Transient Analysis for Steam Pressurizer of Integral Reactor Using Equilibrium Formulations

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1. Introduction

A Steam pressurizer (PZR) of an integral reactor not only maintains the system pressure of Reactor Coolant System (RCS), but also partially accommodates the volume change of the reactor coolant in accordance with the load change. Steam PZR pressure is maintained at the saturated condition where liquid (water) and gas (steam) coexists together in steam PZR. The pressure change of the reactor coolant is compensated by the evaporation of saturated water or the condensation of saturated steam at all times.

In the present study, the transient analysis was conducted by using MATLAB and the steam PZR performance was evaluated. In addition, PZR behavior was investigated in accordance with the system pressure, temperature and water level of PZR, especially, at the in-surge and out-surge situation.

2. Analysis Methods

Figure 2.1 shows an integral reactor where the steam PZR is adopted at its top-side. The paths of mass and heat transfer are depicted in the figure. The integral reactor can be divided into three control volumes i.e. PZR, Bottle-neck (BTN) and RCS.

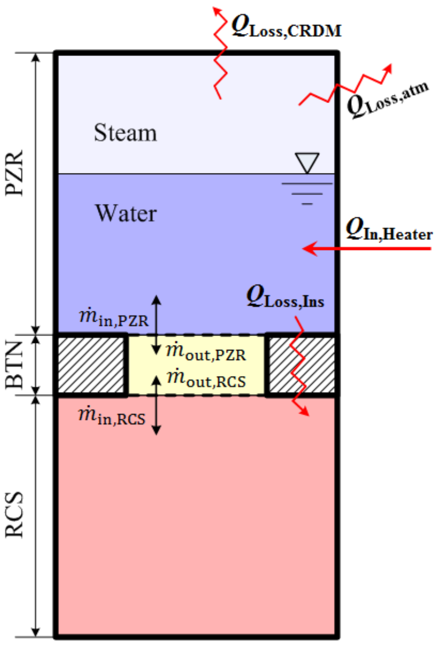

Fig. 2.1 Schematic diagram of an integral reactor

2.1 Governing Equations

The governing equations for mass and energy conservation are set for each control volumes. Simple methods using equilibrium formulations [1, 2] are introduced to trace the transient behavior.

$$\frac{d}{dt}(m)_{\mathrm{PZR,BTN,RCS}} = (\dot{m}_{\mathrm{in}} - \dot{m}_{\mathrm{out}})_{\mathrm{PZR,BTN,RCS}} \quad (1)$$

$$\frac{d}{dt}(mu)_{\mathrm{RCS,BTN}} = (\dot{m}_{\mathrm{in}} i_{\mathrm{in}} - \dot{m}_{\mathrm{out}} i_{\mathrm{out}})_{\mathrm{RCS,BTN}} \quad (2)$$

$$\frac{d}{dt}(mu)_{\mathrm{PZR}} = (\dot{m}_{\mathrm{in}} i_{\mathrm{in}} - \dot{m}_{\mathrm{out}} i_{\mathrm{out}})_{\mathrm{PZR}} + \dot{Q}_{\mathrm{In}} - \dot{Q}_{\mathrm{Loss,atm}} - \dot{Q}_{\mathrm{Loss,CRDM}} - \dot{Q}_{\mathrm{Loss,Ins.}} \quad (3)$$

In the above equations (1)-(3), m and $\dot{m}$ stand for a quantity of mass in the control volume and a mass flow rate at its boundary. u and i stand for a specific internal energy and a specific enthalpy at a given temperature and pressure. The character about $\dot{Q}$ stand for the heat transfer rate and it will be explained more specifically in the following section 2.3 and 2.4.

2.2 Initial Conditions

Table I shows initial conditions of the pressure and the temperature at PZR, BTN and RCS. The pressure and PZR level were set to be 15.0 MPa and 70.0%, respectively. PZR temperature was set to be same as the saturated temperature at PZR pressure. RCS temperature was defined as function of reactor load. BTN temperature was assumed to be the average value of PZR and RCS temperature.

Table I: Initial Conditions

	Pressure (MPa)	Temperature (K)
PZR	15.0	615.31
BTN	15.0	598.90
RCS	15.0	H: 596.15 / C: 568.85

H: Hot-side, C: Cold-side

2.3 Heater Control

Proportional heaters are used for PZR pressure control and those can be linearly controlled in accordance with PZR pressure between 14.8 MPa and 15.2 MPa. Total heater capacity is 600 kW and the amount of input power is as follow.

$$\dot{Q}_{\text{In}} = \left[\frac{15.2\ (\text{MPa}) - P_{\text{PZR}}}{15.2\ (\text{MPa}) - 14.8\ (\text{MPa})}\right] \times [600\ (\text{kW})] \quad (4)$$

In the above equation (4), $\dot{Q}_{\text{In}}$ stands for the input power to the PZR through the proportional heaters. It is assumed that this electrical energy can mix instantly with the internal energy of PZR without time delay.

2.4 Heat Loss

Heat loss makes that internal energy is transferred to outside and the system pressure should be decreased. It is considered three paths of heat loss as follows.

$$\dot{Q}_{\text{Loss,atm}} = h_{\text{Ves}} \cdot A_{\text{PZR}} \cdot (T_{\text{PZR}} - T_{\text{atm}}) \quad (5)$$

$$\dot{Q}_{\text{Loss,CRDM}} = 25 \times [8.9\ (\text{kW})] \quad (6)$$

$$\dot{Q}_{\text{Loss,Ins}} = k_{\text{eff}} \cdot A_{\text{Ins}} \cdot \frac{(T_{\text{PZR}} - T_{\text{RCS}})}{\Delta d_{\text{Ins}}} \quad (7)$$

In the above equations (5)-(7), $\dot{Q}_{Loss,atm}$, $\dot{Q}_{Loss,CRDM}$ and $\dot{Q}_{Loss,Ins}$ stand for heat loss to the atmosphere, Control Rod Drive Mechanism (CRDM) and wet thermal insulation, respectively. h_{Ves} and A_{PZR} stand for the convection heat transfer coefficient of the thermally insulated reactor vessel and surface area of PZR. k_{eff} stands for the effective thermal conductivity of wet thermal insulation. A_{Ins} and Δd_{Ins} express its surface area and thickness.

2.5 Calculation Procedure

A simple situation is considered where reactor load decreases linearly and then increases linearly with the rate of 5%/min. Figure 3.1 shows the temporal change of the temperature among the hot-side, cold-side and mean temperature of RCS.

The computational calculation was conducted by the MATLAB code which solved the governing equations with the given initial conditions. The code algorithm is developed to calculate the system pressure, temperature, input power, heat loss, specific internal energy and specific enthalpy until the internal energy difference is converged to less than 0.01J. The calculation results include the temporal behavior of pressure, temperature, water level, the surge flow rate, etc.

3. Calculation Results

As the time passes from 1 to 960 sec, the reactor load decreases from 100 to 20%. According to the power reduction, the mean temperature of RCS increases from 582.5 to 584.1 K as shown in Fig. 3.1. This leads to the decrease of the density and consequently the volume of RCS increases. As a result, the mass is transferred from RCS to BTN and from BTN to PZR sequentially. The mass transfer makes an in-surge situation and the in-surged water acts to pressurize the saturated steam in PZR. Therefore, the pressure of PZR and the water level of PZR increase as shown in Figs. 3.2-3.3.

As the time passes from 961 to 1920 sec, the reactor load maintains at 20%. In this situation, the system pressure steadily decreases because the internal energy is transferred to outside of the control volume by the heat loss. The proportional heater is controlled by the PZR pressure and it is converged to initial pressure at 15 MPa. The water level of PZR maintains constantly.

As the time passes from 1921 to 2880 sec, the reactor load increases from 20 to 100% and the mean temperature of RCS decreased from 584.1 to 582.5 K.

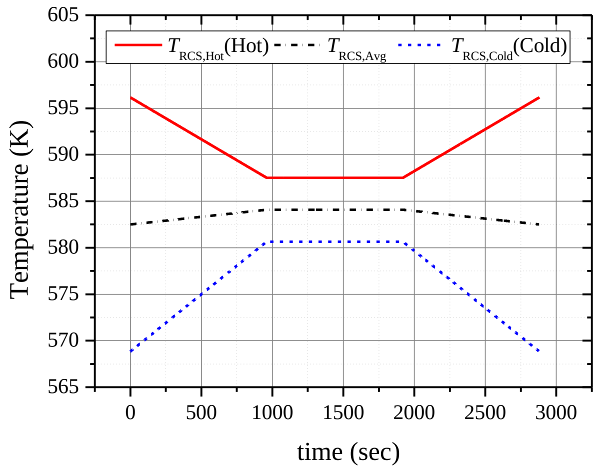

Fig. 3.1 Temperature variation of the RCS

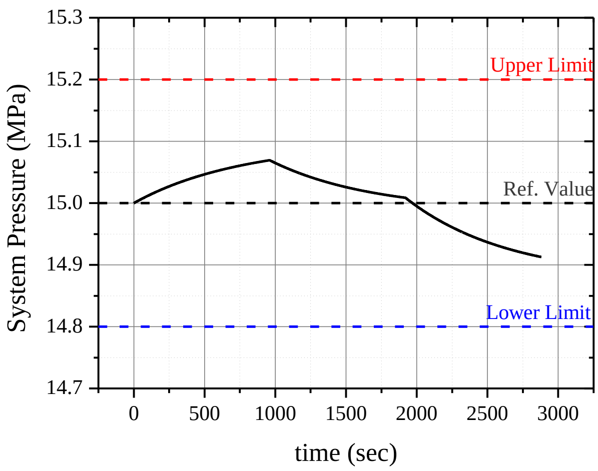

Fig. 3.2 System pressure variation

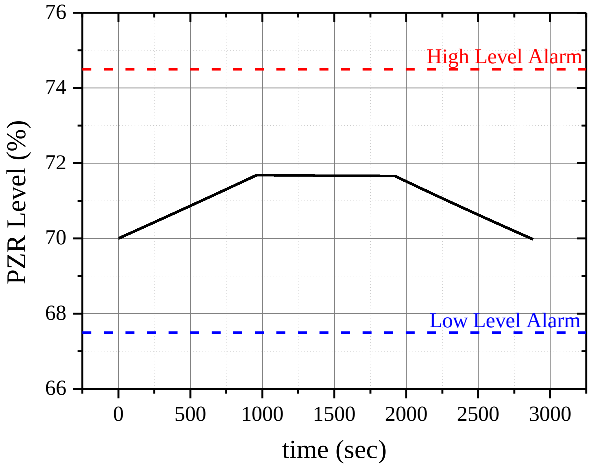

Fig. 3.3 Level variation of PZR

This makes the reactor coolant density increase and the volume decrease. As a result, the mass is transferred from PZR to BTN and from BTN to RCS sequentially. The mass transfer makes out-surge situation and the out-surged water acts to depressurize the saturated steam. The water level of PZR decreases and the volume, where out-surged water was existed, is refilled by the phase changed steam from water in PZR.

4. Conclusions

In the present study, the transient analysis on steam PZR of an integral reactor was conducted using equilibrium formulations for PZR, BTN and RCS, respectively. The results show that the steam PZR operates within the upper and lower limit of PZR pressure and level.

In the present study, it is assumed that the steam and water mix together in a control volume so that the energy is transferred instantly without time delay. For future work, the saturated condition in PZR should be divided into water and steam to get more precise results.

ACKNOWLEDGEMENT

This work was supported by the National Research Foundation of Korea (NRF) funded by the Korea government (MSIP) (No. NRF-2012M2A8A4025974).

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