Transactions of the Korean Nuclear Society Autumn Meeting
Yeosu, Korea, October 25-26, 2018

Sensitivity Analysis on Pressurizer Auxiliary Spray Temperature for an Integral Reactor

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1. Introduction

A Pressurizer (PZR) of integral reactor is located at the top region of the reactor pressure vessel to control system pressure. Four spray nozzles are installed into PZR where those nozzles are connected to a common spray line. There are two sources of this common spray line: (1) PZR main spray line coming from Chemical and Volume Control System (CVCS) letdown line where flow rate is provided by Reactor Coolant Pumps (RCPs). (2) PZR auxiliary spray line coming from CVCS charging line where flow rate is provided by charging pump.

The PZR spray system is designed to meet an administrative cooldown rate (20^{0}C/hr) during shutdown operation from Hot Full Power (HFP) condition to refueling condition. The design cooldown rate that should not be exceed during shutdown operation is set to be 40^{o}C/hr. Because exceeding this rate might increase the possibility of thermal shock.

The main spray is used at the beginning of shutdown operation; however, the auxiliary spray in integral reactor is differently used from Large Nuclear Power Plants (LNPPs). In LNPPs, the PZR auxiliary spray is usually used at the end of shutdown operation. Therefore, the main purpose of the PZR auxiliary spray is just to balance the temperature difference between the PZR and reactor coolant loop when the PZR is completely filled with water [1]. Whereas, in the integral reactor, the auxiliary spray is designed to be used when the PZR main spray is not available anymore as a result of shutting down all RCPs. Since saturated steam still exists in the PZR region, the auxiliary spray is also needed to continue meeting the administrative cooldown rate.

The cooldown rate is achieved mainly by estimating the spray flow rate and its temperature. This paper illustrates the methodology of how the required auxiliary spray flow rate is obtained. In addition, the sensitivity analysis on the spray temperature is conducted to find the optimum temperature range for the auxiliary spray system.

2. Methodology and Analysis

Fig. 1 shows the overall configuration regarding the integral reactor, the PZR spray system, and CVCS charging and letdown lines. Since auxiliary spray is provided from the CVCS charging line. Then its temperature depends on the Regenerative Heat Exchanger (RHX) performance. However, the sizing of RHX is not performed at the basic engineering phase. Therefore, in order to determine the auxiliary spray flow rate, a sensitivity analysis is conducted at different sub-cooled margins where those margins represent temperature difference between PZR and CVCS charging temperature downstream RHX. Ultimately, the auxiliary spray flow rate required to meet the cooldown rate can be obtained.

Mass and energy balance equations are used for PZR region which contains saturated water, saturated steam and inner structures. After discretization and rearranging of mass and energy equations, the following equation is used to determine auxiliary spray mass flow rate [2].

$$\dot{Q}_{\mathrm{in}} = \frac{\left(U^{\mathrm{t}+\Delta \mathrm{t}} - U^{\mathrm{t}}\right) - \left(m^{\mathrm{t}+\Delta \mathrm{t}} - m^{\mathrm{t}}\right) h_{\mathrm{out}}}{\left(h_{\mathrm{in}} - h_{\mathrm{out}}\right) \cdot \Delta t \cdot \rho_{\mathrm{in}}}, \quad (1)$$

where,

$\dot{Q}_{\mathrm{in}}$	Auxiliary spray flow rate (LPM).
$m^{\mathrm{t}+\Delta \mathrm{t}}$	Total mass of steam and water (kg) at given time step.
m^{t}	Total mass of steam and water (kg) at previous time step.
$U^{\mathrm{t}+\Delta \mathrm{t}}$	Total internal energy (kJ) at given time step.
U^{t}	Total internal energy (kJ) at pervious time step.
h_{in}	Enthalpy of auxiliary spray water (kJ/kg) at P (MPa) and T (^{0}C) averaged between given time step and previous time step, where P (MPa) =P_{PZR}+1.0 MPa and T (^{0}C) that corresponds to given sub-cooled margin as $T_{\mathrm{Aux.Spray}}$ (^{0}C) = $T_{\mathrm{PZR}} - \Delta T$.
h_{out}	Enthalpy of PZR effluent at PZR conditions (kJ/kg) averaged between given time step and previous time step.
ρ_{in}	Density of auxiliary spray water (kg/m^{3}) at the equivalent conditions of enthalpy (h_{in}).

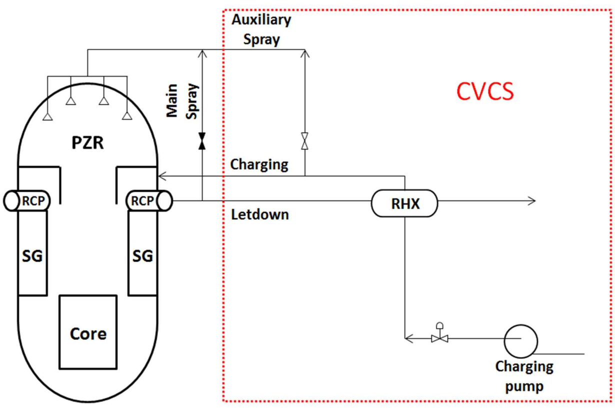

Fig. 1. Schematic of integral reactor PZR spray system

Table I: Different cases for sub-cooled margin

Case	Sub-cooled margin, ΔT ^oC
A	30 ^oC
B	40 ^oC
C	50 ^oC
D	60 ^oC

Table II: Design input data

PZR water volume	49.2	%
PZR steam volume	50.8	%
PZR A508 str. mass	77.4	%
PZR SS304 str. mass	22.6	%
Heat capacity A508	0.5497	kJ/kg ^oC
Heat capacity SS304	0.5546	kJ/kg ^oC

To obtain auxiliary spray flow rate from equation (1), the administrative cooldown rate is set to be 20^{o}C/hr. The cases and sub-cooled margins for the sensitivity analysis are summarized in Table I. Input data used in calculation are summarized in Table II.

The operating range for PZR auxiliary spray line is form 1.3 MPa to 0.3 MPa. Because all RCPs are going to be turned off at 1.3 MPa, and the PZR is completely filled with water at 0.3 MPa.

4. Results

The required PZR auxiliary spray flow rate is obtained for each sub-cooled margin case and the results are summarized in Table III. As sub-cooled margin increases, the required auxiliary spray flow rate decreases gradually. This trend can be easily understood from Equation (1), since the larger sub-cooled margin results in larger enthalpy difference which is the denominator of Equation (1). Therefore, the lower temperature of the spray yields more condensation of PZR steam and less required auxiliary spray flow rate.

The results are compared with the CVCS maximum charging flow rate to check whether or not the PZR auxiliary spray has enough capacity to meet the cooldown rate.

Fig. 2 shows the PZR auxiliary spray flow rate required to meet the cooldown rate for each sub-cooled margin case. In cases A and B, the PZR auxiliary spray flow rates require more than the maximum CVCS charging flow rate. Whereas, the cases C and D need

Table III: Auxiliary spray flow rate (LPM) at given time steps and PZR conditions

Time (hr)	0	1	2	3
PZR T (^{o}C)	191.6	171.6	151.6	131.6
PZR P (MPa)	1.3	0.8233	0.4969	0.2835
Case A	1.44		1.42	
Case B	1.07		1.05	
Case C	0.85		0.84	
Case D	0.71		0.69	

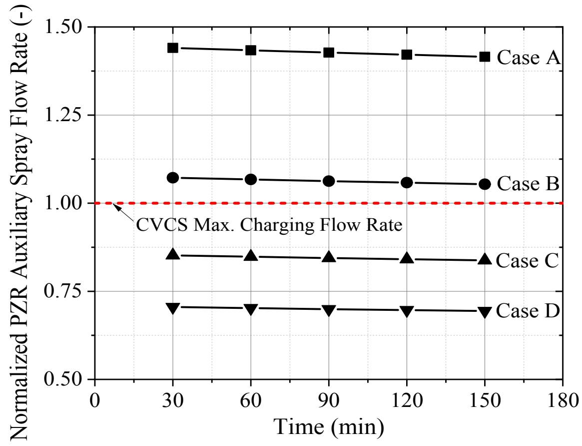

Fig. 2. Auxiliary spray flow rates compared with maximum CVCS charging flow rate

lower PZR spray than maximum CVCS charging flow rate. Therefore, the auxiliary spray temperature at PZR pressure of 1.3 MPa is recommended to be lower than 141.6^{o}C for proper depressurization of the reactor. The CVCS maximum charging flow rate is assumed to be maintained constantly since there is a control valve downstream of the charging pump as depicted in Fig. 1.

5. Conclusion

In this paper, sensitivity analysis on the spray temperature was conducted to find the PZR auxiliary spray flow rate satisfying the administrative cooldown rate. The overall trend shows that lower spray temperature results in lower required spray flow rate. In addition, the PZR auxiliary spray has enough capacity when the temperature is 50^{o}C lower than the PZR temperature. If the spray temperature is much lower than PZR temperature, then the PZR requires much lower spray flow rate. However, necessary precautions should be taken into consideration not to use spray flow with too much low temperature so the thermal shock to PZR inner structures can be avoided.

ACKNOWLEDGMENT

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea Government (MSIT) (2016M2C6A1930039), in addition to funding from King Abdullah City for Atomic and Renewable Energy, Kingdom of Saudi Arabia, within the SMART PPE Project.

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