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CFD SIMULATION OF THERMAL MIXING IN FLOW MIXING HEADER ASSEMBLY OF SMART

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ABSTRACT

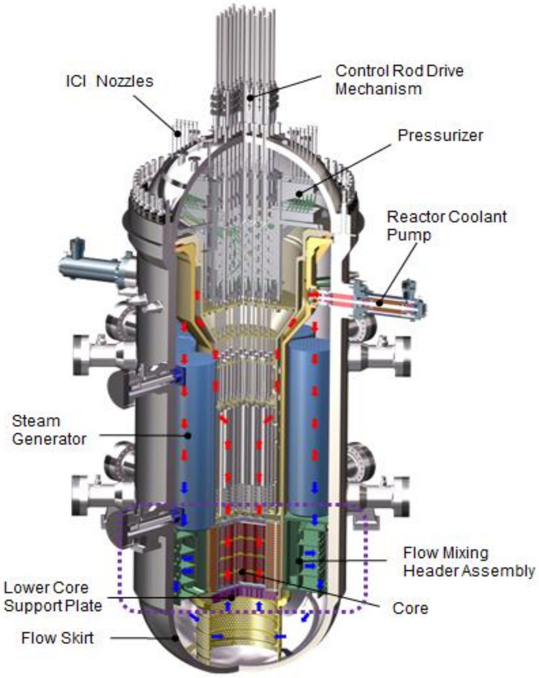
SMART adopts a FMHA having very unique design feature to enhance the thermal mixing capability in failure conditions of some steam generators. Investigations for the mixing characteristics of the FMHA had been performed by using experimental and CFD methods in KAERI. In this study, the temperature distribution at the core inlet region is investigated for several abnormal conditions of steam generators using a commercial CFD code, Fluent 12. When compared with the experimental results, the CFD simulation slightly underestimates or overestimates a mixing parameter within approximately 10%. Comparing turbulence models, the local deviation of dimensionless temperature at the core inlet is less than approximately 8% and the mixing parameter deviation at the core inlet is less than approximately 6%. It is also shown that the mixing parameters at the core inlet are higher than 0.85 satisfying the design requirement of mixing parameter 0.80 in all the simulated conditions. We numerically confirmed that the FMHA applied in SMART has an excellent thermal mixing capability.

INTRODUCTION

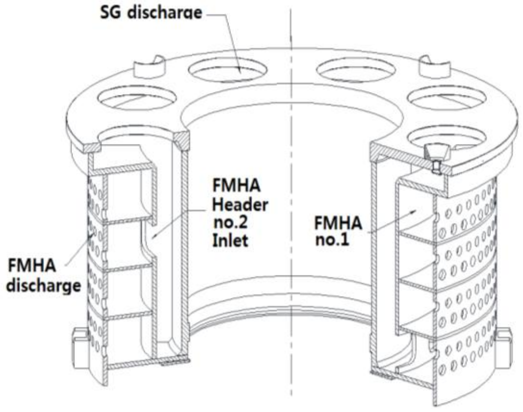
An integral type reactor, a system-integrated modular advanced reactor (SMART), has been being developed in Korea Atomic Energy Research Institute (KAERI) since 1990s and acquired the Standard Design Approval from the Korea Institute of Nuclear Safety (KINS) in 2012. The hybrid safety system currently employed in the standard design of SMART is planned to be upgraded with fully passive safety system until early 2016.

In SMART, steam generators are installed in the annular space between core support barrel outside wall and reactor vessel inside wall (Fig. 1). The core flow and temperature distribution is one of the major concerns in nuclear reactor development (Böttcher et al., 2010, Tak et al., 2008, and Bieder et al., 2007).

SMART adopts a Flow Mixing Header Assembly (FMHA) at the downstream of the steam generators to enhance the thermal mixing and flow distribution capability in failure conditions of some steam generators or reactor coolant pumps. The FMHA is greatly important for enhancing thermal mixing and flow distribution of the coolant during a normal operation, transient and even during accidents. The FMHA rearranges the



(a) Reactor vessel



(b) Flow mixing header assembly

Figure 1. Configuration of the reactor vessel and FMHA of SMART.

fluid discharged from the steam generator with uneven temperature or flow distribution under abnormal conditions, and very finely splits the fluid and intensively increases contacting area between hot and cold coolant. Moreover the deviation of flow distribution is mitigated by the redistributing effects of the FMHA.

Investigations for the mixing characteristics of the FMHA were performed by using experimental (Kim et al., 2012) and CFD (Kim et al., 2011) methods in KAERI. In the experimental study, the temperature distribution at the core inlet region is examined for several abnormal conditions of steam generators and the FMHA showed excellent thermal mixing performance. In the CFD study, the temperature distribution at the core inlet region was investigated using the commercial CFD code, Fluent 12 (Ansys Inc. 2009). Grid dependency and turbulence model (RANS) tests were performed, and numerical simulations were carried out to investigate the detailed mixing characteristics of the FMHA. It was numerically reconfirmed that the FMHA applied in SMART has an excellent thermal mixing capability. In this paper, the CFD results will be introduced briefly.

METHODS

The steady, incompressible, and three dimensional flow with constant properties is assumed in these simulations. All simulations have been carried out with the 2nd-order upwind scheme, the SIMPLE algorithm for pressure-velocity coupling, and the standard wall function for RKE (Realizable *k*-*ε*) and RNG (Renormalization Group *k*-*ε*) turbulence models, and without the low Reynolds correction option for SST (Shear Stress Transport *k*-*ω*). Three different turbulence models such as SST, RNG, RKE summarized in reference (Y.I. Kim et al., 2011, and ANSYS Inc., 2010) are applied. The governing equations read as

$$\frac{\partial\langle u_i\rangle}{\partial x_i}=0 \qquad (1)$$

$$\frac{\partial\langle u_i\rangle\langle u_j\rangle}{\partial x_j}=-\frac{1}{\rho}\frac{\partial\langle P\rangle}{\partial x_i}+\frac{\partial}{\partial x_j}\left[\nu\left(\frac{\partial\langle u_i\rangle}{\partial x_j}+\frac{\partial\langle u_j\rangle}{\partial x_i}\right)-\langle u_i' u_j'\rangle\right] \qquad (2)$$

$$\langle u_i\rangle\frac{\partial\langle T\rangle}{\partial x_i}=\alpha\frac{\partial^2\langle T\rangle}{\partial x_i\partial x_i}-\frac{\partial\langle u_i' T'\rangle}{\partial x_i} \qquad (3)$$

where the angle brackets < > indicate time-averaging, and u and u' are the mean and fluctuating velocities, respectively. P, ρ, ν, and T represent the pressure, density, kinematic viscosity, and temperature of the fluid, respectively.

As the FMHA has many holes, before the main calculation for the FMHA, some validation calculations had been performed on a two-dimensional axisymmetric flow through orifices. As shown in Fig. 2 the numerical result agrees quite well with an empirical correlation (Idelchik, 1997).

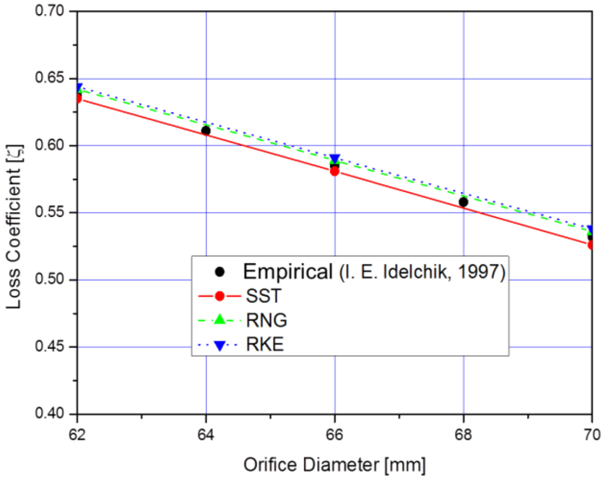


Figure 2. Comparison of pressure loss coefficient through an orifice between an emprical correlation and simulation.

As shown in Fig. 1, the FMHA is located between downstream region of the eight steam generators and upstream region of the core. As the flow patterns through the FMHA is asymmetry, the full geometry such as the FMHA inlet (SG outlet), FMHA, the upstream region of core, and core should be included to simulate the FMHA mixing phenomena. Too much computational resource may be required to model the real geometries such as the fuel assemblies, lower core support plate, and flow skirt. Thus, in order to simplify the analyses and focus on the mixing phenomenon of the FMHA, porous models with prescribed flow resistance are adopted for these components. Figure 3 shows the computational geometry, boundary conditions, and grids at a FMHA plane.

RESULTS AND DISCUSSION

The thermal mixing efficiency of an FMHA is evaluated using a mixing parameter (MP) defined by

$$MP=1-(\theta_{\max}-\theta_{\min}) \qquad (1)$$

where

$$\theta=\frac{(T-T_{avg})_{core\,in}}{(T_h-T_c)_{FMHAin}} \qquad (2)$$

Here, θ is the dimensionless temperature difference at the core inlet indicating the temperature deviation with respect to the average temperature of the core inlet normalized by the temperature difference at the steam generator outlets, and the MP indicates the efficiency of thermal mixing. MP = 1 means that the flow is in a fully mixed state, while MP = 0 implies that it is not mixed at all.

The simulation cases for the FMHA thermal mixing are summarized in Table 1. The grid sensitivity and the flow rate difference between two types of FMHA shape were inspected as a base work shown in detail in the reference (Kim et al., 2011).

Table 1. Simulation cases.

Case	Turb. model	Mesh (million)	FMHA type	Mixing Parameter
A1	RKE	85.1	Type A	0.85
A2	SST	85.1	Type A	0.91
A3	RNG	85.1	Type A	0.88
B1	RKE	93.9	Type B	0.95

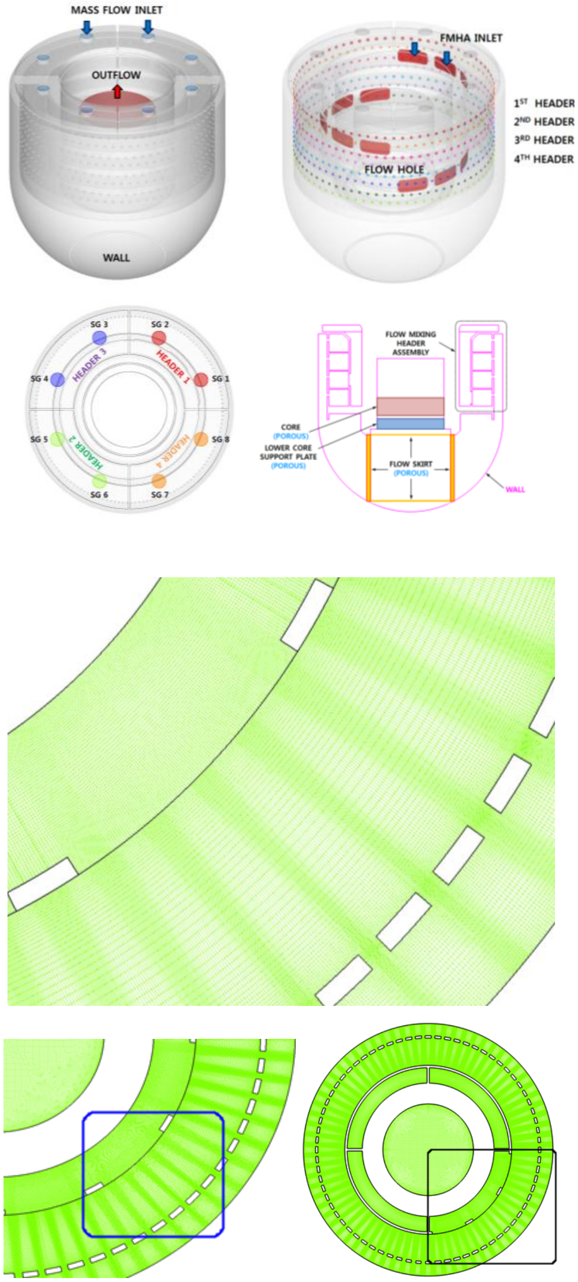


Figure 3. Geometry, boundary conditions, and grid.

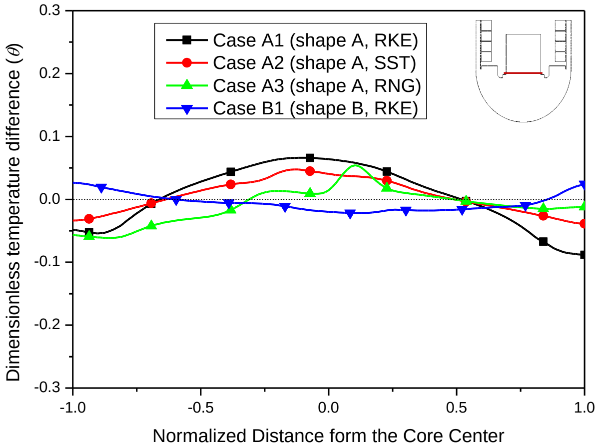
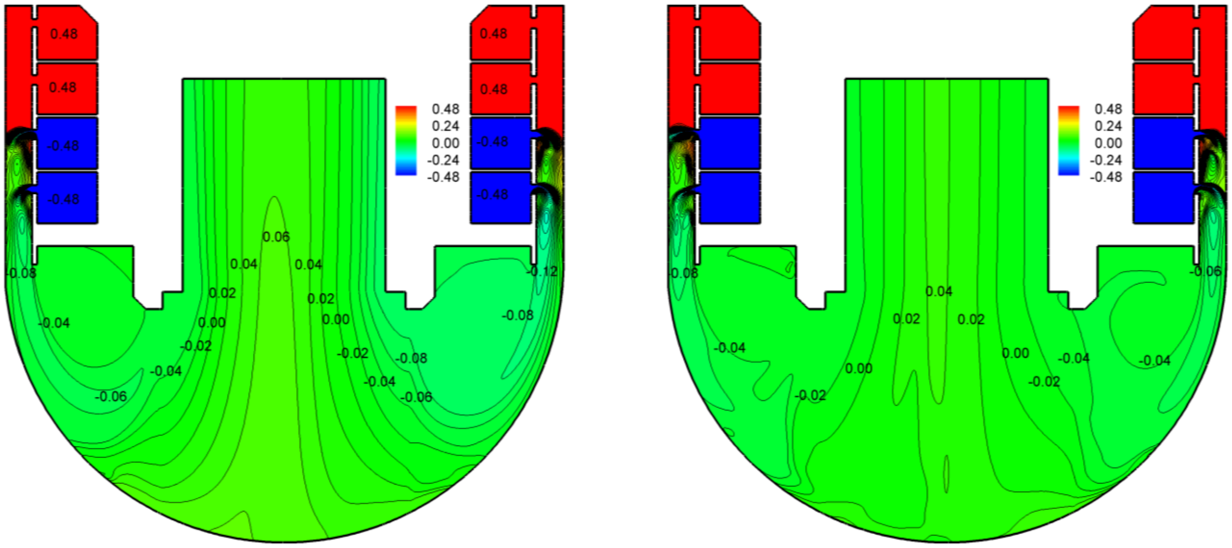


Figure 4. Temperature distribution at a core inlet line.

The deviation of dimensionless temperature difference between a coarse grid (94 million) and a fine grid (144 million) is less than 1.5%. The FMHA type A and B have approximately 50% and 10% local deviations of flow rate through FMHA discharge holes respectively.

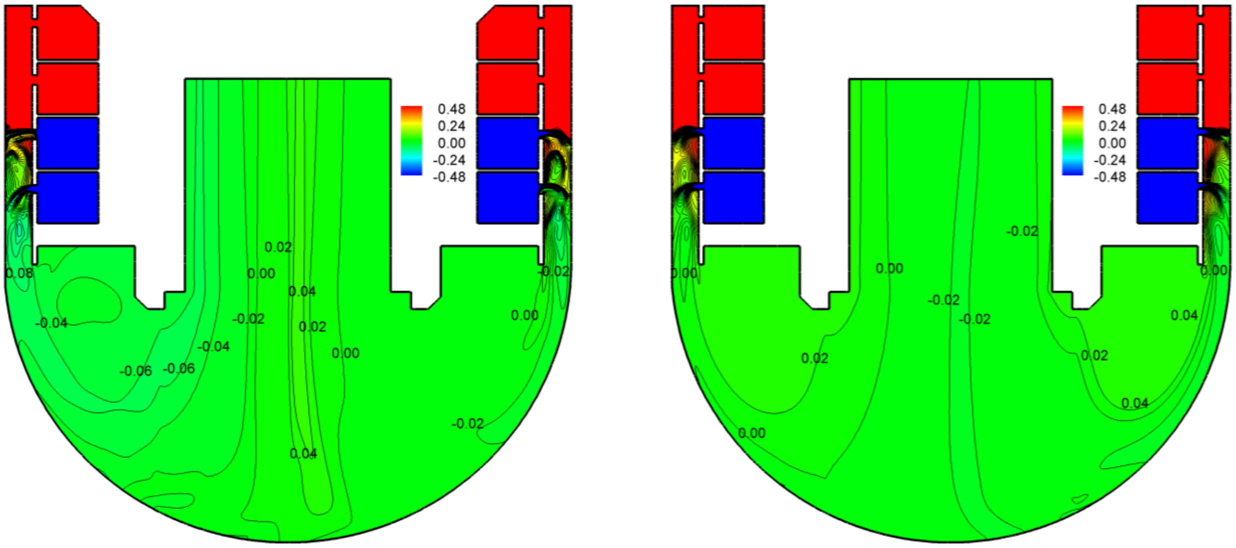
The CFD results for three difference turbulence models are shown in Fig. 4 and Fig. 5. The average pressure loss deviation between turbulence models are within 2% (Kim et al., 2011). The mixing parameter values of cases A1-A3 are calculated as 0.85, 0.91, and 0.88, respectively. In the experiment (Kim et al., 2012), the mixing parameter shows 0.90-0.94. The dimensionless temperature difference between the turbulence models are not noticeable, the local difference are within maximum 8%, the deviation of the mixing parameter difference are within approximately 6%, and the overall distribution shows very similar pattern. Hence three turbulence models can be considered in these kinds of simulations. Considering more stable convergence, RKE model are selected in this paper.

The dimensionless temperature difference for two FMHA shapes of type A and B, having a different flow rate distribution in each discharge holes of FMHA and slightly different average flow resistance, are also compared in Fig. 4(Case A1) and Fig. 5(Case B1). The mixing parameter value of case B1 is calculated as 0.95. In the experiment (Kim et al., 2012), the mixing parameter shows 0.94 for this case. As displayed in these Figs, the FMHA type B having relatively uniform discharge flow rate shows very excellent capability in mixing efficiency. However, to achieve a relatively uniform flow distribution in the circumferential direction under the low flow resistance condition, the SMART FMHA discharge holes are designed to have different diameters, and thus there could be many factors leading to uneven flow distribution at the FMHA such as manufacturing tolerance, analysis model defect, and design error. Meanwhile both of type A and B reduces the temperature difference given at the stream generator discharge below 15% and 5% at the core inlet region by the mixing effect of the FMHA, thus satisfying the design requirement of the FMHA mixing parameter (MP ≧ 0.80). This indicates that mixing capability can be maintained in a certain allowable range of tolerance. In brief, even though the mixing capability



(a) Case A1

(b) Case A2



(c) Case A3

(d) Case B1

Figure 5. Temperature distribution at a center plane.

decreases as the flow rate becomes nonuniform, it still remain acceptable in the FMHA type A.

CONCLUSIONS

CFD simulations were carried out to inspect the mixing performance for the FMHA of SMART. The influence of the turbulence model was tested; the thermal mixing effect of FMHA is not sensitive to the turbulence model, the difference is within 8%. The effect of the flow rate deviation through the FMHA discharge holes on the mixing capability was also investigated: the uniformity of FMHA discharging flow is shown to increase the mixing efficiency.

In brief, the FMHA is capable of mixing the coolant effectively in the case of an asymmetric cooling accident of steam generators such as main steam line break (MSLB) and feedwater line break (FLB). Thus at accidents, the local temperature increase at the core inlet of SMART is negligible.

ACKNOWLEDGEMENT

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