Plant control of high temperature reactor cooled and moderated by supercritical light water

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In this paper, dynamic behavior and plant control system of high temperature supercritical-pressure light water cooled and moderated reactor (SCLWR-H) with descending flow water rods are described. The SCLWR-H has no recirculation system. The core flow rate is less than 1/7 of BWR. In the core there is 3-5 times larger density change than in a BWR core. Thus, the dynamic behavior of the SCLWR-H is different from that of BWR. It is also different from that of a once-through supercritical light water cooled fossil-fired power plant (FPP) because of reactivity feedbacks. The dynamic behaviors of the SCLWR-H and a low temperature fast reactor (SCFR), which was analyzed in the past study, may be also different each other because of the water rods, differences in the coolant density coefficient, and difference in the density change in the cores.

Step responses of the SCLWR-H are calculated against the perturbations of reactivity, flow rate, and pressure. The moderator in water rods makes core power not sensitive to the change of feedwater flow rate. The water rods contain about 76% of the volume of the total water in the core and its density is not sensitive to the flow rate.

The plant control system is designed according to the step responses. The turbine inlet pressure, the main steam temperature, and the core power are controlled by the turbine control valves, the feedwater pumps, and the control rods, respectively. The parameters of the control system are optimized by the test calculations to satisfy the criteria of both fast convergence and stability. The SCLWR-H plant is controlled stably with the designed control system against various perturbations, such as setpoint change of the pressure, the main steam temperature and the core power, decrease in the feedwater temperature, and decrease in the feedwater flow rate.

KEYWORDS: supercritical water cooled, once-through, descending flow water rod, dynamic behavior, control system

I. Introduction

The conceptual design of supercritical pressure light water reactor (SCR) has been developed at the University of Tokyo for 13 years1,2, R&D projects of SCR are going on in many countries. The main features of the SCR concept are the high thermal efficiency and the compact plant system. It adopts once-through direct cycle where the entire core coolant is driven to the turbine. It is similar to a once-through boiler of a supercritical fossil-fired power plant (FPP). The SCR is compared with BWR, PWR and FPP in Fig. 1. It does not need recirculation system, steam-water separator, and steam generators. The enthalpy rise in the SCR core is much higher than those of LWRs because the core flow rate is less than 1/7. The coolant outlet temperature is about 500°C and the thermal efficiency is about 44%. The plant system of the SCR is shown in Fig. 2. The control rods (CR) and the reactor pressure vessel (RPV) are similar to those of PWR. The containment vessel (CV) and the safety system are similar to those of BWR. The balance of plant (BOP) is similar to that of FPP. Except the outlet nozzles of the RPV, the temperatures of these components have been already experienced in LWRs and FPP.

The recirculation flow rate of BWR is about 7.5 times of the feedwater flow rate. Since the SCR has no recirculation system, the core flow rate is less than 1/7 of that of a BWR. In the SCR core, coolant density changes 3-5 times as in BWR core. But the average moderator density is higher than that of BWR because of many water rods. The SCR is also different from FPP because of the reactivity feedbacks of the fuel temperature and the coolant density. In the past study3, dynamic behavior of a low temperature fast reactor (SCFR) was analyzed and its plant control system was designed. The characteristics of a high temperature thermal reactor (SCLWR-H) may be different from those of the SCFR because of the water rods, difference in the coolant density coefficients, and difference in the density changes in the cores. This paper describes the dynamic behavior and the plant control system of the SCLWR-H.

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Fig. 1: Comparison of plant systems
II. Reactor core with descending flow water rods

The fuel assembly of the SCLWR-H is shown in Fig. 3. It contains many water rods for neutron moderation. The volume of the water rods is about 76% of the total water volume in the fuel assembly. It influences the plant dynamic behavior, which will be explained in Section IV. The coolant flows downward in the water rods. The flow path in the RPV is shown in Fig. 4. Part of the feedwater is led to the top dome and cools it. Then it flows downward in the CR guide tubes and the water rods. In the bottom of the fuel assemblies it is mixed with the rest coolant which has descended in the downcomer.

The “downward flow in the water rods” concept has advantages. There is no mixing of hot and cold coolant at the upper plenum. The coolant outlet temperature and the thermal efficiency are kept high. The axial distribution of the water density is shown in Fig. 5. The difference in the average water density is small between upper and lower parts of the core although the coolant density changes about 9 times in the fuel channels. Thus, the axial distribution of the neutron moderation does not change substantially.

III. Plant transient analysis code SPRAT-DOWN

The plant transient analysis code “SPRAT-DOWN” is used. The calculation model is shown in Fig. 6. The hottest single channel and a water rod are divided into 20 nodes. Heat transfer between them is considered. The main feedwater lines are divided into 10 nodes. The downcomer is divided into 20 nodes including the bottom dome. The upper plenum is divided into 20 nodes including the main steam lines. The top dome is divided into 10 nodes including the CR guide tubes. Since the fuel channel and the water rod are modeled as single channels, the volumes of the top dome, the bottom dome, the upper plenum, the downcomer, and the main feedwater lines are divided by the total number of the fuel rods. The mass and energy conservations are calculated.

\[
\frac{\partial \rho}{\partial t} + \frac{\partial G}{\partial Z} = 0 \tag{1}
\]

\[
\frac{\partial (\rho H)}{\partial t} + \frac{\partial (GH)}{\partial Z} = Q'''' \tag{2}
\]

where \( t \): time, \( Z \): position, \( \rho \): density, \( G \): mass flow rate \( H \): specific enthalpy \( Q'''' \): heat generation rate per unit volume
The boundary conditions are the feedwater flow rate, the feedwater temperature and the turbine inlet flow rate. 30% of the feedwater is led to the upper dome and flows in the water rods at normal operation. This ratio is changed when the pressure losses of the two flow paths; one is the downcomer and the other is the water rods, do not balance. The pressure loss in the fuel channel is not considered because relative change of coolant flow is small for the plant control analysis. A multi-channel model considering the radial distribution of the pressure loss will be more realistic for accident analysis where the feedwater flow rate is significantly decreased.

The heat transfer coefficient in the supercritical water is evaluated by the correlation\(^4\) which was developed by the numerical calculation\(^5\) using the Jones and Launder \(k-\varepsilon\) turbulence model\(^6\). As shown in Fig. 7, the feedwater flow rate changes with the core pressure. The axial power distribution is cosine. The reactor power is calculated by the point-kinetics equation with six delayed neutron groups while the decay heat is calculated using a two-group approximation of 120% of the ANS standard\(^7\). Doppler and coolant density feedbacks are considered. The characteristic of the turbine control valves is shown in Fig. 8. The flow chart of the calculation is shown in Fig. 9. The calculation model includes the plant control system which will be explained in Section V.

### Fig. 6: Calculation model

![Calculation model](image)

### Fig. 7: Relation between feedwater and core pressure

![Relation between feedwater and core pressure](image)

### IV. Step responses without control system

It is necessary to analyze the step responses for the design of the plant control system. The feedwater pumps, the control rods and the turbine control valves will be used as the control system. Perturbations from the steady state operation are calculated. Major perturbations will be as follows; increase in the power resulting from withdrawal of a control rod cluster, decrease in the core flow rate resulting from decrease in the feedwater flow rate, and decrease in the main steam flow rate resulting from closing motion of the turbine control valves.

The step responses to these three perturbations are calculated without an operation of a control system. The characteristics of the SCLWR-H are shown in Table 1. The rated values are taken as the initial condition; the core power 100% [2300 MWt], the core pressure 25.0 MPa, the feedwater flow rate 100%, the turbine control valve stroke 50% (corresponding to main steam flow rate 100%) and the main steam temperature 500°C.
Table 1: Characteristics of SCLWR-H

<table>
<thead>
<tr>
<th>Core</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Core diameter / height [m]</td>
<td>3.6 / 4.2</td>
</tr>
<tr>
<td>Number of fuel assemblies</td>
<td>96</td>
</tr>
<tr>
<td>Coolant inlet / outlet temperature [°C]</td>
<td>280 / 500</td>
</tr>
<tr>
<td>Coolant density coefficient [dk/k/(g/cm³)]</td>
<td>0.2</td>
</tr>
<tr>
<td>Doppler coefficient [dk/k/°C]</td>
<td>-1.2×10⁻⁵</td>
</tr>
<tr>
<td>Maximum linear power [kW/m]</td>
<td>39</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>RPV and Main loop</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner diameter / wall thickness / total height [m]</td>
<td>4.34 / 0.35 / 15</td>
</tr>
<tr>
<td>Volume of top dome / upper plenum / bottom dome / down comer [m]</td>
<td>55 / 24 / 21 / 26</td>
</tr>
<tr>
<td>Inner diameter of main feedwater line / main steam line [m]</td>
<td>0.27 / 0.46</td>
</tr>
<tr>
<td>Length of main feedwater line / main steam line [m] (1 loop)</td>
<td>20 / 20</td>
</tr>
<tr>
<td>Number of main loops</td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fuel assembly</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel rod diameter / pitch [mm]</td>
<td>10.2 / 11.2</td>
</tr>
<tr>
<td>Cladding material / thickness [mm]</td>
<td>Ni-alloy / 0.63</td>
</tr>
<tr>
<td>Water rod wall material / thickness [mm]</td>
<td>Ni-alloy / 0.20</td>
</tr>
<tr>
<td>Number of fuel rods / water rods</td>
<td>300 / 36</td>
</tr>
<tr>
<td>Mass flux in fuel channel / water rod [kg/s/m²]</td>
<td>1161 / 45</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>System</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Core pressure [MPa]</td>
<td>25.0</td>
</tr>
<tr>
<td>Turbine inlet pressure</td>
<td>24.5</td>
</tr>
<tr>
<td>Thermal / electric power [MW]</td>
<td>2300 / 1000</td>
</tr>
<tr>
<td>Thermal efficiency [%]</td>
<td>43.5</td>
</tr>
<tr>
<td>Feedwater flow rate [kg/s]</td>
<td>1190</td>
</tr>
</tbody>
</table>

1. Reactivity insertion
A positive reactivity (10 cents) is inserted stepwise as a reactivity perturbation. The feedwater flow rate and the turbine control valve opening are kept constant. The result is shown in Fig. 10. The core power instantly increases to 114%, and then is settled at 100.4%. The reactivity feedbacks from the water density and the fuel temperature are almost the same degree (about 5 cents). The highest value of the main steam temperature and the core pressure are 513°C and 25.5MPa, respectively.

Fig. 10: Step response to withdrawal of control rod cluster (10 cents insertion)

2. Decrease in feedwater flow rate
The feedwater flow rate decreases stepwise to 95%. The control rod position and the turbine control valve opening are kept constant. The result is shown in Fig. 11. In the once-thorough cooling system, decrease in the feedwater flow rate directly leads to decrease in the core flow rate. Thus the main steam temperature increases. Decrease in the core power by density feedback is small because of the existence of the many water rods. The change of the water density is shown in Fig. 12. Since the heat transfer is small between the fuel channels and the water rods, the change of the density in the water rods is much smaller than that in the fuel channels. The volume fraction of the water rods is more than 70%. As a result, the change of the average water density is small. The core power is not so sensitive to the feedwater flow rate. This is one of the characteristics of the core with water rods.

Fig. 11: Step response to decrease in feedwater flow rate (-5%)
3. Decrease in turbine control valve opening

The turbine control valve opening decreases stepwise from 100 to 95%. The control rod position and the feedwater flow rate are kept constant. The result is shown in Fig. 13. The main steam flow rate instantly decreases to 95%. The water density and the core power increases a little resulting from the increase in the pressure. Then, the main steam temperature increases and the power decreases because of the decrease in the core flow rate. The oscillations of these parameters decay slowly.

V. Plant control system

The pressure is sensitive to the turbine control valve opening and the feedwater flow rate. In this study, the turbine inlet pressure is controlled by the turbine control valves as in BWR. The main steam temperature is sensitive to the control rod position and the feedwater flow rate. The main steam temperature is controlled by the feedwater pumps. The core power is controlled by the control rods. The control system is shown in Fig. 14. (In Section VII. 3, another control system is designed in which the main steam temperature and the power are controlled by the control rods and the feedwater pumps, respectively.)

The control system should be designed not to generate divergent or continuous oscillations that exceed the permissible range. The criteria are as follows;

- Damping ratio is less than 0.25. That is most generally used as the criterion for control quality and is applied to existing nuclear power plants.
- Overshoot is less than 15%. [Overshoot = (peak value – settled value) / (settled value – initial value)]

V. Plant control system

The turbine inlet pressure is kept constant by regulating the opening of the turbine control valves. The same logic as in BWR is adopted to regulate the opening ratio. It is proportional to the deviation of the pressure from the setpoint with lead-lag compensation. It is calculated from the following equations:

\[ V_r(t) = 100 \cdot \frac{P_{set} - P(t)}{K} \]  
\[ V(t) = V_r(t) + T_1 \frac{dV_r(t)}{dt} - T_2 \frac{dV(t)}{dt} \]

where
- \( P \) [MPa]: turbine inlet pressure
- \( P_{set} \) [MPa]: pressure setpoint
- \( V_r \) [%]: demand signal of opening
- \( V \) [%]: turbine control valve opening
- \( T_1 \) [s]: lead time
- \( T_2 \) [s]: lag time
- \( K \) [MPa]: gain converting the deviation of the pressure into the valve opening

The maximum speed of the valve stroke is limited to 100 % / 3.5 s which is the same as that of BWR. The values of \( T_1 \) and \( T_2 \) are respectively 2 and 5 s which are also the same as those of BWR.

The setpoint of the turbine inlet pressure increases from 24.5 to 24.75 MPa using only the pressure control system. Sensitivity analysis is carried out with various \( K \) to satisfy the criteria. The pressure overshoots are shown in Table 2.
**Table 2: Setpoint change of pressure from 24.5 to 24.75 MPa**

<table>
<thead>
<tr>
<th>K [MPa]</th>
<th>Pressure Overshoot [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>2.6</td>
</tr>
<tr>
<td>0.2</td>
<td>1.7</td>
</tr>
<tr>
<td><strong>0.25</strong></td>
<td><strong>1.4</strong></td>
</tr>
<tr>
<td>0.3</td>
<td>1.6</td>
</tr>
<tr>
<td>0.4</td>
<td>14</td>
</tr>
<tr>
<td>0.8</td>
<td>20</td>
</tr>
</tbody>
</table>

2. **Main steam temperature control system**

The main steam temperature is kept constant by regulating the feedwater flow rate. It is calculated based on the following equations:

\[
\frac{du(t)}{dt} = K_P e(t) + K_I \int_0^t e(t) dt \quad \text{(5)}
\]

\[
e(t) = \frac{T_{\text{lead-lag}} - T_{\text{set}}}{T_{\text{set}}} \times 100 \quad \text{(6)}
\]

\[
T_{\text{lead-lag}} = T_{\text{meas}} + T_1 \frac{dT_{\text{meas}}}{dt} \quad \text{(7)}
\]

\[
T_{\text{meas}} = T_{\text{steam}} - T_2 \frac{dT_{\text{meas}}}{dt} \quad \text{(8)}
\]

where

- \( u(t) \) [%]: feedwater demand signal
- \( e(t) \) [%]: deviation of main steam temperature from setpoint
- \( T_{\text{steam}} \) [°C]: main steam temperature (real)
- \( T_{\text{meas}} \) [°C]: main steam temperature (measured by thermometer)
- \( T_{\text{lead-lag}} \) [°C]: modified main steam temperature (with lead compensation)
- \( T_{\text{set}} \) [°C]: setpoint of main steam temperature
- \( T_1 \) [s]: lead time
- \( T_2 \) [s]: lag time (time constant of thermometer)
- \( K_P \): proportional gain, \( K_I \): integral gain

Both \( T_1 \) and \( T_2 \) are 20 s. The delay from the demand signal to the feedwater flow rate is 1.0 s. The maximum speed of the change of the feedwater flow rate is limited to 20%/s.

The setpoint of the main steam temperature increases from 500 to 504°C under the operation of the pressure and the main steam temperature control systems. Sensitivity analysis is carried out with various \( K_P \) and \( K_I \). Some typical results are shown in **Table 3**. The feedwater flow rate should be changed as slowly as possible to prevent oscillations of the main steam temperature and the core power at various perturbations even if the settling time is longer. In this study, \( K_P \) and \( K_I \) are determined to be 0.5 and 0.0, respectively.

3. **Power control system**

The core power is controlled by the control rods. The speed of the control rod drive is in proportion to the deviation of the power from the setpoint if the deviation is below a certain value \( b \). If the deviation is larger than \( b \), the control rods keep the maximum speed. The speed is calculated from the following equation:

\[
v = \begin{cases} 
  \frac{v_{\text{max}}}{e/b} & (e < b) \\
  v_{\text{max}} & (e \geq b)
\end{cases}
\]

where

- \( v \) [cm/s]: control rod drive speed
- \( v_{\text{max}} \) [cm/s]: maximum speed
- \( e \) [%]: deviation of the power from the setpoint
- \( b \) [%]: coefficient that converts power deviation to maximum drive speed

The value of \( v_{\text{max}} \) is the same as that of PWR. The setpoint of the power decreases from 100 to 95% under the operation of the pressure, the main steam temperature and the power control systems. Sensitivity analysis is carried out with various \( b \). The settling times and the undershoots of the power and the main steam temperature are shown in **Table 4**. When the value of \( b \) is small, the control rod speed is fast and the settling time is short. However, the undershoot of the main steam temperature is relatively large. The permissible range of the main steam temperature variation is referred to that of a sliding pressure supercritical FPP with automatic frequency control operation because the requirements for the turbines of the SCLWR-H are considered to be the same as those of FPP. When the load fluctuates at a speed of 7%/min between 90 and 100 % with a mean value of 95%, the permissible range is about ±8°C and the plant is actually operated within about ±2°C b). The value of \( b \) is determined to be 25% considering the undershoot of the main steam temperature and the settling time.

**Table 3: Setpoint change of main steam temperature from 500 to 504°C**

<table>
<thead>
<tr>
<th>( K_P )</th>
<th>( K_I )</th>
<th>Settling time [s]</th>
<th>Overshoot [%]</th>
<th>Damping ratio</th>
<th>Minimum power [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>0.0</td>
<td>Not settled</td>
<td>-</td>
<td>-</td>
<td>96.2</td>
</tr>
<tr>
<td><strong>0.5</strong></td>
<td>0.0001</td>
<td>70</td>
<td>0</td>
<td>-</td>
<td>96.2</td>
</tr>
<tr>
<td>0.001</td>
<td>50</td>
<td>0</td>
<td>-</td>
<td>96.2</td>
<td></td>
</tr>
<tr>
<td>0.6</td>
<td>0.0</td>
<td>50</td>
<td>0</td>
<td>-</td>
<td>96.2</td>
</tr>
<tr>
<td>0.7</td>
<td>0.0</td>
<td>40</td>
<td>0</td>
<td>-</td>
<td>96.2</td>
</tr>
<tr>
<td>0.8</td>
<td>0.0</td>
<td>60</td>
<td>0</td>
<td>-</td>
<td>96.2</td>
</tr>
<tr>
<td>1.0</td>
<td>0.0</td>
<td>100</td>
<td>13</td>
<td>0.8</td>
<td>96.0</td>
</tr>
</tbody>
</table>
Table 4: Setpoint change of power from 100 to 95%

<table>
<thead>
<tr>
<th>b [%]</th>
<th>Settling time [s]</th>
<th>Power undershoot [%]</th>
<th>Main steam temperature undershoot [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>50</td>
<td>4</td>
<td>3.6</td>
</tr>
<tr>
<td>20</td>
<td>55</td>
<td>1</td>
<td>2.3</td>
</tr>
<tr>
<td>25</td>
<td>60</td>
<td>0</td>
<td>2.0</td>
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<tr>
<td>30</td>
<td>70</td>
<td>0</td>
<td>1.7</td>
</tr>
<tr>
<td>40</td>
<td>90</td>
<td>0</td>
<td>1.3</td>
</tr>
</tbody>
</table>

VI. Reactor Behaviors with control system

The reactor behavior is analyzed at various perturbations with the designed and optimized control system.

1. Setpoint change of pressure

The setpoint of the turbine inlet pressure increases stepwise from 24.5 to 24.75 MPa. The result is shown in Fig. 15. The turbine control valves are rapidly closed to increase the pressure. At the beginning, the feedwater flow rate decreases because of the increase in the core pressure. Thus, the main steam temperature increases. Successively, the control system increases the feedwater flow rate to keep the main steam temperature 500°C. The power is kept almost constant by the control rods. After 30 s, the plant is settled at a new steady state. There is no overshoot of the pressure. The variation of the main steam temperature is only 3°C.

![Fig. 15: Setpoint change of turbine inlet pressure (+0.25 MPa) with designed control system](image)

2. Setpoint change of main steam temperature

The setpoint of the main steam temperature increases stepwise from 500 to 504°C. The result is shown in Fig. 16. The feedwater flow rate is decreased to increase the main steam temperature. The power is decreased only 2% by the coolant density feedback because it is not sensitive to the flow rate (as explained in Section IV). The control rods are withdrawn to keep the power 100%. The pressure is kept almost constant by the turbine control valves. After 60 s, the plant is settled. The overshoot of the main steam temperature is only 1°C.

![Fig. 16: Setpoint change of main steam temperature (+4°C) with designed control system](image)

3. Setpoint change of power

The power setpoint decreases stepwise from 100 to 90%. The result is shown in Fig. 17. The control rods are inserted to decrease the core power. The main steam temperature decreases with the power. The feedwater flow rate is decreased to 90% so as to keep the main steam temperature 500°C. The turbine inlet pressure is kept constant by the turbine control valves. The pressure loss in the main steam lines decreases because of the decrease in the main steam flow rate. As a result, the core pressure decreases. After 60 s, the plant is settled at a new steady state. There is no undershoot of the power. The variation of the main steam temperature is 4.5°C.

![Fig. 17: Setpoint change of power (-10%) with designed control system](image)

4. Impulsive decrease in feedwater flow rate

The feedwater flow rate drops stepwise from 100 to 95%. The result is shown in Fig. 18. The main steam temperature increases. The pressure and the power decrease. The feedwater flow rate returns to 100% to keep the main steam
temperature 500°C. The pressure and the power are recovered by the turbine control valves and the control rods, respectively. After 30 s, the plant is settled. The variations of the power and the main steam temperature are 5 % and 7°C, respectively. The plant control system keeps the SCLWR-H stable against the perturbation of the feedwater flow rate, although the SCLWR-H has no recirculation system.

5. Decrease in feedwater temperature

The feedwater temperature decreases stepwise from 280 to 270°C. The result is shown in Fig. 19. Since the flow velocity of the feedwater decreases, the core flow rate decreases and then the main steam temperature increases. It is one of the characteristics of the SCR without recirculation. The core power is decreased a little by the density feedback. The feedwater flow rate is increased temporarily to keep the main steam temperature 500°C. After the main feedwater lines, the top dome, the downcomer and the bottom dome are filled with the 270°C water, the core flow rate is recovered. The core power begins to increase and the main steam temperature begins to decrease. Then the feedwater flow rate is decreased to keep the main steam temperature and the control rods are inserted to keep the power. The pressure is almost constant. After 110 s, the plant is settled. The highest values of the power and the main steam temperature are 103 % and 503°C, respectively.

VII. Discussion

1. System behavior

The step response of a low temperature fast reactor (SCFR) to decrease in the feedwater flow rate (100 → 95 %) is shown in Fig. 20. The power variation of the SCLWR-H (shown in Fig. 11) is almost the same as that of the SCFR, although its coolant density coefficient is more than 6 times larger than that of the SCFR. From the viewpoint of plant dynamic behavior, the characteristic of the SCLWR-H is similar to that of fast reactors although it is a thermal reactor. Thus, the core power is not controlled by the feedwater flow rate but by the control rods as in the SCFR.

Compared with the flow rate, the perturbation of the feedwater temperature takes longer time to be stabilized because it directly influences the moderator density in the descending flow water rods. When the feedwater temperature decreases 10°C, the highest power is 103 % while it is only 101 % in the case of the SCFR as shown in Fig. 21.

The feedwater pumps and the control rods have longer time constants than that of the turbine control valves. Thus, the main steam temperature and the power are settled more slowly than the pressure.
2. Effect of coolant density coefficient

The coolant density coefficient strongly depends on the core design, while the Doppler coefficient is almost constant. If it is too large, the SCLWR-H is unstable and the controllability is worse because the power is more sensitive to the flow rate. On the other hand, if it is too small, the controllability is also worse because the density feedback is smaller and then the main steam temperature is more sensitive to the flow rate. For example, the system behaviors at “impulsive decrease in feedwater flow rate” (explained in Section VI. 4) are shown in Table 5 with various coolant density coefficients.

Table 5: Effect of coolant density coefficient at “Impulsive decrease in feedwater flow rate”

<table>
<thead>
<tr>
<th>Coolant density coefficient [dk/k/(g/cm³)]</th>
<th>0.04</th>
<th>0.1</th>
<th>0.2</th>
<th>0.4</th>
<th>0.6</th>
<th>1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power variation [%]</td>
<td>2</td>
<td>3</td>
<td>6</td>
<td>11</td>
<td>18</td>
<td>31</td>
</tr>
<tr>
<td>Main steam temperature variation [°C]</td>
<td>11</td>
<td>10</td>
<td>8</td>
<td>7</td>
<td>6</td>
<td>-</td>
</tr>
<tr>
<td>Settling time [s]</td>
<td>60</td>
<td>40</td>
<td>30</td>
<td>60</td>
<td>90</td>
<td>Not settled</td>
</tr>
</tbody>
</table>

3. Power control by feedwater flow rate

The feasibility of another control system is studied, in which the main steam temperature and the core power are controlled by the control rods and the feedwater pumps, respectively. It can also control the SCLWR-H, but is not as good as that designed in Section V. For example, the plant behavior at “impulsive decrease in the feedwater flow rate” with this control system is shown in Fig. 22. Compared with Fig. 18, the variation of the main steam temperature is larger.

![Fig. 22: Impulsive decrease in feedwater flow rate (- 5 %)](image)

(Power is controlled by feedwater flow rate.)

VIII. CONCLUSION

Although the SCLWR-H is a thermal neutron reactor, the existence of the many water rods makes the core power not sensitive to the feedwater flow rate. This characteristic is similar to that of a fast reactor. Thus, power control by the control rods is better than that by the feedwater flow rate. In the designed control system, the turbine inlet pressure is controlled by the turbine control valves, the main steam temperature is by the feedwater flow rate, and the core power is by the control rods. This control system keeps the SCLWR-H stable against the perturbations of the setpoint of the control system, the feedwater flow rate, and the feedwater temperature. The settling time is governed by both the control systems of the main steam temperature and the power, which have longer time constants than that of the pressure control system. In the future detailed design, a coordinated control system will be considered like LWRs and FPP.

References


