An Application of CUPID Reactor Vessel Module to a Three-Dimensional PWR LBLOCA Simulation

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1. Introduction

As needs for the simulation of multi-dimensional behavior in the safety analysis are increasing, the conventional system thermal-hydraulics codes have devoted their efforts to develop a three-dimensional module. After having developed 1-D system analysis code, MARS, the Korea Atomic Energy Research Institute (KAERI) began to develop the CUPID code to address the need for a multi-dimensional analysis. The CUPID code, which is solved by using an unstructured finite volume method supported by MPI parallel processing, has been developed as a CMFD code to deal with huge mesh to model very complicated geometries realistically. Recently, the reactor vessel model such as a package of interfacial heat and momentum transfer model, wall friction and wall-to-fluid heat transfer model were implemented in the CUPID and named CUPID-RV module. The final goal of this work is the LBLOCA analysis on the rod-by-rod level, and therefore the work is focused on the validation of LBLOCA T/H phenomena and the application to three-dimensional LBLOCA simulation. In this paper, a brief for CUPID reactor vessel module and a three-dimensional LBLOCA simulation for APR1400 on the assembly-by-assembly level as a CUPID-RV application were introduced.

2. Methods and Results

In this section CUPID reactor vessel module and the application results are described.

2.1 CUPID Mathematical Model

A set of two-fluid conservation equations [1], which is used in nuclear system analysis code, is adopted to establish CUPID-RV module.

$$\frac{\partial}{\partial t}(\alpha_g \rho_g) + \nabla \cdot (\alpha_g \rho_g \vec{u}_g) = \Gamma_v + \Gamma_{wall} \tag{1}$$

$$\frac{\partial}{\partial t}(\alpha_l \rho_l) + \nabla \cdot (\alpha_l \rho_l \vec{u}_l) = -\Gamma_v - \Gamma_{wall} \tag{2}$$

$$\frac{\partial}{\partial t}(\alpha_g \rho_g X_n) + \nabla \cdot (\alpha_g \rho_g X_n \vec{u}_g) = 0 \tag{3}$$

$$\begin{aligned}&\frac{\partial}{\partial t}\left(\alpha_g \rho_g \vec{u}_g\right) + \nabla \cdot \left(\alpha_g \rho_g \vec{u}_g \vec{u}_g\right) = -\alpha_g \nabla P + \nabla \cdot \left(\alpha_g \mu_{g,eff} \nabla \vec{u}_g\right) \\ &+\alpha_g \rho_g \vec{g} + \overrightarrow{\mathrm{M}}_g^{mass} + \overrightarrow{\mathrm{M}}_g^{drag} + \overrightarrow{\mathrm{M}}_g^{non-drag} + \overrightarrow{\mathrm{M}}_g^{VM} + \overrightarrow{\mathrm{M}}_g^{WF}\end{aligned} \tag{4}$$

$$\begin{aligned}&\frac{\partial}{\partial t}\left(\alpha_l \rho_l \vec{u}_l\right) + \nabla \cdot \left(\alpha_l \rho_l \vec{u}_l \vec{u}_l\right) = -\alpha_l \nabla P + \nabla \cdot \left(\alpha_l \mu_{l,eff} \nabla \vec{u}_l\right) \\ &+\alpha_l \rho_l \vec{g} + \overrightarrow{\mathrm{M}}_l^{mass} + \overrightarrow{\mathrm{M}}_l^{drag} + \overrightarrow{\mathrm{M}}_l^{non-drag} + \overrightarrow{\mathrm{M}}_l^{VM} + \overrightarrow{\mathrm{M}}_l^{WF}\end{aligned} \tag{5}$$

$$\begin{aligned}&\frac{\partial\left(\alpha_g \rho_g e_g\right)}{\partial t} + \nabla \cdot \left(\alpha_g \rho_g e_g \vec{u}_g\right) = -P\frac{\partial \alpha_g}{\partial t} - P\nabla \cdot \left(\alpha_g \vec{u}_g\right) \\ &+\nabla\left(\alpha_g \vec{q}_g\right) + \frac{P_s}{P} H_{ig}\left[T^s\left(P_s\right) - T_g\right] + \Gamma_v h_g^* \\ &-\left(\frac{P-P_s}{P}\right) H_{gf}\left(T_g - T_l\right) + q''_{g-p} A_{g-p}\end{aligned} \tag{6}$$

$$\begin{aligned}&\frac{\partial\left(\alpha_l \rho_l e_l\right)}{\partial t} + \nabla \cdot \left(\alpha_l \rho_l e_l \vec{u}_l\right) = -P\frac{\partial \alpha_l}{\partial t} - P\nabla \cdot \left(\alpha_l \vec{u}_l\right) \\ &+\nabla \cdot \left(\alpha_l \vec{q}_l\right) + H_{if}\left[T^s\left(P_s\right) - T_l\right] - \Gamma_v h_f^* \\ &+\left(\frac{P-P_s}{P}\right) H_{gf}\left(T_g - T_l\right) + q''_{l-p} A_{l-p}\end{aligned} \tag{7}$$

$$\rho_p \frac{\partial T_p}{\partial t} = k\nabla T_p + S_p \tag{8}$$

2.2 CUPID Reactor Vessel Module

The reactor core model of CUPID-RV is a pack of interfacial heat and momentum transfer model based on a vertical flow regime of MARS, a wall heat transfer model from rod to fluid by the boiling curve, and a wall friction model in a rod bundles. In the calculation, the heat conduction equation is solved at first for a solid rod bundle in a cell, and then, $q''_{g-p} A_{g-p}$, $q''_{l-f} A_{l-f}$, $\overrightarrow{\mathrm{M}}_g^{WF}$, and $\overrightarrow{\mathrm{M}}_l^{WF}$ are calculated using rod surface temperature and rod surface area, channel hydraulic diameter. After that, local void fraction and vertical velocity are used for determining flow regime, and then, $\overrightarrow{\mathrm{M}}_g^{drag}$, $\overrightarrow{\mathrm{M}}_l^{drag}$, H_{ig}, and H_{il} are calculated according to the flow regime.

The key model of the LBLOCA reflood stage is rezoning a heated rod to find out a precise quench front where the transition and film boiling heat transfer correlation from rod to fluid should be changed, for example, from Chen's to Weismann's. For the interfacial model, the weber numbers and minimum value related to the diameter of droplets or bubbles are adjusted for the reflood stage, and then, the interfacial heat transfer and friction terms are changed from the non-reflood to reflood stage.

In order to simulate LBLOCA with the CUPID-RV, critical flow model, gap conductance model, and quenching front model are needed. The Henry-Fauske model[2] and the gap conductance model to consider gap thickness change are adopted to calculate break flow rate and to adjust gap conductance during LBLOCA.

2.3 Application to Large Break Loss of Coolant Accident (LBLOCA) Analysis

A three-dimensional LBLOCA analysis has been conducted using CUPID with the above mentioned physical models. A double ended cold leg break of APR1400 [3] has been simulated with 4 direct vessel injection (DVI) of emergency core cooling water. 47,713 hexahedral meshes were used where 241 fuel assemblies are modeled with 20 axial meshes as shown in Fig. 1.

Two hot legs are set to pressure boundaries, and four cold legs are set to inlet flow boundaries. The full power operation is conducted with constant inlet low rates at 4 cold legs during steady state. To simulate blowdown phase, all of legs are closed and one cold leg is assigned to be a break with critical flow model and 4 DVIs inlet flow boundaries are set. The core power is reduced to about 7% of rated power with chopped cosine shape axial distribution to simulate the decay power. Considering the single failure, two high pressure safety injection pumps (HPSIPs) delivers emergency core cooling (ECC) water into the core when the pressure falls below 12.46 MPa. And 4 safety injection tanks (SITs) start to discharge water when the pressure is below 4.31 MPa. All of legs are set to pressure boundaries after the pressure at a break site get down to ambient pressure to simulate refill and reflood phases.

The calculated contours are shown in Fig. 2 where a steady state calculation has been conducted for the first 100 seconds before the start of the accident. Colors of the reactor vessel represent void fraction distribution where blue shows the liquid and the colors of the fuel assembly indicate the fuel rod wall temperature. Coolant blowdown starts at 100 second and the pressure decreases rapidly to the atmospheric pressure in 20 seconds. At 100.12 second, the pressure reaches the HPSIP setpoint of 12.5MPa and the ECC water is delivered at 140.12 second with 40 seconds of delay time. The SIT discharge starts at 115 second when the pressure is decreased to 4.31 MPa. At around 130 second, refill phase starts and the ECC water recovers the reactor core after 140.12 second. The three-dimensional LBLOCA has been successfully simulated with CUPID in component-scale. As a further study, examination of the safety analysis margin of the one-dimensional LBLOCA analysis will be continued based on the non-uniform radial power distribution model.

The primary variable transients are presented in Fig. 3. In the Fig. 3(a) The break flow concentrates at 100 s and ceases at 125s. The pressure, which is 15 MPa at steady state, drops to 5MPa right after the LBLOCA, and then falls to ambient rapidly. In the Fig. 3(a) and (c), the SI flow from SIT starts at 115 s with fast mode to 175 s and change into slow mode and lasts until 330s. The SI flow from HPSIPs starts at 140 s and lasts long term cooling. The core power reduces from 280 MW to10 MPa according to 7% of rated power with chopped cosine shape in Fig. 3(b). In Fig. 3(d), the blowdown PCT and the refill PCT are observed at 912K at 103s and at 1080K at 152s.

3. Conclusions

In this paper, recent development and validation of CUPID reactor vessel module, CUPID-RV, is discussed. A pack of interfacial and wall heat and momentum transfer model including reflood model was implemented, and three calculations for Edward pipe, FLECHT SEASET 31701 and UPTF 201/III were conducted to validate CUPID-RV capability for critical flow, LBLOCA reflood in rod bundles, and ECC delivery in downcomer. The calculation results indicates that reactor core module seems to be implemented properly, and therefore, it is applied to a reactor calculation, 3-dimensional LBLOCA though it is very challenging due to the complexity of models and correlations used in blowdown, refill and reflood transient analyses. The 3D LBLOCA calculation results indicates that the CUPID-RV module can be applied to the 3-dimensional reactor safety analysis in the future.

ACKNOWLEDGMENTS

This work was supported by the National Research Foundation of Korea (NRF) and the Korea Foundation of Nuclear Safety (KoFONS) grant funded by the Korean government (MSIP & NSSC) (Nuclear Research and Development Program: 2017M2A8A4015005 & 2017M2A8A2055743, Nuclear Safety Research Center Program: 1305011).

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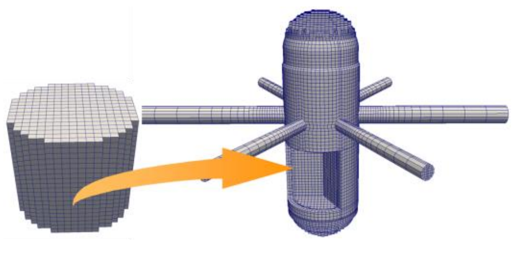
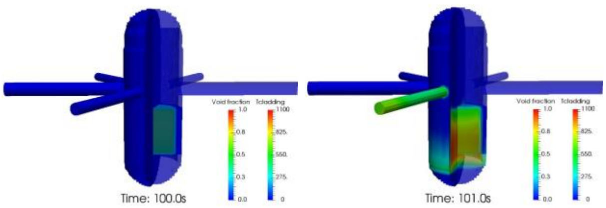
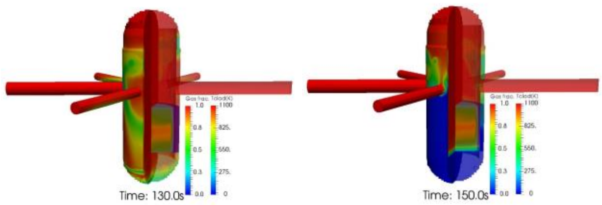


Fig. 1. Three-dimensional Mesh Model for APR1400 LBLOCA Analysis

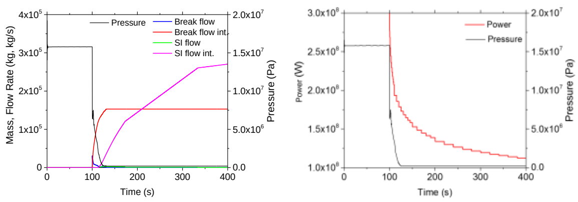


(a) Steady State (b) Blowdown

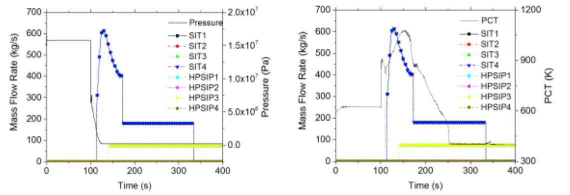


(c) Refill (d) Reflood

Fig. 2. Three-dimensional Contours Obtained from LBLOCA Simulation



(a) Break flow (b) Power



(c) SI flow (d) PCT

Fig. 3. Pimary Physical Properties during LBLOCA Simulation