Simulation Analysis of Load Follow Capability in SALUS-100 via Primary Flow Control without Control Rod Motion

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Keywords : SFR, load follow operation, primary flow control, control rod movement

1. Introduction

With the rapid expansion of intermittent renewable energy sources, ensuring grid stability has become a critical challenge. There is a growing demand for load follow operation in Small Modular Reactors (SMRs) to provide the necessary operational flexibility that can compensate for fluctuating power supplies. Sodium-cooled Fast Reactors (SFRs) with metallic fuel are particularly well-suited for this requirement due to the high thermal conductivity of the metallic fuel and liquid sodium coolant, the strong inherent reactivity feedback, and the absence of Xenon poisoning effect. The excellent passive safety and control characteristics of metallic-fueled SFRs were historically validated in the EBR-II tests, which demonstrated power control solely through primary flow manipulation[1,2]. Building on this concept, this study performs a GAMMA+ based simulation analysis of the load follow operation of SALUS-100. The simulation results demonstrate the feasibility of achieving load follow operations of SALUS-100 solely via primary flow control without control rod movement.

2. Methods and Results

Th reactor power change behavior during the load follow operation can be explained by considering changes in reactivity ($\delta\rho$), power (δP), power/flow ratio ($\delta(P/F)$), and core inlet temperature (δT_i) [1,2]. Reactivity changes due to fissile atom depletion are neglected. A quasi-static approximation for the reactivity perturbation can be:

$$\delta\rho = A\delta P + B\delta(P/F) + C\delta T_i. \qquad (1)$$

The reactivity feedback is characterized by three coefficients: A representing power-dependent feedbacks (Doppler and fuel expansion), B denoting power-to-flow dependent feedbacks (sodium and structural thermal expansion), and C covering inlet temperature-driven feedbacks (Doppler, fuel expansion and core support grid expansion). Assuming a constant core inlet temperature and that the system has reached a steady state with no net change in reactivity ($\delta\rho = \delta T_i = 0$), Eq. (1) reduces to:

$$(A/B)\,\delta P = -\delta(P/F). \qquad (2)$$

During the load follow operation, accordingly, a decrease in flow (F) triggers negative reactivity from the $B\delta(P/F)$ term, which is subsequently balanced by positive reactivity from the $A\delta P$ term as power (P) drops, eventually reaching a new steady state. Eq. (2) also indicates the magnitude of the increase in the P/F ratio is primarily determined by the A/B ratio.

EBR-II studies [1] indicate that metal-fueled SFRs exhibit relatively small A/B ratios, ranging from 0.1 to 0.69 for power levels between 20 and 1000 MWe, with a tendency for the ratio to increase at higher power levels. In contrast, oxide-fueled reactors show significantly larger values, typically between 1.86 and 3.38, primarily due to the low thermal conductivity of oxide fuel. For SALUS-100, the A/B ratio was calculated to be 0.11. Based on Eq. (2), the effect of A/B on the load follow performance via the primary flow control was displayed in Fig. 1. When the structural expansion (P/F) feedback is more dominant than the Doppler effect meaning a smaller A/B ratio, the reactor power responds more sensitively to flow control and exhibits superior P–F linearity. Furthermore, a smaller A/B ratio reduces the magnitude of the P/F increase as flow decreases, thereby minimizing the variations in inlet and outlet temperatures during power transitions.

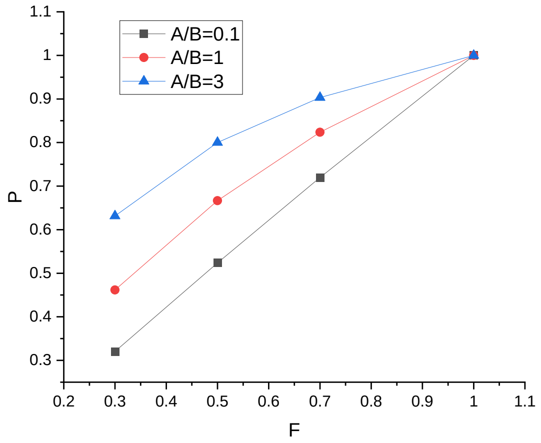
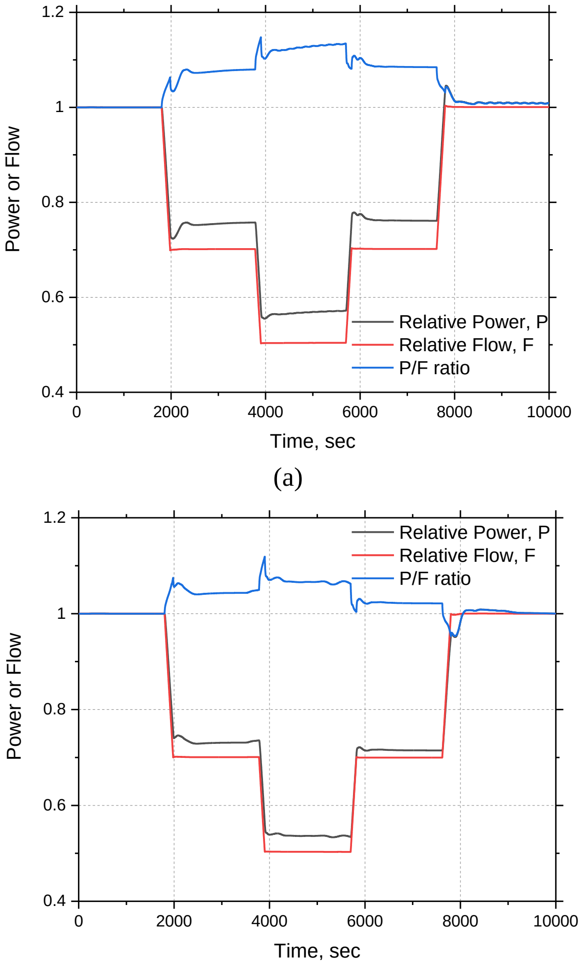


Fig. 1. Effect of A/B on power control performance through primary flow.

SALUS-100 was developed by KAERI as an integrated pool-type SFR with an electric output of 100 MWe, which is specified for a long-cycled metallic fuel SFR plant [3]. To evaluate the load follow performance of SALUS-100, simulation analysis was conducted using the GAMMA+ model, which was originally developed for reactor safety analysis [4]. To regulate the reactor power, the primary, intermediate, and feedwater flow rates were controlled, while the control rods were set to remain stationary. Two control strategies were employed for the simulation. In the first strategy, the primary, intermediate, and feedwater flow rates were adjusted using a forcing function in a stepwise sequence (100% → 70% → 50% → 70% → 100%). In the second strategy, while the primary and feedwater flow rates were still regulated by the forcing function, the intermediate flow rate was automatically controlled to maintain a constant core inlet temperature. During the transition between flow stages, the flow rate was adjusted at a ramp rate of 10% per minute. Following each adjustment, a 30-minute stabilization period was provided to allow the reactor power to reach a new steady state.

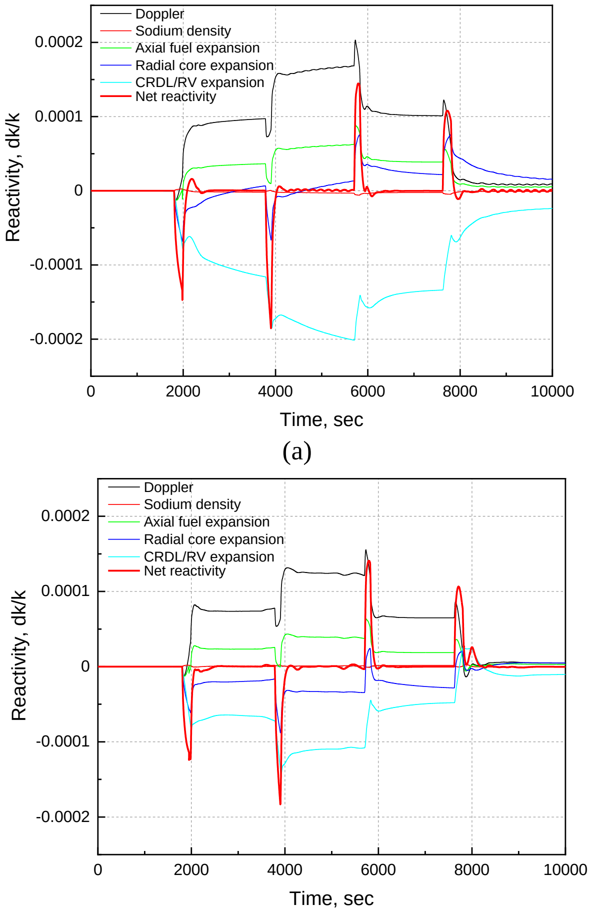
Figure 2 presents the results of the load-following simulation for SALUS-100. The GAMMA+ simulation results successfully demonstrated the feasibility of load follow operation solely through primary flow control, without any control rod movement. Stable power control was achievable under both operation strategies. However, when the intermediate flow rate was adjusted stepwise using a forcing function, the core inlet temperature dropped by more than 10°C. Consequently, as dictated by Eq. (1), this temperature decline led to a more pronounced increase in the *P/F* ratio as the reactor power decreased (Fig. 2a). By maintaining a constant core inlet temperature, the magnitude of the *P/F* increase was reduced, enabling a broader power maneuvering range of 100% to 53% while simultaneously minimizing variations in the core temperature differential (Fig. 2b).



(a)

(b)

Fig. 2. Simulation results of load follow operation via primary flow control without control rod movement; (a) intermediate flow control driven by forced functions, (b) automatic intermediate flow control to maintain constant core inlet temperature.



(a)

(b)

Fig. 3. Reactivity variation during load follow operation; (a) intermediate flow control driven by forced functions, (b) automatic intermediate flow control to maintain constant core inlet temperature.

As shown in Fig. 3a, a decrease in the core inlet temperature during the load follow operation caused the reactor vessel (RV) to contract, thereby inserting significant negative reactivity. This was subsequently offset by the positive reactivity feedback from the Doppler effect, fuel expansion, and radial core expansion, eventually establishing a new power equilibrium. When the inlet temperature was held constant, it was confirmed that stable power control was achieved through a balance between positive reactivity feedback (from Doppler and fuel expansion) and negative reactivity feedback (from core structural and control rod drive line expansion) at each steady-state power level (Fig. 3b). This observation is consistent with the power control mechanism predicted by the reactivity feedback effects in Eq. (2).

3. Conclusions

This study successfully demonstrated the autonomous load follow capability of SALUS-100 through GAMMA+ simulation analysis. The results confirmed that SALUS-100's low *A/B* ratio, a distinct advantage of metallic fuels, facilitates highly sensitive and linear power modulation across a range of 100% to 53% at a control rate of 10%/min solely via primary flow control. A comparative assessment of control strategies revealed that automatically regulating the intermediate flow to maintain a constant core inlet temperature is the most effective approach; it significantly enhances *P–F* linearity and minimizes fluctuations in the core temperature differential, thereby mitigating thermal stress. Nevertheless, maintaining a constant core temperature rise during the load follow operation without auxiliary negative reactivity such as control rod motion is expected to be physically unattainable under the current inherent feedback mechanisms.

ACKNOWLEDGEMENT

This work was supported by the National Research Foundation of Korea (NRF) grant funded the Korea government(Ministry of Science and ICT)(No. RS-2025-25455699).

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