Report on Participation in IAEA CRP: Application of Computational Fluid Dynamics (CFD) Codes for Nuclear Power Plant Design

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1. Introduction

In Nuclear Power Plant (NPP), the variation of reactivity due to the fuel burn-up is controlled by the borated water. Therefore, unexpected boron dilution can cause reactivity excursion. USNRC reported that de-borated water, which is accumulated in the RCP suction piping, can flow into the reactor pressure vessel (RPV) when the reactor coolant pump (RCP) startup after the recovery of the small break loss of coolant accident (SBLOCA) [1]. If the low boron concentration water flows into the core inlet without enough mixing in the downcomer and lower plenum regions, the unexpected reactivity insertion can occur. Therefore, it is important to predict the boron mixing phenomenon by the turbulence effect as well as the convection and diffusion. Recently, IAEA launched a coordinate research project (CRP), 'Application of computational fluid dynamics code for nuclear power plant design', to validate the capability of CFD codes for simulations of nuclear safety-related issues. In the IAEA CRP, ROCOM_12 test was selected as a numerical benchmark exercise to validate the CFD code capability to predict the boron mixing phenomenon.

2. IAEA CRP

2.1 Background

IAEA has been operating various Coordinate Research Projects (CRPs), which were designed to encourage and assist R&D on, application of, and nuclear energy for peaceful uses. Under the circumstance that the applications using Computational Fluid Dynamics (CFD) codes are increasing in the nuclear analysis field, in particular, where the multi-dimensional phenomena are dominant, IAEA launched the CRP to address the application of CFD computer codes for optimizing the design of water cooled nuclear power plants in 2013.

In the CRP, 16 participants were involved in 4 benchmarks: PTS, boron dilution, and two types of rod bundle tests. KAERI participated in the boron dilution benchmark with in-house code, CUPID, and the analysis results from 4 participants were compared.

2.2 ROCOM_12 Test [2]

ROCOM is a 1:5 model of a PWR of GERMAN KONVOI type that consists of 4 loops. The inner diameter and height of RPV are 1,000 mm and 2,400 mm, respectively. The wire mesh sensors were installed to measure the flow distribution in the cold leg inlet nozzle, core inlet plane, and downcomer. Each sensor has two-dimensional grids that consist of the measuring points of 216, 15x15, and 29x64, respectively.

The slug mixing experiment ROCOM_12 was performed with simulating the slug volume of de-borated water. The initial and boundary condition of ROCOM_12 is summarized in Table 1.

Table I: Initial and boundary condition of ROCOM_12

Ramp length	Volume flow rate	Slug volume	Initial slug position
14.0 s	185.0 m^3/h	8.0 m^3	10.0 m

3. Result of ROCOM Benchmark

3.1 Computational Grid and Models

For the ROCOM benchmark, KAERI used the CUPID code, which has been developed since 2007 [3]. CUPID is capable of boron dilution simulation because it has relevant physical models such as the boron transport model, and turbulence model. A hybrid-type grid with hexagonal and tetrahedral meshes was generated by using SALOME open source software. The geometry of ROCOM was divided into four parts: 1) the cold legs and downcomer, 2) lower plenum, 3) tubes, and 4) upper plenum and hot legs. The grid for each part was generated and then compound grid was generated. Total number of grid was 4,679,887.

Standard k-ε turbulence model was used. As a sensitivity test for the turbulence model, the low Reynolds number model and SST k-ω model were tested together. It is well known that the SST k-ω turbulence model requires much smaller Y-plus value than the standard k-ε model, which uses the wall function. Thus, a finer grid was also generated and tested.

As the result of model sensitivity and grid tests, standard k-ε turbulence model showed the best performance in the coarse grid (4M) while the SST k-ω model showed the best in the finer grid (12M). Even though the SST k-ω model required much more grids and, as a result, more computational time, it did not assure the better prediction result in this benchmark. So, KAERE submitted the final result, which was calculated using the standard k-ε turbulence model.

3.2 Space-averaged and Maximum Boron Concentrations

Boron concentrations at three measuring planes were calculated: at the upper downcomer, lower downcomer and core inlet. Figure 1 and Figure 2 show the maximum and averaged boron concentration at each measuring plane, respectively. The averaged boron concentrations were underestimated while the maximum values agreed well. It is responsible for the bypass of boron through three open cold legs and this bypass effect was not quantitatively validated since the boron bypass rate was not measured. In addition, the calculation result showed that the boron reached to the upper downcomer flows downward faster than the experimental data without enough mixing. This is another reason for the under-prediction of averaged boron concentration at the measuring planes.

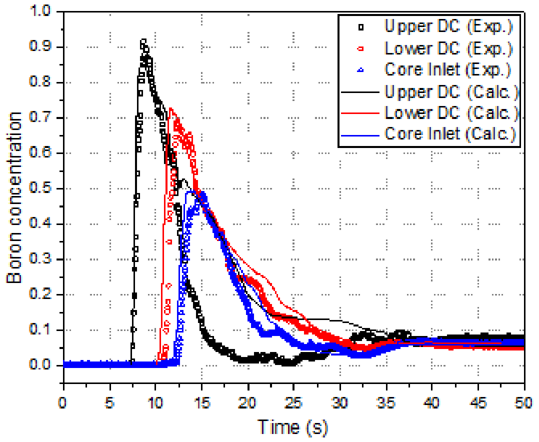

Fig. 1 Maximum boron concentration at three planes

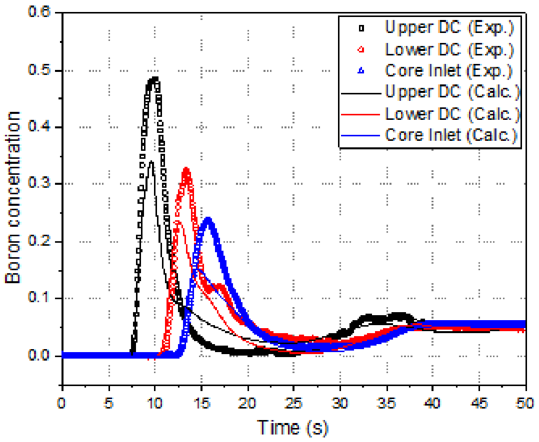

Fig. 2 Averaged boron concentration at three planes

3.3 Transient of Local Boron Concentrations

Local boron concentrations at five measuring points were simulated. Two points were located at the upper and lower downcomer, and other three points at the core inlet.

Fig. 3 shows the transient behavior of boron concentrations at two local points in the upper (point1) and lower downcomer (point2). The transient trend of boron concentrations at point1 and 2 were predicted well. However, the peak values at the point 1 and 2 were underestimated as the averaged boron concentration was underestimated.

Fig. 4 shows the transient behavior of boron concentration at three local points in the core inlet. Experimental data showed that the boron filled from the outer radial point of the core inlet and then, inner radial point and middle radial point in order. However, the simulation result showed that the boron filled from the outer radial point and then, middle radial point and inner radial. In addition, it can be shown that the boron concentrations in the middle and inner radial points were under-predicted because the perforated drum plays strong role as a flow resistance.

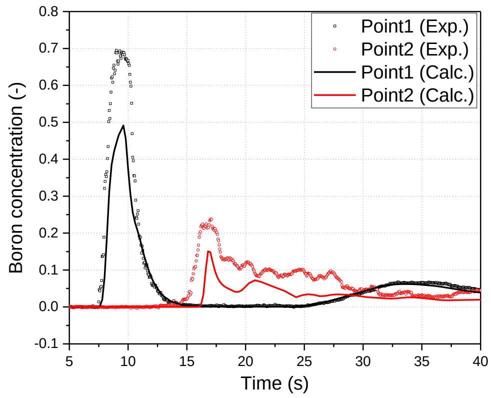

Fig. 3 Transient of boron concentration at two local points in upper and lower downcomer

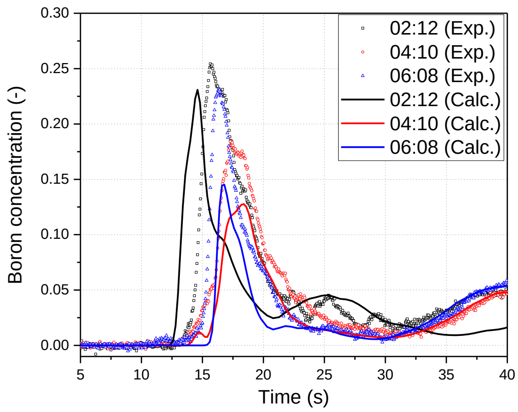

Fig. 4 Local boron concentrations at three points in core inlet

Table II: Summary of computational setup

Participant	Code	Turb. Model	Mesh
KAERI	CUPID2.0	Standard k-e with Low Re Model	4.6M
HZDR	CFX18	SST	6.5M
VNIIAES	STAR-CCM+	Realizable k-e	Unknown
BARC	OpenFoam	LES	8M/19M

3.4 Final Comparison Results

The computational setup of each participant in the CRP was summarized in Table II. KAERI, HZDR, and VNIIAES used RANS turbulence model while BARC used LES turbulence model with finer mesh. 13 computational results were compared: 1) boron concentration at one point in the upper downcomer, 2) azimuthal distribution of boron concentration in the upper downcomer, 3) boron concentration at one point in the lower downcomer, 4) azimuthal distribution of boron concentration in the lower downcomer, 5-7) boron concentration at three points in the core inlet, 8) space averaged boron concentration in the upper downcomer, 9) space averaged boron concentration in the lower downcomer, 10) space averaged boron concentration in the core inlet, 11) maximum value of boron concentration in the upper downcomer, 12) maximum value of boron concentration in the lower downcomer, and 13) maximum value of boron concentration in the core inlet.

In 13 comparisons, the accumulated RMS of errors predicted by KAERI was the minimum, 1.12. Details of comparison results will be published in the final report of the CRP soon.

5. Conclusions

Boron dilution benchmark was simulated using the CUPID code in the platform of IAEA CRP. As the result of the CRP, 4 calculation results submitted by the participants using the commercial or in-house CFD codes were compared. CUPID predicted the overall boron concentrations mixing behavior when it compared to other participants. However, it could be concluded that CUPID has enough capabilities to properly simulate the boron mixing behavior in the downcomer and lower plenum, which was asymmetrically injected from one cold leg.

ACKNOWLEDGMENTS

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