3-Dmensional Analysis of the Two-Phase Natural Circulation Flow

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1. Introduction

To observe and evaluate the two-phase natural circulation phenomena through the gap between the reactor vessel and the insulation in the APR1400 under the external vessel cooling, the T-HERMES (Thermo-Hydraulic Evaluations of Reactor vessel cooling Mechanisms by External Self-induced flow) program has been performed in KAERI [1]. The HERMES-HALF study [2], which is one of the T-HERMES programs, is a non-heating experimental study on the two-phase natural circulation through the annular gap between the reactor vessel and the insulation. In the present research, the HERMES-HALF experiments were simulated numerically to analyze the effect of the amount of the air injection on void fraction and mass flow rate of cooling water in nuclear cavity.

2. Methods and Results

CFX-5.7 was used as a numerical analysis tools to solve the unsteady, three-dimensional Reynolds averaged Navier-Stokes equations for multi phase flow with zero equation turbulence model.

2.1 Governing Equations

Continuity equation

$$\frac{\partial}{\partial t}(\gamma_\alpha \rho_\alpha) + \nabla \cdot (\gamma_\alpha \rho_\alpha \vec{U}_\alpha) = 0$$

Momentum equation

$$\frac{\partial}{\partial t}(\gamma_\alpha \rho_\alpha \vec{U}_\alpha) + \nabla \cdot (\gamma_\alpha (\rho_\alpha \vec{U}_\alpha \otimes \vec{U}_\alpha))$$

$$= -\gamma_\alpha \nabla P_\alpha + \nabla \cdot \left(\gamma_\alpha \mu_\alpha \left(\nabla \vec{U}_\alpha + (\nabla \vec{U}_\alpha)^T \right) \right) + \vec{M}_\alpha$$

Volume conservation equation

$$\sum_{\alpha=1}^{N_P} \gamma_\alpha = 1$$

where, α represents phase, γ is void fraction of each phase and N_p means number of phases.

The complete set of hydrodynamic equations represent $4N_p+1$ equations in the $5N_p$ unknowns, U_α, V_α, W_α, γ_α, P_α. We need N_p-1 more equations to close the system. These are given by constraints on the pressure, namely that all phases share the same pressure field

$$P_\alpha = P \qquad for\ all \quad \alpha = 1, \cdots\cdots, N_p$$

Interphase momentum transfer, $\vec{M}_\alpha$, can be written as follows

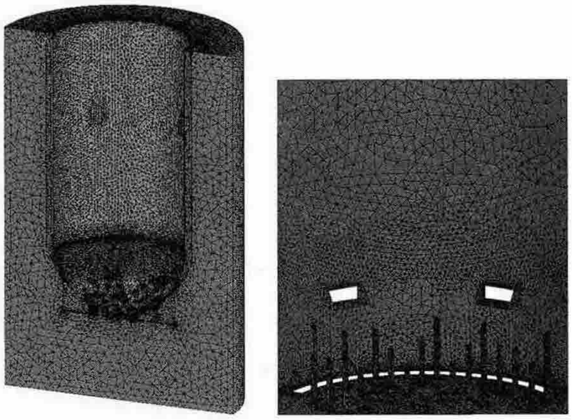
$$\vec{M}^D_{\alpha\beta} = c^d_{\alpha\beta}\left(\vec{U}_\beta - \vec{U}_\alpha\right),$$

$$c^d_{\alpha\beta} = \frac{3}{4}\frac{C_D}{d_p} r_\beta \rho_\alpha \left|\vec{U}_\beta - \vec{U}_\alpha\right|, or = \frac{C_D}{8} A_{\alpha\beta} \rho_\alpha \left|\vec{U}_\beta - \vec{U}_\alpha\right|$$

where, $A_{\alpha\beta}$ is an interfacial area between phase α and β.

In the present calculation, Grace drag model was adopted to model the drag coefficient.

2.2 Grid System and Boundary Conditions



(a) front view (b) shear key & ICI nozzle

Figure 1. Grid system.

To increase the grid quality, the overall grid system, as shown in Figure 1, was generated circumspectly using ICEM CFD 4.0 which can handle the complex geometry.

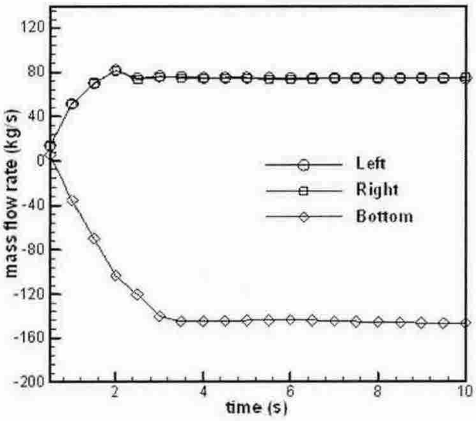
Considering the symmetry of the geometry, half region was considered. Four different air velocities are set at the hemisphere of the vessel as inlet boundary conditions to simulate the corresponding amount of steam generation under severe accident. Opening condition is used for air ventilation. No slip condition for water and slip condition for air are set at all walls.

2.3 Calculation Strategy

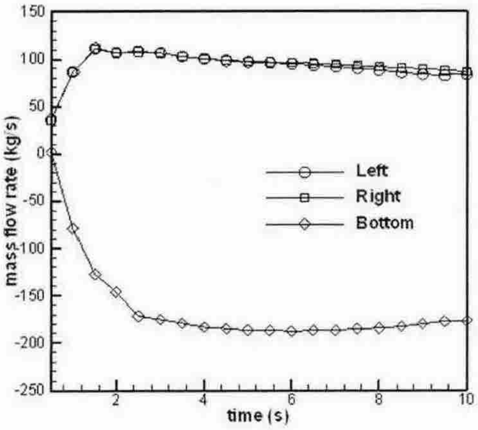
Injected air diameter is 0.005m and surface tension between air and water was set as 0.0725 N/m. Initial water level is 1.5m below from the top of the vessel. Cavity and water pool are filled with the stationary water initially. Total calculation time is 10 seconds after the air injection and time step is set as 0.05 second. Parallel computation was implemented using 5 Pentium IV 2.4 GHz PC and 72 hours were required to complete the calculation.

2.4 Mass Flow Rate of Cooling Water

Figure 2 shows the mass flow rate of cooling water at each hole which is named as left, right and bottom hole, according to the amount of injected air. The left (or right) hole has a rectangular shape (0.2×0.375m), the height from the bottom of the reactor vessel to the center of the left(or right) port is 3.384m. The area of the bottom hole is 0.15m^2. Case C2($\dot{m}_{air}$=0.342kg/s) has two times larger amount of injected air than Case C1($\dot{m}_{air}$=0.171kg/s). It shows that increase of air injection does not lead the linear increase of the mass flow rate of cooling water. The circulation mass flow rates of cooling waters in cases of C1 and C2 are calculated as 149kg/s and 171kg/s, respectively. These values coincide with the HERMES-HALF experimental data (C1:132kg/s, C2:151kg/s) within 13% error bounds.



(a) Case C1



(b) Case C2

Figure 2. Mass flow rate of cooling water

2.5 Void Fraction Distribution

Figure 3 represents the void fraction distribution. In figure 3, the z means the relative height from the bottom of the reactor vessel. Sudden increase of void fraction occurs due to the flow separation around the shear key and subsequent drop is found at the minimum gap of cavity. It is thought that void fraction distribution is proportional to the amount of air injection.

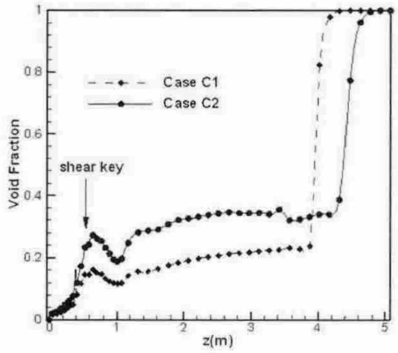


Figure 3. Void fraction distribution.

3. Conclusion

Three-dimensional, unsteady and multi-phase natural flow in nuclear cavity was simulated to analyze the flow characteristics. Two different cases, according to the amount of air injection, were calculated.

From the results, we conclude that the amount of air injection does not have a significant effect on the mass flow rate of cooling water, but its effect is considerable for the void fraction distribution.

By extending the present numerical analysis, shear key and ICI nozzle effects on flow characteristics will be performed in near future.

Acknowledgments

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References

[1] K. S. Ha, R. J. Park, H. Y. Kim, S. B. Kim, and H. D. Kim, A Study on the Two-Phase Natural Circulation Flow through the Annular Gap between a Reactor Vessel and Insulation System, Int. Comm. in Heat and Mass Transfer, Vol. 31, No. 1, pp.43-52, 2004.

[2] K. S. Ha, R. J. Park, S. B. Kim, and H. D. Kim, Preliminary HERMES-HALF Experiments and Natural Circulation Flow Analyses using RELAP5/MOD3,2004 KNS Spring Meeting, May, 2004.