# Preliminary CFD of boron mixing in the i-SMR under a natural circulation

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## 1. Introduction

The i-SMR safely achieves boron-free operation by employing an integrated control rod drive mechanism and innovative nuclear fuel[1,2]. However, overseas regulations may require a diverse means for reactor shutdown, such as an emergency borating system.

This paper presents preliminary CFD results for boron-water mixing in the i-SMR under a natural circulation condition. The process for conducting a transient CFD spanning 100 million grids is described.

The objective of this study is to determine the time required for borated water to be uniformly mixed when it is injected 72 hours after reactor shutdown.

## 2. Numerical method

To account for the turbulent effect in the fluid flows, the $k-\omega$ SST model was adopted. In addition, a boron transport equation was used. The reactor core and steam generator regions were modeled using a porous-media approach. Simulations were performed using STAR-CCM+[3]

A flow simulation in the SMR requires more than 100 million grids. Moreover, approximately 5000 seconds of physical simulation time may be required to monitor the transient mixing under natural circulation conditions.

There are two approaches for expensive simulation:

- Approach 1: All conservation equations are solved simultaneously in a transient way. The simulation continues until the flow reaches a steady state. This approach is common but impractical given the number of grids and the computational time required.
- Approach 2: The boron concentration is so low that it does not affect the flow. In the first step, the natural circulation flow is obtained using a steady solver. The boron transport equation is not considered in the first step. In the second step, only the transient boron transport equation is solved based on the steady-state flow field. This approach enables a long-time boron-mixing simulation.

## 3. Validation

To confirm approach 2, two problems were considered. Figure 1 shows a conceptual problem: steady-state laminar natural convection with boron transport. Figure 2 compares the simulation results obtained using two approaches. Two results are very similar, validating approach 2.

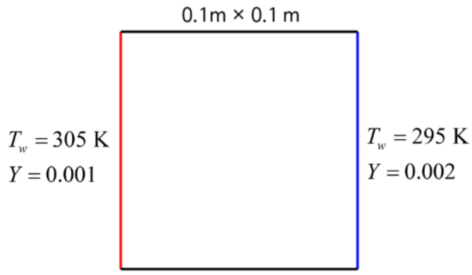


Fig.1 Steady-state natural convection with boron transport

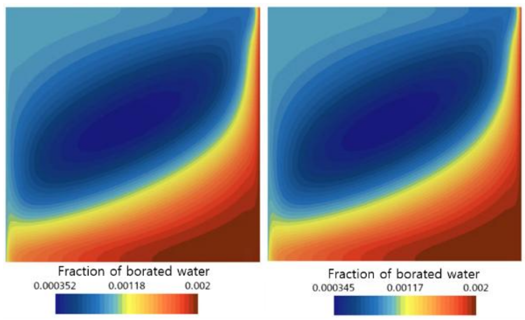


Fig.2 Steady-state concentration distributions: (Left) Approach 1, (Right) Approach 2

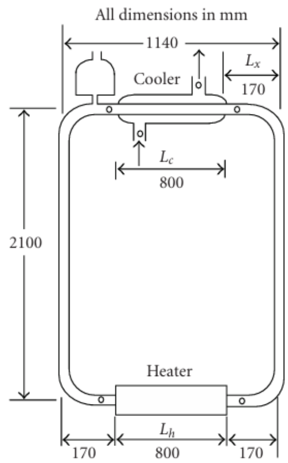


Fig. 3 Schematic of the experimental loops [4]

We also applied approach 2 to the natural circulation experiment [4] (Fig. 3). Figure 4 compares the predicted natural circulation flow with the experimental data. The predictions agree fairly well with the experimental data, confirming the validity of approach 2.

Approach 2 was used to predict long-time boron mixing in the i-SMR.

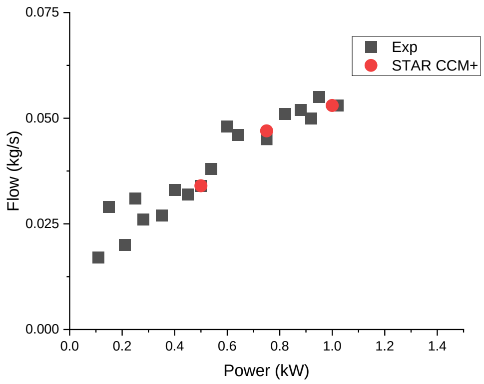


Fig. 4 Comparison of natural circulation flow rates

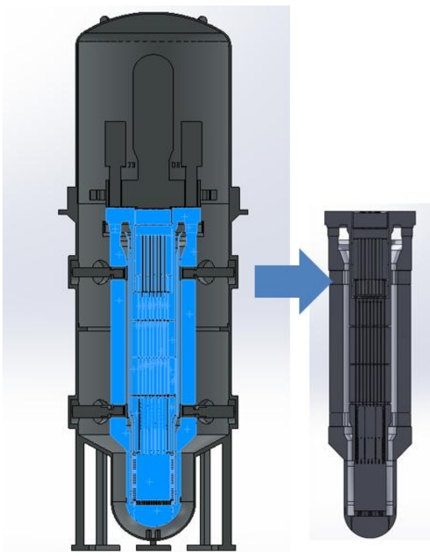

Fig. 5 The flow domain was extracted from the i-SMR geometry model

## 4. Computational Domain and Boundary Conditions

### *4.1 geometry*

The flow domain was extracted from the i-SMR geometry model (Fig. 5). To reduce the number of grids, the pressurizer domain was excluded because the flow is nearly motionless there. The bypass was also excluded because the coolant mass flow rate was approximately 2% of the total mass flow rate.

### *4.2 mesh*

A hexahedral mesh was employed, and the trimmed cell mesher was utilized to enhance accuracy in complex geometries. In addition, a prism layer mesher was applied to resolve the viscous boundary layer. The final grid consisted of approximately 170 million cells.

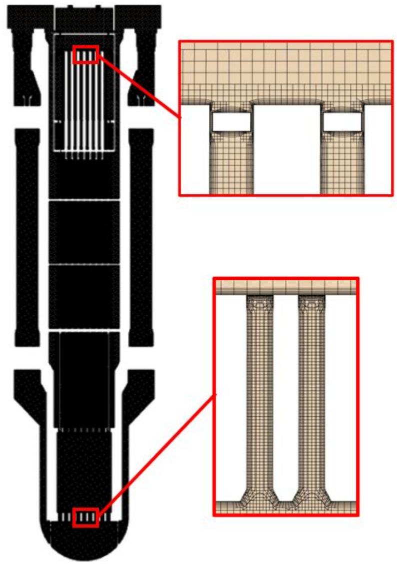

Fig. 6 Mesh structure of i-SMR geometry model

### *4.3 Boundary Conditions*

Under the forced circulation condition, +509.6 MW and −509.6 MW were applied to the core and stream generator regions, respectively. A mass flow rate of 2657.04 kg/s was imposed on the pump inlet, and a pressure of 15.51 MPa was applied to the pump outlet. The pump inlet temperature was set equal to the pump outlet temperature. All reactor walls were treated as adiabatic. The initial temperature was set to 568.65 K.

Under the natural circulation condition, the reactor power was reduced to 2% of the nominal value. Accordingly, thermal powers of +10.4 MW and −10.4 MW were assigned to the core and steam generator regions, respectively. The other conditions were the same as those in the forced circulation.

## 5. Results and discussion

To verify the applicability of the proposed approach, the numerical results were validated against a conceptual problem and experimental data. The results showed good agreement, confirming that the decoupled approach can accurately predict both flow behavior and boron transport under natural circulation conditions. Based on this validation, the method was applied to the i-SMR(Fig.7). A grid-independence test was conducted, and the boron mixing behavior was simulated using the validated flow field. Figure 8 shows the velocity and temperature distributions under steady-state natural circulation conditions.

The results show that boron is transported along the natural circulation flow path(Fig 9). By tracking the transient boron distribution, the circulation time of the loop was estimated to be approximately 480 s.

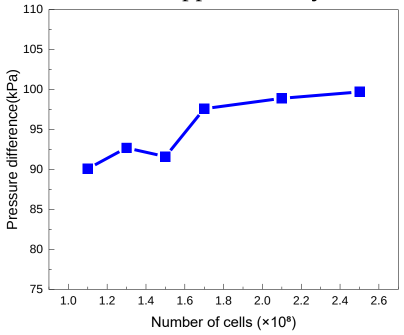


Fig. 7 Grid-independence test result under the forced-circulation condition

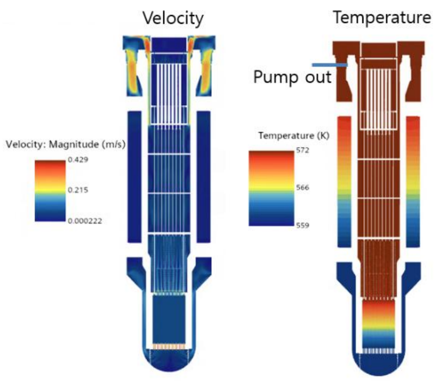


Fig. 8 Steady-state natural circulation results

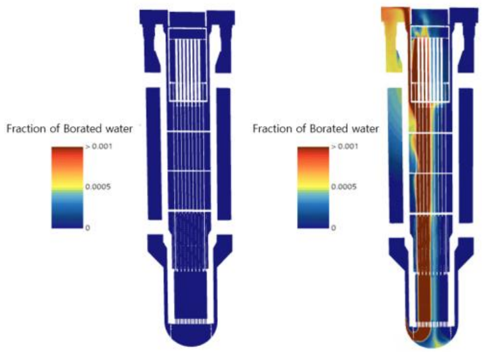


Fig. 9 (Left) Initial boron distribution, (Right) Boron distribution at time 550 s

## 6. Conclusions

In this study, an efficient numerical approach was developed to simulate boron mixing under natural circulation conditions. The proposed method decouples the flow field calculation from the boron transport equation under the assumption that the boron concentration does not affect the flow field.

The validity of the approach was confirmed through comparisons with a conceptual problem and experimental data, demonstrating that the method can reliably predict both flow behavior and boron transport.

The proposed approach provides a practical and reliable framework for analyzing boron mixing in large-scale reactor systems where direct experimental data are not available.

Furthermore, the method can be extended to evaluate boron mixing under various design conditions. Future work will focus on quantifying the time required for uniform mixing of borated water.

## ACKNOWLEDGEMENTS

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