Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 29-30, 2014

CFD Simulation on the Main Steam Line Break Accident with the ATLAS (SLB-GB-02T) in Terms of Thermal Mixing and Asymmetry Effects

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1. Introduction

The 3rd domestic standard problem (DSP-03) exercise was started on October 9, 2012. A double-ended guillotine break accident of the main steam line (MSLB) was selected to be the analysis topic of the DSP-03 based on a technical discussion between the participants and the operating agencies (KAERI and KINS) at kick-off meeting of the DSP-03.

The analysis groups of DSP-03 are divided by 3 groups to concentrate on a special phenomenon such as scalability and 3D effects. The object of group A is to analyze scalability between the ATLAS facility and the APR1400 plant using a various 1D system codes such as SPACE and MARS. The object of group B is to conduct a multi-dimensional analysis of the 3D phenomena on the downcomer (DC) and the core during MSLB accident using TRACE, MARS-3D and CFD codes. The group C performs a typical 1D analysis to suggest the standard nodalization of the safety analysis and to evaluate the code accuracy.

The MSLB accident was initiated by a double-ended guillotine break at one of Steam Generator (SG). The MSLB accident is characterized as an increase in heat removal by the secondary system. This causes excessive heat removal from reactor coolant system and decrease in reactor coolant temperatures. As a result, the core reactivity is increased by the negative moderator and Doppler reactivity coefficients. The viewpoint of MSLB analysis is to know whether the thermal asymmetry effect is sustained on the core or not when the cold water flows from the affected SG to the affected RCS loop and the hot water flows from the intact SG to the intact RCS loop.

KHNP CRI, as a participant of the group B, performs the CFD analysis to analyze the thermal mixing and asymmetry effect on the downcomer and the core using the ANSYS CFX version 14.57 code. In general, CFD code still has a limitation on the application of two-phase phenomena, but the applicability and accuracy in the single phase flow condition is validated by many researchers in recent years. Based on the experiment, the primary fluid is maintained under subcooled liquid phase without the vapor phase, and thereupon CFD code can be applicable in the simulation of ATLAS vessel flow.

In this paper, the CFD analysis model is bounded by the ATLAS vessel, and the RCS loop flow rate and temperature is treated as a boundary condition using the experiment data. Firstly, a steady-state analysis is conducted and this result is analyzed as below.

- Major fluid behavior such as pressure, temperature, flow rate is compared with experiment data
- a axial pressure distribution in the downcomer and the core

Based on the steady-state results, a transient calculation is performed and the boundary conditions are determined by the experimental data. 2 cases are calculated as below

- Case1: Period from the break initiation time to the reactor trip time by low SG pressure (LSGP) signal. This period represents that the temperature difference between the affected loop and the intact loop is relatively lower than case 2 and the flow rate is relatively faster than case 2.
- Case2: time at a maximum temperature difference between the affected loop and the intact loop before the start of safety injection pumps. This case represents a most conservative situation in the viewpoint of thermal asymmetry.

These results are discussed about the thermal mixing and asymmetry in the downcomer and the core using a statistical approach, standard deviation in the spatial planes.

2. CFD Models and Boundary Conditions

In this section CFD models such as a general modeling information, a grid information, a turbulence model and boundary conditions are described.

2.1 General Modeling Information

As described in the section 1, the analysis geometry is bounded as the ATLAS vessel included a bypass lines which are the DC-UH and the DC-HL bypass. The active core is consists of 390 heated rods, 6 un-heated rods, guide tubes and 10 spacer grids. The detailed geometries of the heated, un-heated rods and guide tubes are preserved in the CFD geometry. The 10 spacer grids are modeled as porous media.

Two methods about the porous media are provided in CFX code, which are a superficial velocity formulation and a true velocity formulation. The superficial velocity formulation is considered that the pressure drop in spacer grids is treated as a momentum source not included the volume porosity of the spacer grids in the governing equations thus the flow velocity is decreased when the water flows into the spacer grids.

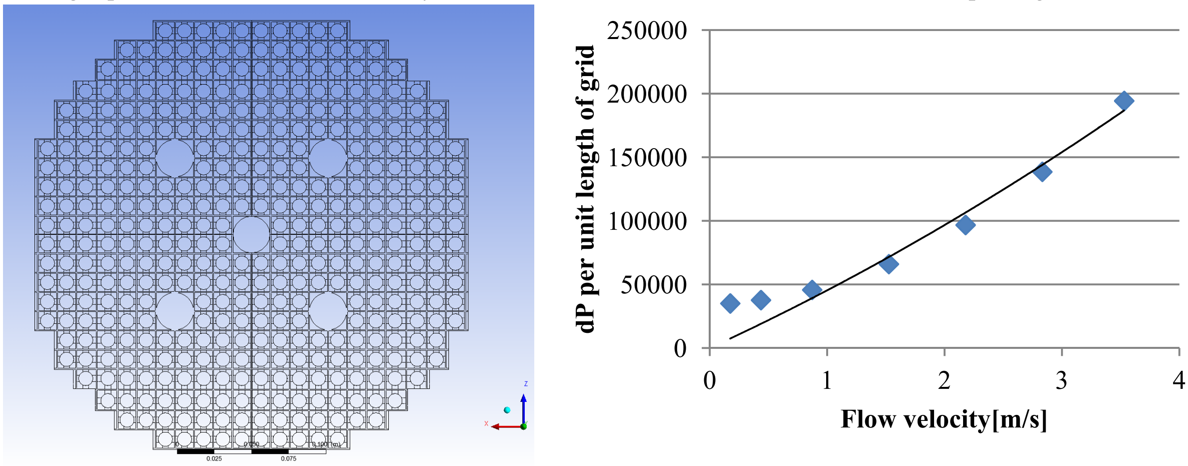

Fig. 1. CFD model of the spacer grid (Left) and pressure drop correlation under various flow velocity condition (Right)

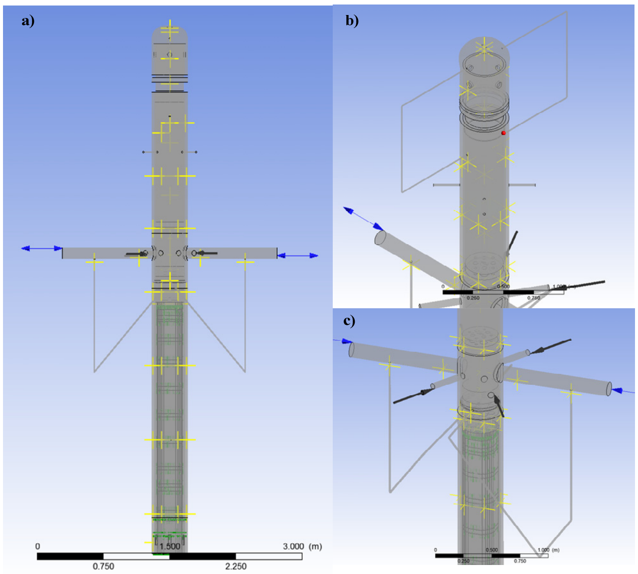

Fig. 2. CFD geometry of the ATLAS vessel: (A) Full configuration, (B) DC-UH bypass geometry and (C) DC-HL bypass geometry

The true velocity formulation takes the volume porosity into account for the momentum equations so that the flow velocity is increased when the water flows into the spacer grids. Therefore, the true velocity formulation is suitable to simulate the inner flow and heat transfer from the heated rods located in the spacer grids. To apply the true velocity formation, the pressure drop correlation of spacer grid is required, which is expressed as flow velocity versus differential pressure. As shown in Fig. 1, the pressure drop correlation is obtained by a steady-state CFD calculation.

Two bypass lines from DC to HL and two bypass lines from DC to UH are preserved in the modeling of CFD geometry. HL and CL pipe line is simplified to apply the experiment data such as flow rate, fluid temperature and pressure.

2.2 Grid Information, Turbulence Model and Boundary Conditions

The internals of the ATLAS vessel consist of complex geometries such as flow skirt, upper guide structures, heated rods and guide tubes thus a large number of meshes are expected if meshes of the ATLAS vessel are generated by a tetrahedral mesh. To reduce a total number of meshes, hexahedral-dominant mesh is applied in an active core and a lower plenum region. The other compartments meshes are generated by a tetrahedral mesh. Table I indicates final mesh information for a CFD calculation.

Table I: CFD grid information

Mesh type	Number of elements
Tetrahedrons	8,517,613
Prisms	2,548,479
Hexahedrons	9,701,809
Pyramids	153
Total	20,768,054

Table II: Summary of boundary condition for the transient

Loop flow variables	Case 1 @14s	Case 2 @200s
Flow rate@CL1A[kg/s]	2.41	2.425
Flow rate@CL1B[kg/s]	2.97	2.555
Flow rate@CL2A[kg/s]	2.55	0.644
Flow rate@CL2B[kg/s]	3.10	0.864
Temperature@CL1A[^{o}K]	558.81	457.42
Temperature@CL1B[^{o}K]	558.42	456.37
Temperature@CL2A[^{o}K]	557.58	552.93
Temperature@CL2B[^{o}K]	558.12	552.47

Turbulence model is selected as Shear Stress Transport (SST) model, which is classified as Reynolds Averaged Navier-Stoke (RANS) equation model and is widely used at a typical engineering problem. Inlet boundary condition (B.C.) is defined as flow rate B.C at four CL pipe and outlet B.C. is defined as pressure B.C. at two HL pipe, which are obtained from the experiment data

In transient calculation, 2 cases are selected as described in the section 1. Detailed boundary condition is shown in Table II. In the case 1, transient calculation is performed from a steady state at full power condition to 14sec after the break initiation. In the case 2, a calculation is performed by a steady-state calculation like a null transient calculation at most conservative condition. This condition assumed that the maximum temperature difference between the affected loop and the intact loop is maintained like a quasi steady state.

3. Steady-State Results and Discussions

In this section a calculation results of a steady-state is discussed about the hydraulic behavior of the steady state in the ATLAS facility. This discussion is not limited in the MSLB phenomena.

3.1 Global Hydraulics Behavior

The system pressure and temperature are well predicted and the difference between the calculation data and the experiment data is less than 0.5%. The loop flow rate has a deviation about 1% from the experiment data. An uncertainty of the measured experimental data is evaluated as 2.65% in the test report [1]. Thus, the flow rate is also well predicted by considering the measurement uncertainty.

Table III: Results of the steady-state condition

Variables		Exp.	CFD	Difference [%]
Pressure (Normalized by HL2 pressure)	Downcomer Pressure	1.0044	1.0062	0.18
	Lower Plenum Pressure	1.0068	1.0079	0.11
	Upper Head Pressure	0.9991	0.9997	0.06
	Hot leg-1 Pressure	0.9998	1.0000	0.02
	Hot leg-2 Pressure	1.0000	1.0000	0.00
	Cold leg-1A Pressure	1.0054	1.0066	0.12
	Cold leg-1B Pressure	1.0059	1.0066	0.07
	Cold leg-2A Pressure	1.0051	1.0066	0.15
	Cold leg-2B Pressure	1.0051	1.0066	0.16
Temperature (Normalized by HL2 temperature)	Hot leg-1 Fluid Temperature	0.9984	1.0020	0.36
	Hot leg-2 Fluid Temperature	1.0000	1.0018	0.18
	Cold leg-1A Fluid Temperature	0.9955	0.9944	-0.11
	Cold leg-1B Fluid Temperature	0.9949	0.9944	-0.04
	Cold leg-2A Fluid Temperature	0.9944	0.9944	0.00
	Cold leg-2B Fluid Temperature	0.9947	0.9944	-0.03
	Active core Max. Temp			
	TH-CO-G1-MAX	1.0100	1.0049	-0.50
	TH-CO-G2-MAX	1.0098	1.0049	-0.49
	TH-CO-G3-MAX	1.0075		
Flow rate [kg/s]	DC-UH1 Bypass Flow Rate	No data	0.7481	NA
	DC-UH2 Bypass Flow Rate	No data	0.7476	NA
	DC-HL1 Bypass Flwo Rate	No data	1.629	NA
	DC-HL1 Bypass Flwo Rate	No data	1.635	NA
	Hot leg-1 Flow Rate	32.74	32.7	-0.12
	Hot leg-2 Flow Rate	32.74	32.7	-0.12
	Cold leg-1A Flow Rate	15.03	15.20	1.16
	Cold leg-1B Flow Rate	17.69	17.50	-1.05
	Cold leg-2A Flow Rate	15.36	15.20	-1.02
	Cold leg-2B Flow Rate	17.41	17.50	0.51

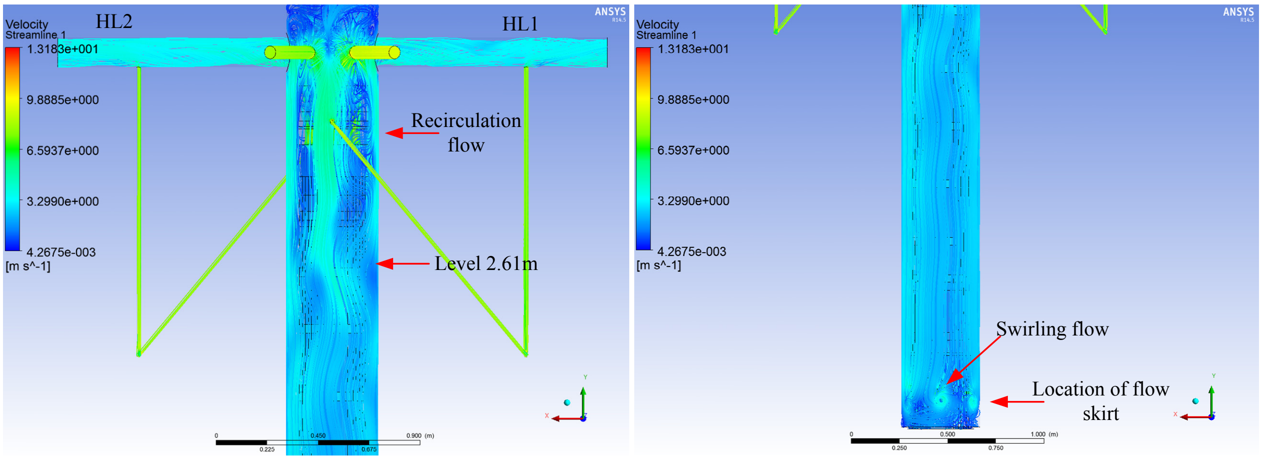

Fig. 3. Velocity streamline at the downcomer (Left : near the loop leg, Right : near the lower level of the downcomer)

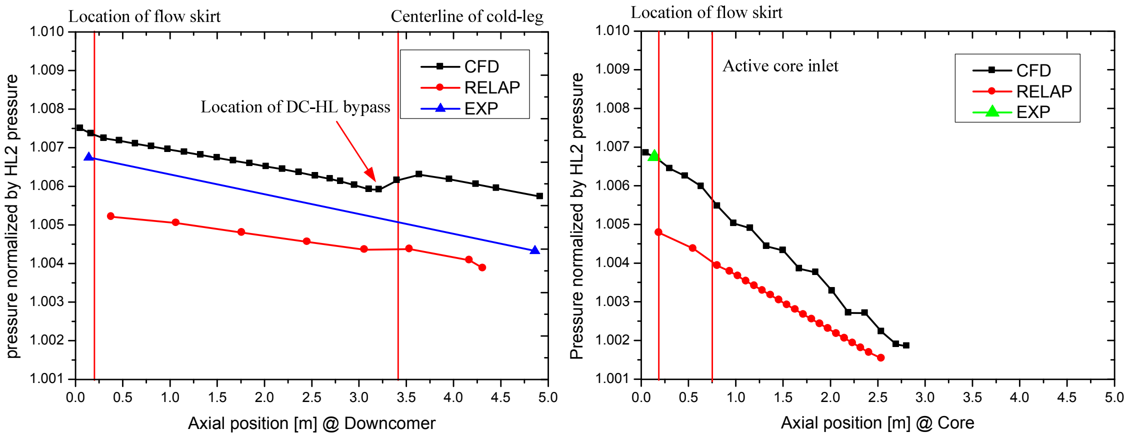

Fig. 4. Pressure distribution at the downcomer and core (Left : downcomer, Right : core)

As illustrated in the left of Fig. 3, the flow injected through the cold-legs impinges against the out surface of the core support barrel. This induces the recirculation flow from the loop leg level to 2.61m which can affect the thermal mixing phenomena. Meanwhile, the flow is straightened from 2.61m to the lower downcomer. Near the location of flow skirt, the swirling flow can be predicted due to turbulence which also affects to the thermal mixing. These phenomena could not be measured in the present measurement instrumentation.

3.2 Pressure Distribution Characteristics

As shown in the left of Fig. 4, CFD results have a deviation from the test data about 1% along the axial height of the downcomer. The test data have only 2 point of pressure data in the downcomer thus the pressure distribution at the middle of the downcomer is unknown. In the CFD results, pressure suddenly dropped near the 3.1m because the DC-HL bypass line is installed in this region. The deviation of RELAP results is larger than the CFD results but a general trend is similar with the CFD data.

The pressure of test data has only 1 point near the lower plenum in the core region as illustrated in the right of Fig. 4 and it is well predicted with the CFD data. The RELAP results have a deviation about 0.2 %.

4. Transient Results and Discussions

In this section a calculation results of a transient are discussed about the thermal mixing and asymmetry in the downcomer and the core under comparable two cases as mentioned in section 1. To compare the thermal mixing and asymmetry effect between 2 cases, a normalized variable should be determined because the inlet temperature condition is different with each other. In this study, planes of a normal vector along the steamline are generated at the downcomer and core region. Firstly, an average temperature at each plane is calculated, which can be defined as Eq. 1.

$$T_m^* = \frac{1}{\sum_{cell} A_{cell}} \sum_{cell} \left[A_{cell} T_{cell}^* \right] \quad (1)$$

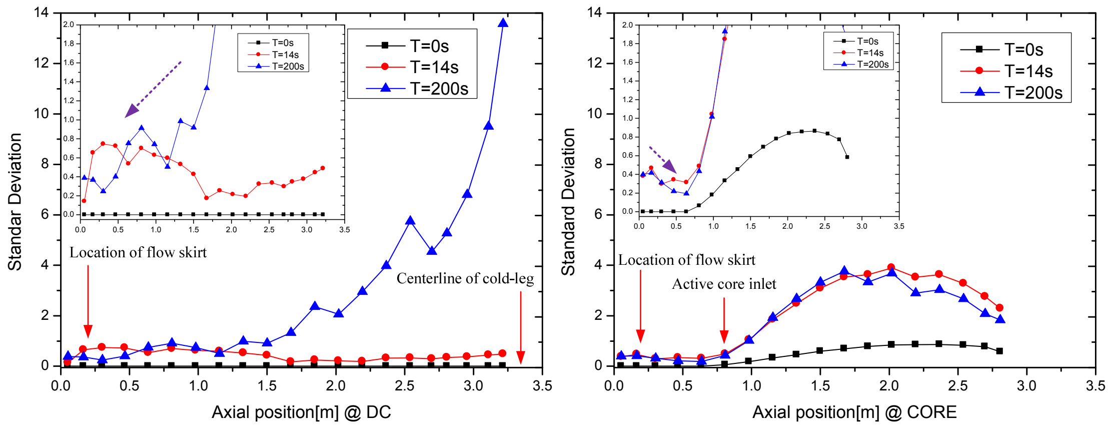

Fig. 5. Standard deviation distribution at the downcomer and the core

Then, a standard deviation of temperature at each plane can be calculated and is defined as Eq. 2.

$$\sigma = \sqrt{\frac{1}{\sum_{cell} A_{cell}} \sum_{cell} \left[A_{cell} (T_{cell}^{*} - T_{m}^{*})^{2} \right]} \qquad (2)$$

Eq. 2 represents extent of the thermal asymmetry in the spatial planes along the main streamline. Fig. 5 represents the distribution of standard devitation in the downcomer and the core at time zero, 14 seconds and 200 seconds. The time zero means the steady state condition at full power of the ATLAS. At 200 seconds, the difference between the affected loop temperature and the intact loop temperature is about 100 ^{o}K.

As shown in the left of Fig. 5, standard deviation is almost zero at time zero because there is no temperature difference between the affected loop and the intact loop in the steady state condition. Meanwhile, standard deviation is increased near the active core inlet about 0.75m. This is because the heating effect from the heated rods. The fluid temperature near the heated rods is higher than the center of an equivalent cooling channel in a heated rods lattice thus the standard deviation starts to increase in the active core.

After the initiation of the MSLB, standard deviation is increased at the downcomer and the core. At 200 sec, the standard deviation in the downcomer near the centerline of cold-leg is about 14 but the standard deviation is exponentially decreased to about 0.2. This means the thermal mixing is well produced in the downcomer under the maximum temperature difference between the intact loop and the affected loop. After the flow passes through the flow skirt, thermal mixing is continuously produced due to the geometrical effect because there are complex structures in the lower plenum such as unheated rods and spacer grids. As shown in the right of Fig. 5(small scale figure), the standard deviation is decreased until the height of active core inlet. Above the height of the active core inlet, the standard deviations at 14 seconds and 200 seconds are increased due to the heating effect.

5. Conclusions

CFD analysis is performed to analyze the flow characteristics of the ATLAS facility in the steady state at full power and the thermal mixing and asymmetry in the MSLB accident. The results of CFD analysis for steady-state give us the understanding of detailed flow characteristics in the steady-state such as the recirculation flow near the cold-leg, the swirling flow near the flow skirt and detailed pressure distribution. The results of the transient condition shows that the flow mixing is well produced in the downcomer and the lower plenum region. This study is the first attempt inside the nuclear industry circles to analyze the 3D effect on the ATLAS test facility. However, the reinforcement of the measurement instrumentations in the ATLAS facility might be necessary to analyze the 3D effects.

ACKNOWLEDGEMENT

This work was performed within the program of the 3rd ATLAS Domestic Standard Problem (DSP-03), which was organized by the Korea Atomic Energy Research Institute (KAERI) in collaboration with Korea Institute of Nuclear Safety (KINS) under the National Nuclear R&D Program funded by the Ministry of Education, Science and Technology (MEST) of the Korean government. The authors are as well grateful to the 3rd ATLAS DSP-03 program participants: KAERI for experimental data and the Council of the 3rd DSP-03 program for providing the opportunity to publish the results.

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