Numerical Simulation for ROCOM PTS Test using Generalized k-ω Turbulence Model

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1. Introduction

Depending on the complex structure and extreme condition, various situations can arise in a nuclear power plant. When a design basis event occurs such as a loss of coolant accident, the situation becomes more difficult to predict as lower-temperature fluid is injected under higher-pressure condition. Reactor pressure vessels (RPVs) injected with emergency core coolant (ECC) water are subject to supercooling and significant pressure conditions, which can be accompanied by pressurized thermal shock (PTS). A detailed understanding of coolant mixing in ECC water injection situations is essential for the structural integrity of the RPV.

Various experiments have been conducted to evaluate the thermal-hydraulic behavior of coolant mixing at different temperatures and densities. The European project named FLOMIX-R was carried out via the Rossendorf coolant mixing (ROCOM) PTS test facility to quantitatively evaluate the coolant mixing [1]. This experiment evaluated mixing due to density differences between the primary loop and ECC water. The focus was on quantitatively evaluating these experiments through numerical investigation. However, there are still differences between experiments and computational fluid dynamics (CFD) analysis. To reduce these differences, a generalized k-ω (GEKO) turbulence model was developed that can flexibly respond to various conditions through free coefficient adjustment technique [2].

The objectives of current study are to simulate coolant mixing performed in ROCOM experiments and analyze it with different turbulence models. Furthermore, parametric analyses are performed through the free coefficient adjustment of the GEKO turbulence model.

2. Analysis Method and Conditions

2.1 ROCOM D10m10 Test

The ROCOM PTS test facility was established to verify a coolant mixing code representing the geometry of a German KONVOI-type pressurized water reactor. In this study, an experiment called as D10m10 was chosen from 21 experiments performed in the FLOMIX-R project and simulated by using ANSYS Fluent.

The purpose of this experiment was to investigate coolant mixing caused by density differences between the primary loop and ECC water. The ECC water had a 10% higher density and constant flow rate in a single nozzle was 10% of the loop flow rate. After 5 seconds after the loop flow rate was established, the ECC water was injected into the ECC nozzle for 10 seconds.

2.2 Analysis Model

As shown in Fig. 1, the RPV of the ROCOM test facility was constructed as a 3D CAD model considering specific design. The inlet nozzle cross-section was considered as a comparison region of analysis results. CFD model with 10 million polyhedral cells was developed adapting the y^+ value to be less than 1, as depicted in Fig. 2.

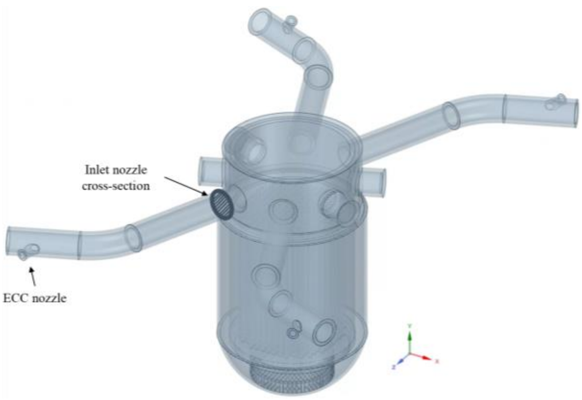

Fig. 1. CAD model of RPV in ROCOM PTS test facility

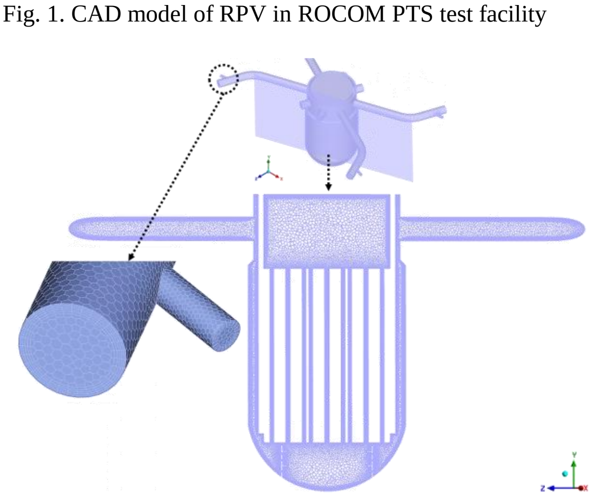

Fig. 2. CFD model of the RPV with cutaway view

2.3 Turbulence Models

The experiment was simulated using Large-Eddy Simulation (LES) turbulence model with SIMPLE algorithm and WALE subgrid-scale model [3]. The LES model has been known to generally provide higher prediction accuracy than the Reynolds Averaged Numerical Simulation model for PTS phenomena [4].

GEKO was adopted to effectively reflect various flow characteristics, and the Shear Stress Transport (SST) k-ω model was also introduced as a comparison model. There are six parameters of the GEKO model: C_{SEP}, C_{NW}, C_{MIX}, C_{JET}, C_{CORNER} and C_{CURV} [2]. C_{SEP} and C_{NW}, which control flow separation and near-wall flow, respectively, were considered as important parameters for the analysis. The adjustable ranges are listed in Table 1, and the maximum, default, minimum values were adopted as variables in this study.

Table I: Available ranges of GEKO parameters

Parameter	Minimum	Default	Maximum
C_{SEP}	0.70	1.75	2.50
C_{NW}	-2.00	0.50	2.00

3. CFD Analyses

CFD analysis was performed to simulate the ROCOM experiment. ECC water mixing scalars at the inlet nozzle cross-section were depicted along with the experimental results in Fig. 3 and Fig. 4. The structural similarity index measure (SSIM) technique was used to compare the analysis results, by which the structural similarity of each contour was able to be understood. It was confirmed that LES shows higher accuracy than the GEKO default turbulence model.

To gain a deeper understanding of the GEKO turbulence model and better simulation for the experimental results, a parametric analysis was carried out by adjusting the parameters of GEKO. As shown in Fig. 5, the highest accuracy was derived where C_{SEP} and C_{NW} were 2.50 and -2.00, respectively. The lowest accuracy was found in the case of 0.70 and 0.50. However, overall it showed better results than SST k-ω, but not better than LES.

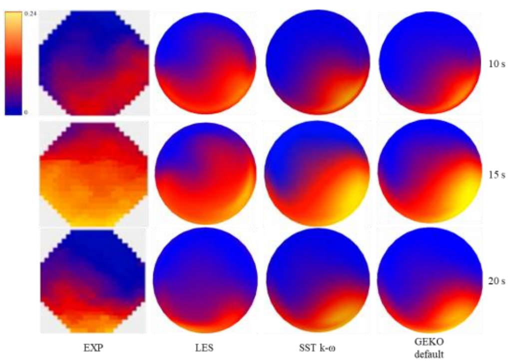

Fig. 3. Comparison of ECC mixing scalar at the inlet nozzle

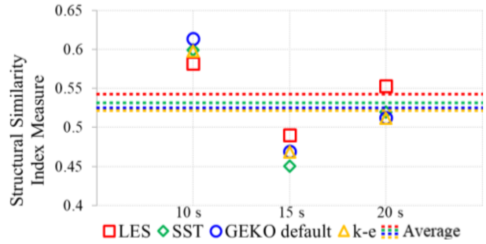

Fig. 4. Comparison of CFD analysis SSIM results

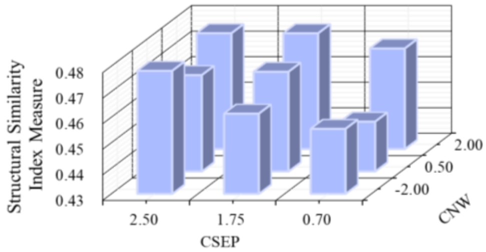

Fig. 5. Parametric analysis results at l5 s

4. Conclusions

An experiment performed at the ROCOM PTS test facility was numerically examined in this study, and the following key findings were obtained:

(1) It was confirmed that the LES presented the highest similarity to the experimental results of than other two models.
(2) By adjusting the two types of parameters with nine values of GEKO, instead of using the SST k-ω, more reasonable mixing phenomenon was achieved with a comparable numerical cost.
(3) It is anticipated that the accuracy of the GEKO turbulence model can be improved by introducing more values within the available range and additional parameters.

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