



Power Control System of Small Modular Pb-Bi Fast Reactor (SMPBR)

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Abstract. With the development of nuclear technology, the existing fissile nuclides can not meet the long-term needs of human beings. The development of fast neutron reactor using fissionable nuclides is the trend of nuclear energy development. Small modular Pb-Bi Fast Reactor (SMPBR) is a fast neutron reactor with liquid Lead Bismuth Eutectic (LBE) as coolant. In order to become a competitive reactor, SMPBR is usually characterized by high power density, strong load following ability and convenient transportation. Due to the current lack of relevant experience of lead-bismuth fast reactors in China, there are certain difficulties in the design of lead-bismuth fast reactors and the design of control systems. So in this work, the control system for the SMPBR is based on the sodium-cooled fast reactor. Firstly, the influence of control rod, inlet flowrate and inlet temperature is studied by single variable method respectively. Secondly, according to the relationship between the parameters, the control system of regulating power of moving control rods and not moving control rods is designed. Then, a robust PI controller is designed according to the dynamic characteristics of reactor. Combining the influence of control rods and flow on power and power to design controllers with different operating schemes.

Keywords: Small modular Pb-Bi Fast Reactor · Control system · Flowrate

1 Introduction

With the development of industry and the depletion of fossil energy, people urgently need to seek new sustainable energy. Nuclear energy is a kind of clean and sustainable energy. At present, our nuclear energy mainly comes from fissile nuclides. However, there are few fissile nuclides on the earth, so only reasonable use of fissionable nuclides can solve the energy problem [1, 2]. Fast neutron reactor is a chain fission reaction which takes place by using fast neutrons. Its obvious characteristic is that it can use fissionable nuclides. At the same time, fast neutron reactors also have good safety [3]. The control system is the basic guarantee for the operation of nuclear power, so it is necessary to study the control system of fast reactor.

The current power control method is mainly to adjust the power by controlling the movement of the control rod [4, 5]. However, from the perspective of nuclear power plant

safety, power control should respond to different equipment failures through multiple control methods. Therefore, it is necessary to study the power adjustment method outside the control rod. Previously, some literature pointed out that it is feasible to control high-power sodium-cooled fast reactors by means of flow regulation, and that small-lead bismuth fast reactors have advantages over sodium-cooled fast reactors by way of flow regulation [6, 7]. Therefore this paper studies and compares the effect of control rods and flow rate on power, and studies the effect of inlet temperature changes on the primary circuit. Because China lacks experience with lead-bismuth fast reactors, this article uses the study of sodium-cooled fast reactor control system as a reference for the subsequent design of lead-bismuth fast reactor.

2 Model and Methods

The primary circuit of the lead-bismuth fast reactor and the sodium-cooled fast reactor are similar in structure, and both include the core, hot pool, cold pool, and steam generator as shown in Fig. 1.

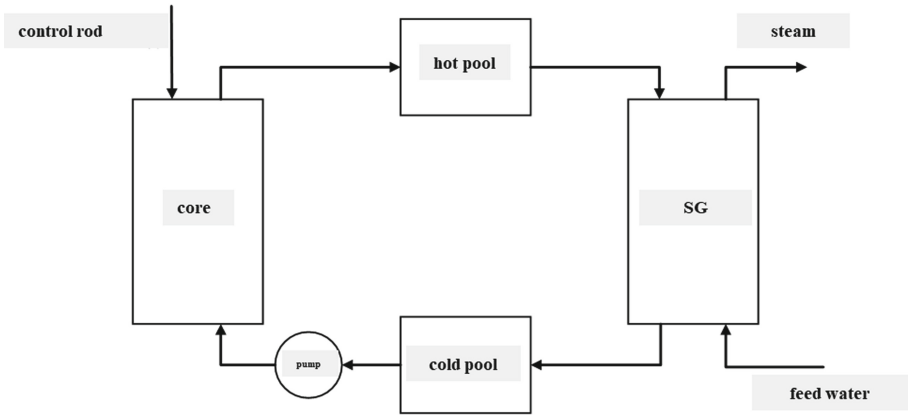


Fig. 1. Primary loop model

2.1 Point Reactor Kinetics Equations

The core uses a point reactor equation with six groups of delayed neutrons, as shown below [8]:

$$\frac{dn(t)}{dt} = \frac{\rho(t) - \beta}{\Lambda} n(t) + \sum_{i=1}^6 \lambda_i C_i(t) \quad (1)$$

$$\frac{dC_i(t)}{dt} = \frac{\beta_i}{\Lambda} n(t) - \lambda_i C_i(t), \quad i = 1 \sim 6 \quad (2)$$

$$\beta = \sum_{i=1}^6 \beta_i \quad (3)$$

where, $n(t)$ — neutron density/neutron number-m-3; $\rho(t)$ — total reactivity in the core/dk-k-1; $C_i(t)$ — delayed neutron precursor concentration of group $i/m-3$; λ_i — precursor decay constant of group i/s ; β_i — delayed neutron share of group $i/\%$; Λ — neutron generation time/s.

2.2 Thermal Dynamic Model

According to energy conservation, the dynamic heat transfer equation of fuel coolant is as follows [9]:

$$\frac{dT_f}{dt} = \frac{f_f P_0}{\mu_f} N_r - \frac{\Omega}{\mu_f} (T_f - T_m) \quad (4)$$

$$\frac{dT_m}{dt} = \frac{(1 - f_f) P_0}{\mu_c} N_r + \frac{\Omega}{\mu_c} (T_f - T_m) + \frac{2}{\tau_c} (T_{in} - T_m) \quad (5)$$

$$\frac{dT_{out}}{dt} = \frac{(1 - f_f) P_0}{\mu_c} N_r + \frac{\Omega}{\mu_c} (T_f - T_m) + \frac{2}{\tau_c} (T_m - T_{out}) \quad (6)$$

where, T_f — average temperature of fuel/ $^{\circ}\text{C}$; T_m — average temperature of coolant/ $^{\circ}\text{C}$; T_{in} — inlet temperature of coolant/ $^{\circ}\text{C}$; T_{out} — outlet temperature of coolant/ $^{\circ}\text{C}$; f_f — thermal coefficient of fuel; P_0 — full power/W; μ_f — thermal capacity of fuel/ $\text{J } ^{\circ}\text{C}^{-1}$, $\mu_f = mf C_{p,f}$; μ_c — thermal capacity of coolant/ $\text{J } ^{\circ}\text{C}^{-1}$, $\mu_c = m_c \cdot C_{p,c}$; $C_{p,f}$ and $C_{p,c}$ — constant pressure specific heat capacity of fuel and coolant/ $\text{J kg}^{-1} ^{\circ}\text{C}^{-1}$; Ω — heat transfer coefficient between fuel and coolant/ $\text{W } ^{\circ}\text{C}^{-1}$; τ_c — delay time/s $\tau_c = \mu_c/(W_p C_{p,c})$; W_p — flow rate of coolant/ kg s^{-1} .

2.3 Hot and Cold Pool

After the coolant flows out of the core, it exchanges heat with the steam generator through the hot pool, and the cooled flows into the core through the cold pool to complete the circulation. To simplify the simulation, the following assumptions are made:

- (1) The coolant is fully mixed in the hot and cold pool, that is, the outlet temperature is equal to the average temperature of the hot and cold pool;
- (2) The hot and cold pool are insulated.

According to energy conservation, the energy equation of hot and cold pool as follows:

$$\frac{dT_{hot}(t)}{dt} = \frac{F_{hot}}{V_{hot}} (T_{hot,in} - T_{hot}(t)) \quad (7)$$

$$\frac{dT_{cold}(t)}{dt} = \frac{F_{cold}}{V_{cold}} (T_{cold,in} - T_{cold}(t)) \quad (8)$$

where: $T_{hot}(t)$, $T_{cold}(t)$ — outlet temperature of hot and cold front pool/°C; $T_{hot,in}(t)$, $T_{cold,in}(t)$ — inlet temperature of hot and cold lead bismuth pool/°C; F_{hot} , F_{cold} — volume flow of hot and cold lead bismuth pool/m³ s⁻¹; V_{hot} , V_{cold} — effective capacity of hot and cold lead bismuth pool/m³.

2.4 Reactivity

There are many factors affecting the reactivity of the reactor. This paper considers five main factors: the reactivity introduced by the control rod, the Doppler effect of the fuel, the effect of the coolant density, the axial expansion of the core, and the radial expansion of the core.

Fuel's Doppler effect, coolant density effect, core axial expansion and core radial expansion can be expressed by the following equations:

$$\rho_{Doppler} = \rho_{f,T} = \alpha_f \ln(T_f/T_{f,0}) \quad (9)$$

where, $T_{f,0}$ — fuel temperature at initial time/°C.

$$\rho_{c,t} = 0.5\alpha_{c,t}(T_m - T_{m,0}) + 0.5\alpha_{c,t}(T_{out} - T_{out,0}) \quad (10)$$

where, $T_{m,0}$ — average temperature of coolant at initial test time/°C; $T_{out,0}$ — outlet temperature of coolant at initial test time/°C.

$$\begin{aligned} \rho_a &= \int_{T_{m,0}}^{T_m} d\rho = \int_{T_{m,0}}^{T_m} a \cdot \alpha_a \cdot z_0^2 \cdot e^{z_0^2(1+\alpha \cdot T_m)^2} \cdot (1 + \alpha \cdot T_m) dT \\ &= \frac{a \cdot z_0^2 \cdot e^{z_0^2}}{2} e^{(1+\alpha_a \cdot T_m)^2} - \frac{a \cdot z_0^2 \cdot e^{z_0^2}}{2} e^{(1+\alpha_a \cdot T_{m,0})^2} \end{aligned} \quad (11)$$

where: t_0 — initial time/s.

$$\rho_r = \alpha_r \cdot (T_m - T_{m,0}) \quad (12)$$

Connect the above models according to the relationship in Fig. 1, where the steam generator module is simplified using boundary conditions.

3 Results and Discussion

The PID controller has a simple structure and is easy to implement. It is widely used in industrial production. This paper uses a PI controller to control the movement of the control rod and the opening of the main pump because there is no large delay. Verification of steady-state parameters selecting a sodium-cooled fast reactor with a thermal power of 65 MW.

Introduce step reactivity to study the characteristics of the control rod when controlling power. At 200 s, +50 pcm were introduced, the change of reactivity as shown in Fig. 2.

When the step reactivity is introduced, the reactivity increases and the power increases. When the change of power is detected, the control rod moves to introduce

negative reactivity, the total reactivity decreases rapidly and the power decreases. The power change after introducing step reactivity is shown in Fig. 3.

Figure 4 shows the change of reactivity from 100% power step to 90% FP. Firstly, the negative reactivity is introduced into the control rod movement, and the power decreases. At this time, k_{eff} less than 1 and the core is in subcritical state. Then, the temperature of fuel and coolant decrease and the introduction of positive reactive power recovery, k_{eff} gradually increased to 1, and the system reached a new balance.

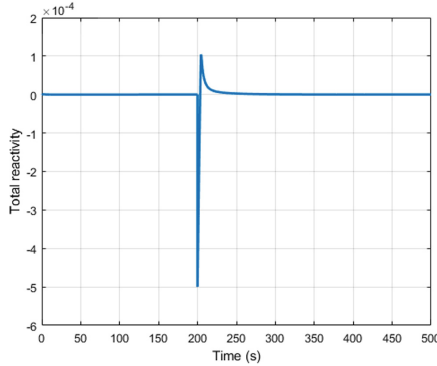


Fig. 2. Total reactivity change when +50 pcm step is introduced.

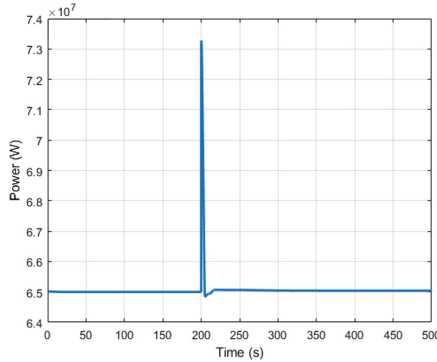


Fig. 3. Power change when +50 pcm step is introduced.

Figure 4 shows the change of reactivity from 100% power step to 90% FP. Firstly, the negative reactivity is introduced into the control rod movement, and the power decreases. At this time, k_{eff} less than 1 and the core is in subcritical state. Then, the temperature of fuel and coolant decrease and the introduction of positive reactive power recovery, k_{eff} gradually increased to 1, and the system reached a new balance.

Figure 5 shows the power changes from 100% power step down to 90% FP, 80% FP, 70% FP, 60% FP and 50% FP respectively. It can be seen from the Fig. 5 that the control system can have good control effect in a large power range.

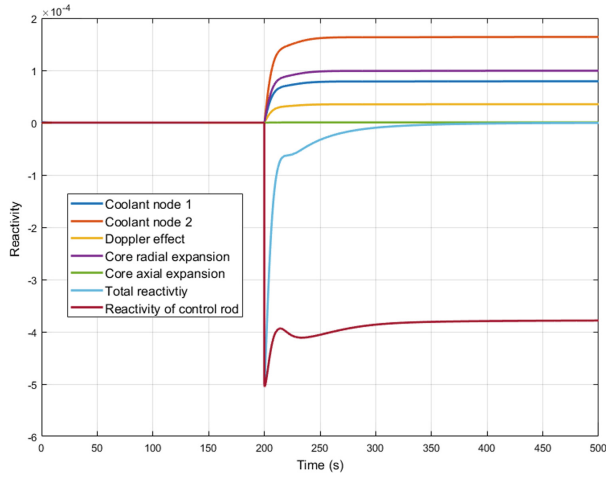


Fig. 4. Reactivity change when power from full power step decrease to 90%FP.

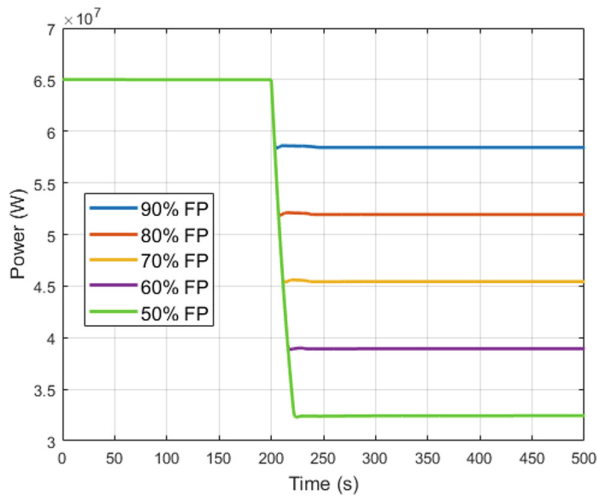


Fig. 5. Power change when power step decrease.

3.1 Adjust Power by the Coolant Flow Rate

The change of coolant flow will affect the core temperature, thus introducing reactivity to adjust the power. That is, the power can be adjusted by introducing reactivity through coolant flow changes without moving the control rods.

Figure 6 shows the change of reactivity when +50 pcm reactivity is introduced. It can be seen from the figure that when the reactivity step increases, the coolant flow will decrease, the coolant temperature will increase to introduce negative reactivity, the power will decrease, the fuel temperature will increase, the Doppler effect will introduce

negative reactivity, the final total reactivity is 0, and the system will be stable at a new point.

Figure 7 shows the power change after reactive step disturbance. It can be seen from the Fig. 7 that the power increases after the introduction of reactivity, and then the flow rate decrease, the negative reactivity is introduced due to the increase of coolant temperature. Finally, the power down to original level.

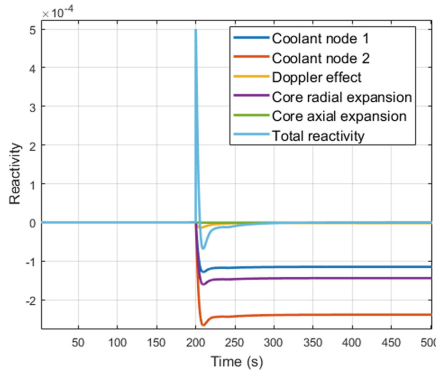


Fig. 6. Reactivity change when + 50 pcm step is introduce.

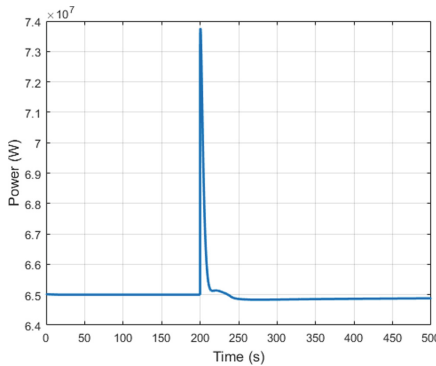


Fig. 7. Power change when + 50 pcm step is introduce. (right)

In order to verify the effectiveness of adjusting the flow in a large power range, Fig. 8 shows the power change when the power is reduced to 90%, 80%, 70%, 60%, 50% by controlling the flow rate. As can be seen from the Fig. 8, it is feasible to adjust the power by controlling the coolant flow as well as the control rod adjustment. Figure 9 shows the flow rate curves at different power levels.

It can be seen from the Fig. 9 that when the power level drops to 50% FP, the flow needs to drop to 45% of the flow at full load, and when the power needs to continue to drop, the flow still needs to drop. Because of the safety design of fast reactor, the coolant usually has good natural circulation ability, so the influence of natural circulation needs

to be considered when the flow is too small, so the current model still needs to be further improved.

Figure 10 shows the reactivity at different power levels. It can be seen from the figure that when the coolant flow decreases, the increase of coolant temperature introduces negative reactivity and the decrease of power. With the decrease of fuel temperature, the temperature difference between fuel and coolant decreases, and the heat exchange decreases. The decrease of fuel temperature leads to positive reactivity, while the increase of coolant temperature leads to negative reactivity. At the same time, due to the increase of coolant temperature, the average temperature of core rises, and the core expands to introduce negative reactivity.

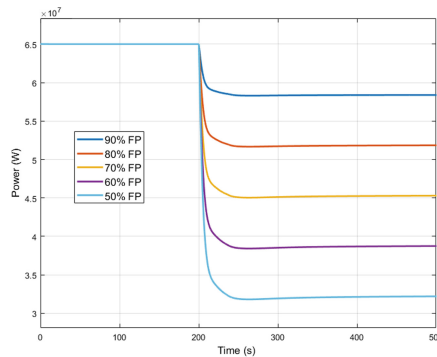


Fig. 8. Power adjustment by adjusting the coolant flow rate.

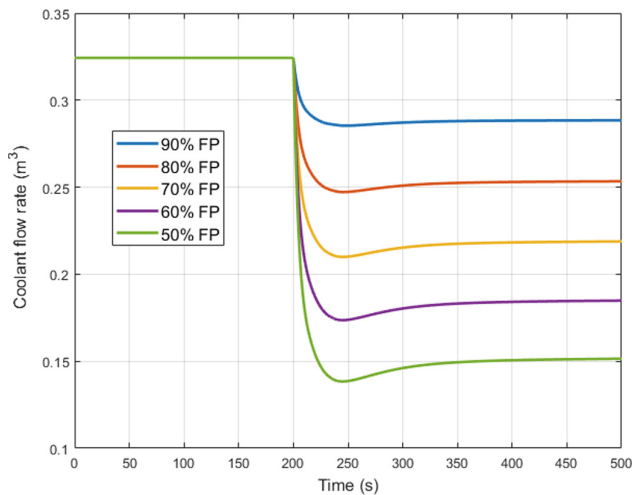


Fig. 9. Flow rate adjustment.

As can be seen in Fig. 10, the Doppler effect of fuel and the density effect of coolant are the most obvious. However, almost all of the reactivity coefficients are related to

the structural parameters, so the design parameters can be used to adjust the reactivity coefficients when the flow rate is adjusted by the reactivity feedback. By selecting different materials of reflector and supporting structure to adjust the reactivity coefficient, the power can be controlled by controlling the flow rate.

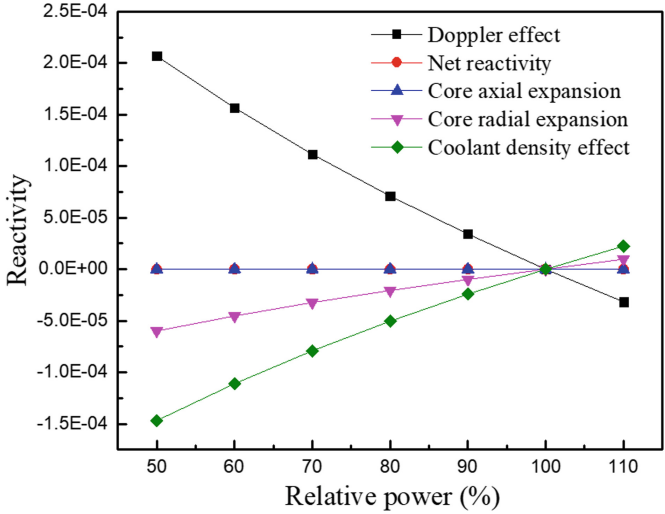


Fig. 10. Reactivity at different power levels

Generally, it is more difficult to achieve negative temperature reactivity feedback for a sodium-cooled metallic fuel large fast reactor than it is for other types of fast reactors proposed so far such as an LBE-cooled reactor with small core and nitride fuel [6]. So it is easier for miniaturized lead-bismuth fast reactor to control power through coolant flow rate. There are advantages to flow rate control:

- 1) Add new power regulation methods to improve reactor safety;
- 2) For small lead-bismuth fast reactors, it can assume part of the control rod function, thereby simplifying the control rod system and providing assistance for miniaturization and centralization.

3.2 Influence of Core Inlet Temperature on the Primary Circuit

At present, China lacks experience with small lead-bismuth fast reactors, so the control system of lead-bismuth fast reactors is based on sodium-cooled fast reactors. In order to design a more flexible load variation that is more suitable for small lead-bismuth fast reactors, it is necessary to study the dynamic characteristics of the primary circuit. In this section, the influence of the parameters of the steam generator on the primary circuit is studied through the change of the primary circuit inlet temperature.

Figure 11 shows the change of reactivity when the inlet temperature of the primary circuit rises 5 °C with no control system. After the temperature of the primary circuit

outlet of the steam generator step rises $5\text{ }^{\circ}\text{C}$, the core temperature rises, introducing negative reactivity. Without the control of the control system, the power decreases, the core outlet temperature decreases, and positive reactivity is introduced. However, as the inlet temperature increases, the increase in the temperature of the coolant node 1 introduces negative reactivity. The average core temperature increases, the core expansion introduces negative reactivity, and the total reactivity decreases first and then increases. Power continues to drop and stabilizes at a new power level as shows in Fig. 12. The presence of cold pools plays a buffering role, but at the same time the delay time increases.

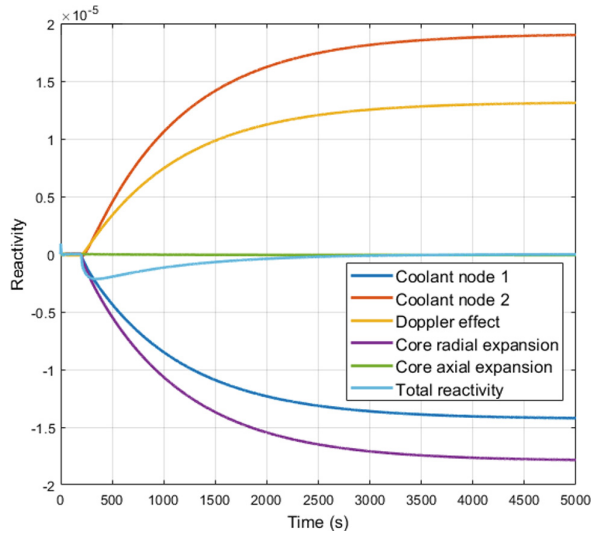


Fig. 11. Reactivity change when temperature step rises $5\text{ }^{\circ}\text{C}$.

Figure 13 shows the change of reactivity after a $5\text{ }^{\circ}\text{C}$ step in the inlet temperature after the power level is controlled using the regulated flow method. It can be seen from the figure that when the inlet temperature rises, and the increase in the temperature of the coolant node 1 introduces negative reactivity so the power decreases as in the Fig. 14, the coolant flow rate increases after the control system detects as in the Fig. 15. However, as the flow rate increases, the outlet temperature decreases to introduce positive reactivity. Because the cold pool acts as a buffer, the power changes slowly, the power remains almost unchanged under the control of the system. But there is a significant increase in the adjustment time due to the cold pool. The system rebalances when the temperature of cold pool increase to the temperature of SG outlet.

The inlet temperature of core increases, the power does not change, the way of increasing the flow rate leads to the fuel temperature hardly changes, as shown in Fig. 13, the Doppler effect has almost no reactivity introduced, ensuring the safety of the fuel.

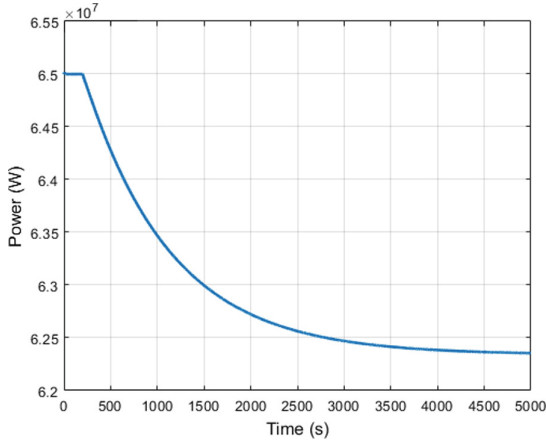


Fig. 12. Power change when temperature step rises 5 °C.

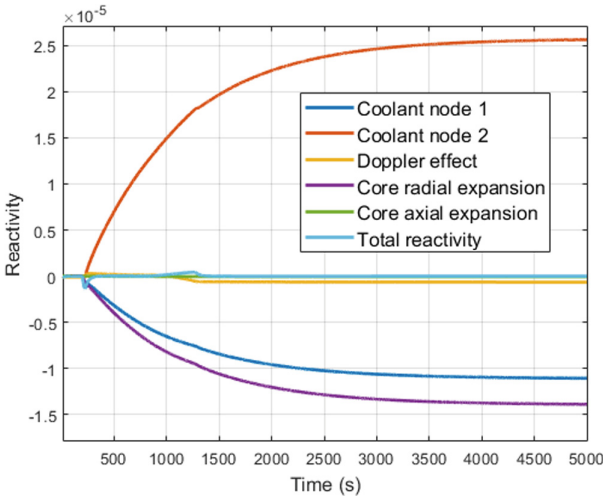


Fig. 13. Reactivity change when inlet temperature step rises 5 °C.

In summary, it is feasible to control the power by controlling the flow. Flow regulation takes advantage of the reactor’s reactive feedback, so the feedback factor is critical. Fortunately, these parameters can be adjusted by design, including the geometry of the reactor, the choice of materials, and so on. Therefore, the control system can provide reference indicators for the design of the reactor as well as the process design. The cold pool can buffer the parameters of the steam generator and increase the delay time. The selection of cold pool capacity can be designed in conjunction with the operation scheme, and the control system can also provide a control scheme by combining control rod movement and flow adjustment.

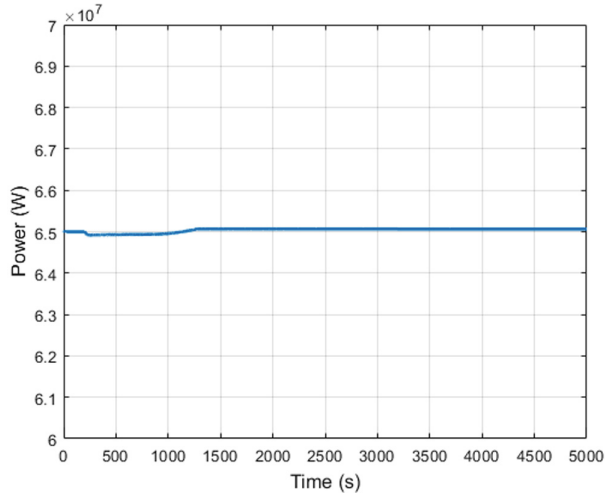


Fig. 14. Power change when inlet temperature step rises 5 °C.

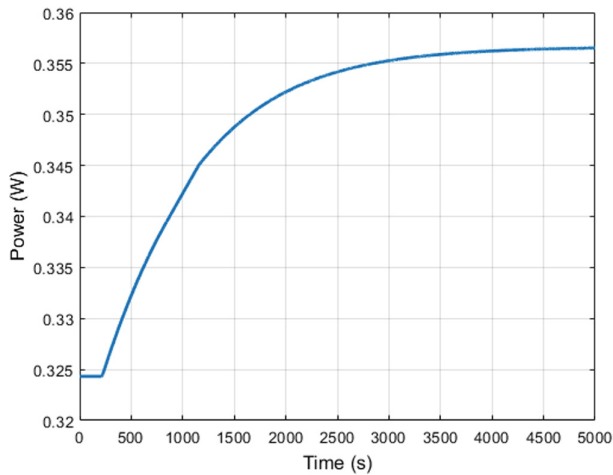


Fig. 15. Flow change with time

In summary, it is feasible to control the power by controlling the flow. Flow regulation takes advantage of the reactor's reactive feedback, so the feedback factor is critical. Fortunately, these parameters can be adjusted by design, including the geometry of the reactor, the choice of materials, and so on. Therefore, the control system can provide reference indicators for the design of the reactor as well as the process design. The cold pool can buffer the parameters of the steam generator and increase the delay time. The selection of cold pool capacity can be designed in conjunction with the operation scheme, and the control system can also provide a control scheme by combining control rod movement and flow adjustment.

4 Conclusion

In order to design the primary loop control system of the small lead-bismuth fast reactor, the dynamic characteristics of the primary circuit of the sodium-cooled fast reactor are studied in this paper. The power is adjusted by controlling the flow of the rod and the coolant, and the inlet temperature to the primary circuit. The main conclusions are as follows:

- (1) The PI controller has a good control effect, has good robustness to step disturbances, and can adjust power over a wide range.
- (2) The method of adjusting power by flow rate is feasible in a large power range. Provided a reference for the design of the primary loop control system.
- (3) It is feasible to use reactive feedback to adjust the power, and the process design of the core can be guided by the indicators of the control system.
- (4) The cold pool buffers the fluctuation of the parameters of the steam generator, and also increases the delay time. The selection of the capacity of the cold pool should be combined with the operation scheme.

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