A MARS Modeling for Reactor Multi-Dimensional Flow Mixing Problem

Dong-Jin Euh, Tae-Soon Kwon
Korea Atomic Energy Research Institute (KAERI)
djeuh@kaeri.re.kr

1. Introduction

A mixing behavior of fluids having different property in the nuclear reactor is very important during a transient operation such as a reactivity insertion owing to the rapid boron concentration or overcooling transient. In pressurized water reactors (PWR), boron acid is added to the water coolant to compensate the excess reactivity of fresh fuel loadings. Due to different mechanisms or system failures, slugs of low borated water can accumulate in the primary cooling system. This can happen, e.g. as a consequence of a small break loss of coolant accident (SB LOCA), when coolant circulation is interrupted, steam produced in the reactor core is condensed in the steam generator, and a slug of low boron condensate will accumulate at the cold leg of the primary circuit. During start-up of coolant circulation after refilling the primary circuit with emergency cooling (ECC) water or by switching on the first main coolant pump (MCP), this slug will be transported into the reactor core causing a significant reactivity insertion by decreasing the amount of neutron absorber. The mixing of the deborated condensate with borated water in the reactor pressure vessel is in that case the only mitigative mechanism to prevent severe accident consequences.

The mixing is also relevant in overcooling transients, when the coolant temperature in one or more loops decreases, e.g. due to a leak in the secondary side steam system[1]. A strong decrease of the coolant temperature does also cause a reactivity insertion due to the enhanced moderation of neutrons. Mixing is relevant not only for nuclear safety, but also for structural integrity. In the case of LOCAs, cold ECC water will be injected into the hot primary circuit. When plumes of cold water get in contact with the reactor pressure vessel (RPV) wall, thermal stresses occur, which can be dangerous for the RPV integrity. Mixing is even of relevance for normal reactor operation, e.g. for determination of the coolant temperature distribution at the core inlet in the case of partially switched off MCPs.

As a recent license issue of the new reactors, the postulated deborated characteristics are considered as important scenarios. As an example, undesirable deborated water can be entered the reactor by an inadvertent CVCS operation, which can induce boron dilution in the core and then a criticality. The estimation of the arriving time to criticality without operation action is very important for the accident management. For the safety analysis, a perfect mixing assumption is usually adopted at the upstream of the core, in the meanwhile, the reactor inventory is assumed to be minimal value for conservatism, since it can lead the dilution effect more severely.

Most of the computational system codes that are used for the nuclear reactor transient operation and postulated accident scenarios adopt a one-dimensional approach, which has a significant limit to extend their application to the pool based multi-dimensional behavior. To overcome the shortcomings, the system codes have been improved to have the multi-dimensional capability recently. MARS, one of the well-known safety analysis code, has a multi-dimensional flow analysis module, named “multid”. The current study, the MARS performance for the mixing behavior is verified by developing a multi-dimensional model for the nuclear reactor.

2. Model for reactor flow mixing simulation

2.1 Model for the reactor simulation based on the pipe concept for the reactor vessel

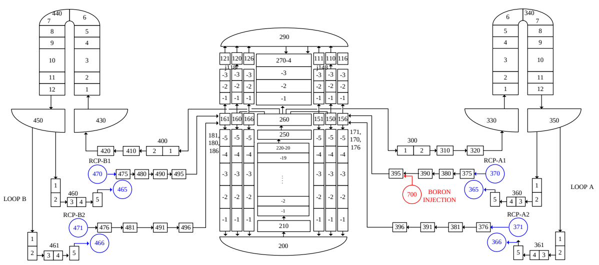


Fig. 1. Pipe model for the reactor simulation

Fig. 1 shows a proposed conventional pipe model for a reactor mixing simulation for the safety analysis in the current study. Generally, the core has three pipe nodes for the average channels, hot channels, and core bypass channels for reactor safety analysis. The core bypass channels are importantly considered for heat transfer although the flowrate is very low. However, since the current study focuses on the momentum aspect of the flow mixing phenomena, the modified model neglected the core bypass channels. Also, the upper head region is simulated by a pipe model by merging the volumes connected to the core bypass channels. The hot channel nodes are merged to the average core channels. Downcomer is simulated by six pipes divided azimuthally to clarify the multi-dimensional phenomena in the downcomer annulus region. The six pipes is connected each other by cross flow junctions. Since the current analysis is for the primary mixing and does not consider the heat transfer, steam generated secondary side system and all the heat structures were eliminated. Still the core is simulated one dimensional pipe model, the model can analyze the mixing phenomena inside not the core but downcomer.

The mixing phenomena is investigated by injecting tracer fluid into a cold leg. The plant is a close loop, which means that the injected tracer fluid is circulated and comes again the injection point. The current analysis changed the closed loop to an artificial open loop to investigate the code performance for the mixing phenomena in respect of the separated effect. The four pump components are changed into boundary volumes for the supply and letdown in the simulated model. So, a steady flow is injected to each the pump discharge cold leg and goes through the reactor downcomer, core, hot leg, and steam generators. Finally the flow is discharged to boundary volumes from the pump suction legs. The simulation is performed under the constant pressure condition, the pressurizer component was also removed. The component information was quoted from the APR1400 reactor design. [2]

2.2 Multi-dimensional model for reactor vessel

The mixing phenomena has a strong multi-dimensional behavior. The model based on the pipes is one dimensional approach, which has a limit to predict the multi-dimensional phenomena of the fluid mechanism although the downcomer is modeled by azimuthally divided with six pipes.

To clarify the mixing behavior, two "multid" components were adopted for the downcomer and core, respectively. The new model for the reactor mixing simulation is represented by Fig. 2.

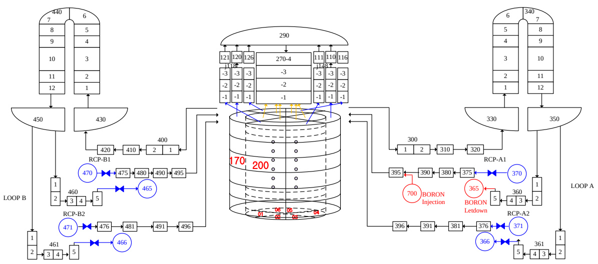


Fig. 2. New model for the reactor mixing simulation

The lower downcomer region including the cold leg and hot leg nozzle elevation is modelled by a "multid" component. The feature of nodalization of the new model is same as the previous conventional pipe model, which has axially 6 and azimuthally 6 nodes. The new model has a fixed geometrical dimension for the lower downcomer region based on inner diameter and outer diameter. The volume of each node is controlled by volume porosity factor. Junctions are also controlled by an area factors. All the geometrical and pressure loss factor parameters are quoted from the conventional base model. Figure 3 shows the downcomer multi-dimensional model. The connection to the upper downcomer annulus is performed by multi junctions. The bottom of the downcomer is connected to the top of the lowest volume of core multi-dimensional component, which represents lower head corresponding to the volume-200 of the conventional pipe model.

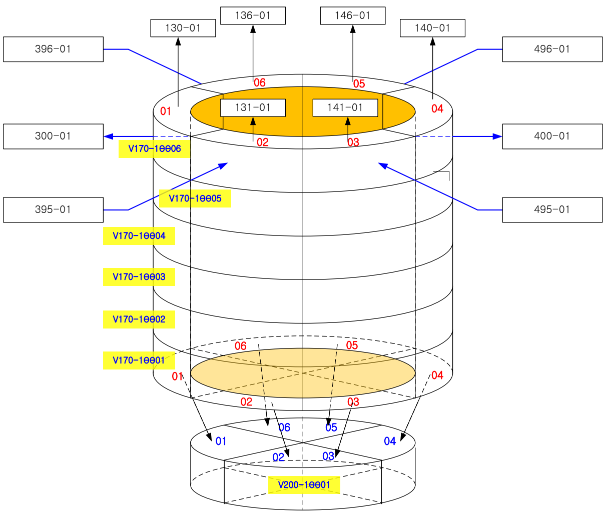


Fig. 3. Downcomer multi-dimensional model for the downcomer

The core region is simulated by 6 azimuthal node and 24 axial nodes. The axial 24 elevations represent one level for the lower head, one level for the low plenum, 20 levels for core, and 2 levels for upper plenums. The geometrical information is quoted from the conventional pipe model. The top of the core model is connected to the upper head and hot legs.

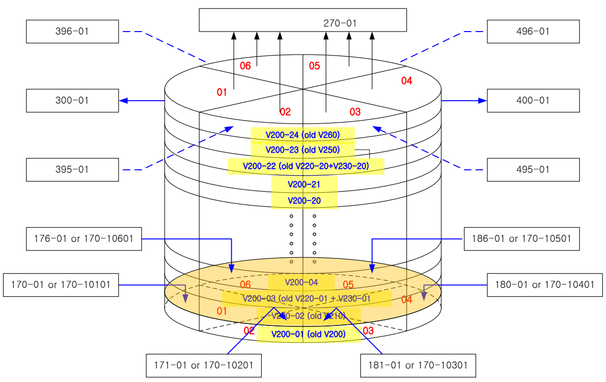


Fig. 4. Core multi-dimensional model

2.3 Boundary conditions

The temperature and pressure condition is based on hot zero power condition. Since the current phenomena assumes an isothermal condition, no power was added to the system. The initial and boundary thermal hydraulic conditions are summarized by Table 1.

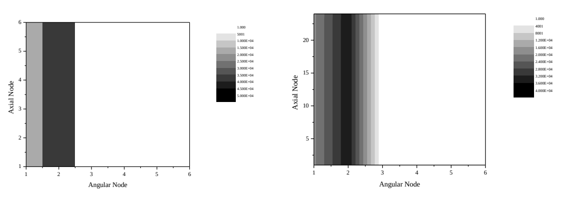
Table 1. Major boundary conditions

Design Parameter	Value
Normal Power, MWt	0
Hot leg P., MPa	15.6
Core Inlet Temp., K	564
Core Outlet Temp., K	597
Reactor Flow, kg/s	20990

After a steady state achieved, the tracer fluid is injected to a cold leg of loop A1.

3. Results

Fig. 5~7 show the resultant mixing behavior of the injected tracer fluid from the cold leg 1A. In the figure, x-axis is azimuthal node number and y-axis is a axial node number. The dark degree is that of the tracer concentration. The injected tracer fluid does not show significant mixing in the reactor for the nominal flow condition as shown in figure 5. The hot leg split of the injected tracer is almost one side, of which the ratio is 0.998:0.002. The second case is low flow case. In general the low flow condition a more mixing phenomena is expected but the results don't show the trend. The results are similar to the high flow condition case. The hot leg split of the injected tracer is almost one side either, of which the ratio is 0.993:0.007. The above two flow boundary condition is balanced flow. So, if the code does not have proper model for the turbulent dispersion force, the force balance is hard to simulate the mixing behavior. If the flow itself is unbalanced, the momentum transfer can show the mixing phenomena. So, unbalanced flow condition is simulated by considering 100% flow at loop 1A and 90% flow for the other 3 cold leg flows. The results are shown in Fig. 7, which show a meaningful mixing behavior in the downcomer and core. The resultant hot leg split is 0.878: 0.1218. Although the absolute values should be validated with accurate evidential database, the mixing phenomena is well represented in the new model.



(a) (b)

Fig. 5. Mixing behavior of (a) downcomer and (b) core, respectively for the nominal flow condition

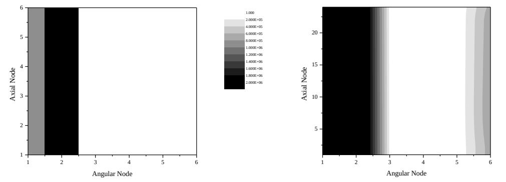


Fig. 6. Mixing behavior of (a) downcomer and (b) core, respectively for the 2% of nominal flow condition

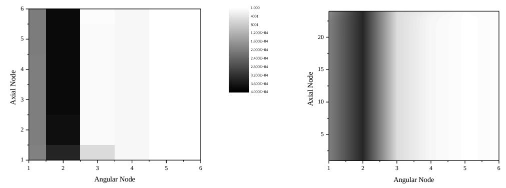


Fig. 7. Mixing behavior of (a) downcomer and (b) core, respectively for the unbalanced flow condtion: 100% of loop 1A flow and 90% of loop 1B and 2A, 2B flow of nominal value.

3. Conclusions

In the present paper, a multi-dimensional performance of the system code, MARS to predict the mixing behavior inside reactor vessel. For the verification, the lower downcomer and core were modeled by using "multid" component of MARS. As the results, the new model can simulate the multi-dimensional behavior of the reactor mixing problem. However, a methodology for application the turbulent dispersion characteristics is required for the proper mixing phenomena especially for the flow conditions having a balance momentum force between boundaries.

REFERENCES

[1] S. Kliem et al., Description of the Slug Mixing and Buoyancy Related Experiments at the Different Test Facilities (Final Report on WP2), EU/FP5 FLOMIX-R Report, FLOMIX-R-D09. FZRossendorf, Germany, ISSN 1437-322X, 2004.
[2] "Standard Safety Analysis Report for Korean Next Generation Reactor," KEPCO Report, Korea(1999).
[3] MARS code manual, Volume II: input requirement, KAERI/TR-2811/2004, KAERI(2004).