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Numerical Simulation of Fluid Mixing in Upper Annular Space of SMART during Early Stage of non-LOCA

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1. Introduction

As a part of the safety enhancement program for a system-integrated modular advanced reactor (SMART), KAERI (Korea Atomic Energy Research Institute) is developing a passive safety injection system (PSIS) to supply cold borated water into a reactor coolant system (RCS) without any operator actions or AC power under the occurrence of postulated design basis accidents [1-3]. The PSIS consists of four independent trains, each of which is furnished with a gravity drained core makeup tank (CMT) and a safety injection tank (SIT). The CMT is designed to provide makeup and boration functions to the RCS during the early stage of a loss of coolant accident (LOCA) and a non-LOCA. In this paper, we investigate numerically the fluid mixing characteristics in the upper annular space of SMART, especially when single-phase natural circulation is formed between the CMT and RCS following a non-LOCA such as a main steam line break.

2. Methods and Results

2.1 Computational Setup

Assuming a steady incompressible and turbulent flow of a variable-property Newtonian fluid, the following RANS equations are solved using a commercial CFD code, Fluent 12.0 [4], with a user-defined scalar (UDS) transport equation for the boron concentration.

$$\frac{\partial \langle u_i \rangle}{\partial x_i} = 0 \tag{1}$$

$$\rho \langle u_j \rangle \frac{\partial \langle u_i \rangle}{\partial x_j} = -\frac{\partial \langle p \rangle}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial \langle u_i \rangle}{\partial x_j} + \frac{\partial \langle u_j \rangle}{\partial x_i}\right) - \rho \langle u_i' u_j' \rangle\right] + g(\rho - \rho_0) \tag{2}$$

$$\rho \langle u_i \rangle \frac{\partial \langle T \rangle}{\partial x_j} = \alpha \frac{\partial^2 \langle T \rangle}{\partial x_i \partial x_i} - \frac{\partial \langle u_i' T' \rangle}{\partial x_i} \tag{3}$$

$$\frac{\partial}{\partial x_i}\left(\rho \langle u_i \rangle \phi - \Gamma \frac{\partial \phi}{\partial x_i}\right) = 0 \tag{4}$$

Simulations are carried out using a segregated double-precision solver. A second-order upwind method is adopted for the discretization of momentum, turbulent, and scalar transport equations, SIMPLE algorithm for pressure-velocity coupling, and realizable k-ε turbulence model with a standard wall function for the Reynolds stresses in Eq. (2), which is chosen based on additional sensitivity tests [5].

Figure 1 shows a schematic of the CFD model used in this study. The computational domain covers a quarter (or 90° segment) of the upper annular cavity connected with the CMT through a pressure balance line (PBL) and a safety injection line (SIL), including the flow path next to a pressurizer and the outlet duct extended to steam generator cassettes. The vertical distance between the PBL and SIL is S/d=10, where d is the SIL diameter. The inlet and outlet boundaries are divided into two parts, which are responsible for the natural circulation through the RCS and the CMT, respectively. As to the boundary condition, a circulatory flow rate of $\dot{m}_{CMT}$ with a constant temperature of T_{CMT} and boron concentration of C_{CMT} are prescribed at the CMT inlet, and $\dot{m}_{RCS}$ (=10$\dot{m}_{CMT}$), T_{RCS} and C_{RCS} (=0.5C_{CMT}) are specified at the RCS inlet, while outflow boundary conditions are imposed at the outlets. Other surfaces are treated as adiabatic no-slip smooth walls except the side planes with symmetry conditions. Also note that the grid system consists of approximately 16 million hexahedral volume cells in total, and y^+ at the wall nearest cell lies in a typical bound for the use of a standard wall function.

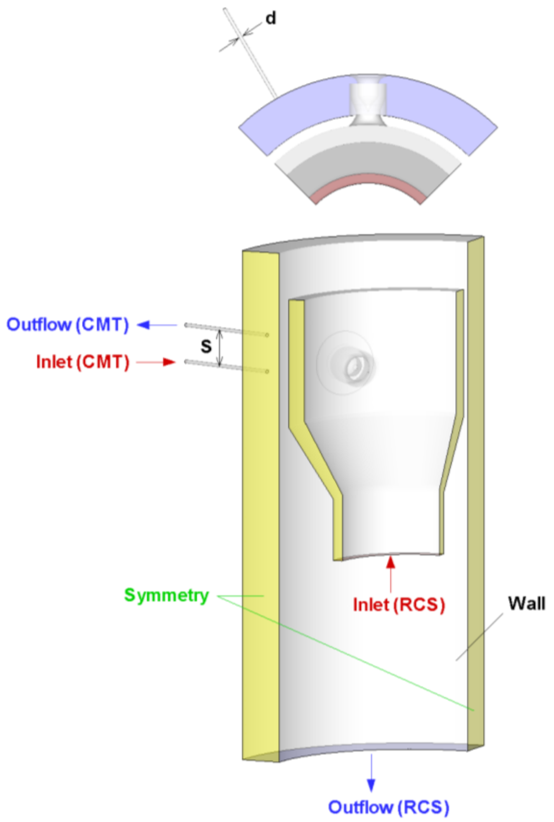

Fig. 1. Computational domain and boundary condition

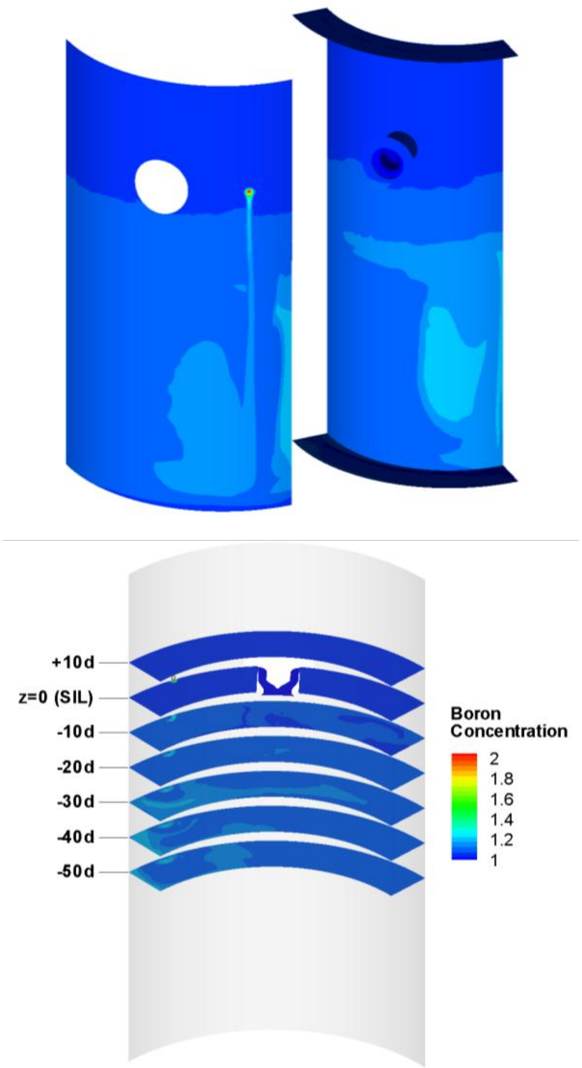

Fig. 2. Normalized boron concentration at the inner and outer surfaces of annular space (top) and at several cross-sectional planes (bottom)

2.2 Mixing Characteristics

Figure 2 shows the boron concentration normalized by C_{RCS} at the inner and outer surfaces of the upper annular space and at several vertical locations. Cold borated water released from the CMT is found to descend in the annular space due to its higher density, being mixed with the high-temperature fluid circulating through the RCS, and flowing into the RCS. On the other hand, most of the fluid passing through the PBL appears to come from the RCS. This observation indicates, in turn, that the majority of cold borated water in the CMT effectively contributes to the reactivity control during the early stage of a non-LOCA.

2.3 Distribution Rate

Table 1 summarizes the boron concentration and the rate of flow distribution obtained from the simulation. The boron concentration at each outlet is estimated as $C_{RCS,out}$=1.1C_{RCS} and $C_{PBL,out}$=C_{RCS}, and the rate of flow distribution from the RCS to the CMT is calculated as 0.1, which is almost the same as the ratio of the CMT circulation flow rate to that through the RCS. Together with the boron concentration depicted in Fig. 2, these results suggest again that the majority of cold borated water with higher concentration flowing from the CMT may be injected into the RCS and only a fraction of less than about 0.1% may be re-introduced into the CMT via the PBL, while most of the fluid flowing into the CMT may be the high-temperature low-concentration fluid from the RCS.

Table 1. Summary of numerical results

RCS outlet concentration, $C_{RCS,out}/C_{RCS}$		1.1
PBL outlet concentration, $C_{PBL,out}/C_{RCS}$		1.0
Fraction of flow distribution	From RCS to RCS	90.0 %
	From RCS to CMT	10.0 %
	From CMT to RCS	99.9 %
	From CMT to CMT	0.1 %

3. Conclusions

In this paper, the fluid mixing characteristics in the upper annular space of SMART are investigated numerically when single-phase natural circulation is formed between the RCS and CMT during the early stage of a non-LOCA. The results obtained show that the majority of cold borated water in the CMT flows into the RCS, and thus effectively contributes to the reactivity control.

Acknowledgement

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