Validation of Thermal Model for Fuel Assembly Canister Test Simulator (FACTS) Using Experimental Data

Ju-Chan Lee*, Doyun Kim, Changhwan Shin, and Seunghwan Yu

KAERI, 111, Daedeok-daero 989Beon-gil, Yuseong-gu, Daejeon, Republic of Korea
* *Corresponding author: sjclee@kaeri.re.kr*

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1. Introduction

Thermal analysis of spent nuclear fuel dry storage systems must demonstrate that the temperatures of the fuel and structural materials remain within allowable limits. In particular, the fuel cladding temperature must remain below 400 °C [1] under normal operational and storage conditions.

Traditional thermal analyses often oversimplify fuel assemblies, leading to conservative temperature predictions. Although such conservatism enhances safety margins, it can also reduce the transportation and storage efficiency.

KAERI has developed the Fuel Assembly Canister Test Simulator (FACTS) to simulate the thermal characteristics of a single PLUS7 fuel assembly.

In this study, a thermal model for the FACTS was developed using COBRA-SFS [2], and the reliability of the analysis model was validated by comparing it with experimental data.

2. Experimental and Numerical Methods

2.1 Overview of the FACTS Test Apparatus

Fig. 1 shows the design drawing of the FACTS, including the thermocouple layout. The FACTS comprises of a simulated fuel assembly, a fuel basket, and a canister. The simulated fuel assembly consists of a 16 × 16 rod array with 236 heater rods, four guide tubes, and one instrumentation tube.

A total of 114 thermocouples were installed to measure the temperature of the model. The canister can be filled with helium, air, or evacuated to a vacuum state.

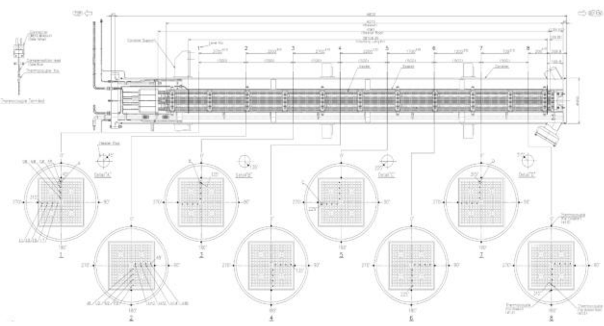

Fig. 1. Schematic of FACTS and thermocouple layout

2.2 Thermal analysis modeling

Thermal analysis model for the FACTS was developed using COBRA-SFS. The thermal model includes the fuel assembly, basket, canister, and upper and lower plenums. Heat transfer mechanisms considered include conduction, convection, and radiation. Material properties and thermal-hydraulic correlations were selected based on established references.

A Nusselt number of 3.66 was used for convective heat transfer coefficient in the spent fuel rod array. The axial wall friction factor inside the basket, considering a square array of fuel rods, was set to f = 100/Re. The pressure losses in the grid spacers were considered as K = 1 in the analysis model.

The basic analysis condition considered a vertical orientation in a helium atmosphere with a decay heat of 1 kW, an internal pressure of 1 bar, and an ambient temperature of 23 °C.

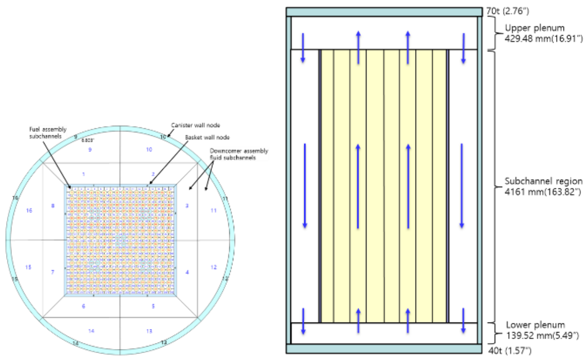

Fig. 2. Thermal analysis model of FACTS.

3. Results and Discussion

3.1 Thermal Analysis Results

Thermal analyses were conducted under various conditions, including helium and air atmospheres, multiple decay heat levels, and internal pressure conditions, including vacuum environments.

The maximum cladding temperature in an air atmosphere was calculated to be up to 42 °C higher than in a helium atmosphere. As the internal pressure increased, the gas density also increased, enhancing the natural convection effect and resulting in a lower fuel cladding temperature. Furthermore, with increasing internal pressure, the location of the maximum temperature shifted toward the upper section of the canister. In the vacuum conditions, the maximum cladding temperature in the air atmosphere increased by approximately 50 °C compared to the helium atmosphere.

Table 1. Calculated temperatures for various internal pressure (He, 1kW)

Location	Maximum temperatures (°C)		
	P = 1 bar	P = 2 bar	P = 3 bar
G8 (Rod-104)	156.7	151.9	141.2
E8 (Rod-72)	152.7	148.0	137.7
C8 (Rod-40)	143.9	139.5	129.9
A8 (Rod-08)	128.6	124.4	116.1
Basket	111.5	107.8	101.1
Canister	45.3	45.3	45.0

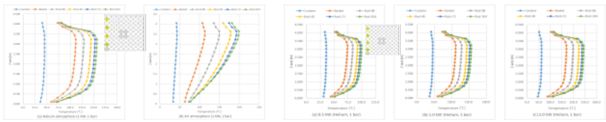

Fig. 3. Temperature profiles: helium and air atmospheres (left), various decay heats (right)

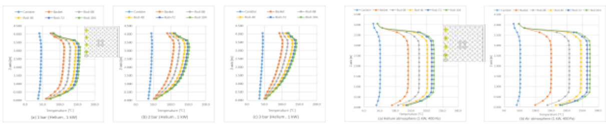

Fig. 4. Temperature profiles: various internal pressure (left) & vacuum conditions (right)

3.2. Validation of the Analysis Model

Thermal tests were conducted under helium atmospheres at 1 and 3 bar with decay heats of 0.5, 1.0, and 2.0 kW. Tests were also performed under vacuum conditions in both helium and air atmospheres. The experimental data were compared with the COBRA-SFS results to validate the analytical model.

Under all test conditions, including various decay heats, internal pressures, and vacuum conditions, the COBRA-SFS model predicted the maximum cladding temperatures within approximately 5–13% of the test results, the basket temperatures within 8–13%, and the canister surface temperatures within 5%. Axial temperature profiles also showed good agreement between the analysis and test results.

Table 2. Comparison of measured and predicted temperatures for different decay heats (Helium, 3 bar)

Location	Maximum temperature (°C)					
	Q = 0.5 kW		Q = 1.0 kW		Q = 2.0 kW	
	Test	Analysis	Test	Analysis	Test	Analysis
G8 (Rod-104)	79.1	91.1	123.4	141.9	196.9	224.7
E8 (Rod-72)	78.0	89.1	121.4	138.5	193.7	218.8
C8 (Rod-40)	74.4	84.7	114.8	130.7	182.9	205.7
A8 (Rod-08)	67.5	76.9	101.9	116.9	161.1	182.3
Basket	55.0	68.6	80.2	101.8	123.9	155.9
Canister	36.1	36.4	46.9	46.0	65.7	61.3

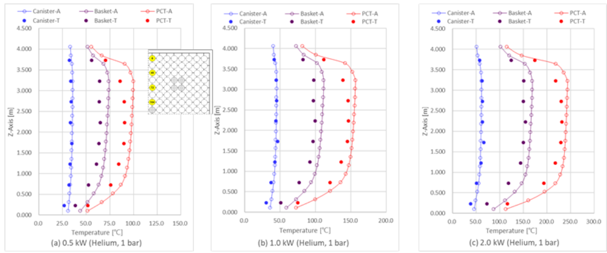

Fig. 5. Comparison of thermal test and analysis results for various decay heats (1 bar)

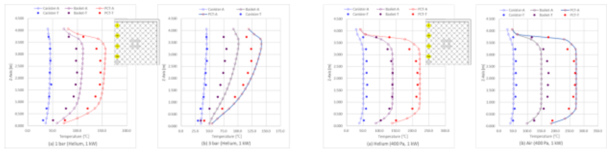

Fig. 6. Comparison of thermal test and analysis results: 1 bar & 3 bar (left), vacuum conditions (right)

4. Conclusions

A thermal analysis model for the FACTS was established and its validity was confirmed by comparing it with thermal test results. The key findings are as follows:

1. The thermal analysis model developed using COBRA-SFS effectively simulated natural convection inside the canister.
2. The fuel cladding temperatures predicted by the analysis consistently agreed with the experimental data within an error range of approximately 5–13%.
3. The canister surface temperature also agreed with the analysis and test results within 5%, confirming the reliability of the thermal boundary conditions applied to the canister surface.
4. Although the axial temperature was slightly higher in the analysis than in the tests, the reliability of the analysis model was validated, as both showed similar temperature profiles.

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