Comprehensive Preliminary Numerical Analysis of Natural Convection Heat Transfer in a TN-32B Cask

Tae Yeong Jung [a], Jin Hyeon Kim [a], Do Yun Kim [b], Jae-Ho Jeong [a*]
[a]*School of Mechanical Engineering, Chung-Ang University, Seoul, Republic of Korea*
[b]*Korea Atomic Energy Research Institute (KAERI), Daejeon, Republic of Korea*
[*]*Corresponding author: jaehojeong@cau.ac.kr*

***Keywords :** spent nuclear fuel, dry storage cask, rod-resolved CFD, natural convection, TN-32B*

1. Introduction

The interim storage of spent nuclear fuel has become increasingly critical as wet storage capacities approach saturation. Dry storage systems are therefore being considered as an expanded management option in Korea. These systems rely exclusively on passive heat removal mechanisms, including natural convection and thermal radiation, to maintain fuel cladding temperatures below regulatory limits. Accurate evaluation of regulatory temperature limits requires high-fidelity representation of the internal thermal–hydraulic field.

The TN-32B dry storage cask has been investigated within the Electric Power Research Institute (EPRI) High Burnup Dry Storage Research Project, which provides publicly available thermal benchmark data suitable for model validation. During storage, the peak cladding temperature must remain below 400 °C. Reliable prediction of this limit depends on accurate characterization of buoyancy-driven internal circulation and associated temperature distributions.

Most previous numerical studies have adopted porous media formulations to represent the fuel assembly region in order to reduce computational cost. Although such approaches reproduce global thermal behavior, homogenization of the flow field prevents resolution of rod-level temperature gradients that may influence local peak cladding temperatures. In the present study, a geometrically detailed, quarter-symmetry rod-resolved CFD model of the TN-32B cask is developed without porous simplification. The objective is not only to validate the rod-resolved formulation against benchmark measurements but also to establish a high-resolution reference solution that can serve as a baseline for future porous-model comparison and uncertainty assessment.

2. Numerical Methodology and Results

2.1 Computational Model

The TN-32B cask contains 32 pressurized water reactor (PWR) fuel assemblies enclosed within a sealed canister. A 90° quarter-symmetry model was constructed to reduce computational expense while preserving full geometric fidelity within the fuel region. Symmetry boundary conditions were imposed on the radial planes.

The fuel assemblies were represented using a rod-resolved configuration in which individual fuel rods and spacer grids were explicitly modeled. Volumetric heat generation was applied exclusively within the active fuel region using an axially normalized decay heat profile derived from EPRI benchmark data. Helium was defined as the working fluid, and steady-state natural convection conditions were assumed. Buoyancy effects were modeled using the Boussinesq approximation. The estimated Rayleigh number within the fuel assembly region was on the order of 10^8, supporting the assumption of laminar flow. Temperature-dependent thermophysical properties were assigned to major structural components.

Structured meshes with near-wall refinement were employed to ensure $y^+ < 1$ within the helium region. The final quarter-symmetry rod-resolved model consisted of approximately 1.25×10^8 computational cells. Radiative heat transfer was imposed at the upper boundary, while an equivalent conductive thermal resistance was applied at the lower boundary to represent the supporting pad effect. The overall computational domain and geometric resolution of the rod-resolved configuration are illustrated in Fig. 1, which highlights the explicit representation of individual fuel rods and spacer grids. The principal computational conditions are summarized in Table I.

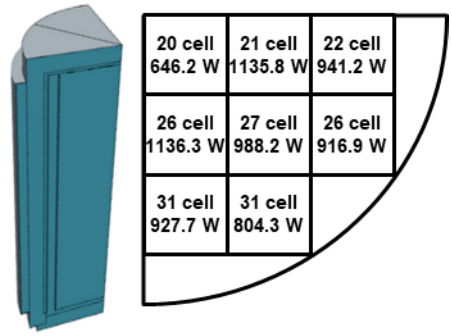


Fig. 1. Quarter-symmetry rod-resolved computational domain of the TN-32B dry storage cask. Individual fuel rods and spacer grids are explicitly represented.

Table I: Summary of computational conditions

Parameter	Value
Coolant	Helium
Total decay heat	36.8 [kW]

Internal Pressure	2,200 [mbar]
Ambient Temperature	25 [℃]
Turbulence Model	Laminar (Boussinesq approximation)
Total Cells	1.25×10^8 cells

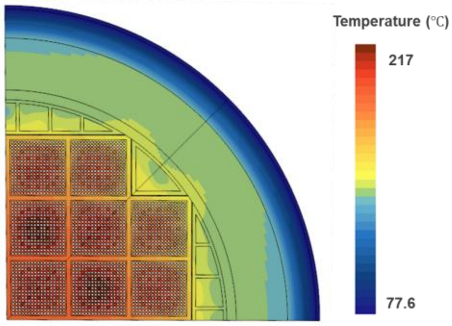
2.2 Results and Validation

The axial temperature distribution obtained from the rod-resolved simulation is presented in Fig. 2. Elevated temperatures are observed in the central fuel region, with gradual axial variation toward the upper and lower boundaries. This distribution reflects the development of buoyancy-driven natural convection and heat exchange with surrounding structures.

The helium velocity vector field shown in Fig. 3 reveals a characteristic natural circulation loop, consisting of upward flow along heated fuel assemblies and downward return flow adjacent to the outer canister wall. This circulation pattern governs the internal convective heat removal mechanism. The velocity magnitude remains below O(0.1 m/s), consistent with the estimated Rayleigh number and supporting the laminar flow assumption.

The predicted maximum cladding temperature remains well below the regulatory limit of 400 °C. To evaluate predictive performance, axial temperature results were compared with EPRI benchmark measurements, as summarized in Table II. The rod-resolved CFD model reproduces the overall axial temperature trend with satisfactory agreement, particularly in the mid-height and upper regions. The agreement observed in these regions indicates that the model adequately captures the dominant buoyancy-driven heat transfer mechanism within the fuel assembly domain.

The largest deviation occurs near the lower elevation (0.23 m), where the predicted temperature exceeds the measured value by approximately 28%. This discrepancy is primarily attributed to uncertainty associated with the modeling of equivalent conductive resistance at the lower boundary and localized heat transfer behavior near the support structure. Despite this localized deviation, the rod-resolved formulation demonstrates reasonable overall agreement with benchmark data while providing detailed information regarding localized thermal gradients and internal circulation structures that are inherently averaged in porous media formulations.



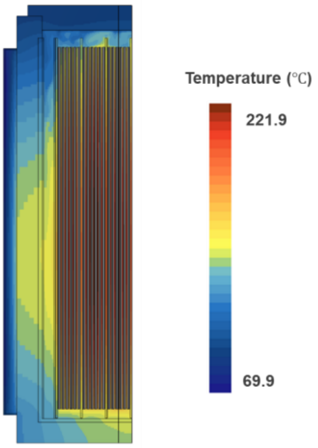


Fig. 2. Temperature distribution in the axial plane of the quarter-symmetry rod-resolved TN-32B model after implementation of radiative and conductive boundary conditions.

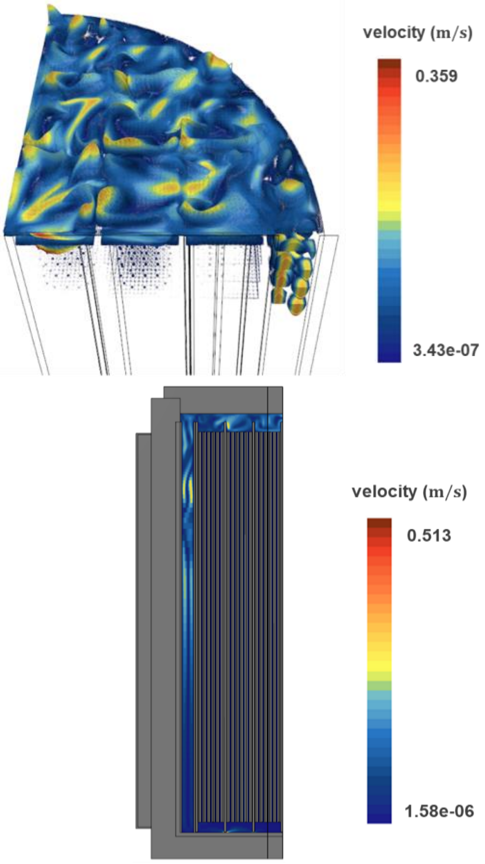


Fig. 3. Helium velocity vector field showing buoyancy-driven natural circulation inside the TN-32B cask.

Table II: Comparison of measured and CFD-predicted axial temperatures.

Elevation (m)	Temperature(℃)	
	measured Data	calculated with CFD
3.81	150.7	150.9
3.56	171.5	165.6

2.97	194.2	189.4
2.39	199.6	201.2
1.90	198.0	204.0
1.52	193.9	203.5
1.02	181.8	196.7
0.64	164.9	187.7
0.23	131.9	169.3

3. Conclusions

A geometrically detailed, quarter-symmetry rod-resolved CFD model of the TN-32B dry storage cask was developed to investigate internal natural convection heat transfer without porous media simplification. Explicit representation of individual fuel rods and spacer grids enabled high-resolution prediction of localized temperature gradients and buoyancy-driven flow structures within the fuel assembly region.

Implementation of radiative boundary conditions at the upper surface and equivalent conductive resistance at the lower boundary enhanced physical consistency in the axial temperature distribution. Comparison with EPRI benchmark data demonstrated reasonable predictive agreement, thereby supporting the validity of the proposed modeling framework.

The present framework establishes a high-fidelity reference model that can serve as a baseline for subsequent validation studies, sensitivity analyses, and safety margin assessment of TN-32B dry storage systems.

ACKNOWLEDGEMENTS

This work was supported by the Nuclear Safety Research Program through the Regulatory Research Management Agency for SMRs(RMAS) and the Nuclear Safety and Security Commission (NSSC) of the Republic of Korea. (No. RS-2024-00509653).

This work was supported by the National Research Foundation of Korea(NRF) grant funded by the Korea government(MSIT) (No. RS-2024-00457356).

REFERENCES

[1] Electric Power Research Institute (EPRI), High Burnup Dry Storage Research Project Cask Loading and Initial Results, EPRI, Palo Alto, CA, 2019, 3002015076.

[2] Electric Power Research Institute (EPRI), High-Burnup Used Fuel Dry Storage System Thermal Modeling Benchmark: Round Robin Results, EPRI, Palo Alto, CA, 2020, 3002013124.

[3] J. A. Fort, D. J. Richmond, J. M. Cuta, and S. R. Suffield, Thermal Modeling of the TN-32B Cask for the High Burnup Spent Fuel Data Project, Pacific Northwest National Laboratory, PNNL-28915, 2019.

[4] Electric Power Research Institute (EPRI), International Thermal Modeling Benchmark Description for a High-Burnup Used Fuel Dry Storage System, EPRI, Palo Alto, CA, 2020, 3002018498.

[5] U.S. Nuclear Regulatory Commission (NRC), Interim Staff Guidance (ISG)-11, Revision 3, 2003.