive RCPs startup event for a conceptual SMR in natural circulation power operation mode. For the accident analysis, the one-dimensional system analysis code, TASS/SMR [3], was employed to model the SMR system that is capable of both natural and forced circulation. First, the paper describes two tuning methods for achieving the target natural circulation flow rate under steady-state conditions with the system code. Then, it details the sensitivity analysis results for the initial flow rate over a certain range and highlights the opposite trend observed according to the steady-state flow rate tuning methods.

2. Approach for adjusting natural circulation flow rates in TASS/SMR

Fig. 1 illustrates a schematic diagram of a closed loop with pump. In the system, the pressure drop for natural circulation can be expressed simply as below:

$$\Delta P_{loop} - \Delta P_{pump} = \Delta P_{grav} \quad (1)$$

where $\Delta P_{loop} = \sum_{i=1}^{4} \Delta P_i$ which is a pressure drop in the loop by form loss, ΔP_{pump} is a pressure drop when the fluid passes pump, and $\Delta P_{grav} = (\rho_c - \rho_h)gh$ which is a pressure differential due to buoyancy (gravitational force). Compared to forced circulation, there are two notable differences: 1) ΔP_{grav} is negligible in the forced circulation but it is a major driving force in the natural circulation, 2) ΔP_{pump} is a pressure gain term in forced circulation but it is a pressure loss term in natural circulation (the sign becomes minus).

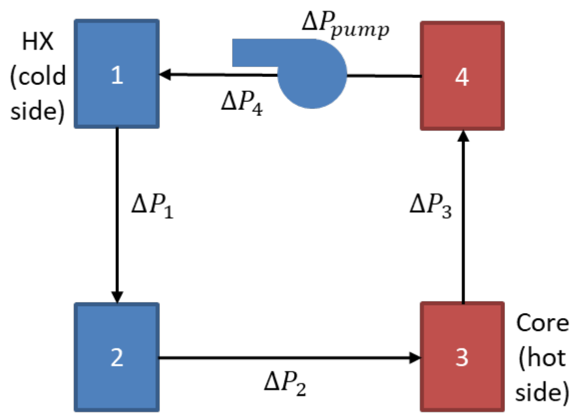

Fig. 1. Schematic diagram of a closed loop with pump

In the system code, the natural circulation flow rate would be converged at a certain value that satisfies Eq. (1). Nonetheless, in safety analysis, system parameters are usually considered within a range rather than as a single value, taking into account uncertainties and limiting conditions for operation (LCO). Therefore, it is necessary to converge the system flow rate to various target values, such as the minimum design flow rate or maximum design flow rate, in addition to the nominal condition. The TASS/SMR code provides two tuning approaches to converge the flow rate within the target value during steady-state calculations. One approach is the adjustment of the multiplication factor for form loss coefficient ω_{loop}, which can be represented as:

$$\omega_{loop}\Delta P_{loop} - \Delta P_{pump} = \Delta P_{grav}. \qquad (2)$$

The natural circulation flow rate decreases as ω_{loop} increases, which can physically occur due to the formation of deposits within the system. The other approach is the adjustment of the RCP head multiplication factor ω_{pump} that can be written as:

$$\Delta P_{loop} - \omega_{pump}\Delta P_{pump} = \Delta P_{grav}. \qquad (3)$$

The natural circulation flow rate decreases as ω_{pump} increases; the opposite trend is observed in forced circulation. The physical meaning of ω_{pump} corresponds to the pump performance.

Fig. 2 shows the multiplication factor for form loss coefficient and pump head required to achieve a target flow rate in natural circulation within the SMR system. The reference state is when both multiplications are one. Multiplication factors are adjusted to achieve a flow rate from 10% lower to 10% higher. It turns out that more adjustment is required for the form loss coefficient than for the pump head to achieve the same amount of flow rate change. Specifically, the form loss coefficient needs to be decreased or increased more than twice when the natural circulation flow rate needs to increase or decrease only by 10%.

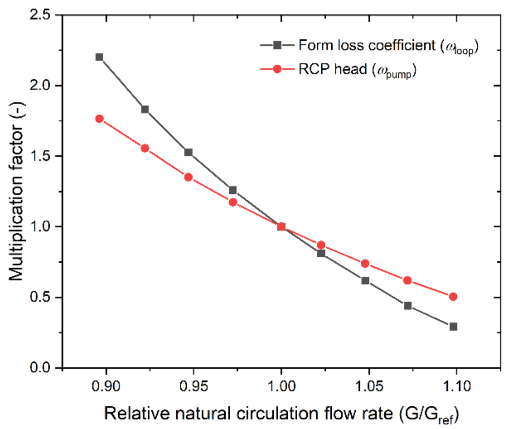

Fig. 2. Multiplication factor to achieve the target flow rate in natural circulation

3. Sensitivity analysis of initial flow rate adjustment for startup of inactive RCPs

The sensitivity analysis for the initial flow rate was performed to investigate the impact on inactive RCPs startup during natural circulation power operation. It is assumed that the RCP speed increases from zero to the maximum speed linearly within 10 seconds. The loss of offsite power (LOOP) followed by turbine trip was not considered so that RCPs would constantly accelerated until the maximum speed is reached. Under different flow rate conditions, the initial DNBRs were adjusted to maintain same available overpower margin (AOPM). The sensitivity analysis results with adjustment of the form loss multiplication factor and pump head multiplication factor are presented in Fig. 3 and Fig. 4, respectively.

The major phenomena observed in both cases are as follows:

i. The startup of the inactive RCPs causes an increase in RCS flow rate.
ii. Due to increased flow rate at the core, the core average coolant temperature decreases.
iii. The negative moderator temperature feedback causes the core power to increase, resulting in the generation of a variable overpower trip (VOPT) signal.
iv. Upon scram rod insertion, the core power sharply decreases.
v. The residual heat is removed to the secondary side.

When adjusting the form loss multiplication factor (Fig. 3), a higher initial flow rate is more limiting for MDNBR. A higher initial flow rate condition can be obtained by using a smaller form loss multiplication factor. Due to reduced flow resistance in the loop, RCS flow rate during RCP startup increases more rapidly. Consequently, this results in stronger positive reactivity insertion, higher core power increase, and lower MDNBR.

Conversely, when adjusting the pump head multiplication factor (Fig. 4), it is found that a lower initial flow rate is a more limiting condition for the MDNBR. A lower initial flow rate is established by a higher pump head multiplication factor. As a result, the RCS flow rate increases sharply during the RCP startup due to the higher pump head. This leads to a more limiting MDNBR through the same reactivity feedback mechanism.

A comparison of results between the adjustments of form loss and pump head multiplication factor can be more clearly observed in Fig. 5.

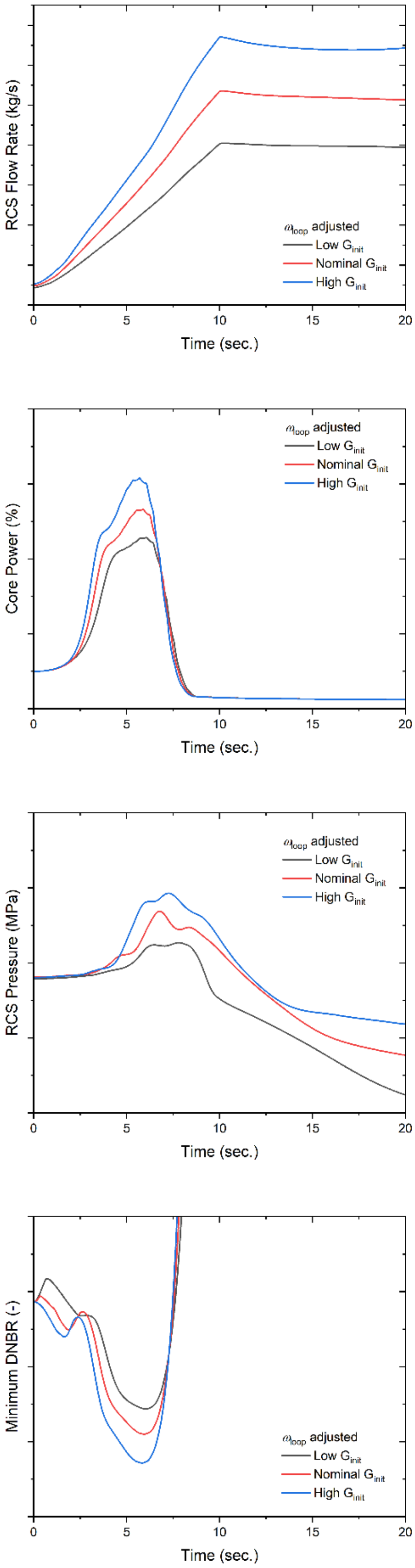

Fig. 3. Sensitivity analysis result of initial flow rate adjusted by ω_{loop} for the startup of inactive RCPs

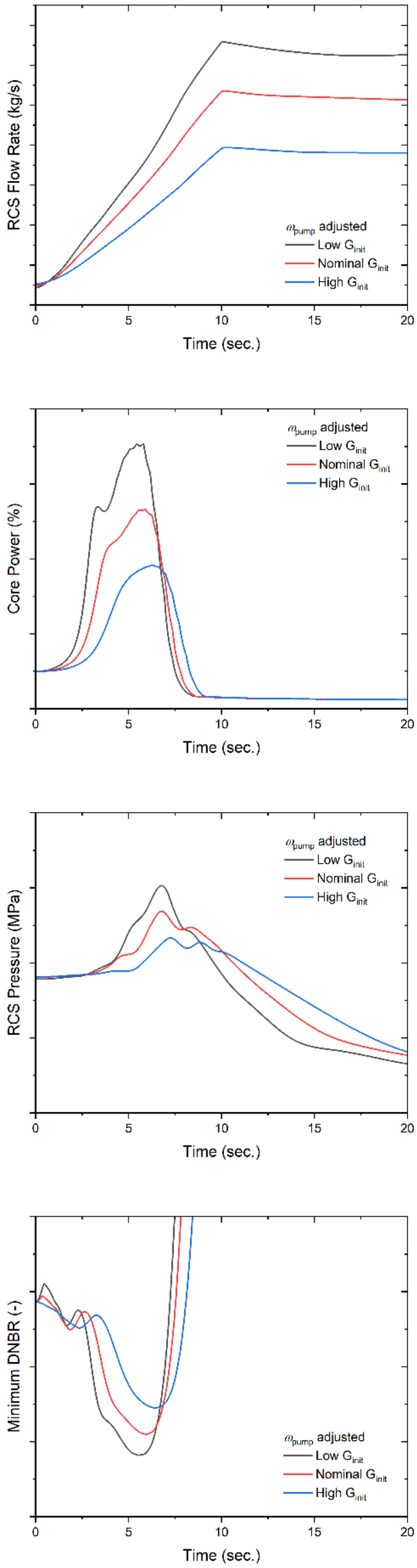

Fig. 4. Sensitivity analysis result of initial flow rate adjusted by ω_{pump} for the startup of inactive RCPs

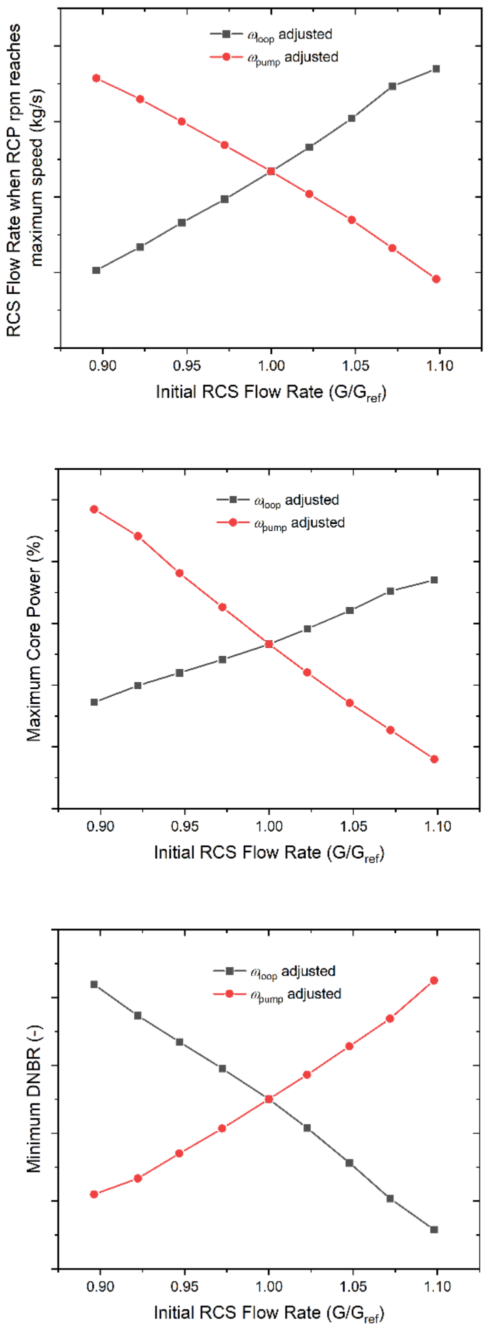

Fig. 5. Comparison of major parameters in sensitivity analysis result of initial RCS flow rate between adjustment of ω_{loop} and ω_{pump}

4. Conclusions

This study presented the preliminary accident analysis results for the startup of inactive RCPs during natural circulation power operation in a conceptual SMR system. Using the TASS/SMR code, we examined two methods for tuning natural circulation flow rates under steady-state conditions and performed sensitivity analyses to assess the impact of initial flow rate adjustments.

First, the sensitivity analysis confirmed that the initial flow rate is a crucial factor significantly influencing the accident analysis result. Second, varying the form loss coefficient or pump head multiplication factor can lead to completely opposite trends relative to the initial flow rate concerning MDNBR. Specifically, a higher initial flow rate resulting from reduced form loss proved to be more limiting for MDNBR, whereas a lower initial flow rate due to increased pump head resulted in a more limiting condition.

Future work will involve more detailed sensitivity analyses to identify which tuning method is more appropriate to reflect realistic physical phenomena.

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