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THE DYNAMIC MODELING OF THE PRESSURIZER SURGE TANK TRANSIENTS IN LIGHT WATER REACTOR NUCLEAR POWER PLANTS*

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Abstract– in nuclear power plants using pressurized water as the main coolant maintaining system pressure within prescribed limits is necessary. The volume of the main coolant expands and contracts with average temperature variations causing insurges and outsurges in the surge tank volume which is called "pressurizer". The surge tank acts in a way in which coolant pressure is maintained within prescribed limits. The surge tank is equipped with a spray and relief system as well as electric heating elements. The pressure is controlled by the increase in bubble populations through heating and / or flashing or steam condensation through water sprays.

This paper analyses the transient behavior of the surge tank in a WWER type pressurized water nuclear power plant. An analytical method is developed for predicting pressure and water level variations in the surge tank following in or out surge processes. The analysis also takes into consideration the variation of the thermodynamic mass qualities inside the surge tank. The results obtained are compared with RELAP5/Mod3 and RELAP5/Mod2 as valid codes. D'Auria's model (FFT method) is employed for this comparative analysis.

Keywords – Surge tank, pressurizer, WWER, insurge, outsurge, physical phenomena, FFT method

1. INTRODUCTION

After the TMI accident many people realized the importance of simulating system transients with greater accuracy. For a pressurized water reactor, the accurate prediction of system pressure is essential since system pressure is a key parameter in controlling system transient. For this purpose, the fundamental understanding and a reliable modeling of surge tank phenomena during transients are needed to simulate overall nuclear power plant behavior.

Early methods of analyzing liquid surge into a surge tank (Fig. 1) utilized the assumption of the isentropic (adiabatic and reversible) compression of the vapor. Bosley, Leddick and Drucker [1] showed that this assumption is unrealistic. Since the predictions by the equilibrium model were not satisfactory for rapid transients, non-equilibrium models were developed [2-4]. The previous non-equilibrium surge tank models use two-region models with two control volumes. A better prediction of surge tank dynamics, however, requires the three-region models consisting of two liquid regions and one vapor region, due to the stratification when the subcooled water is surged into the surge tank. Baggoura and Martin [5] developed the three-region model with a kinetic theory model for evaporation and condensation. There are several other analytical and/or experimental studies of pressurizer behavior model [6-10], but the contribution of solubility of boron in liquid phase on the solution boiling point was not considered.

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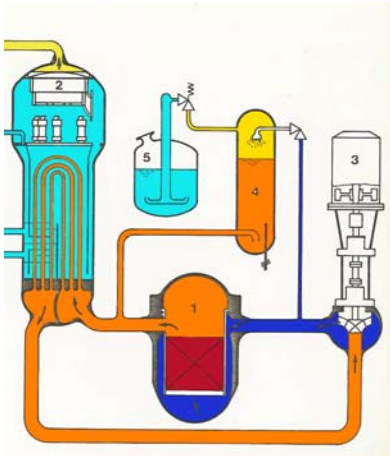

Fig.1. Simple scheme of primary loop of a typical nuclear power plant, (1-Reactor Pressure Vessel, 2-Steam Generator, 3-Primary Pump, 4-Surge Tank, 5-Relief Tank)

Thus, the previous models are improved by the present three-region model which uses all of the important phenomena occurring in the surge tank of a WWER type reactor. As we haven't got access to an experimental facility to compare experimental results with the model output, the results obtained are compared with RELAP5/Mod3.2 and RELAP5/Mod2 as valid codes. There is a fundamental difference between a calculated physical parameter obtained with the computer and the measured physical parameter; in measurements we are dealing with realities, but when we use the computer we are dealing with models which are representing realities, however, there are many cases in which an experimental verification is not possible or not available. In such a situation it is some times possible to have an estimate about the uncertainty by calculating the response in question by different models. The deviations among the results in different models might give an indication of the uncertainty due to the choice of a particular model.

2. SURGE TANK MODEL

The surge tank model of this work has the following aspects (Fig.2):

1. Three-region (Fig.3): the surge tank volume is divided into three regions according to phase condition and energy. Region 1 is the vapor and non-condensable gas (if any) region containing dropping liquid droplet equipped with spray nozzles and relief and safety valves. Region 2 is the saturated liquid region containing rising bubbles. Region 3 appears when the surge water enters the surge tank. This region is equipped with electric heating elements. Region 2 and 3 are the solution phase with boron as a solute.
2. A thermodynamic non-equilibrium condition for all three regions.
3. Consideration of the actual and collapsed water level.
4. Consideration of the important thermal-hydraulics, thermodynamics and physical phenomena including wall condensation and boiling, interfacial heat and mass transfer, heat transfer rate between the liquid and the wall, the effect of non condensable gas and the effect of boron, bubbling rise and rain-out model, mixing of the cold (incoming jet) with the hot water already present in the surge tank.

The basic assumptions of the proposed surge tank model are as follows:

1. The three-regions have the same pressure.
2. Each region has the average uniform enthalpy at each time step.
3. Spray–condensate mixture reaches saturation temperature before entering the liquid phase.

4. Delay times of bubbles rise and condensates fall are neglected.

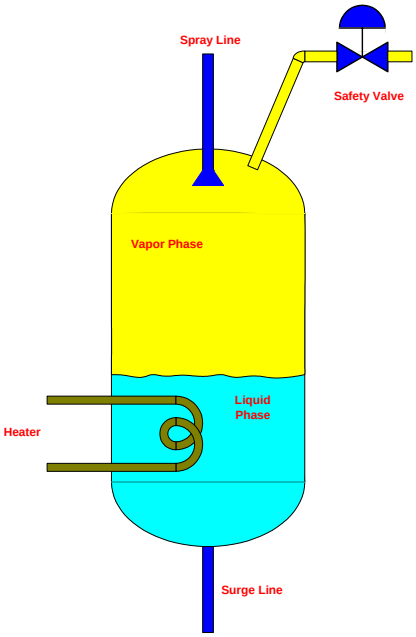

Fig. 2. Simple surge tank scheme

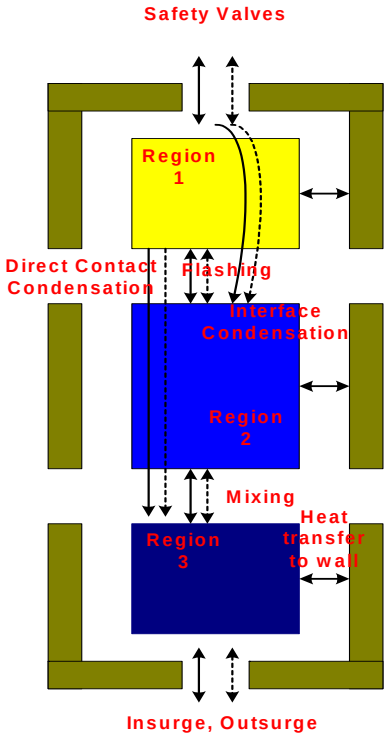

Fig. 3. Heat and mass transfer scheme

3. GENERAL GOVERNING EQUATIONS

Conservation of mass across the deformable control volume can be written as

$$d/dt \int_{cv}\rho dv+\int_{cs}\rho \upsilon_r.ndA=0 \tag{1}$$

where υ_r is the velocity of control surface boundary. Hence, for any region, the above expression yields to

$$dM_i/dt=\sum m_i, \quad i=1,2,3 \tag{2}$$

Conservation of energy across the deformable control volume can be written as

$$\sum Q_i+\sum W_i= d/dt \int_{cv}e\rho dv+\int_{cs}\rho h\upsilon_r.ndA \tag{3}$$

where e is specific energy and Eq. (3) can be written as follows

$$\sum Q_i-PdV/dt=d\,(mh-PV)/dt+\sum m_i h_i \tag{4}$$

Volume balance and equation of state are as follows

$$dV_{total}/dt=\sum dM_i\upsilon_i/dt=0, \quad i=1,2,3 \tag{5}$$

$$\upsilon_\upsilon= \upsilon_\upsilon(h_\upsilon,P);\ \upsilon_l= \upsilon_l(h_l,P) \tag{6}$$

and for two phases

$$\upsilon_i=X_i\upsilon_{fg}+\upsilon_f \tag{7}$$

With some manipulations, the governing Eqs. (2-7) can be simplified to yield the following

$$dP/dt=-\sum(M_i.J_i.dh_i/dt+\upsilon_i m_i)/\sum(M_i.G_i) \tag{8}$$

where $i=1, 2, 3$ J_i is $\partial\upsilon_i/\partial P$ for single phase and

$(X_i d\upsilon_{fg}/dP+d\upsilon_f/dP)$-

$(X_i dh_{fg}/dP+dh_f/dP).\upsilon_{fg}/h_{fg}$ for two phases

G_i is: $\partial\upsilon_i/\partial h$ for single phase and υ_{fg}/h_{fg} for two phases

To solve the previous non linear equations we use the finite difference method. In this case, superscripts n and k represent the time and iteration step, respectively, (i=1, 2, and 3)

$$(P^{k+1}- P^n)/\Delta t=-\sum [M_i^{k+1}.J_i^k.(h_i^{k+1}- h_i^k)/\Delta t+\upsilon_i^k m_i^{k+1}]/\sum(M_i^{k+1}.G_i^k) \quad (9)$$

After pressure, mass and enthalpy are determined, the water level in the surge tank is calculated from the liquid volume (i=1, 2)

$$L^{n+1}= [\sum (M_i^{n+1}.\upsilon_i^n)-V_{bottom}]/\pi R^2 \quad (10)$$

where V_{bottom} is the volume of the bottom hemispherical part, and is generally different from the measured level, because the water in the surge tank is assumed to be collapsed. To calculate the collapsed level, υ_i is replaced by the saturated specific volume υ_f.

4. PHYSICAL MODEL

a) Heater

The function of heater in the surge tank is to maintain the steady state pressure of the system. The heater elements are energized when the system pressure is reduced.

For the heater blocks, the heater power Q_P is determined from the following equation:

$$Q_P=Q_{Pmax}(P_{off}-P)/ (P_{off}-P_{on})$$

where

$$Q_P=Q_{Pmax}, \quad \text{for } P<P_{on} \text{ and } Q_P=0, \quad \text{for } P>P_{off} \text{ or } L< L_{off}$$

b) Spray, spray condensation

Various flow characteristics for the spray valve can be assumed linear and nonlinear. The spray flow rate m_{sp} is represented by the second degree polynomial of surge tank pressure in the following form

$$m_{sp}=m_{sp(max)} ([1-(P-P_{off})^2/ (P_{on}-P_{off})^2]$$

where

$$m_{sp}=0, \quad \text{for } P<P_{off} \text{ and } m_{sp}=m_{sp(max)}, \quad \text{for } P>P_{on}$$

The rate of condensation due to spray m_{cs} can be expressed as

$$m_{cs}=m_{sp}(h_f-h_{sp})/ (h_g-h_f)$$

c) Bubble rising and rain-out model

During the pressure decrease, subcooled water and superheated vapor in the surge tank reach a saturated state. The bubbles generated by depressurizing escape from region 2 at the rate of m_{be}, which is determined by

$$m_{be}=\alpha_l A\upsilon_{bub}\rho_g$$

where υ_{bub} is bubble velocity at the interface and is calculated from the relation defined by Wilson [11].

With the same approaches, the rate of the liquid droplets reaching the interface m_{bc} can be calculated as

$$m_{bc}=\alpha_v A \upsilon_d \rho_f$$

where υ_d is liquid droplet velocity at the interface and given as a constant variable.

d) Boiling point elevation due to boron effect

As in the liquid region we have boron, as a nonvolatile solute, which causes the increase at the boiling point temperature of the liquid phase. Then, during modeling we consider this effect.

When the solute is nonvolatile, the development for the solution boiling point rise, $\theta=T-T_0$ is as follows [12]

$$Lna_b=Ln\gamma_b x_b=-\ \theta\ h_{fg}/RT_0(T_0+\theta)$$

where a_b, γ_b are the activity and activity coefficient of boron in solution and R is gas constant.

For very dilute solutions the activity coefficient is unity; then the activity is identical to the mol fraction x_b. In this case, the above equation is directly related to the mol fraction of solute.

e) Wall condensation and boiling

(a) Above the liquid level:

(1) $T_w<T_{sat}$

Due to insurge phenomenon, the saturation temperature in the surge tank is increased. Since the wall temperature of the surge tank is lower than the saturation temperature, condensation of vapor on the wall occurs. The rate of condensation on the wall, m_{wc}, can be calculated as follows:

$$m_{wc}=Q_w(t)/h_{fg}$$

where Q_w is the wall heat content changed by wall condensation and can be calculated by the following equation:

$$Q_w(t)= A_w(t)C_{pw}\rho_w\int_0^1 T(x,t)dx$$

where $A_w(t)$ is wall area exposed to vapor phase, and $T(x,t)$ is calculated by solving the following equation:

$$\partial T/\partial t=\alpha\partial^2 T/\partial x^2$$

where α is the thermal diffusivity of the vessel and initial and boundary condition is:

$$T(x,0)=Tsat(P)$$

$$\partial T(0,t)/\partial x =H(T_v-T(0,t))$$

$$\partial T/\partial x \big|_{x=l}=0$$

where l is wall thickness and H, T_v are heat transfer coefficient and temperature of region1. In this case, the effect of non-condensable gases on wall heat transfer (H) is dominated.

(2) $T_w>T_{sat}$

In this case, the heat transfer that occurs by natural convection to vapor and mass transfer is zero.

(b) Below the liquid level

(1) $T_w<T_{sat}$

Heat transfer is by natural convection to single phase liquid and mass transfer is zero.

(2) $T_w > T_{sat}$

Heat transfer is by boiling, while conduction in the metal governs. In this case we assume the heat transfer coefficient is infinite, hence the rate of boiling on the wall, m_{wb}, can be calculated as follows:

$$m_{wb}=Q_b/h_{fg} \text{ and } Q_b=(\rho C_p V)_{wall} dT$$

f) Interfacial heat and mass transfer

Heat transfer between region 2 and 3 can be done by conduction and convection. During insurge phenomenon, when the water level is higher than the depth of the penetration of the subcooled insurge water, the contribution of convection and conduction is low, but when the water level is low, the insurge water is mixed with the water in the surge tank, and convection dominates.

The following relation between the heat transfer coefficient H and Stanton number St is used to calculate heat transfer coefficient (G is mass flux)

$$St=H/GC_p$$

Here also we should consider the effect of non-condensable gas on G and H. Heat transfer rate Q_s is determined by

$$Q_s=HA\,(T_v-T_l)$$

Mass transfer rate m_d between two phases can be calculated by the gas kinetic theory

$$m_d=PA/(2\pi RT)^{1/2}$$

With definition of a fraction factor ε, condensation rate m_{sc} and evaporation rate m_{se} from the interfacial surface is as follows:

$$m_{sc}=\varepsilon md(P),\ m_{se}=\varepsilon m_d(P^{sat})$$

P^{sat} is saturation pressure at liquid temperature.

g) Relief valves

Since the pressure downstream of the surge tank relief valves is so low with respect to pressure in the surge tank, the critical flow through the orifice of the valves is assumed. The critical flow models used in the present work are Henry-Fauske, Moody and isentropic expansion models like RELAP5/Mod3 [13].

h) Non-condensable gas effect

Since region 1 may have non-condensable gases, for any heat and mass transfer between this region and wall or region 2 the effect of non-condensable gases on heat and mass transfer is considered [14, 15]. As shown in Figures 4 and 6, due to this effect, the pressure of the model is slightly greater than the RELAP models.

5. SUMMARY DESCRIPTION OF RELAP5 CODE

The light water reactor (LWR) transient analysis code was developed at the Idaho National engineering Laboratory (INEL) for the U.S. Nuclear Regulatory Commission (NRC). Code applications include analysis to support rulemaking, licensing audit calculations, evaluation of accident mitigation strategies, evaluation of operator guidelines, and experiment planning analysis. Specific applications have included simulations of operational transients such as loss of feed water, loss of offsite power, station blackout, and

turbine trip. RELAP5 is a highly generic code that, in addition to calculating the behavior of a reactor coolant system during a transient, can also be used for simulating a wide variety of thermo hydraulic and thermal transients in both nuclear and nonnuclear systems involving mixtures of steam, water, noncondensable, and solute[13].

6. WWER-1000 PRESSURIZER DATA

A steam surge tank is connected to the hot leg of loop No 4 through a pipe (D 426/40mm) of 18000 mm length. The surge tank spray pipeline is connected to the cold leg of loop No 1.

Spray can be also performed through a makeup pipeline. A set of heaters is installed in the surge tank. The heaters are intended to keep pressure within a set margin in case of its decrease. The steam dome of the surge tank is connected to the bubble condenser by steam dump pipelines. Steam removal is carried out through three safety valves or through an emergency gas removal system. The main pressurizer parameters are as follows:

Total volume	79 m^3
Nominal water volume	55 m^3
Total height	15910 mm
Inner diameter	3000 mm
Outer diameter	3330 mm
Number of heat blocks	28
Power per heater block	90 kW
Working temperature	346 °C
Design pressure	17.7 MPa
Working pressure	15.7 MPa
Number of surge tank relief valves	3

7. RESULTS AND DISCCUSION

a) Partially full insurge transient

This transient was intended to simulate the insurge transient when the system is initially at equilibrium. It is assumed that the surge tank is filled with saturation water to 1/3 of tank height. The cold water is then insurged from the surge line until the water level reaches to 2/3 of tank height. In this state the incoming cold water stratifies below the hot water and the gas phase is a a bit superheated. The most important process occurring during a partially full insurge transient is wall condensation. As shown in Fig. 4, the model of wall condensation is quite accurate and reliable with respect to RELAP5/Mod3 and RELAP5/Mod2 as valid codes.

b) Outsurge transient

This transient was intended to simulate the outsurge transient from an initially equilibrium state. In this case, transient is started by the discharge of saturation water from the surge line. The initial water level is 2/3 of the surge tank height. Steam formation due to flashing on both the heaters and the wall boiling are the important phenomena. As shown in Fig. 5, the model of flashing and boiling are quite accurate compared with RELAP5/Mod3 and RELAP5/Mod2 as valid codes, but as RELAP5/Mod3 and RELAP5/Mod2 do not take into account the influence of dissolved boron, during the first 20 seconds, the model profile is steeper than the RELAP models.

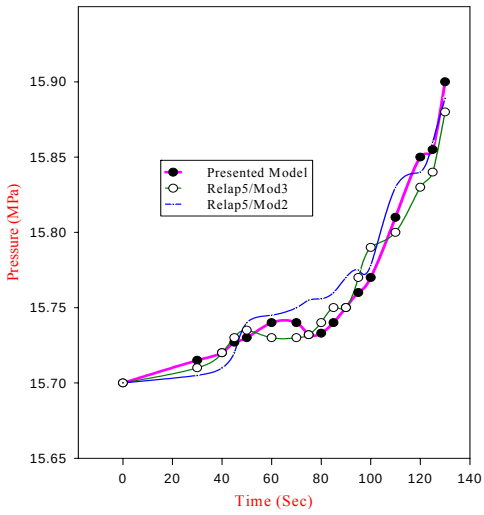

Fig. 4. Partially full insurge transient

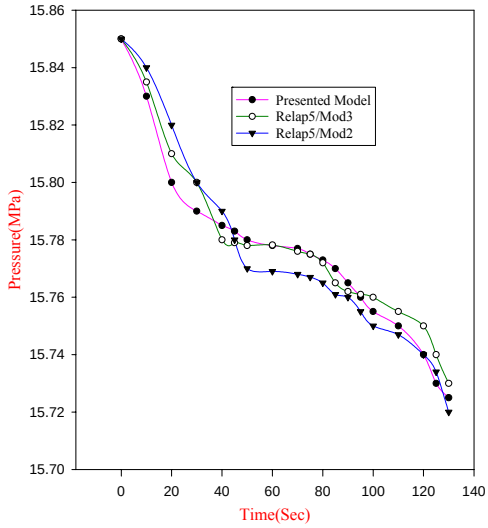

Fig. 5. Outsurge transient

c) Outsurge after insurge transient

Figure 6 shows the pressure behavior due to outsurge after insurge transient. This transient was intended to simulate an operation mode of the surge tank when the liquid temperature is not uniform. This transient is started by discharging the cold water which have entered into the surge tank during insurge from the surge line.

First, it is assumed that the surge tank is filled with saturation water to 1/3 of tank height and the cold water is insurged from the surge line. The cold water is then discharged immediately. For insurge, all the phenomena are the same as described in section 5.1, while in outsurge, the pressure behavior is quite different from that described in the simple outsurge transient. In Section 5.2, when outsurge starts from an initial saturation state, all the water in the surge tank is available for flashing during pressure drop. However, in the insurge-outsurge transient, the water can flash when its pressure drops below the saturation pressure. This means that the cold water in the bottom of the surge tank does not flash immediately.

When the pressure reaches to the saturation pressure corresponding to the initial temperature, the heat transfer to the cold wall reduces the effect of flashing, and because of that, the pressure drop for this case is more rapid than simple outsurge case. As shown in Fig. 6, the model output has very good consistency with RELAP5/Mod3 and RELAP5/Mod2 as valid codes.

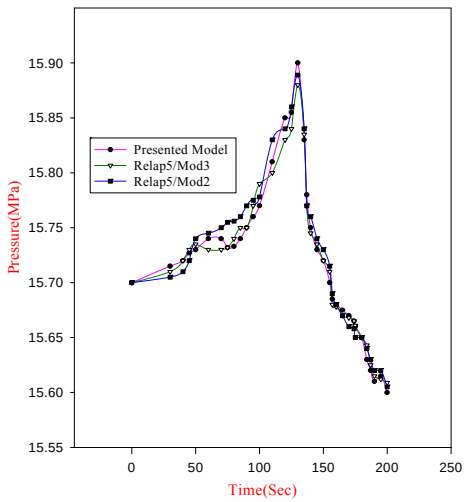

Fig. 6. Outsurge after insurge transient

8. CONCLUSIONS

In this paper, a description of the mathematical models used to simulate the surge tank and the surge tank thermal-hydraulic behavior has been presented. The model includes detailed presentations of the physical phenomena taking place inside the surge tank. The model shows that the wall condensation and non-condensable gas effects dominate during insurge transient, and that a three-region model is required for outsurge after insurge transient. Also, during outsurge transient the effect of flashing and solubility of boron dominates. Since there is no access to an experimental facility to compare experimental results with the model output, the results obtained are compared with RELAP5/Mod3 and RELAP5/Mod2 as valid codes. The method of comparison used was D'Auria (FFT) method [16, 17]. This comparison shows that the results are in agreement with the above complex and valid codes.

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