A Three-Dimensional Analysis of Emergency Core Cooling System for the SMART

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1. Introduction

SMART (System-integrated Modular Advanced ReacTor) is an integral type reactor developed in KAERI [1]. The reactor assembly contains major primary systems such as fuel, core, eight helical coiled steam generators, a pressurizer, four reactor coolant pumps (RCP), and control element drive mechanisms in a single pressurized reactor vessel. The integrated arrangement of these components enables the removal of the large size pipe connections between major reactor coolant systems, and thus fundamentally eliminates the possibility of large break loss accidents. This feature, in turn, becomes a contributing factor for the safety enhancement of the integral type reactor. Thus, only the small break loss accident (SBLOCA) is postulated to assure that there are sufficient liquid coolant inventory to cover the reactor core throughout the accident.

A one-dimensional analysis of the primary reactor coolant system might result in large uncertainties due to the complex coolant flow geometry. In this paper, a three-dimensional thermal hydraulic code is developed for the analysis of the SBLOCA of the SMART. The calculation method of the code is the same as the CUPID code developed in KAERI [2,3]. The primary coolant system is modeled with 25147 hexahedral meshes. A SBLOCA caused by an emergency core cooling system (ECCS) line break was simulated and the results were evaluated.

2. Governing Equations

The two-phase governing equations are employed for the transient two-phase analysis. The continuity, momentum, and energy equations are;

$$\frac{\partial}{\partial t}(\alpha_k \rho_k) + \nabla\cdot(\alpha_k \rho_k \underline{u}_k) = \Gamma_k \tag{1}$$

$$\frac{\partial}{\partial t}(\alpha_k \rho_k \underline{u}_k) + \nabla\cdot(\alpha_k \rho_k \underline{u}_k \underline{u}_k) = -\alpha_k \nabla P + \nabla\cdot[\alpha_k \tau_k] + \alpha_k \rho_k \underline{g} + P\nabla\alpha_k + M_k^{mass} + M_k^{drag} + M_k^{VM} \tag{2}$$

$$\frac{\partial}{\partial t}[\alpha_k \rho_k e_k] + \nabla\cdot(\alpha_k \rho_k e_k \underline{u}_k) = -\nabla\cdot(\alpha_k q_k) + \nabla\alpha_k \tau_k : \nabla\underline{u}_k - P\frac{\partial}{\partial t}\alpha_k - P\nabla\cdot(\alpha_k \underline{u}_k) + I_k + Q'''_k \tag{3}$$

where α_k, ρ_k, $\underline{u}_k$, P_k, and Γ_k are the k-phase volume fraction, density, velocity, pressure, and interface mass transfer rate, respectively. M_k represents the interfacial momentum transfer due to the mass exchange, the drag, and the virtual mass.

3. Numerical Methods

The governing equations are discretized using the FVM (Finite Volume Method) where all the primary variables are defined at cell center. The discretized equations are solved by the semi-implicit method. At first, the momentum equations are solved explicitly as:

$$\underline{u}^*_{k,i} = \underline{\gamma}^n_{k,i} + \beta_{k,i}\nabla P^n_i, \tag{4}$$

where, superscript * indicates a temporal value. Then the new velocity is implicitly linked to a new pressure from the momentum equation as given by:

$$\underline{u}^{n+1}_{k,i} = \underline{\gamma}^n_{k,i} + \beta_{k,i}\nabla P^{n+1}_i. \tag{5}$$

Summing up the phasic continuity equations we obtain:

$$\sum_k \frac{\nabla\cdot(\alpha_k \rho_k \underline{v}_k^{n+1})}{\rho_k} = \Gamma_v^{n+1}\left(\frac{1}{\rho_v} - \frac{1}{\rho_l}\right) - \frac{\alpha_v}{\rho_v}\frac{\rho'_v}{\Delta t} - \frac{(1-\alpha_v)}{\rho_l}\frac{\rho'_l}{\Delta t}, \tag{6}$$

where variables with no superscript are the old values. The pressure equation can be derived by combining Eqs.(4), (5), and (6).

$$D_i P'_i + \sum_j D_{ij} P'_j = D_i^S \tag{7}$$

The four scalar equations are integrated over a computing cell. In this step, the convection terms are treated using implicit velocities while the convected quantities such as the void fraction and density are treated explicitly. For the non-linear terms, first order Taylor series expansions at the old time step are used to linearly obtain variables at new time step.

4. Numerical Results

The largest SBLOCA is assumed by the instantaneous guillotine rupture of the ECCS line connected to the RPV. Four pipes of 50.8 mm in diameter were installed at the elevation of the RCP for the emergency core cooling system (ECCS) injection. And one of the two ECCS pipes is assumed to be broken as the initiating event. Only one ECCS pump delivers safety injection water into the reactor vessel. The other two ECCS pumps are not available due to a single failure of diesel generator.

A steady state condition at 100% power was simulated before the calculation of SBLOCA. Fig.1 and Fig.2 show the pressure and void fraction profile at the steady state.

The primary system pressure decreases rapidly with the loss of coolant as shown in Fig. 3. The continuous decrease of primary pressure results in the actuation of the ECCS, which compensates for the inventory loss of primary coolant. The ECCS bypass through the break is hardly occurs and all the ECCS flow reaches to the core. This is illustrated in Fig. 4. The steam was clearly separated from the liquid so that the void fraction is very high at the top of the RPV as shown in Fig. 5. This results in the decrease in the mass flow rate through the break. Fig. 6 shows that the coolant level is fairly above the top of the core and becomes to recover at about 2000 seconds with the ECCS actuation.

5. Conclusions

A three-dimensional thermal hydraulics code has been developed for the analysis of SBLOCA for the SMART. The rapid transient two-phase flow with flashing, boiling and condensation was successfully simulated. The ECCS injection bypass through the break was negligible and dose not effect the coolant recovery.

REFERENCES

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[3] H. Y. Yoon et al., “An Unstructured SMAC Algorithm for Thermal Non-equilibrium Two-Phase Flows,” *International Communications in Heat and Mass Transfer,* Vol. 36, 16–24 (2009).

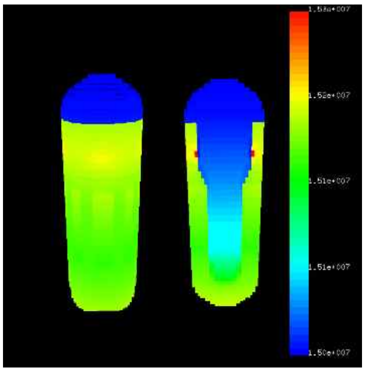

Figure 1. Steady State Pressure Profile

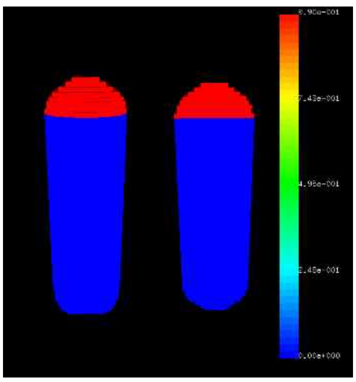

Figure 2. Steady State Void Profile

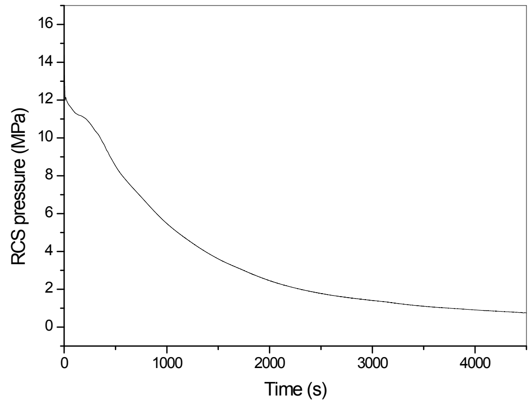

Figure 3. RCS Pressure

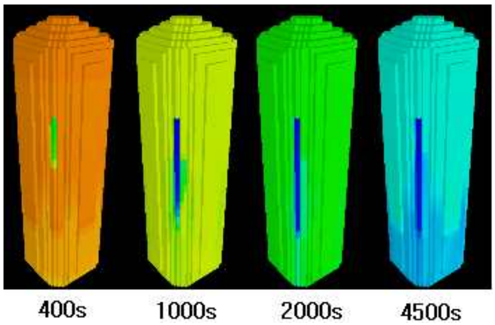

Figure 4. RCS Temperature

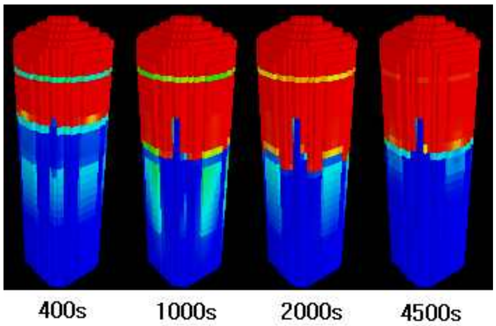

Figure 5. RCS Void Fraction

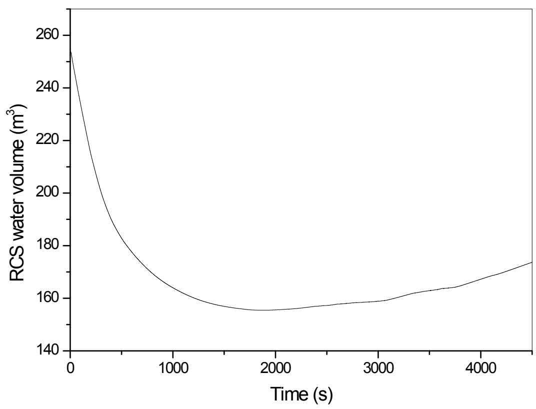

Figure 6. RCS Water Volume