Numerical analysis of APR1400 Steam Generator by CUPID/MARS heat structure coupling

Jae Ryong Lee[a*], Seung Jun Lee[a], Ik Kyu Park[a], Han Young Yoon[a], Hyoung Kyu Cho[b]
[a]*Korea Atomic Energy Research Institute,1045 Daeduk-daero, Daejeon, Korea, 305-353*
[b]*Seoul National University, 1, Gwanak-ro, Gwanak-gu, Seoul, 151-744, Korea*
[*]*Corresponding author: jrlee@kaeri.re.kr*

1. Introduction

Steam generators (SG) are one of major components of pressurized water reactors (PWRs). Since a thermal-hydraulic behavior in the secondary side of steam generator such as two-phase boiling flow, flow-induce vibration of U-tubes is quite complicated, the importance to numerically investigate the flow behavior has been arisen. To design and analyze steam generators, many computer codes have been developed and used around the world.

In this study, the coupled CUPID and MARS code was used for the simulation of boiler side of the PWR steam generator. This paper presents the description of the coupling method, validation for porous media approach against the rod bundle experiment and the preliminary simulation results of PWR steam generator using the coupled code..

2. Numerical Methodology

2.1 Governing equation

The CUPID code [1] adopts the two-fluid model for two-phase flows. In the two-fluid model, the mass, energy, and momentum equations for liquid and vapor phases are established separately, and then, they are linked by the interfacial mass, momentum, and energy transfer models. For a mathematical closure, the constitutive relations for the interfacial momentum transfer, the interfacial heat transfer and the wall heat partitioning are necessary.

2.2 Physical models and correlations

The CUPID code requires a set of constitutive models for a two-phase flow analysis such as the regime map, interfacial area, interfacial heat and mass transfer, interfacial drag. Besides, in porous media approach for huge subchannel flow behavior such as rod bundle in reactor core or tube bundle in steam generator, the CUPID code provides a special package such as flow regime map, interfacial area density, interfacial momentum and heat transfer to capture two-phase thermal hydraulics, which is widely used in system-scale codes such as MARS [2] and SPACE [3] for robustness and easy implementation.

2.3 Data transfer between CUPID and MARS

The coupling between two codes was conducted by sharing the heat structure surface temperatures and the second outmost solid temperatures at every time step by using the interactive control function of the MARS [4]. By using the function, designated pointer variables can be exchanged between MARS and CUPID when the latter calls the dynamic linked library (DLL) of the former. At first, MARS solves the hydrodynamic equations and the conduction equations with given boundary conditions, including the U-tube outer wall temperatures. Then, the second outmost temperature of the heat structure (T_{solid}) in Fig. 1, is transferred from MARS to CUPID. With this solid temperature, CUPID solves the heat balance equation in order to obtain the outer wall temperature (T_{wall}). In this step, CUPID uses flow variables inside the secondary side (for example, the fluid temperature (T_{fluid}), liquid velocity, etc.) calculated by itself.

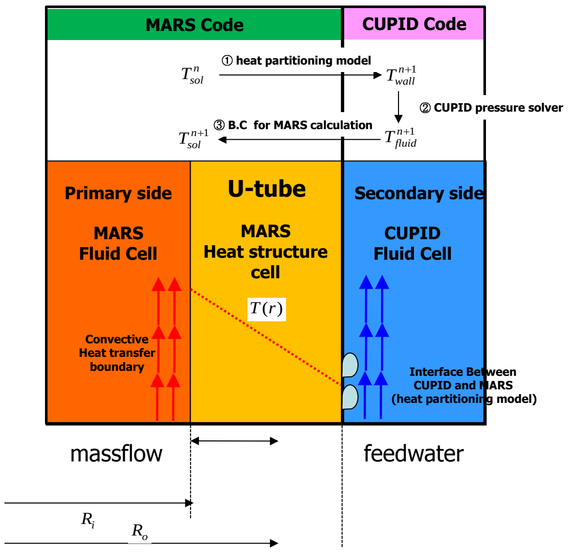

Fig. 1 Coupling method between CUPID and MARS.

2.3 Coupling strategy

For CUPID/MARS coupled simulation, the APR1400 steam generator is taken into account. Fig. 2 shows the one-dimensional nodalization for MARS calculation. The CUPID code handles the secondary side of the steam generator, whereas the MARS code covers the primary side of RCS. Although a pair of steam generator is considered in 1D nodalization, the CUPID code resolves only one of them because the steady state is assumed in entire system. For the boiler region of steam generator, the CUPID code focuses not on the whole geometry but only U-tube region. Since the upper plenum is not taken into consideration, the recirculation ratio is assumed to be a steady state value. The recirculation flow through the downcomer into economizer is assumed to be constant value considering the recirculation ratio. In respect to the computational geometry for CUPID, the tube bundle is modeled as a porous media.

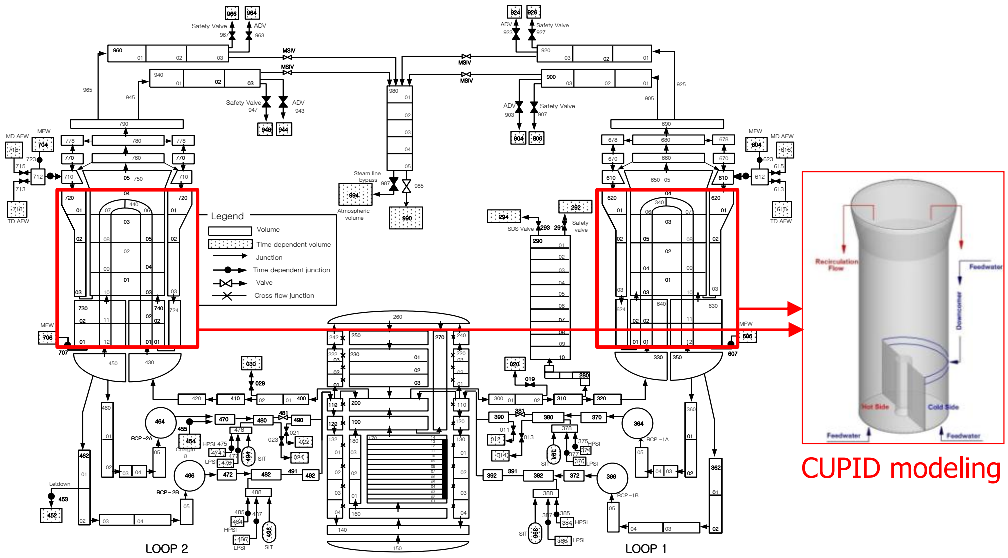

Fig. 2 APR1400 nodalization for CUPID/MARS coupled simulation

3. Results and Discussion

3.1 Grid generation

Since the CUPID code is based on the non-orthogonal body-fitted grid system, the steam generator is modeled by polygonal prism mesh. At first, a radially polygonal meshes are generated, then they area axially extruded. The grids in riser region are enlarged as increasing of height instead of adding additional grids. The divider at bottom region is assumed to be an adiabatic thin wall. All the other structures inside are handled by porous media. Since it is not possible to obtain the porosity manually because of complicated structure configuration as well as unstructured polygonal grid system, an algorithm by using Pro/Toolkit is developed to automatically obtain the porosity with taking into account each non-orthogonal mesh [5]. Prior to access the Pro/Toolkit, 3D CAD file with solid modeler (Pro/E® is used in this study) and computational grid system should be prepared separately. Then, both files are read by Pro/Toolkit algorithm. Finally, the porosity is calculated to take into consideration of flow and obstacle region, respectively.

3.2 Simulation results

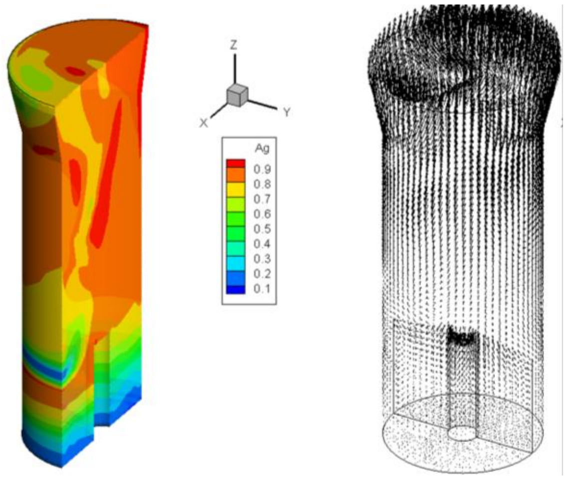

Fig. 3 void fraction distribution and velocity vectors

The coupled code is run from an initial state, and the physical time is 20 sec. Since both codes have their own subroutine to calculate the time step size, the less one is chosen. Normally the time step size of the CUPID code is less than one of MARS due to relatively small size of the computational grid. The MARS code is updated using the time step size from the CUPID code. Since the CUPID code is parallelized based on the domain decomposition technique, a real calculation time can be shortened as much as the processors are involved. About an hour takes to calculate the case in Fig.3 with 6 processors in PC.

Fig. 3 shows the qualitative results of coupled simulation. The configuration for CUPID calculation, three different flow inlets: hot side from bottom, cold side from bottom, and economizer from downcomer. A top surface is assumed to be flow outlet. The heat from the MARS fluid cell is successfully transferred to the CUPID fluid cell with having satisfied the energy balance at the tube surface. As time goes by, the fluid temperature in secondary side increases beyond the saturation temperature, and then the gas phase occurs at upper region.

4. Conclusions

In the present study, the multi-scale thermal-hydraulic analysis method using the coupled CUPID/MARS code was applied for the simulation of the steam generator. The primary side of the steam generator and other RCS was simulated by MARS and the secondary side was calculated by CUPID with porous media approach. For coupled simulation, the porous medium was applied in order to take into account the effect of the U-tube bundle and other supporting structure which play a role to be a flow resistance.

More realistic physical model such as moisture separator slug behavior should be developed for the near future. The application of the coupled simulation should be extended to the accident scenario. In addition, the quantitative comparison between the coupled simulation and measurements will be investigated. Transient scenario also needs to be reproduced by the coupled code.

Acknowledgement

This work was supported by the National Research Foundation of Korea (NRF) and the Korea Radiation Safety Foundation (KORSAFe) grant funded by the Korean government (MSIP & NSSC) (Nuclear Research and Development Program: 2012M2A8A4025647, Nuclear Safety Research Center Program: 1305011).

REFERENCES

[1] H.Y. Yoon et al., “Recent Improvements in the CUPID Code for a Multi-Dimensional Two-Phase Flow Analysis of Nuclear Reactor Components, Nuclear Engineering and Technology, 46, pp.655-666 (2014)
[2] J.J. Jeong, K.S. Ha, B.D. Chung and W.J. Lee, “Development of a multi-dimensional thermal-hydraulic system code, MARS 1.3.1,” Annals of Nuclear Energy, 26(18), pp.1611-1642 (1999)
[3] KAERI Thermal Hydraulic Safety Research Division, “SPACE Code Manual -Models and Correlations,” KAERI (2011)
[4] H.K. Cho, Y.J. Cho and H.Y. Yoon, “Heat structure coupling of CUPID and MARS for the multi-scale simulation of the passive auxiliary feedwater system,” Nuclear Engineering and Design, 273, pp.459–468 (2014)
[5] S.Y. Lee, C.E. Park and J.J. Sohn, “Development of the Porosity Calculation Procedure using Pro/E and Pro/Toolket,” Proceeding of Korean Nuclear Society Meeting, Gwangju, Korea, May 30-31 (2013)