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Steam Line Break accident analysis with multi-scale/multi-physics methodology

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1. Introduction

Steam line break accident (SLB) in the nuclear reactor is one of the representative Non-LOCA accidents in which thermal-hydraulics and neutron kinetics are strongly coupled each other. Thus, there have been enormous effort to investigate SLB analysis with multi-physics methodology which has been used to make it possible to visualize the nuclear reactor fuel assembly region realistically. The coupled calculation between thermal-hydraulics and three-dimensional neutron kinetics is essential and necessary to obtain the realistic solution. [1, 2]

Recently, CUPID-RV, has been developed for three-dimensional reactor thermal-hydraulics analyses. The purpose of the CUPID-RV is to quantitatively examine a safety margin for hypothetical accidents such as LOCA and SLB and consequently secure the integrity of the NPP design. In addition, neutron kinetics code, MASTER [3], has been coupled for realistic behavior of reactor power output and system-scale code, MARS is coupled for thermal-hydraulics behavior of the rest of reactor coolant system (RCS).

2. Numerical Methodology

2.1 Coupling Scheme

To describe two-phase flows, a transient two-fluid three-field model is adopted in the CUPID code [4]. The three fields represent a continuous liquid, an entrained liquid (i.e., droplets), and a vapor field. In the three-field model, the mass, energy, and momentum equations for each field are established separately and, then, they are linked by the interfacial mass, energy, and momentum transfer models.

For a mathematical closure, the equations of the states and the constitutive relations for the interfacial drag force, the interfacial heat transfer and the wall boiling model are necessary. The reactor core model of CUPID-RV includes the interfacial heat and momentum transfer model based on a vertical flow regime, a wall heat transfer model from rod to fluid by the boiling curve, and a wall friction model in a rod bundles.

The reactor core model of CUPID-RV includes pressure drop model for precise visualization of the flow distribution in the reactor core. The turbulent mixing between neighboring subchannel can be occurred due to the turbulent fluctuation and the flow disturbance by structures such as grid spacer mixing vane. In this study, Equal volume exchange and void drift (EVVD) model is applied.

2.2 Reactor modeling

For the multi-dimensional analysis inside of the reactor pressure vessel (RPV), in-house preprocessor, RVMesh-3D, is developed. First of all, two-dimensional mesh is made according to the resolution the user would like to investigate. As shown in Fig 1, the resolution for the fuel assembly region as well as downcomer can be freely changed. The total number of subchannel-scale mesh is about 72,000 including radially 10 meshes for downcomer region.

For generating an entire RPV geometry, the two-dimensional mesh is extruded with axial geometric parameter which can be defined in a simple text-based input file. Important parameter for three-dimensional geometry, heights of each layer for lower plenum, fuel assembly region, barrel in/outside at leg level, upper region, etc. In addition, the number of cold leg and hot leg and their angular pitch are also defined in input file. Thus the whole geometry of RPV can be generated. Total number of meshes for assemble-scale and subchannel-scale is about 21,000 and 5,300,000, respectively. The resolution is freely changed according to the two-dimensional mesh. Each subregion such as downcomer and lower plenum can be easily changed spatial resolution. Various resolutions have been done for mesh sensitivity so that current mesh system is applied for transient calculation.

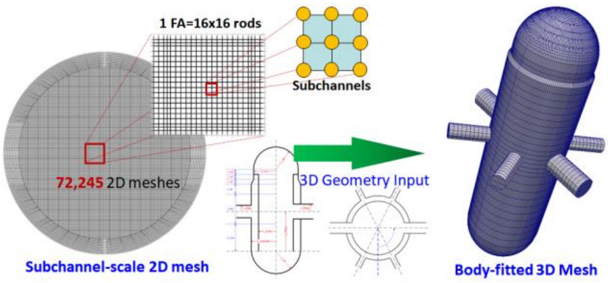

Fig. 1. Mesh generation of RPV using RVMesh-3D

3. Results

Multi-physics calculation is carried out for normal operation condition of the Pressurized Water Reactor (PWR) OPR1000. Since CUPID-RV can be parallelized based on domain decomposition scheme, the simulation is run in parallel computing hardware. The computational domain is partitioned into 250 subdomain and METIS library is used for arbitrary domain partitioning. From the subchannel-scale simulation, detailed thermal-hydraulic distribution can be obtained as shown in Fig. 2. Here, the power distribution is the solution of the MASTER code. Chopped-cosine shape of an axial power distribution can be observed for steady state simulation.

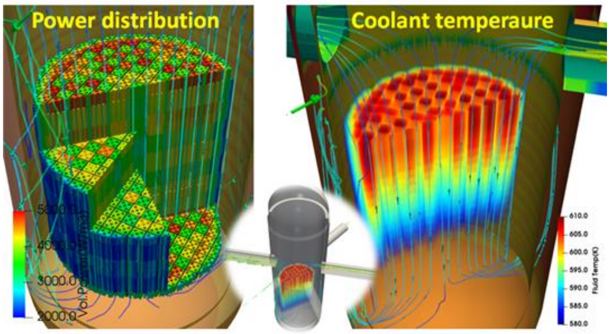

Fig. 2. Steady state distribution of the reactor core

For transient calculation, SLB accident when the off-site power is still available is simulated. In this accident, it is important to examine the mininum DNBR after reactor is tripped. Thus short transient is calculated. When the SLB accident occurs, cold coolant from one of steam generator (SG1) is injected into the reactor core through two cold legs. Consequently, reactor core power increases due to sudden injection of cold coolant from the SG. The setpoint of overpower trip signal activation is set to 121%. The time-history of core power is plotted in Fig. 3. The neutron power (black line in Fig. 3) is directly calculated by the neutron kinetics code, MASTER. Since the CUPID-RV includes heat structure model, the thermal power can be obtained by integrated heat flux from outer surface of fuel cladding.

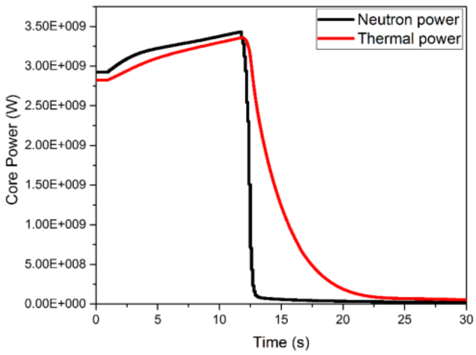

Fig. 3. Core power behavior

The snapshot of power and thermal-hydraulics distribution is shown in Fig. 4. Left figure is power distribution, and liquid temperature and DNBR is visualized at top-right and bottom-right, respectively. At time is 12.3. sec in which the core power reaches almost setpoint, the power distribution at lower fuel assembly region is locally increased.

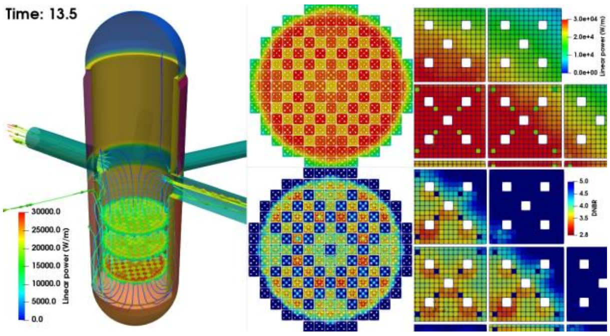

Fig. 3. Power and DNBR distribution prior to reactor trip

4. Conclusion

The steady state of the reactor vessel was obtained by CUPID-RV/MASTER co-simulation. The steady state is properly reproduced according to the normal operation condition of OPR1000. Consequently, the SLB accident scenario was simulated. By abrupt injection of cold coolant, incomplete thermal mixing occurred in lower plenum and asymmetric distribution of coolant was injected into the fuel assembly region. Correspondingly, radially asymmetric power distribution was captured in the fuel assembly region.

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