Multi-dimensional Analysis for SLB Transient in ATLAS Facility as Activity of DSP (Domestic Standard Problem)

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1. Introduction

ATLAS test facility is an integral test loop for simulation of various thermal hydraulic phenomena in APR1400 (Advanced Power Reactor 1400 MWe). [1] The test result of the facility has been utilized in DSP (Domestic Standard Problem) activity to investigate the calculation capability of the thermal hydraulic system analysis code and enhance understandings for safety-related phenomena. DSP-01 focused the DVI line break SBLOCA (Small-Break Loss-of-Coolant Accident) simulation in the ATLAS facility, and the DSP-02 was performed with analyzing the cold leg SBLOCA scenario.

DSP-03, which was launched in 2012, selected the SLB (Steam Line Break) transient in the ATLAS test as a reference scenario.[2] In particular, participants of DSP-03 were divided in three groups and each group has focused on the specific subject related to the enhancement of the code analysis. The group A tried to investigate scaling capability of ATLAS test data by comparing to the code analysis for a prototype, and the group C studied to investigate effect of various models in the one-dimensional codes.

This paper briefly summarizes the code analysis result from the group B participants in the DSP-03 of the ATLAS test facility. The code analysis by Group B focuses highly on investigating the multi-dimensional thermal hydraulic phenomena in the ATLAS facility during the SLB transient. Even though the one-dimensional system analysis code cannot simulate the whole system of the ATLAS facility with a nodalization of the CFD (Computational Fluid Dynamics) scale, a reactor pressure vessel can be considered with multi-dimensional components to reflect the thermal mixing phenomena inside a downcomer and a core. Also, the CFD could give useful information for understanding complex phenomena in specific components such as the reactor pressure vessel.

2. Test Condition of the ATLAS

2.1 Description of the ATLAS facility

ATLAS is a half-height and 1/288-volume scaled test facility with respect to the APR1400. ATLAS was designed according to the well-known scaling method suggested by Ishii and Kataoka [3] to simulate various test scenarios as realistically as possible. ATLAS can be used to investigate the multiple responses between the systems for a whole plant or between the subcomponents in a specific system during anticipated transients and postulated accidents. In addition, ATLAS can be used to provide unique test data for the 2 hot legs and 4 cold legs for a RCS (Reactor Coolant System) with a DVI (Direct Vessel Injection) of emergency core cooling (ECC) as shown in Fig. 1. This will expand the currently available data bases for code validation. The detailed scaling analysis results for ATLAS are summarized in the literature [4].

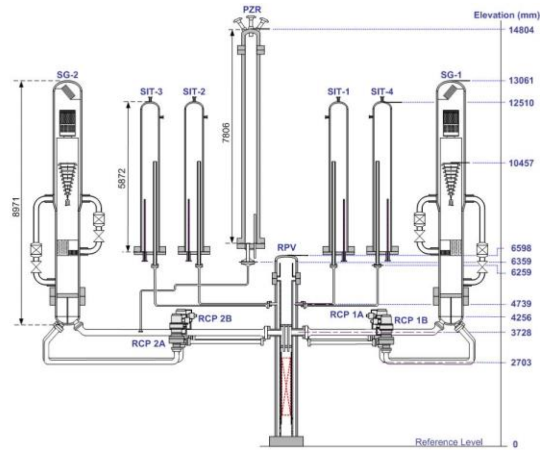


Fig 1. Overview of the ATLAS facility [1]

2.2 SLB transient scenario for the DSP-03

For the DSP-03 activity, the experimental result of SLB simulation in the ATLAS facility was delivered to the participants. The test ID is SLB-GB-02T and it simulated a double-ended guillotine break accident of the main steam line of the APR1400. With an aim of simulating the accident in the prototype as realistically as possible, a pertinent scaling approach was taken, especially focussing on a break flow. The main objectives of this test were not only to provide physical insight into the system response of the APR1400 during the SLB accident but also to produce an integral effect test data to validate the safety analysis codes in the DSP-03 exercise.

The SLB-GB-02T test in the ATLAS facility simulated a double-ended guillotine break at the main steam piping located between the outlet nozzle of the SG (Steam Generator) #1 and the corresponding MSIV (Main Steam Isolation Valve). In the SLB-GB-02T test, considering the safety analysis results for the SLB accident of the APR1400, a single-failure of a loss of a diesel generator, resulting in the minimum safety injection flow to the RPV (Reactor Pressure Vessel), was assumed to occur coincidently with the reactor trip. Therefore, the safety injection water from the SIP (Safety Injection Pump) was only available through the DVI-1 and -3 nozzles, and the safety injection water from the SIT (Safety Injection Tank) was available through all of the DVI nozzles.

The SLB transient in the ATLAS facility showed asymmetric cooling behavior in the primary system due to the increased heat removal rate from the broken steam generator. It affected the different distribution of the natural circulation flow and the fluid temperature in the cold legs of intact and broken loops, so that the coolant in a reactor pressure vessel presented multi-dimensional behavior such as asymmetric temperature distribution in the downcomer or thermal mixing phenomena in the lower plenum. Due to a limitation in the nodalization and constitutive relation of one-dimensional system analysis code, prediction capability for those complex thermal hydraulic phenomena can be improved by adopting multi-dimensional components or analysis tools.

3. Analysis Result

3.1 Organization of Group B in DSP-03

The participants of B group in ATLAS DSP-03 are KEPCO NF, KHNP CRI, SENTECH, EN2T, FNC. The objective of B group is to observe multi-dimensional thermal hydraulic phenomena in vessel using system codes or CFD codes. In this study, TRACE and MARS were used as system codes, CFX was used as CFD (Computational Fluid Dynamics) codes.

KEPCO NF and EN2T developed their own TRACE 3D inputs, and SENTECH developed MARS 3D input. The CFX inputs were developed by KHNP CRI and FNC based on the ATLAS drawings. Due to the lack of vessel axial k-factor information to develop vessel 3D input for system code, KHNP CRI provided axial pressure drops in vessel from CFX calculation results.

3.2 TRACE code analysis

TRACE code was utilized to predict the SLB transient in the ATLAS facility. In order to compare thermal hydraulic phenomena in 1D calculation results with 3D calculation results, TRACE 3D model was additionally developed. In TRACE 3D model, vessel was converted to VESSEL component instead of traditional vessel model which uses PIPE components and single junctions. Except vessel, however, other components inputs were maintained TRACE 1D input. Also, axial k-factors in vessel were modified based on CFD calculation results. Vessel pressures in axial direction were sparsely measured in experiments. KHNP CRI calculated vessel pressures in axial direction were calculated by CFD codes in order to understand thermal hydraulic phenomena in vessel and identify spacer grid effects in the core. Vessel pressure trends in axial direction of calculation results were generally in a good agreement with experimental data.

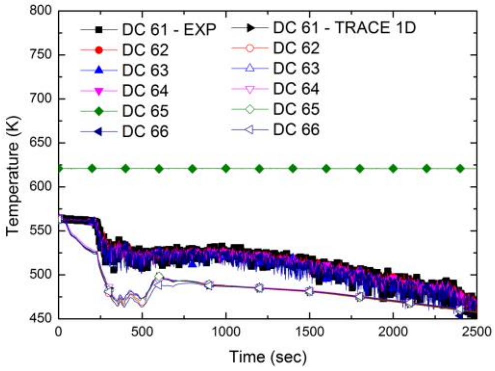
As a typical result of the TRACE code analysis, Fig. 2 shows water temperatures on upper downcomer which are located to underneath DVI nozzle. At the beginning of transient in TRACE 1D when it is before the SIP injection, water temperature is decreased. However, temperature is maintained to 553 K until SIP injection in TRACE 3D calculation. It seems that injected cold water from cold leg by natural circulation is affected on temperature calculation of upper downcomer in TRACE 1D calculation. Moreover, SIP water goes well to next downcomer channel as shown in temperature distribution in 1D calculation.

3.3 MARS code analysis

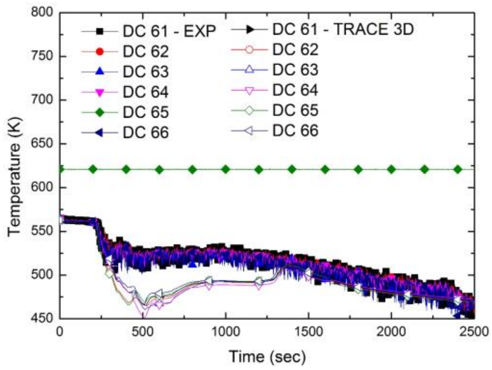
In the activity of MARS code calculation, a reactor vessel was modeled by the MULTID component to investigate the multi-dimensional system effect of a nuclear power plant. The reactor vessel consists of an active core, core bypass, core support instrument, downcomer, upper plenum, and lower plenum.

The 3D input deck was developed for the part of the reactor pressure vessel using the existing 1D input deck. The development of the 3D input deck was modeled using the MULTID component classifying the multi-dimensional thermal-hydraulic volumes, heat structures, and fuels. To model the multi-dimensional thermal hydrodynamic volume and junction, the reactor vessel was modeled with 5 radial rings, 6 azimuthal sectors, and 29 axial nodes. Here, the axial node of each component was based on the exiting one-dimensional (1D) input deck. The active core was modeled with $3\times6\times20$(r-θ-z) nodes. It is assumed that the fuel assemblies are homogeneously distributed only in inner 3 radial rings. The outer 1 radial ring region is modeled as the core bypass. The outer-most 1 radial ring, 6 azimuthal sectors and 27 axial nodes are used for the downcomer region. All junctions were connected to the volumes in the MULTID component. To model the multi-dimensional heat structure, the heat structure corresponding to the multi-dimensional thermal hydrodynamic volume and junction, was modeled again for the multi-dimensional reactor pressure vessel.

Figure 3 shows the comparison of fluid temperature of the downcomer. The temperature distribution consists of the six azimuthal sectors. When comparing the calculated value and the experimental data, the fluid temperatures were lower than that of the experimental data, because the fluid temperature of the 3D calculation was more removed excessively through the affected steam generator when comparing with the experimental data.

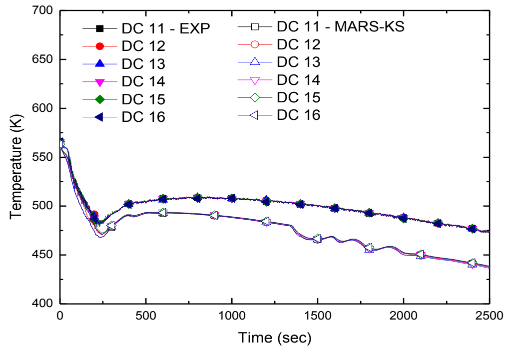


(a)TRACE 1D Calculation Results

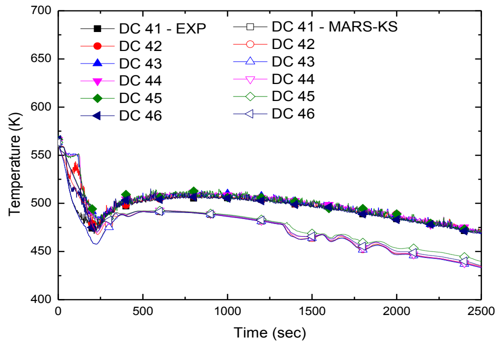


(b) TRACE 3D Calculation Results

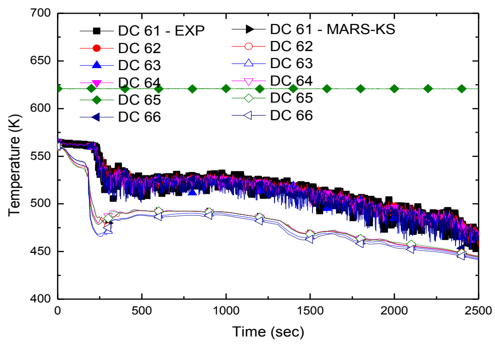
Fig. 2 Water Temperature in Upper Downcomer



(a) Fluid temperature of the lower downcomer



(b) Fluid temperature of the inlet part of downcomer



(c) Fluid temperature of the upper downcomer

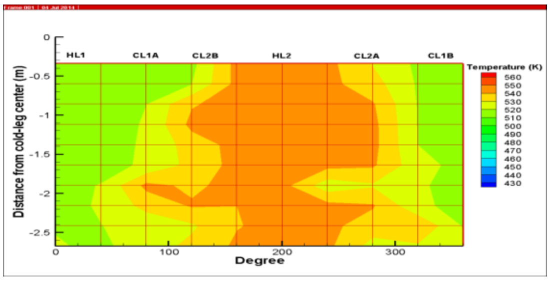
Fig. 3 Comparison of fluid temperature of the downcomer in MARS-KS code calculation

3.4 CFX code analysis

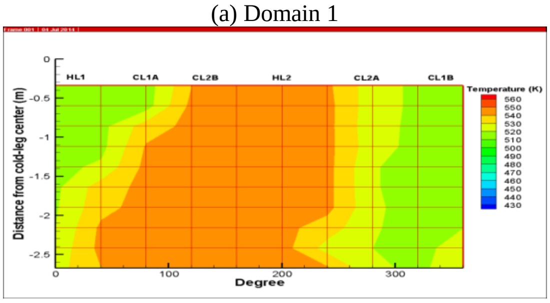
CFD analysis has been conducted to observe the 3D phenomena that cannot be simulated properly using the MARS-KS code. In addition, the CFD analysis has been performed in order to confirm the need for the selection of an appropriate default domain in the CFD analysis for thermal-hydraulic behavior in the downcomer of the ATLAS reactor.

3D geometry and mesh models for the CFD analysis have been generated using the ANSYS-ICEM with the original figure and dimension of the ATLAS reactor. In case of the lower plenum region, the geometry model has been simplified with the same flow volume of the original lower plenum instead of the complicate figure of that region. The tetrahedral meshes have been produced with about 200 million of elements. Especially, fine meshes were distributed in the regions that have a change greatly in the figure such as the cold leg, the flow skirt flow path and so on in order to improve the convergence.

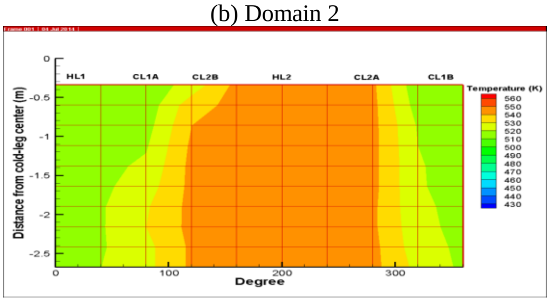
Temperature distributions in the downcomer at 100, are shown in the Fig. 4. Locally different temperature behavior was shown in three domains. In case of the domain 3, the water in the upper part of the downcomer exist relatively hotter than the lower part of that.



(a) Domain 1



(b) Domain 2



(c) Domain 3

Fig. 4 Temperature contour on the downcomer of the ATLAS reactor at 100 sec

On the other hand, CFX code was utilized to model complex structure of the reactor pressure vessel of the ATLAS facility, in order to provide detailed information with respect local loss coefficient. This work also contributed to enhance the understanding multi-dimensional flow phenomena inside the reactor pressure vessel. Figure 5 shows the flow distribution in the lower plenum region. The flow skirt of ATLAS facility is designed as a slot type but the flow skirt of APR1400 is designed as a porous type. Due to the difference design between ATLAS and APR1400, the detailed flow distribution is quite different from the real design as expected. We expected that the most flow flows into the lower plenum region below the space grid 1 after the flow passed through the flow skirt but the flow is bypassed the spacer grid 1. This can result the thermal mixing and asymmetric effect in the core region.

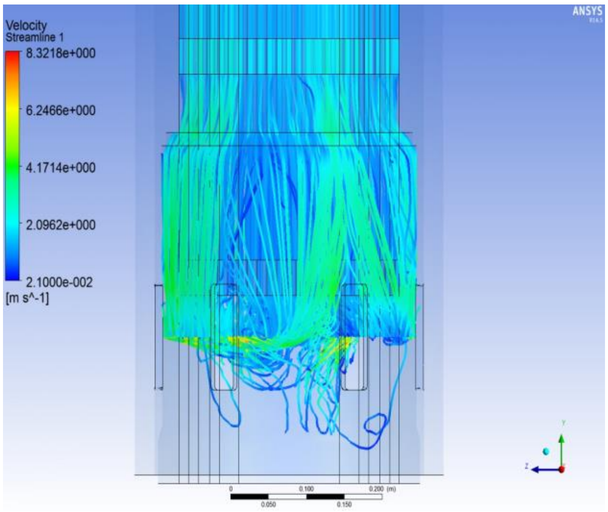


Fig. 5 Water velocity strealine in the lower plenum near the flow skirt (Side view)

4. Concluding Remarks

From the analysis activity of Group B in ATLAS DSP-03, participants adopted a multi-dimensional approach to the code analysis for the SLB transient in the ATLAS test facility. The main purpose of the analysis was to investigate prediction capability of multi-dimensional analysis tools for the SLB experiment result. In particular, the asymmetric cooling and thermal mixing phenomena in the reactor pressure vessel could be significantly focused for modeling the multi-dimensional components. The work of B group participants includes various actions such as the application CFD calculation results to system code and the utilization of the multi-dimensional components for modeling the reactor pressure vessel in one-dimensional system analysis code.

From the analysis results of B group, following conclusions were obtained as below.

1) Due to an asymmetric cooling by two steam generators, the fluid was injected to the reactor pressure vessel through cold legs with different flow rate and temperature between two loops. In spite of the asymmetric injection of the reactor coolant, both of the experimental results and the

one-dimensional code calculation combined with the multi-dimensional modules showed that the temperature of lower downcomer is uniformly distributed. It means that the fluid in the lower dowcomer was well mixed and this phenomenon was appropriately captured in the code analysis result.

2) CFD calculation results show that the trend of pressure drop in the reactor pressure vessel is well predicted experimental results by comparison code and experimental results. Additionally, axial K-factor in the vessel for 1D and 3D inputs were obtained by trial and error method from pressure drop of CFD calculation results. This information could contribute to the more accurate modeling of the reactor core in the ATLAS facility.

The 3D modeling for the reactor pressure vessel contributed to a better prediction for multi-dimensional temperature distribution in the downcomer and thermal mixing behavior. However, for more accurate calculation result, further study is required including following items.

1) Sensitivity study on the nodalization effect for the downcomer and the core : Three-dimensional module in the system analysis code cannot capture the complex and local behavior of the fluid in a scale as small as CFD codes. So that, more sensitivity study and quantitative comparison to the experimental result will be able to provide an optimized guideline to model the reactor pressure vessel with the multi-dimensional components.
2) Accurate prediction for the flow distribution in the reactor pressure vessel : Modeling the reactor pressure vessel with multi-dimensional components requires the accurate modeling of friction factor and form loss at all junctions in three directions. Since this can significantly affect the flow distribution, precise model for the reactor pressure vessel based on the CFD calculation results or the experimental results is essential to predict the multi-dimensional behavior.
3) Application of overall guidelines for modeling other one-dimensional components : Although the multi-dimensional phenomena in the reactor pressure vessel is of importance, overall thermal hydraulic behavior in the reactor coolant system during the SLB transient is highly affected by the modeling of one-dimensional components, such as natural convection in the primary loop, break flow on the steam line, heat loss of the primary and secondary systems, and the boil-off in the steam generator. Therefore, after the modeling guideline for those components is sufficiently reflected in the analysis model, it is necessary to evaluate the prediction capability of multi-dimensional modules in the system code.

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