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CFD Analysis of Flow Distribution in the Lower Reflector Region of a High-Temperature Gas-Cooled Reactor

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1. Introduction

High-temperature gas-cooled reactors (HTGRs) are being actively investigated as advanced reactor concepts for high-temperature heat and electricity generation. In Korea, the Korea Atomic Energy Research Institute (KAERI) is developing the HElium Cooled Thermal Application Reactor (HECTAR) based on a prismatic HTGR configuration [1, 2]. In such reactors, helium coolant passes through numerous coolant channels in the core and subsequently flows through the lower reflector region before entering the lower plenum. Therefore, the flow behavior within the lower reflector region can directly affect the coolant distribution and inlet conditions of the lower plenum.

The lower reflector region of HECTAR consists of several successive flow structures, including lower reflector blocks, a transition block, a flow distribution block, and flow passages leading to the lower plenum. As coolant streams from multiple core channels pass through these structures, they undergo contraction, turning, merging, and redistribution, resulting in complex three-dimensional flow behavior. In particular, jet interaction and recirculating flow within the flow distribution region can influence how uniformly the coolant is redistributed before entering the lower plenum. Because resolving these flow structures using simplified system-level models is difficult, computational fluid dynamics (CFD) provides a useful approach for examining the detailed flow behavior during the conceptual design stage.

In the present study, a preliminary steady-state CFD analysis was performed for a single lower-reflector element of HECTAR. The analysis focused on coolant redistribution and flow-mixing characteristics before the coolant enters the lower plenum.

2. Methodology

The computational domain represents a single lower-reflector element of HECTAR and consists of the lower reflector blocks, lower transition block, lower flow distribution block, and flow passages leading to the lower plenum, as shown in Fig. 1. Detailed geometric dimensions and operating conditions are omitted due to proprietary restrictions, and the calculated quantities are presented in normalized form. Symmetry conditions were imposed on the lateral boundaries of the lower plenum inlet passages to limit the computational domain.

The CFD simulations were performed using ANSYS CFX 2025R1 under a steady Reynolds-averaged Navier–Stokes (RANS) framework. The Menter-SST turbulence model with automatic blended near-wall treatment was employed, and the thermophysical properties of helium were evaluated using REFPROP v10. A reference operating condition was imposed at the inlet, with the total coolant flow uniformly distributed among the inlet channels. A pressure-outlet condition was imposed at the downstream boundary, and all solid surfaces were treated as adiabatic no-slip walls.

Fully conformal meshes were generated throughout the computational domain, with representative mesh configurations shown in Fig. 1. Local refinement was applied near solid surfaces and particularly within the lower flow distribution region, where large velocity gradients and complex jet interactions were expected. Three mesh resolutions containing approximately 90.9, 115.2, and 156.8 million cells were considered for the grid-sensitivity assessment. For the fine mesh, the mean (y^+) values of the major subdomains ranged from approximately 0.4 to 1.1. More than 99% of the cells also satisfied the prescribed mesh quality criteria for orthogonality, expansion ratio, and aspect ratio. Grid sensitivity was assessed using the area-averaged velocity magnitude and turbulent kinetic energy at the lower plenum inlet.

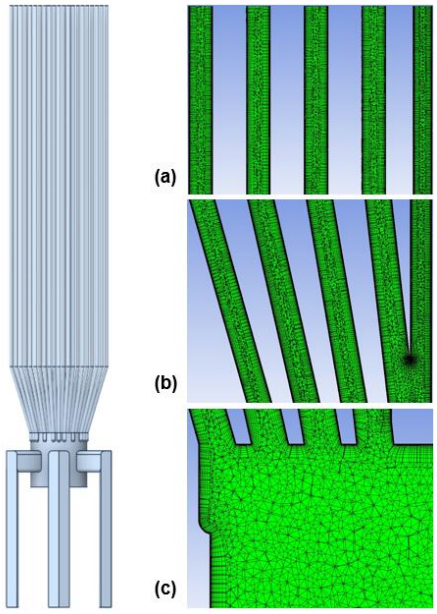


Fig. 1. Computational domain and mesh configurations : (a) lower reflector, (b) transition region, and (c) flow distribution region.

3. Results

Table 1 summarizes the grid sensitivity results based on the area-averaged velocity magnitude and turbulent kinetic energy at the lower plenum inlet. The relative difference from the fine mesh solution, $\epsilon_{rel,\phi}$, was defined as

$$\epsilon_{rel,\phi} = \left|(\phi - \phi_{fine})/\phi_{fine}\right| \times 100\% \, .$$

The medium and fine meshes differed by approximately 1.6% and 0.02% in the two quantities, respectively.

Table 1. Grid-sensitivity assessment relative to the fine mesh.

Mesh	Cells [M]	$\epsilon_{rel,U}$ [%]	$\epsilon_{rel,k}$ [%]
Coarse	90.9	5.73	0.11
Medium	115.2	1.62	0.02
Fine	156.8	Ref.	Ref.

Figure 2 shows the velocity magnitude distribution on a representative vertical (yz) plane. The coolant streams passing through the lower reflector are redirected and merged through the transition block before entering the lower flow distribution region. In particular, the merged stream forms a relatively high-momentum jet that penetrates deeply into the flow distribution block and reaches the opposite structural surface. Although the detailed flow pattern may vary with the inlet flow rate, the persistence of this jet indicates that the flow within the block cannot be regarded as being dominated by spatially uniform bulk mixing under the present condition.

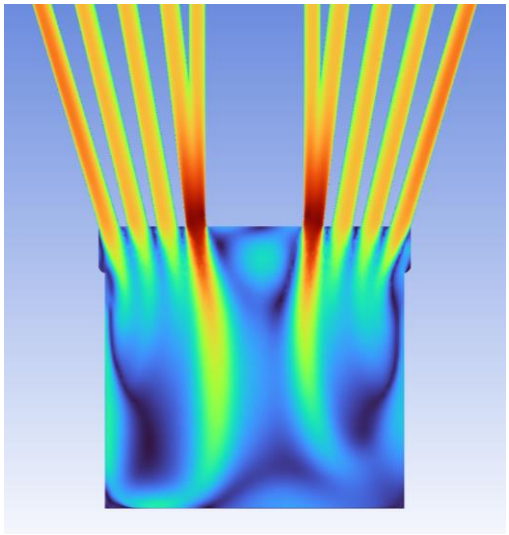


Fig. 2. Normalized velocity magnitude distribution on the vertical yz plane.

The velocity distribution on the xy plane in Fig. 3 shows additional local flow structures within the flow distribution block. Multiple jets entering the confined flow distribution region develop as both free jets and wall-attached jets depending on their trajectories and interaction with the surrounding structures. Consequently, several low-velocity regions are formed within the flow distribution block and near the outlet passages. The coexistence of high-momentum jets and low-velocity regions indicates that coolant redistribution occurs through localized jet interaction, impingement, and recirculating flow rather than through homogeneous mixing over the entire volume. Nevertheless, interactions among the individual streams progressively redistribute the coolant before it enters the lower plenum inlet passages.

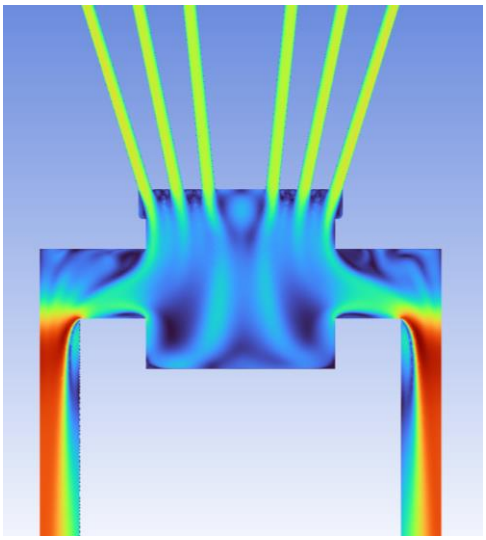


Fig. 3. Normalized velocity magnitude distribution on the vertical xy plane.

To quantify the flow maldistribution at the lower plenum inlet, the coefficient of variation of the passage mass flow rates was defined as

$$CV_{\dot{m}} = \frac{\sigma_{\dot{m}}}{\bar{\dot{m}}} \times 100 \,,$$

where $\sigma_{\dot{m}}$ can be calculated as

$$\sigma_{\dot{m}} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(\dot{m}_i - \bar{\dot{m}})^2} \,.$$

The resulting $CV_{\dot{m}}$ was approximately 0.77%, while the maximum deviation from the mean mass flow rate was approximately 1.43%. Despite the locally non-uniform flow structures within the flow distribution block, these values indicate a relatively uniform distribution of coolant among the lower-plenum inlet passages.

These flow features also show that the lower flow distribution block involves several interacting turbulent flow mechanisms, including confined multiple jet flow, free-jet/wall-jet interaction, and recirculating flow. Such flows can be sensitive to turbulence model assumptions, particularly when strong shear layers, jet impingement, and recirculation coexist. Therefore, although the present steady RANS analysis provides a preliminary description of the overall coolant redistribution and mixing characteristics, the influence of turbulence modeling on the local flow structures should be further investigated in subsequent studies.

4. Conclusions

A preliminary steady-state CFD analysis was conducted for a single lower-reflector element of HECTAR to investigate coolant redistribution and mixing before the flow enters the lower plenum. The medium and fine meshes differed by approximately 1.6% in the area-averaged velocity magnitude and 0.02% in turbulent kinetic energy, indicating limited grid sensitivity in the selected global quantities.

The calculated flow field showed the coexistence of high-momentum jets, wall-attached jets, low-velocity regions, and recirculating flow within the lower flow distribution block. Some merged jets retained sufficient momentum to penetrate across the flow distribution region, indicating that coolant redistribution was governed by localized jet interactions rather than spatially uniform bulk mixing under the present condition. The coefficient of variation of the lower plenum inlet mass flow rates was only 0.77%, indicating a relatively uniform overall flow distribution. These results provide preliminary information on the flow conditions supplied to the lower plenum. Further studies will examine the sensitivity of the local flow structures to turbulence modeling and operating conditions.

ACKNOWLEDGEMENT

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