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Performance Analysis of Shutdown Cooling System using Steam Generator in an Integral Reactor

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1. Introduction

After the operation of a nuclear reactor is stopped, the reactor coolant should be cooled to remove the residual heat of a reactor core and the sensible heat of a coolant and structure continuously. Generally, the reactor coolant with high temperature after the stop of a reactor operation is firstly cooled by the secondary system or auxiliary feed water system (or passive residual heat removal system), and then is cooled to the refueling temperature by the shutdown cooling system (SCS) [1]. During the refueling process, the reactor coolant remains at the refueling temperature by the shutdown cooling operation. In a conventional SCS, the cooling of the reactor coolant is achieved by using the shutdown cooling heat exchanger (SCHX). The reactor coolant circulates through the primary side of the SCHX by the shutdown cooling pump (SCP), while the component cooling water (CCW) circulates through the secondary side of the SCHX by the CCW pump.

In a commercial power reactor, the major components, i.e. the reactor core, steam generator (SG), pressurizer, and reactor coolant pump, are separately installed. On the contrary, the reactor vessel of an integral reactor contains all the major components together. Especially, the SGs of the integral reactor are placed near the reactor core, and are immersed in the reactor coolant below the water level of the reactor vessel. Hence, the SG can be utilized for the shutdown cooling of the integral reactor, where the cold CCW is injected to the secondary side of the SG to cool down the reactor coolant [2]. When the SCS using the SG is adopted, the SCHX and SCP of the conventional SCS can be eliminated, and it enables the shutdown cooling operation during the refueling operation. Such design of the SCS in the integral reactor has advantages in the aspect of simplification of the design and operation. In the present study, the cooling performance of the SCS using the SG is analyzed, and the result is compared with that of the conventional SCS.

2. Methods and Results

2.1 Analysis method

2.1.1 Conventional SCS

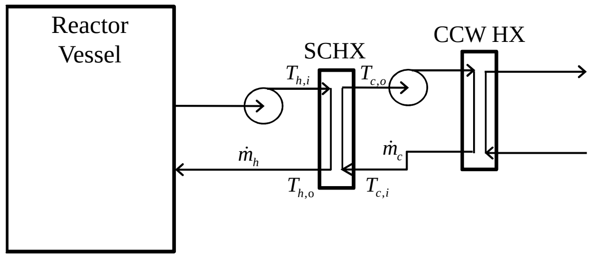

Fig. 1. Schematic diagram of the conventional SCS.

The shutdown cooling operation is started when the temperature and the pressure of the reactor coolant system (RCS) are 176.7 ^{o}C (shutdown cooling temperature) and 2.8 MPa. The RCS temperature and pressure are reduced to 50 ^{o}C (refueling temperature) and 0.1 MPa by the shutdown cooling operation, which is maintained during the shutdown cooling operation.

The schematic diagram of the conventional SCS is shown in Fig. 1. During the shutdown cooling operation, the residual heat of the reactor core and the sensible heat are removed by the SCHX. The reactor coolant flows out from the reactor vessel by the SCP, and is directly injected to the primary side of the SCHX. For cooling of the reactor coolant, the CCW is injected to the secondary side of the SCHX by the CCW pump. The mass of the reactor coolant in the reactor vessel is not changed during the shutdown cooling operation. Hence, the reactor vessel is defined as the control volume, and only the energy balance in the control volume is considered to obtain the temperature of the reactor coolant, which is expressed as

$$m_{rcs}c_{p,rcs}\frac{dT_{rcs}}{dt} = 1.2\dot{Q}_{decay} + \dot{Q}_s - \dot{Q}_{SCHX}\,, \qquad (1)$$

where m_{rcs}, $c_{p,rcs}$, and T_{rcs} are the mass, specific heat, and temperature of the reactor coolant, respectively. $\dot{Q}_{decay}$ denotes the core decay heat, and additional heat of 20% is conservatively considered. $\dot{Q}_s$ and $\dot{Q}_{SCHX}$ are the sensible heat of the structure and the heat removal from the SCHX.

The heat removal from the SCHX is calculated by the NTU method, and is expressed by

$$\dot{Q}_{SCHX} = \varepsilon C_{\min}\left(T_{h,i} - T_{c,i}\right), \qquad (2)$$

where $C_{\min}$ is the minimum heat capacity rate. $T_{h,i}$ and $T_{c,i}$ are the inlet temperature on the primary and secondary side. ε is effectiveness, which is defined as

$$\varepsilon = \left[\left(\frac{1-\varepsilon_1 C_r}{1-\varepsilon_1}\right)-1\right]\left[\left(\frac{1-\varepsilon_1 C_r}{1-\varepsilon_1}\right)-C_r\right], \quad (3)$$

$$\varepsilon_1 = 2\left\{1+C_r+\left(1+C_r^2\right)^{1/2}\left(\frac{1+\exp\left[-\mathrm{NTU}\left(1+C_r^2\right)^{1/2}\right]}{1-\exp\left[-\mathrm{NTU}\left(1+C_r^2\right)^{1/2}\right]}\right)\right\}^{-1}, \quad (4)$$

where $C_r = C_{\min}/C_{\max}$, and NTU = $UA_{\mathrm{SCHX}}/C_{\min}$. U and A_{SCHX} denote the overall heat transfer coefficient and the heat transfer area in the SCHX. U is known only at the shutdown cooling temperature and the refueling temperature. It is assumed that U varies linearly according to the temperature of the reactor coolant.

Since the mass flow rates in the primary and secondary side of the SCHX are known, NTU, ε, and the heat removal from the SCHX are sequentially obtained. The temperature of the reactor coolant is calculated using Eq. (1), which is assumed as the inlet temperature on the primary side of the SCHX in the next time step calculation. Using the heat removal from the SCHX, the outlet temperature on the primary and secondary side of the SCHX can be calculated. The outlet temperature on the primary side of the CCW heat exchanger (CCW HX) is calculated by using the heat removal from the CCW HX and the outlet temperature on the secondary side of the SCHX, which is assumed as the inlet temperature on the secondary side of the SCHX in the next time step calculation.

2.1.2 SCS using the SG

The schematic diagram of the SCS using the SG is shown in Fig. 2. In such design, instead of the SCHX, the SGs in the reactor vessel are utilized to remove the residual heat of the reactor core and the sensible heat. The CCW is directly injected to the secondary side of the SG by the CCW pump, and the heat is transferred to the CCW HX. Hence, the SCP is not necessary. In the SCS using the SG, the mass of the reactor coolant in the reactor vessel is not also changed during the shutdown cooling operation. Hence, only the energy balance is considered to obtain the temperature of the reactor coolant in the same control volume with the conventional SCS.

The heat removal from the SG is calculated using LMTD method. To compare the results with those of the conventional SCS, the mass flow rate of the CCW from the CCW HX is set to be same, which becomes the mass flow rate of the secondary side of the SG. The mass flow in the primary side of the SG is occurred by the natural circulation of the reactor coolant, which is induced by the decay core heat and the heat removal

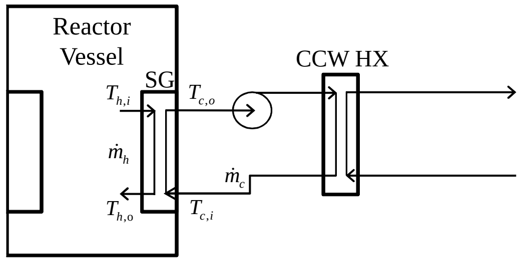

Fig. 2. The schematic diagram of the SCS using the SG.

from the SG. The mass flow in the primary side of the SG is calculated by

$$\dot{m}_h = \sqrt{\frac{2\Delta\rho_{rcs} g H \bar{\rho}_{rcs} A^2}{K}}, \quad (5)$$

where $\Delta\rho_{rcs}$ is the density difference between the hot and cold region in the reactor vessel. H, K, and A are the elevation difference between the reactor core and the SG, loss coefficient, and inlet area of the primary side of the SG, respectively.

The heat removal from the SG is calculated by

$$\dot{Q}_{SG} = \dot{m}_h c_{p,h}\left(T_{h,i}-T_{h,o}\right) = \dot{m}_c c_{p,c}\left(T_{c,o}-T_{c,i}\right) = UA_{SG}\Delta T_{lm}, \quad (6)$$

where A_{SG} and ΔT_{lm} are the heat transfer area of the SG and LMTD. Eq. (6) indicates that the amount of heat transfer on the primary and secondary side of the SG is the same with the amount of heat transfer calculated by using the overall heat transfer coefficient and LMTD. The outlet temperature on the primary and secondary side of the SG is unknown. Hence, two equations are derived from Eq. (6), and they are solved in an iterative manner. To reduce the calculation load, Eq. (5) is calculated by using the values in the previous time step. Once the heat removal from the SG is obtained, the temperature of the reactor coolant is calculated using Eq. (1), where $\dot{Q}_{SCHX}$ is replaced by $\dot{Q}_{SG}$, which is assumed as the inlet temperature on the primary side of the SG in the next time step calculation. The outlet temperature on the primary side of the CCW HX is calculated by using the heat removal from the CCW HX and the outlet temperature on the secondary side of the SG, which is assumed as the inlet temperature on the secondary side of the SG in the next time step calculation.

2.2 Results and discussion

The shutdown cooling operation is started when the RCS is in the condition of 176.7 °C and 2.8 MPa. The RCS can be cooled to such condition within 3.5 hours after the stop of the reactor operation. Hence, the calculation is conducted from 3.5 hours to 100 hours, and time step of 40 seconds is used.

Firstly, the shutdown cooling operation using two trains is considered. Fig. 3 shows the time variation of the temperature of the reactor coolant during the shutdown cooling operation by the conventional SCS and SCS using the SG. Both results show that the temperature of the reactor coolant decreases from $176.7\,^{\circ}C$ to $50\,^{\circ}C$. However, it takes more time in the case of the conventional SCS. The reactor coolant cooled down below $50\,^{\circ}C$ by the SCS using the SG after 21.1 hours from the stop of the reactor operation, while the reactor coolant cooled down below $50\,^{\circ}C$ by the conventional SCS after 90 hours from the stop of the reactor operation. Such results show that the SCS using the SG has advantages in the simplification of the design and the economical aspect.

For safety of the reactor vessel during cooling of the RCS, the cooldown rate has to be limited to below the $40\,^{\circ}C/hr$. Such condition can be satisfied by control of the mass flow rate of the CCW from CCW HX. In the case of the conventional SCS, the whole mass flow rate is injected to the secondary side of the SCHX, except for 0.12 hour from the start of the shutdown cooling operation, where 28% of the whole mass flow rate is injected to the SCHX. On the other hand, in the case of the SCS using the SG, 15% of the whole mass flow rate is injected to the SG during 11.5 hours after the start of the shutdown cooling operation. Then, 25% of the whole mass flow rate is injected. The rest of the CCW bypasses the SG, which appropriately cools down the CCW passing through the SG. Results show that the heat transfer performance of the SG is much better than that of the SCHX.

Fig. 4 shows the result of the shutdown cooling operation using one train for both SCSs. In the conventional SCS, the whole mass flow rate of the CCW is injected to the SCHX. However, in the SCS using the SG, the mass flow rate of the CCW varies from 14% to 25% of the whole mass flow rate. Although only one train is used during the shutdown cooling operation, the SCS using the SG can cool down the reactor coolant near $50\,^{\circ}C$, which also show that the SCS using the SG has better cooling performance.

3. Conclusions

The concept of the SCS using the SG in the integral reactor is proposed. Cooling performance of the proposed SCS is calculated, and is compared with that of the conventional SCS using the SCHX and SCP. The results show that the SCS using the SG makes the SCS simple and has better cooling performance. Hence, the proposed SCS can be considered as a useful option for SCS designs in the integral reactor.

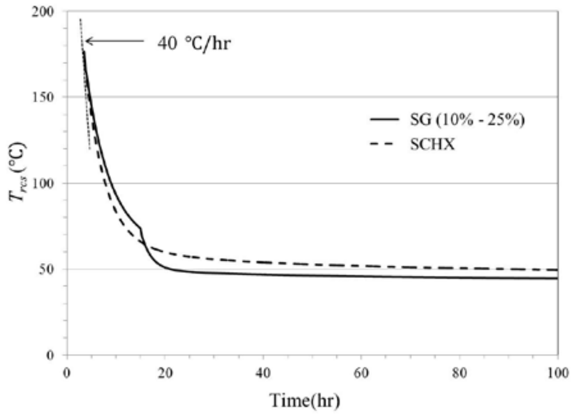

Fig. 3. Variation of the temperature of the reactor coolant during the shutdown cooling operation by the conventional SCS and the SCS using the SG (2 trains).

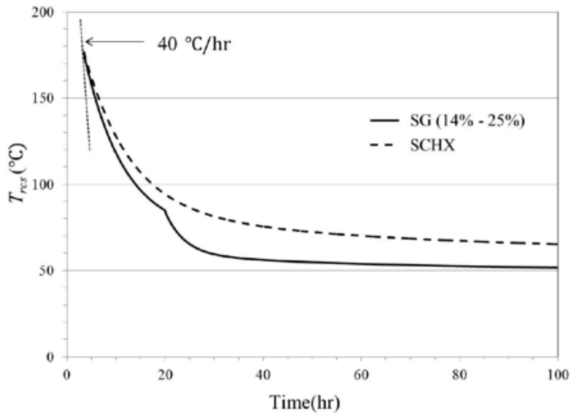

Fig. 4. Variation of the temperature of the reactor coolant during the shutdown cooling operation by the conventional SCS and the SCS using the SG (1train).

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