International Journal on Advanced Science Engineering Information Technology

Vol.8 (2018) No. 5
ISSN: 2088-5334

# Control System of a Super-Fast Reactor with Single Flow Pass Core

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***Abstract*—The one-pass supercritical pressure light water fast reactor has different core structure from that of the two-pass cooling type one. The distance between inlet and outlet channels of the one-pass supercritical pressure light water fast reactor is shorter with less core water inventory due to the removal of the gap channels. Its responses to a perturbation are similar to those of the two-pass core. However, change of the outlet temperature regarding to a perturbation of power to flow ratio in the one-pass cooling type fast reactor is larger. It is important to suppress the change as small as possible to keep the integrity of the reactor structure. Early designs of power and pressure control systems of a supercritical pressure light water fast reactor are applicable to control the power and pressure parameters, but it is not for the early outlet temperature control system that considered only the outlet temperature deviation as the feedback. An improved outlet temperature control system that considers both the signals of outlet temperature and power deviations as the control feedbacks can be applied in the one-pass cooling-type fast reactor with adjustment on the control's parameters. Optimized control's parameters can suppress the change of the outlet temperature significantly without oscillation. By using the control system, responses of the one-pass supercritical pressure light water fast reactor to the designated perturbations satisfy the criteria.**

***Keywords*— fast reactor; one-pass; control; temperature change; criteria.**

## I. Introduction

Research and development (R&D) of the Generation-IV nuclear reactors have been carried out worldwide under the coordination of the Generation-IV International Forum (GIF). Supercritical Pressure Light Water Reactor (SCWR) is selected as one of the new reactor concepts considering its significant improvements in the thermal efficiency (44%) and economics. It uses light water as the coolant, but the capital cost can be reduced by 20-30% lower than those of the current light water reactors (LWRs) [1], [2]. In Japan, the new type of light water reactor has been studied at The UT (University of Tokyo) and Waseda University since 1989 [1], [3]. It consists of thermal and fast reactors developments. The version of the fast reactor is expected to be more economical due to its higher density of power with the possibility of fuel breeding.

Early concepts of supercritical pressure light water (SCW) fast reactor were proposed based on technologies of LWRs and SCW fossil-fueled power plants [4]–[7]. Improvements to the core design were carried out to achieve better thermal characteristics and safety features [8]–[11]. Safety and plant dynamics analyses, as well as control system design, was carried out for the SCW fast reactor to confirm the safety and thermal characteristics [12]–[16]. Startup thermal analyses of the SCW fast reactor were also carried out to confirm its thermal characteristics during startup [17].

In the recent improvement of the SCW fast reactor core design, single flow (one-) pass core applied for core structure simplification and for addressing the remaining issues of flow stability, the technique of control rod insertion, refueling and shuffling of fuel [18]. It is the latest design that adopts a one-pass core cooling-type different from the previous SCW fast reactor core designs which adopted two-pass core cooling-type. Comparison of the SCW fast reactor structures is shown in Fig. 1 [8]–[10], [18]. TABLE I shows the detail information of the fast reactor core designs [10], [18]. Use of the one-pass core leads to a shorter mileage of the core coolant flow by half times, while the inlet-outlet coolant temperatures are the same. Axial gradients of change of the coolant temperature and density are sharper, and the outlet coolant temperature might be sensitive to a perturbation of power to flow ratio. Furthermore, the space of gap channels connecting the first and the second pass of the two-pass core is removed in the one-pass core. The gap channels provide more water inventory in the two-pass core, which enhances the accident mitigation of total failure of all reactor coolant pumps by passive flow generation due to coolant heat up [14]. These differences might influence the plant dynamics of the one-pass core SCW fast reactor.

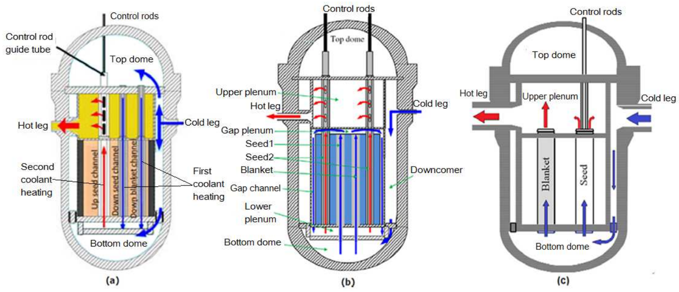



Fig. 1 Core designs of SCW fast reactors (a) up and down flow direction 2-pass core, (b) all up flow direction 2-pass core, (c) one-pass core

TABLE I
COMPARISON OF SCW FAST REACTOR CORE DESIGNS

| **Core characteristics** | **Super FR with two-pass core** | **Super FR with single flow pass core** |
|---|---|---|
| Electric Power | 1000 MW | 1000 MW |
| Operating pressure | 25 Mpa | 25 Mpa |
| Inlet-outlet temperature | 280-500 °C | 280-500 °C |
| Length of active core | 3.6 m | 2.4 m |
| Diameter of core | 1.86 m | 2.45 m |
| Flow rate | 1199.7 kg/s | 1204.7 kg/s |
| Core structure | Two-pass | One-pass |

Safety characteristics of the one-pass core cooling-type SCW fast reactor were analyzed to confirm its safety performance regarding the use of the one-pass cooling [19]-[22]. The plant dynamics, however, was not clarified yet. It is important to keep the integrity of reactor structures which include the upper tie plates, reactor outlet structures, pipes of outlet coolant, steam to the mechanical converter (turbines) and so on by keeping small enough any variation of the outlet coolant temperature. The variation could be occurred due to either a change of power demand or an undesired perturbation. Regarding the variation, the operation parameters must be well controlled. This paper discusses the plant dynamics of the one-pass core cooling-type SCW fast reactor. Type of PID-like controllers is applied as it was successfully applied in nuclear reactors [15], [16], [23], [24]. Applicability of the controller type in controlling operating parameters of power, steam temperature, and pressure of the SCW fast reactor regarding the adoption of the one-pass core cooling-type is discussed. It is expected to confirm the controllability of the new design of the Super FR. Stability of the control systems is observed roughly. It will be discussed in detail in a separated paper. In this paper, terms of one-pass core cooling-type and single flow pass core have the same meaning. Regarding the similar material between the Super FR and the SCW fossil-fired power plant, criteria of the permissible range (±8 °C) and achievement (±2 °C) of the steam temperature variation in recent SCW fossil-fired power plant are applied [16].

## II. MATERIAL AND METHOD

Code of Supercritical Pressure Reactor Accident and Transient Analysis (SPRAT) is used in this study. It was developed and validated at the UT [12], [15], [16]. The code calculations are based on the relation among the governing equations of point kinetics, conservations of mass and energy, and fuel rod heat transfer. Eqs. (1,2) show the equations of mass-energy conservations which ρ is density (kg/m$^3$), $G$ is mass flow (kg/s), $t$ is time (s), $z$ is position (m), $h$ is enthalpy (J/kg), $l_f$ is mesh height (m), $A_f$ is area of surface of fuel pin (m$^2$), and $Q''$ is heat flux (W/m$^2$).

Mass conservation law:

$$\frac{\partial \rho(z,t)}{\partial t} + \frac{\partial G(z,t)}{\partial z} = 0 \qquad (1)$$

Energy conservation law:

$$\frac{\partial\{\rho(z,t)h(z,t)\}}{\partial t} + \frac{\partial\{G(z,t)h(z,t)\}}{\partial z}$$
$$= \begin{cases} \frac{1}{A_f} l_f Q''^{k}_{n}(z,t) & \text{.......(flow channel with fuel rods)} \\ 0 & \text{........(flow channel without fuel rods)} \end{cases} \qquad (2)$$

The code adopts one-dimensional model which radial average power is taken as the representative of power of all fuel rods. The hottest fuel rod is taken as the hottest channel where the highest linear heat rate is generated and highest cladding temperature might take place.

In this study, the existing code is modified based on the one-pass core cooling-type SCW fast reactor. The plant dynamics calculation model of the reactor is shown in Fig. 2. Thermal-hydraulic calculations are conducted in each reactor part, which is divided numerically into meshes. The feed water line is divided into 10 meshes, lower plenum is 20 meshes, fuel channel is 36 meshes, gas plenum is 18 meshes, and upper plenum is the same mesh number as steam line, 10 meshes. Reactor coolant starts flowing from the feed water line to the next part as the direction of arrows in the figure. Calculations of the coolant water properties (flow rate, density, enthalpy, and temperature) are carried out in each mesh in each time step based on the governing equations. Calculation results of each mesh will influence the calculation of the previous and the next meshes.

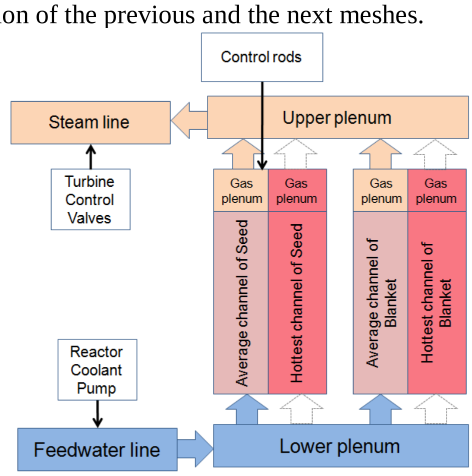



Fig. 2 Nodalization for plant dynamics calculation of the one-pass cooling SCW fast reactor

### III. RESULTS AND DISCUSSION

#### *A. Plant Dynamics of One-pass Cooling SCW Fast Reactor*

Plant dynamics characteristics of the one-pass core cooling-type SCW fast reactor without control system are analyzed by giving the same perturbations as in previous study [16]. Fig. 3 shows the response of the one-pass cooling-type reactor to a perturbation of 5% stepwise decrease of feed water coolant flow rate, with keeping constant the positions of control rods and the aperture of turbine control valve. The perturbation leads to a significant increase on the steam temperature to 103% (520 $^{o}$C). Meanwhile, the power reduction is because of feedbacks of negative Doppler and density reactivity. The pressure is reduced because of smaller inlet coolant flow without a change of turbine control valves aperture at the outlet line. These responses are similar to those of the two-pass core which the steam temperature is the most sensitive to the perturbation. In this reactor, the reactor coolant pump is also used as the actuator of the steam temperature control system the same as in the two pass core [16].

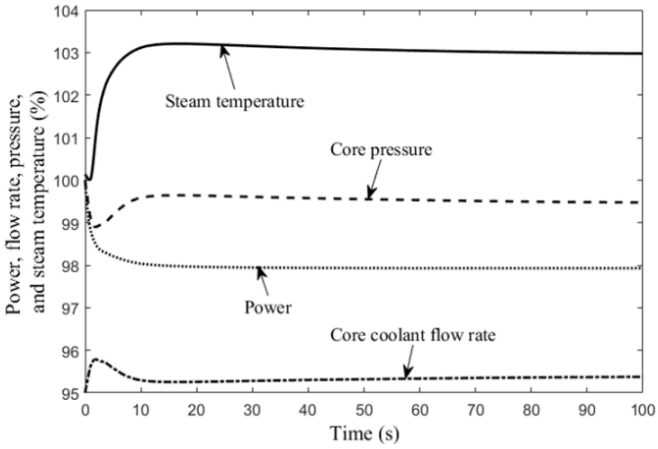



Fig. 3 The response of the one-pass cooling SCW fast reactor to a stepwise decrease of the feed water flow rate by 5%

Step response of the one-pass cooling SCW fast reactor to a 5% reduction of the turbine control valve aperture is shown in Fig. 4 with keeping constant the height of control rod and feed water pumps operation. The core pressure increases rapidly to more than 26 MPa (104%) due to the diminution of the outlet channel. It decreases the core coolant discharge through the outlet pipe leading to heat accumulation in the coolant and an increase of the steam temperature. The steam temperature increases up to about 520 $^{o}$C (103%). Reactivity feedbacks of Doppler and coolant density decrease the power. It is similar to the two pass core characteristics that the core pressure is the most sensitive to the change in turbine control valves position. Therefore, the turbine control valves are used as the actuator of the pressure control system in this reactor.

Fig. 5 shows the plant responses to perturbation of a 0.1$ stepwise reactivity insertion by withdrawing the control rods. The feed water flow rate and the turbine control valve aperture are kept constant. The reactor power is raised suddenly by almost 10% due to the prompt jump of neutron population, but then it decreases gradually because of the Doppler and density reactivity feedbacks. The coolant density coefficient of a fast reactor is small, and the Doppler reactivity is more dominant than the density reactivity, similar to that of the two-pass cooling-type SCW fast reactor [16]. The power achieves steady state condition within about 30 s with a value of power less than 102%. The pressure rises because of heat accumulation in the coolant leading to a decrease of core water flow. The high ratio of power to water flow causes a significant increase in the steam temperature achieving more than 539 $^{o}$C (106%). The control rod is used as the actuator of the power control system in this reactor.

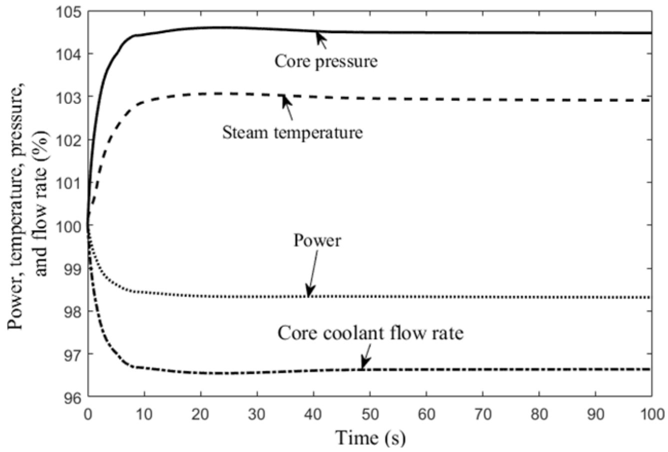



Fig. 4 Step response of the one-pass SCW fast reactor to a reduction of turbine control valve aperture by 5%

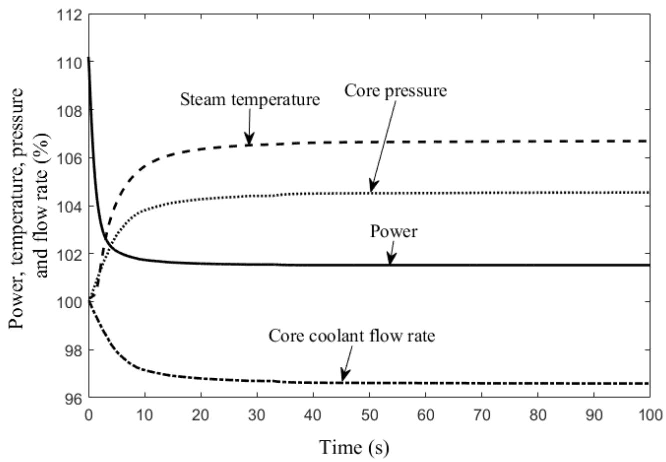



Fig. 5 Step response of the one-pass SCW fast reactor to insertion of 0.1$ reactivity

In the previous study of the control system of an SCW fast reactor, change of the outlet temperature is the main issue to be addressed. Comparison of the steam temperature responses to perturbations between the two-pass and one-pass cooling-types SCW fast reactors are shown in Fig. 6. It is shown that response of the outlet temperature in the one-pass core tends to be larger than that of the two-pass core for the same perturbation. It might be due to less water inventory regarding the removal of gap channels. Structure of single pass with a shorter distance between inlet and outlet channels leads to a direct effect of a power to flow perturbation overall core coolant temperature.

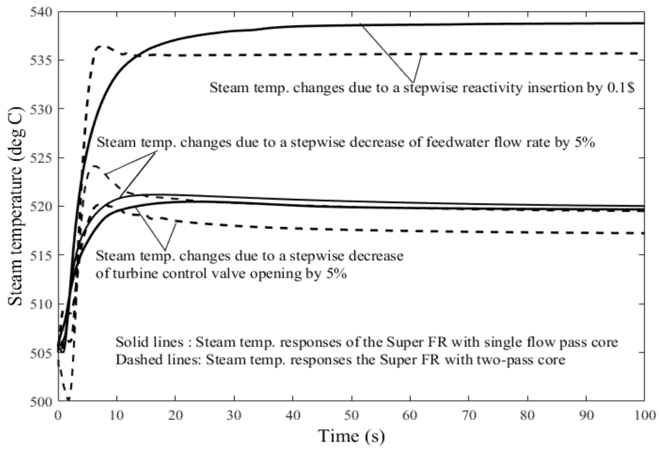



Fig. 6 Comparison of steam temperature responses between two-pass and one-pass cooling-types SCW fast reactors to perturbations without control systems

### *B. Control System of The One-pass Cooling SCW Fast Reactor*

Regarding the similar plant dynamics of the one-pass core to that of the two pass core, the same control systems as those of the two-pass cooling SCW fast reactor are applied with adjustment on the control's parameters.

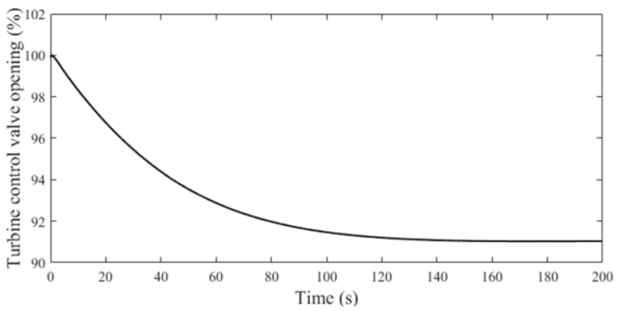
#### *1) Pressure Control System*

The pressure control system refers to that of a BWR the same as in the two-pass cooling SCW fast reactor as shown in Eqs. (1-2) where *V*(t) is the opening of the turbine control valve with the control's parameter of *K* [16].

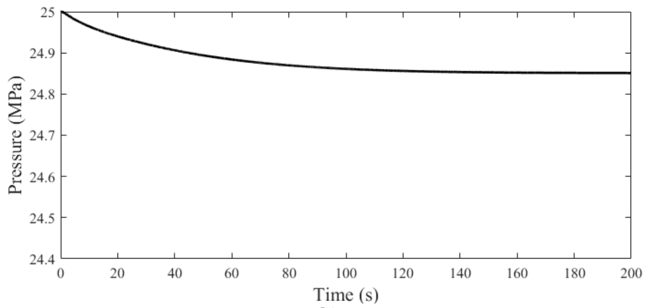
$$V_r(t) = 1 - \frac{P_{set} - P(t)}{K} \quad (1)$$

$$V(t) = V_r(t) + 2\frac{dV_r}{dt} - 5\frac{dV}{dt} \quad (2)$$

The signal of pressure deviation is used for adjusting the valves opening. The allowable highest speed of the valve rotation is limited to 100%/3.5 s the same as those of BWRs and two-pass SCW fast reactor [16]. The gain *K* is set as 39.6 MPa to suppress the overshoot against a perturbation the same as in the previous study. Step response of the pressure control system to a 10% reduction in power-desired value shows that the pressure is well controlled as shown in Fig. 7. The pressure is just slightly decreased due to the adjustment of the valves opening. The margin of the control system stability will be discussed in a separated paper.




(a)




(b)

Fig. 7 Performance of the pressure control system regarding a 10% stepwise decrease of power set point: (a) Change of turbine control valve opening, (b) Response of the pressure

#### *2) Power Control System*

Power control system in this study takes the same power control system as in the two-pass cooling-type SCW fast reactor as expressed in Eq. (3).

$$v = \begin{cases} v_{\max} \dfrac{q_{set} - q}{q_{set}} \dfrac{1}{b} & \left( \dfrac{q_{set} - q}{q_{set}} < b \right) \\ v_{\max} & \left( \dfrac{q_{set} - q}{q_{set}} \geq b \right) \end{cases} \quad (3)$$

Power is kept following the desired value by adjusting the position of control rods. The signal of power deviation will drive the movement of the control rods with the allowable highest speed of 1.9 cm/s referring to that of PWR. How fast the power control system brings back the power to its set point depends on the control's parameter of by which is set to 0.7 the same as that in two-pass SCW fast reactor. Performance of the power control system to a 10% stepwise reduction of the power set point is shown in Fig. 8. It shows that the actual power follows the power set point well and stably by using the control system.

#### *3) Outlet Temperature Control System*

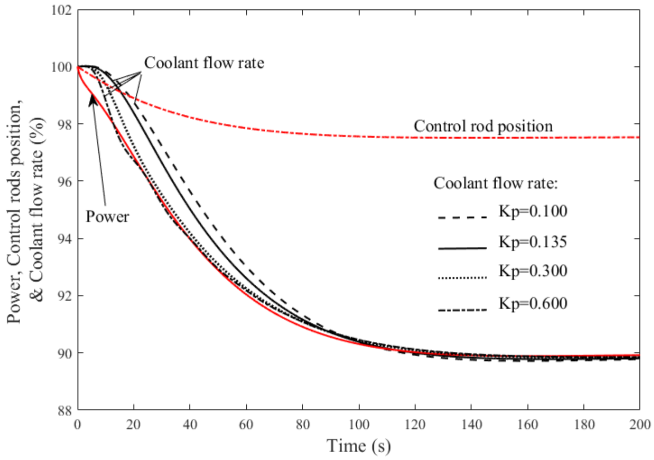
Early outlet temperature control system was designed by considering only one signal of steam temperature deviation, as the feedback as shown in Eq. (4) which *u* is control signal, and $K_P$ is control's parameter [15].

$$\frac{du}{dt} = K_P \frac{T - T_{set}}{T_{set}} \quad (4)$$

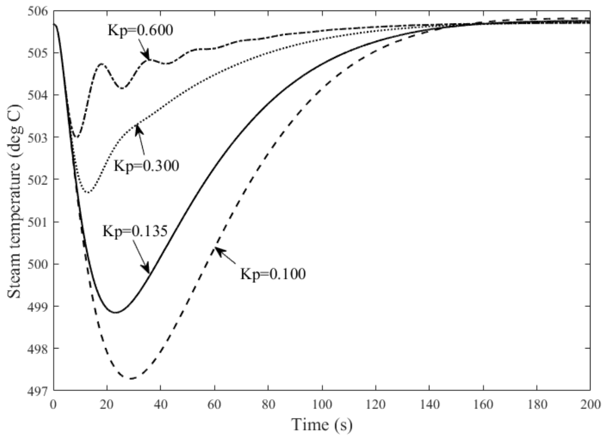
Large variation of outlet temperature was introduced in the two-pass SCW fast reactor by using the control system because of the slow response of the feed water flow in following the change of power [16]. It also occurs in one-pass SCW fast reactor, which is shown in Fig. 8. The variation of steam temperature is larger, and tuning of the control's parameter results in an oscillation of the coolant flow rate at a high value of the $K_P$ as shown in Fig. 8(a), leading to an oscillation of the steam temperature as shown in Fig. 8(b).

Improvement of the steam temperature control system was carried out by considering the signal of power deviation as the feedback of the control system as shown in Eq. (5) [16].

$$\frac{du}{dt} = K_P \frac{T - T_{set}}{T_{set}} + X_P \frac{q_{set} - q}{q_{set}} \quad (5)$$




(a)

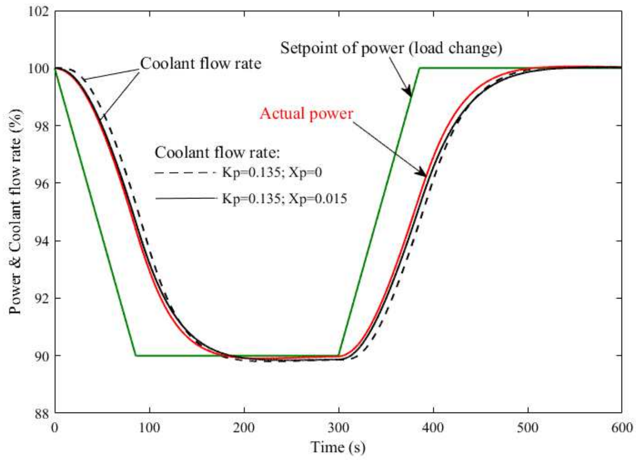



(b)

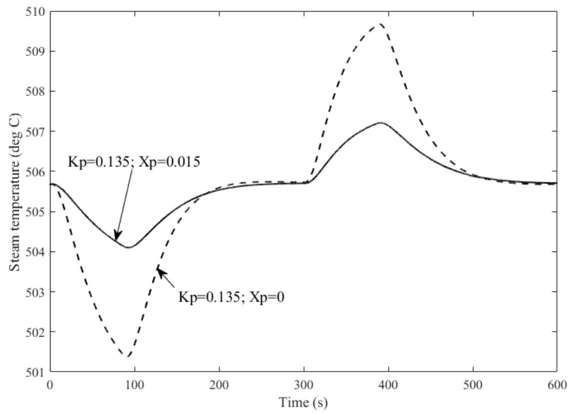
Fig. 8 Step response of the one-pass SCW fast reactor to a 10% reduction of the power desired value: (a) Change of power and coolant flow; (b) Change of the steam temperature

It is applied in the one-pass SCW fast reactor and Fig. 8 shows the simulation results of the control's performance. Even though the change of outlet temperature regarding a perturbation is larger in the one-pass SCW fast reactor, the improved steam control system is still applicable with the tuning of the control's parameters of $K_P$ and $X_P$. The coolant flow rate could follow the change of power well without oscillation as shown in Fig. 8(a). The optimized value of the control's parameters could be found to result in a small variation of the steam temperature as shown in Fig. 8(b). A systematic method might be applied to get the exact value of the optimized parameters.

A typical load change as in recent fossil-fueled power plant (7%/min with a range of 90-100% load), and a 4 $^{o}$C stepwise increase of the outlet temperature desired value are applied in the one-pass SCW fast reactor to examine the performance of the control system. The response of the fast reactor to the typical load change is shown in Fig. 9. The power as well as the water flow rate could follow the demand of the load without oscillation as shown in Fig. 9(a). However, consideration of the power deviation as the feedback of the steam control system shows better performance. The variation of the steam temperature is much smaller as shown in Fig. 9(b). The temperature variation satisfies the criteria.



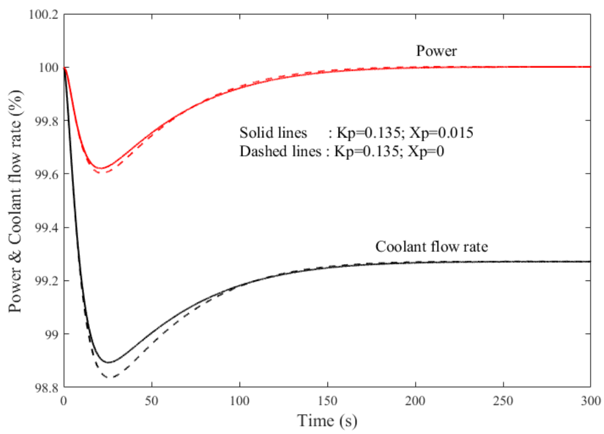

(a)



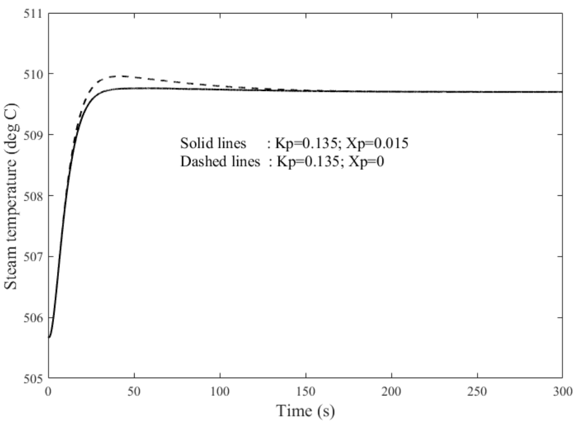

(b)

Fig. 9 Response of the one-pass SCW fast reactor to a typical load change: (a) Change of the power and coolant flow; (b) Response of the steam temperature

The response of the one-pass SCW fast reactor to a change of a 4 $^{o}$C stepwise increase of the outlet temperature desired value is shown in Fig. 10. Change of the outlet temperature desired value needs a change of power to flow ratio. Fig. 10(a) shows that higher power to flow ratio is resulted to achieve the higher steam temperature set point without any significant overshoot of the temperature change as shown in Fig. 10(b). Consideration of the signal of power deviation in the steam control system results in a better performance of controlling the temperature.




(a)




(b)

Fig. 10 The response of the one-pass SCW fast reactor to a 4 °C stepwise increment in outlet temperature desired value: (a) Change of power and coolant flow rate; (b) Change of steam temperature

## IV. CONCLUSION

Control systems of the one-pass core cooling-type SCW fast reactor (also known as Super-Fast Reactor) are clarified. The core structure of the single flow pass core does not influence significantly on the performance of the existing pressure and power control systems. However, a variation of the outlet temperature regarding designated perturbations is more considerable. Use of the early outlet temperature control system, which considered only the outlet temperature deviation as the feedback, does not satisfy the criteria. An improved steam temperature control system as used in the two-pass SCW fast reactor is applicable in the one-pass SCW fast reactor due to consideration of both the steam temperature and power deviation signals as the feedbacks. However, adjustment of the control's parameters is needed. Consideration of both the steam temperature and power deviation signals as the feedback with optimized control's parameters could suppress the temperature varied significantly without oscillation.

## ACKNOWLEDGMENT

The authors would like to deliver a great thank to Prof. Yoshiaki Oka for permission to use the SPRAT code for the study. His invaluable expertise was beneficial for the first author during the first author's study at Waseda University. It has initiated the current study and the future study.

## REFERENCES

[1] Y. Oka, S. Koshizuka, Y. Ishiwatari, A. Yamaji, Super Light Water Reactors and Super Fast Reactors, Springer New York Dordrecht Heidelberg London, 2010.

[2] T. Schulenberg, L. K.H. Leung, Y. Oka,"Review of R&D for Supercritical Water Cooled Reactors", J. of Progress in Nuclear Energy, Vol. 77, 2014, p. 282-299.

[3] Y. Oka, H. Mori, Supercritical Pressure Light Water Cooled Reactors, Springer Tokyo Heidelberg New york Dordrecht London, 2014.

[4] T. Jevremovic, Y. Oka, S. Koshizuka, "Conceptual Design of an Indirect-cycle, Supercritical Steam Cooled Fast Breeder Reactor with Negative Coolant Void Reactivity Characteristics", J. Ann. Nucl. Energy, Vol. 20, 1993, p. 305-313.

[5] T Jevremovic, Y. Oka, S. Koshizuka, "Core Design of a Direct-cycle Supercritical-Water-Cooled Fast Breeder Reactor, J. Nucl. Technol, Vol. 108, 1994, p. 24-32.

[6] T. Mukohara, S. Koshizuka, Y. Oka, "Core Design of a High-Temperature Fast Reactor Cooled by Supercritical Light Water", J. Ann. Nucl. Energy, Vol. 26, 1999, p. 1423-1436.

[7] Y. Oka, S. Koshizuka, "Design Concept of Once-Through Cycle Supercritical-Pressure Light Water Cooled Reactors", SCR-2000, Nov. 6-8, 2000, Tokyo.

[8] L. Cao, Y. Oka, Y. Ishiwatari, Z. Shang, "Core Design and Subchannel Analysis of a Superfast Reactor", J. Nucl. Sci. Technol, Vol. 45, 2008, p. 138-148.

[9] J. Yoo, Y. Ishiwatari, Y. Oka, J. Liu, " Conceptual Design of Compact Supercritical Water-Cooled Fast Reactor with Thermal Hydraulic Coupling", J. Ann. Nucl. Energy, Vol. 33, 2006, p. 945-956.

[10] Q. Liu, Y. Oka, "Core Design for Super Fast Reactor with All Upward Flow Core Cooling", J. Ann. Nucl. Energy, Vol. 57, 2013, p. 221-229.

[11] Q. Liu, Y. Oka, "Improvements ofTwo-pAss Core Design for Super Fast Reactor," J. Ann. Nucl. Energy, Vol. 69, 2014, p. 108-115.

[12] S. Ikejiri, Y. Ishiwatari, Y. Oka, "Safety Analysis of a Supercritical-Pressure Water-Cooled Fast Reactor under Supercritical Pressure", J. Nucl. Eng. Design, Vol 240, 2010, p. 1218-1228.

[13] T. Kamata, Y. Oka, "Total Loss of Flow Accident Characteristics of Super FR with New Coolant Flow", J. Nucl. Eng. Design, Vol. 257, 2013, p. 155-160.

[14] H. Li, Y. Oka, Y. Ishiwatari, "Safety Analysis of a Supercritical Water Cooled Fast Reactor with All-Upward Two-Pass Flow", J. Ann. Nucl. Energy,Vol. 59, 2013, p. 1-9.

[15] T. Nakatsuka, Y. Oka, S. Koshizuka, "Control of a Fast Reactor Cooled by Supercritical Light Water", J. Nucl. Technol., Vol. 121, 1998, p. 81-92.

[16] Y. Ishiwatari, C. Peng, S. Ikejiri, Y. Oka, "Improvement of Feedwater Controller for The Super Fast Reactor", J. Nucl. Sci. Technol., Vol. 47, No. 12, 2010, p. 1155-1164.

[17] Sutanto, Y. Oka, "Time Dependent Start-up Thermal Analylis of a Super Fast Reactor", J. Nucl. Eng. Design, Vol. 263, 2013, p. 129-137.

[18] Q. Liu, Y. Oka, "Single Pass Core Design for a Super Fast Reactor", J. Ann. Nucl. Energy, Vol. 80, 2015, p. 451-459.

[19] Sutanto, Y. Oka, "Safety Analysis of a Super Fast Reactor with Single Flow Pass Core", Trans. of The American Nuclear Society, Vol. 109, Washington DC., November 10-14, 2013, p. 1092-1094.

[20] Sutanto, Y. Oka,"Accident and Transient Analysis of a Super Fast Reactor with Single Flow Pass Core", J. Nucl. Eng. Design, Vol. 273, 2014, p. 165-174.

[21] Sutanto, Y. Oka, "Analysis of Anticipated Transient Without Scram of a Super Fast Reactor with Single Flow Pass Core", J. Ann. Nucl. Energy, Vol. 75, 2015, p. 54-63.

[22] Sutanto, Y. Oka, "Passive Safety System of a Super Fast Reactor", J. Nucl. Eng. Design, Vol. 289, 2015, p. 117-125.

[23] M. Zarei, "A Multi-point Kinetics Based MIMO-PI Control of Power in PWR Reactors", J. Nucl. Eng. Design, Vol. 328, 2018, p. 283-291

[24] S.M.H. Mousakazemi, N. Ayoobian, G. R. Ansarifar, "Control of The Reactor Core Power in PWR Using Optimized PID Controller with The Real-Coded GA", Annals of Nucl. Energy, Vol. 118, 2018, p. 107-121.