

Rod-aided Passively Autonomous Load-Follow Operation in the Soluble Boron-Free SMR

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1. Introduction

Soluble boron has been widely used in water-cooled reactors for reactivity control because it enables global reactivity adjustment without significant power shape distortion. However, its use reduces operational flexibility due to slow reactivity response, may lead to less favorable moderator temperature coefficient characteristics, and requires a complex chemical and volume control system. These drawbacks are particularly unfavorable for small modular reactors (SMRs), for which simplicity, safety, and flexible operation are important design objectives.

To address these issues, soluble boron-free (SBF) SMR concepts have been developed. Among them, the ATOM core has shown the potential to overcome the traditional limitations of SBF designs through the use of a centrally-shielded burnable absorber and a truly-optimized PWR (TOP) lattice [1-3]. These design features improve excess reactivity control, fuel utilization, and reactivity feedback characteristics, making the core suitable for load-follow operation.

Previous studies demonstrated passive autonomous load-follow operation (PALFO) in the ATOM core by adjusting the steam generator feedwater flow rate without active reactivity control [4]. Control-rod-based load-follow operation was also investigated as a separate approach for active power maneuvering [5]. Building upon these previous studies, the present work proposes a rod-aided PALFO strategy, in which steam-generator-driven PALFO remains the primary load-follow mechanism while limited control rod assistance is introduced to improve the load-follow capability under more demanding operating conditions. Particular attention is given to the challenging 100–20–100 load-follow scenario, which requires deep power reduction and stable recovery to full power.

Transient analyses were performed for a two-batch ATOM core with the TOP lattice at the beginning-of-cycle and the 90% end-of-cycle conditions using the in-house time-dependent nodal code KANT coupled with thermal-hydraulic analysis [6]. The objective is to evaluate the feasibility and transient characteristics of rod-aided passively autonomous load-follow operation for the demanding power maneuvering scenario.

2. Methods and Results

2.1 Neutronics and Thermal-Hydraulics Modeling

The transient analysis was performed using the in-house multi-purpose reactor analysis code, KAIST Advanced Nuclear Tachygraphy (KANT), which is based on the NEM-CMFD acceleration scheme and coupled with thermal-hydraulics. KANT also includes a helical coil steam generator (HCSG) module and an autonomous control rod logic, Mode-Y, for load-follow simulations. Since the analyzed core is a light-water reactor, a conventional two-step procedure was adopted. Burnup-dependent few-group cross sections, temperature reactivity feedback data, and assembly discontinuity factors were generated using the Serpent-2 Monte Carlo code with the ENDF/B-VII.1 library [7].

Figure 1 shows the calculation flowchart of KANT for TH-coupled transient analysis. In the nodal calculation, the cross sections are updated by reflecting control rod insertion, fuel and coolant temperature changes, and fission product poisoning effects including Xe-135 and Sm-149.

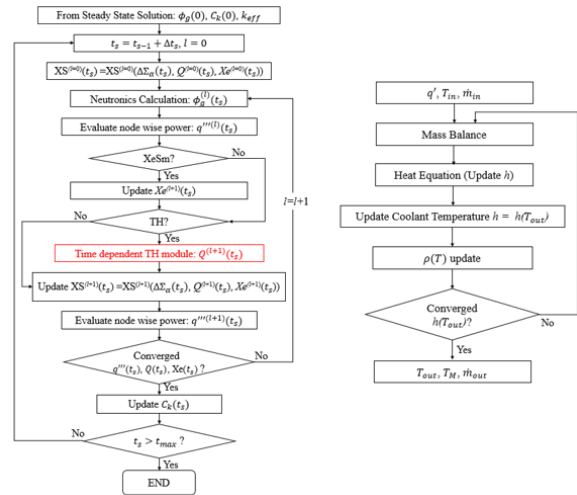


Figure 1 Calculation flowchart of KANT

2.2 PALFO with Helical Coil Steam Generator

The proposed load-follow strategy is fundamentally based on passive autonomous load-follow operation (PALFO) using an in-house once-through helical coil steam generator (HCSG) solver. As shown in Figure 2, the feedwater flow rate on the secondary side was adjusted to change the primary-side inlet coolant temperature through heat transfer in the steam generator. Due to the negative moderator temperature coefficient of the soluble-boron-free core, the resulting inlet

temperature variation induces a reactivity change and thereby changes the reactor power.

In this scheme, the steam generator side provides the primary driving mechanism for load-follow operation, and the reactor power passively approaches the target load through coupled neutronic and thermal-hydraulic feedback.

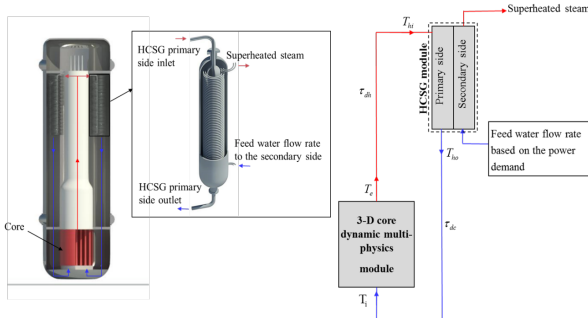


Figure 2 Mechanism of PALFO with HCSG

2.3 Mode-Y Logic for Rod-aided PALFO

To supplement PALFO under demanding transients, limited control rod assistance was introduced using the embedded Mode-Y logic. In the present strategy, PALFO remains the primary load-follow mechanism, while rod motion is used only as a supplementary action. This approach was adopted because, under severe load-follow scenarios, relying solely on passive feedback may require an excessively large variation in the coolant temperature.

Figure 3 shows the widened dead-band adopted in the present rod-aided PALFO strategy. In conventional rod-only load-follow operation, the dead-band of Mode-Y is typically on the order of 1°C, allowing frequent and sensitive rod motion in response to coolant temperature deviation. In contrast, the dead-band used in this study was intentionally widened so that rod intervention begins only when the core-average coolant temperature deviation exceeds approximately $\pm 3.0^\circ\text{C}$. Accordingly, the transient response is governed primarily by PALFO within the widened temperature band, while control rods are activated only when additional reactivity support becomes necessary. Figure 4 shows the control rod pattern used in this study. The core includes shutdown, regulating, and gray banks, and the regulating and gray banks were utilized for rod-aided load-follow operation.

Once the temperature deviation exceeds the prescribed limit, the Mode-Y logic determines rod insertion or withdrawal with predefined speeds according to the magnitude and direction of the deviation. Therefore, the proposed strategy can be regarded as a hybrid load-follow approach that retains the passive nature of PALFO while mitigating excessive coolant temperature variation through limited rod assistance.

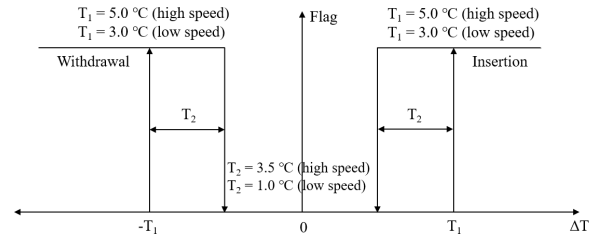


Figure 3 Temperature dead-band of Mode-Y in rod-aided PALFO

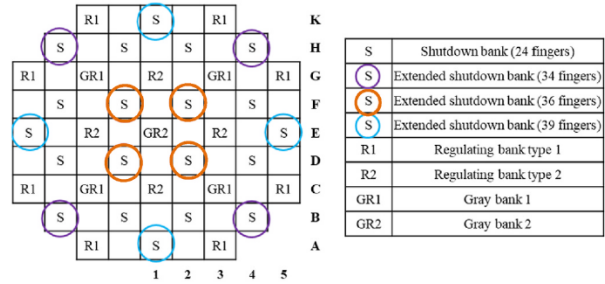


Figure 4 Control rod pattern for the ATOM core

2.4 Computation conditions

The load-follow scenario considered in this study is shown in Figure 5. A 100–20–100 demand power history was imposed to evaluate the performance of rod-aided PALFO under a severe transient condition. In this scenario, the reactor power decreases from 100% to 20% within 3 h, remains at 20% power for a given period, and then returns to 100% power with the same ramp rate. The cycle was repeated to examine the transient response during successive load-follow maneuvers.

Transient simulations were carried out for both the BOC equilibrium condition and the 90% EOC equilibrium condition. All calculations were performed using a fixed time step of 3 s.

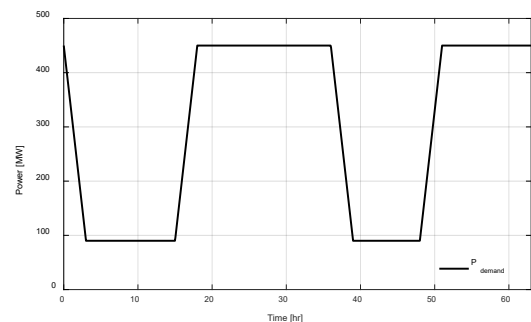


Figure 5 Power scenario

2.5 Rod-aided PALFO at BOC condition

Figure 6 shows the transient results of the proposed rod-aided PALFO at the BOC condition for the 100–20–100 load-follow scenario. As shown in Figure 6, the core

power closely follows the demand power throughout the transient, indicating that the proposed strategy can successfully accommodate the rapid power maneuver from full power to 20% power within 3 h and the subsequent return to full power.

The corresponding control rod movement is shown in Figure 7. Among the available control rod banks, R2 was the primary bank involved in the transient maneuver. This indicates that the supplementary rod action required for rod-aided PALFO remained limited even under the demanding load-follow condition.

Figure 8 shows the axial shape index (ASI) during the transient. Although ASI changed noticeably in response to the repeated power reduction and recovery, its maximum value remained about 0.19, indicating acceptable axial power shape behavior during load-follow operation.

The coolant temperature behavior is presented in Figure 9. For the ATOM core adopting the constant average coolant temperature strategy, the inlet coolant temperature is expected to be approximately 580 K at the 20% power condition. In the present simulation, the maximum inlet coolant temperature was about 583 K, indicating that the coolant temperature response remained reasonably close to the expected level and within an acceptable range during the transient.

Figure 10 shows the peaking factor variation during the transient. The changes in radial, axial, and 3D peaking factors were limited over the entire maneuver, indicating that the proposed rod-aided PALFO strategy did not induce significant power peaking penalty while achieving the target load-follow performance.

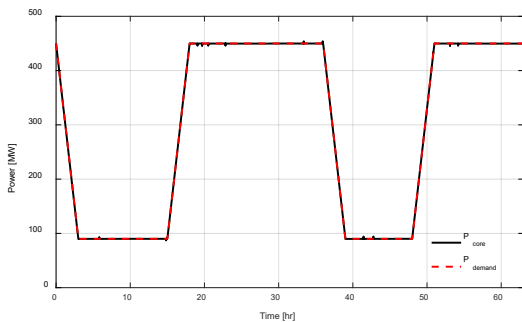


Figure 6 Core power response at the BOC condition

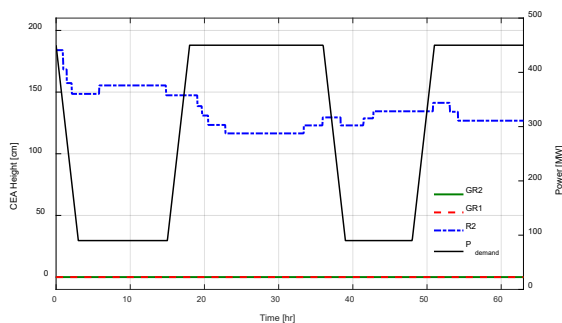


Figure 7 Control rod position at the BOC condition

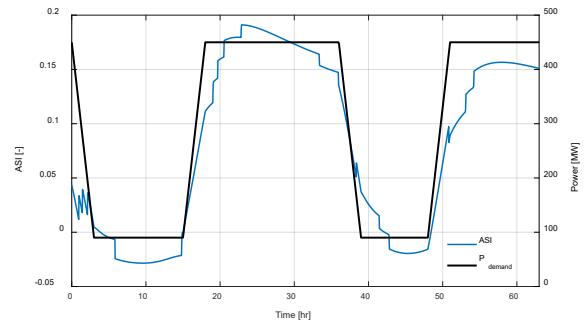


Figure 8 ASI variation at the BOC condition

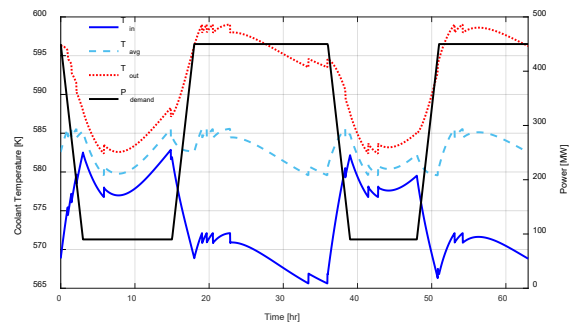


Figure 9 Coolant temperature response at the BOC condition



Figure 10 Peaking factor variation at the BOC condition

2.6 Rod-aided PALFO at 90% EOC condition

Figure 11 shows the rod-aided PALFO results at the 90% EOC condition. As shown in Figure 11, the core power closely follows the demand power throughout the 100–20–100 transient.

As shown in Figure 12, R2 was the primary bank used during the transient, while GR1 was additionally activated for ASI control, reflecting the Mode-Y logic. Figure 13 shows that the ASI reached about -0.25 during the 20% power interval, which is considered acceptable since it occurred in a very low-power region. The coolant temperature response in Figure 14 was similar to that at the BOC condition, without excessive excursion.

Figure 15 shows that the peaking factors remained stable during the transient. The maximum three-

dimensional pin peaking factor was about 1.94 in the 20% power region, which is still a relatively low value.

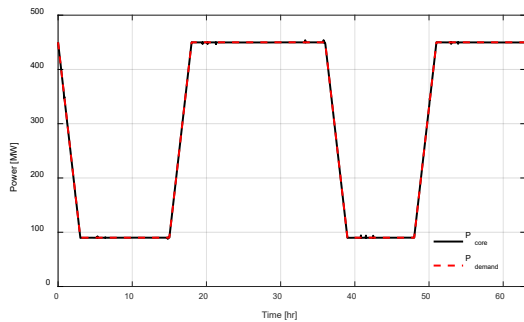


Figure 11 Core power response at the 90% EOC condition

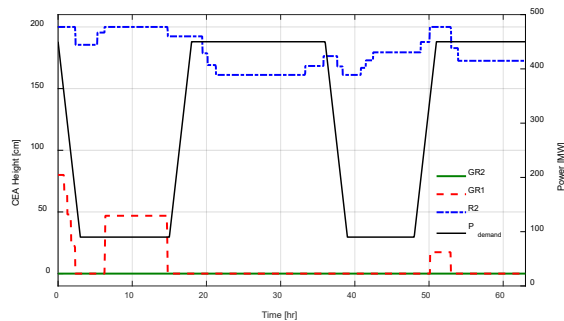


Figure 12 Control rod position at the 90% EOC condition

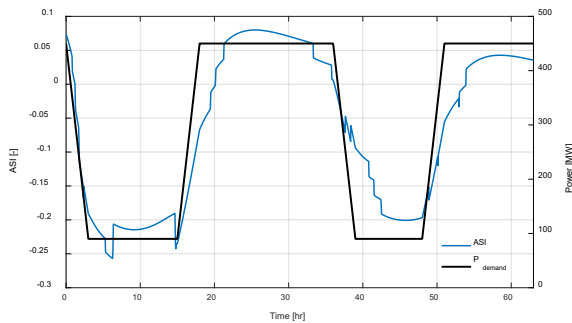


Figure 13 ASI variation at the 90% EOC condition

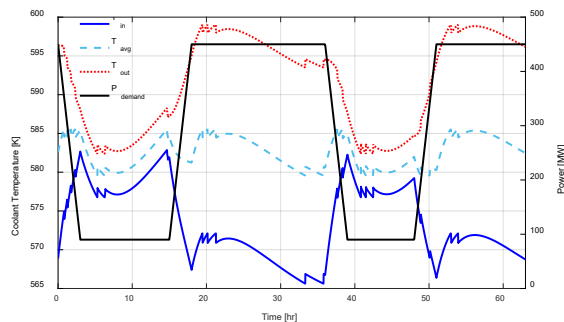


Figure 14 Coolant temperature response at the 90% EOC condition

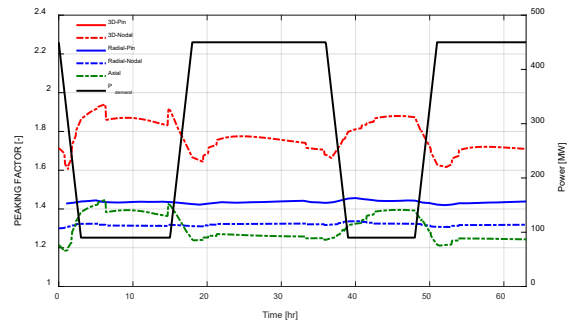


Figure 15 Peaking factor variation at the 90% EOC condition

3. Conclusions

A rod-aided PALFO strategy was investigated for the soluble boron-free ATOM core under the 100–20–100 load-follow scenario. The proposed approach combines steam-generator-driven passive load-follow operation with limited control rod assistance activated only when the coolant temperature deviation exceeds a widened dead-band.

Transient analyses at both BOC and 90% EOC conditions showed that the core power closely followed the demand power, while rod motion, ASI variation, coolant temperature change, and peaking factors remained acceptable. These results demonstrate that rod-aided PALFO can improve the load-follow capability of the ATOM core under severe transient conditions without losing the predominantly passive character of PALFO.

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