Numerical Investigation on Transient Behavior of Steam-gas Pressurizer in Integral PWR

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1. Introduction

The steam-gas pressurizer incorporated in the integral reactors such as REX-10 [1] or AST-500 maintains certain content of noncondensable gas to provide the system pressure in primary circuit and the subcooling at core outlet. With steam and nitrogen gas as the gaseous mixture in upper volume, it pursues the progress in the passive feature of reactor, excluding active equipments. The presence of noncondensable gas, however, requires a new mathematical model to predict transient behavior of steam-gas pressurizer. A dynamic model for steam-gas pressurizer is proposed in this study. It is two-region nonequilibrium model whereby pressurizer volume is separated into two distinct regions by an interface, i.e. gaseous mixture and liquid, with each establishing its own thermodynamic state. Mass and energy equations are applied to the three components; steam, nitrogen and liquid water. Physical phenomena to be modeled include surge (SU), rainout (RO), flashing (FL), inter-region heat and mass transfer (ITR), wall condensation (WC). The mathematical model is numerically solved by iterative computing to calculate the pressure with respect to time. The dynamic response of the steam-gas pressurizer in a transient is simulated.

2. Mathematical Formulation

2.1 Conservation equations

With regard to mass balances, the model accounts for all the processes of mass transfer which occurs between vapor and liquid phases inside the steam gas pressurizer, as well as surge flow from primary loop as:

$$dM_{liq} / dt = \dot{M}_{SU} + \dot{M}_{RO} - \dot{M}_{FL} + \dot{M}_{ITR} + \dot{M}_{WC} \tag{1}$$

$$dM_{stm} / dt = \dot{M}_{FL} - \dot{M}_{ITR} - \dot{M}_{RO} - \dot{M}_{WC} - \dot{M}_{RV_{stm}} \tag{2}$$

$$dM_{N_2} / dt = \dot{M}_{IN_{N_2}} - \dot{M}_{RV_{N_2}} \tag{3}$$

where *IN* and *RV* designate the nitrogen injection rate and relief valve discharge rate. The energy conservation equation is written in terms of the convective energy flows and the mechanical work as follows:

$$\begin{aligned} M_{liq} \frac{dh_{liq}}{dt} &= \dot{M}_{SU} h_{SU} + \dot{M}_{RO} h_F - \dot{M}_{FL} h_G + \dot{M}_{ITR} h_G \\ &+ \dot{M}_{WC} h_F - \dot{M}_{liq} h_{liq} + \dot{P}_{tot} V_{liq} \end{aligned} \tag{4}$$

$$\begin{aligned} M_{stm} \frac{dh_{stm}}{dt} &= \dot{M}_{FL} h_G - \dot{M}_{ITR} h_G - \dot{M}_{RO} h_F - \dot{M}_{WC} h_G \\ &- \dot{M}_{RV_{stm}} h_{stm} - \dot{M}_{stm} h_{stm} + \dot{P}_{stm} V_{gas} \end{aligned} \tag{5}$$

$$M_{N_2} \frac{dh_{N_2}}{dt} = \dot{M}_{IN} h_{IN_{N_2}} - \dot{M}_{RV_{N_2}} h_{N_2} - \dot{M}_{N_2} h_{N_2} + \dot{P}_{N_2} V_{gas} \tag{6}$$

2.2 Closure relations

The above conservation equations form a system in which the unknowns outnumber the equation by 9 (*P*, *h*, *M* of three components) to 6; thus one needs three more constitutive relations for closure. One is Gibbs-Dalton law for gas phase. Then the total pressure exerted by the gaseous mixture is equal to the sum of partial pressure of steam and nitrogen. With respect to time, it can be expressed as:

$$\dot{P}_{tot} = \dot{P}_{stm} + \dot{P}_{N_2} \tag{7}$$

Another relation is the thermodynamic equilibrium condition in gas phase. The temperature of steam and nitrogen, determined by respective partial pressure and enthalpy, are the same as following:

$$T_{stm}(P_{stm}, h_{stm}) = T_{stm}(P_{N_2}, h_{N_2}) \equiv T_{gas} \tag{8}$$

The other expression for time derivative of the total pressure can be obtained from the constraint of the fixed pressurizer volume:

$$\dot{V}_{SGP} = d(M_{gas} \cdot v_{gas} + M_{liq} \cdot v_{liq}) / dt = 0 \tag{9}$$

The specific volume of gaseous mixture is determined by definition. The equations-of-state for them are:

$$v_{gas} = v_{gas}(P_{stm}, P_{N_2}, h_{stm}) \tag{10}$$

$$v_{liq} = v_{liq}(P_{tot}, h_{liq}) \tag{11}$$

It is noted that enthalpy of nitrogen is not included since it can be determined from above three parameters by thermodynamic equilibrium condition. Substituting Eqs. (10) and (11) into (9), one obtains

$$\dot{P}_{tot} = - \frac{ M_{gas} \begin{bmatrix} \dot{P}_{N_2} ((\partial v_{gas} / \partial P_{N_2}) - (\partial v_{gas} / \partial P_{stm}) + \\ (\partial v_{gas} / \partial h_{stm}) \cdot (H_{stm} - V_{gas} \dot{P}_{N_2}) / M_{stm} \end{bmatrix} + (\partial v_{liq} / \partial h_{liq}) \cdot H_{liq} + v_{gas} \dot{M}_{gas} + v_{liq} \dot{M}_{liq} }{ \begin{aligned} & M_{gas} ((\partial v_{gas} / \partial P_{stm}) + (\partial v_{gas} / \partial h_{stm}) \cdot V_{gas} / M_{stm}) \\ & + M_{liq} \cdot (\partial v_{liq} / \partial P_{tot}) + V_{liq} \cdot (\partial v_{liq} / \partial h_{liq}) \end{aligned} } \tag{12}$$

2.3 Local phenomena models

The mass transport between gas and liquid phase is of great importance to decide the response of the steam-gas pressurizer. Due to variation of pressure or internal energy, liquid droplets are generated in steam volume to fall to liquid region (RO) or vapor bubbles are formed in liquid volume to rise to upper region (FL). The rate of rainout and flashing is calculated in similar way:

$$W_{RO} = \rho_f u_d (1-\alpha_v) A \tag{13}$$

$$W_{FL} = \rho_g u_b \alpha_l A \tag{14}$$

Especially, when deciding the void fraction of the liquid region, one should take into account bubble rise of boiling at the core as well as bulk evaporation, due to the configuration of integral reactor. The inter-region mass transfer is the net effect of the condensation and evaporation of molecules across the interface, which is calculated from gas kinetic theory as:

$$W_{ITR} \simeq \frac{f}{1-0.5f}\left[\frac{M}{2\pi R}\right]^{1/2}\left(\frac{P_v}{T_v^{1/2}}-\frac{P_s}{T_s^{1/2}}\right)\cdot A \tag{15}$$

It is known that the presence of noncondensable gas significantly affect the intensity of steam condensation. To calculate the mass rate of wall condensation, the condensation model proposed by Kim [2] is employed, which is based on the heat and mass transfer analogy.

3. Numerical Solution Method

Since Eqs. (8) is not a formulated function, but a relation achievable from the steam table, a linear matrix system is not formed with conservation equations and closure relations; therefore, the iteration method is used to get the solutions. The mass flow rates are calculated using the properties at previous iteration step. Then with an initial guess of $\dot{P}_{N_2}$, $\dot{P}_{tot}$ and $\dot{P}_{stm}$ are obtained from Eqs. (12) and (7). Then the updated steam enthalpy is calculated from Eqs. (5). It determines the temperature of gaseous mixture, and subsequently, new nitrogen gas enthalpy is obtained by constraint of thermodynamic equilibrium in gas volume. As the time derivative of nitrogen enthalpy is equal to $(h_{N_2}^{k+1} - h_{N_2}^{n})/\Delta t$, the value of $\dot{P}_{N_2}$ in right-hand side of Eqs. (6) is updated. This recursive process is continued until the magnitude of pseudo errors of both $\dot{P}_{N_2}$ and gas temperature get less than the prescribed tolerances. The water level in the pressurizer is also computed from a differential equation of liquid volume at the end of every time step.

4. Test calculation

For the steam-gas pressurizer equipped in REX-10, a simple transient simulation is carried out in which the outsurge takes place due to the reduction in core power by half. The developed steam-gas pressurizer module is combined with a system analysis code for REX-10 [1] from which the surge flow rate is received.

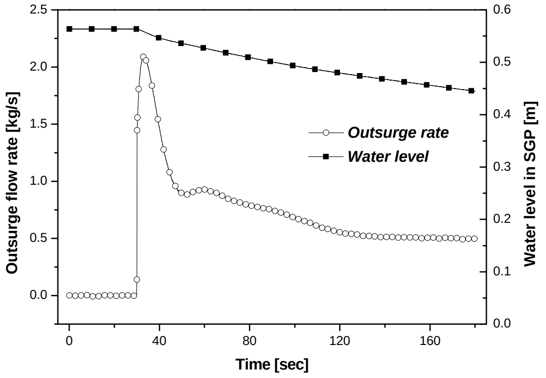

Fig. 1. Outsurge rate and liquid level

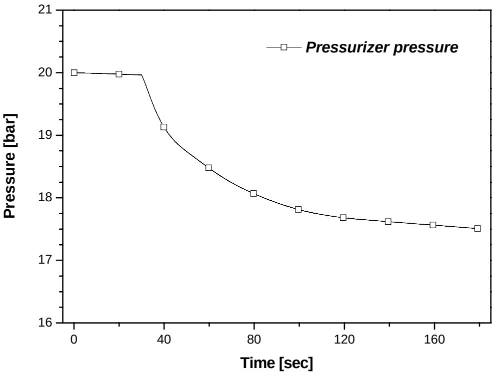

Fig. 2. Pressurizer system pressure versus time

Outsurge flow caused by contraction of water volume in the primary circuit and the corresponding decrease in liquid level are given in Fig. 1. When the core power drops at 30 sec from steady-state, the strong outsurge flow is formed at initial stage and water level is reduced by 21% for 150 seconds. The pressurizer pressure goes below 18 bar to approach a new stabilized state as given in Fig. 2.

5. Conclusions

A numerical model to simulate the dynamic behavior of the steam-gas pressurizer with nitrogen gas has been presented and a simple simulation is carried out. The comparison with experimental data is required for the validation of the proposed model.

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