Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 22-23, 2025

Thermal Modeling in a Vacuum Environment for Dry Storage of Spent Nuclear Fuel

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Keywords : *thermal analysis, vacuum drying, thermal conductivity, dry storage, spent fuel*

1. Introduction

Vacuum drying process is commonly used to provide a dry environment for spent fuel storage. During the vacuum drying, residual moisture must be sufficiently removed, and the pressure must be maintained at less than 400 Pa (3 Torr) for 30 minutes [1]. During the vacuum drying, the temperature of the spent fuel may increase rapidly due to the reduced convection and air thermal conductivity. In this study, the vacuum theory was examined and the thermal conductivity of air was calculated at reduced pressure. In addition, the effects of vacuum pressure and thermal conductivity of air on the temperature of the fuel cladding were evaluated by performing sub-channel analysis for the FACTS (Fuel Assembly Canister Test Simulator). Finally, the thermal test and analysis results were compared to verify the reliability of the analysis results.

2. Methods and Results

2.1 Determination of thermal conductivity of air at vacuum pressure

The thermal conductivity of air varies with the temperature and pressure. The decrease in thermal conductivity of air between two plates within an enclosed cavity as a function of pressure and temperature can be calculated using Eq. (1) [2]. This equation applies to the slip flow region of rarefied gas at medium vacuum pressure.

$$(1)\quad \frac{k_r}{k_o} = \frac{1}{1 + C\frac{T}{P\,\delta}}$$

Where, k_r: reduced thermal conductivity of air (W/m·K)
k_o : thermal conductivity of air at atmospheric pressure (W/m·K)
C : Lasance constant (7.657E-5 N/m-K)
δ : gap thickness (m)

The thermal conductivity reduction rate was calculated based on a distance of 3.35 mm between fuel rods in the PLUS-7 assembly and a distance of 90 mm between the basket and the canister in the FACTS.

Table 1 shows the thermal conductivity reduction rate according to the vacuum pressure. Under a vacuum drying pressure of 400 Pa, the thermal conductivity of air decreased by about 3% inside the fuel assembly. Therefore, in the analysis of the vacuum drying process, the canister temperature can be predicted even by considering the thermal conductivity of air at atmospheric pressure.

Table 1. Thermal conductivity reduction rates of air

Vacuum pressure	Thermal conductivity reduction rates (k_r/k_0)	
	Fuel assembly @250 ℃	Canister @150 ℃
10,000 Pa	0.999	1.000
4,000 Pa	0.997	1.000
1,000 Pa	0.988	1.000
400 Pa	0.971	0.999
100 Pa	0.893	0.996
40 Pa	0.772	0.991

2.2 Sub-channel analysis model

The FACTS was selected as the sub-channel analysis using the COBRA-SFS [3]. Fig. 1 shows a sub-channel analysis model. PLUS-7 assembly has a 16 x 16 array of fuel rods with a diameter of 9.5 mm and a nominal pitch of 12.85 mm. For the vacuum, no enhancement of the convective heat transfer was assumed (Nu =1.0). Radiation heat transfer in the canister was considered, and the surface emissivity of stainless steel was considered to be 0.36. The decay heat of fuel assembly was considered to be 1.0 kW.

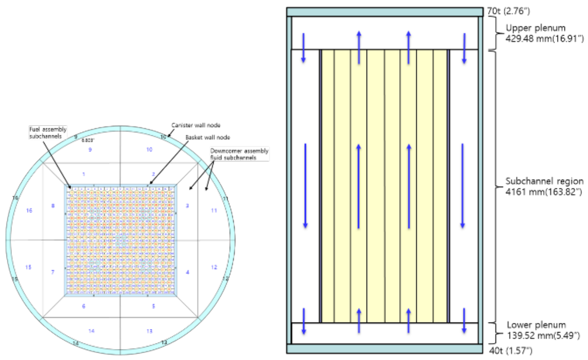


Fig. 1. Sub-channel analysis model for FACTS.

2.3. Thermal analysis according to the vacuum pressure and thermal conductivity of air

Thermal analysis was performed based on vacuum pressure and thermal conductivity of air for the FACTS. In the analysis according to vacuum pressure, the thermal conductivity of gas was used as the thermal conductivity of air at atmospheric pressure. In the analysis according to the thermal conductivity of air, a vacuum pressure of 400 Pa was considered.

Table 2 shows the analysis results according to vacuum pressure. At pressures below 10 kPa, the canister showed the same temperature distribution. This shows that heat is transferred through conduction and radiation without natural convection due to the decrease in air density.

Table 3 shows the analysis results according to the thermal conductivity of air. While the thermal conductivity of air decreased by 10%, the PCT increased by about 1.5°C. The small effect of the thermal conductivity of air on the PCT indicates that radiation heat transfer is more dominant than heat conduction in a vacuum. Since the thermal conductivity reduction rate of air is 3% at a pressure of 400 Pa, the thermal conductivity of air can be used in the analysis of vacuum drying conditions.

Table 2. Summary of temperatures for the FACTS according to vacuum pressure

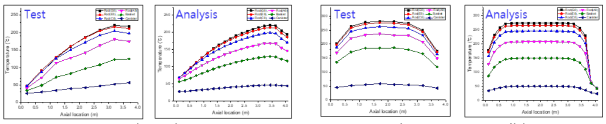
Location	Calculated temperatures (°C)					
	Air (100kPa)	Vacuum pressure (Pa)				
		1.0E5	1.0E4	1000	400	100
Rod-104	221.1	244.1	273.8	273.8	273.8	273.8
Rod-72	214.6	236.7	265.3	265.3	265.3	265.3
Rod-40	199.1	219.1	245.6	245.6	245.6	245.6
Rod-08	169.4	184.9	208.4	208.5	208.5	208.5
Basket	130.4	132.2	150.4	150.5	150.5	150.5
Canister	48.4	46.6	52.6	52.7	52.7	52.7
Ambient	20.0	20.0	20.0	20.0	20.0	20.0

Table 3. Summary of temperatures for the FACTS according to thermal conductivity

Location	Calculated temperatures (°C)					
	Air (100kPa)	Thermal conductivity ratio (k_a/k_o)				
		1.0	0.9	0.8	0.7	0.6
Rod-104	221.1	273.8	275.2	276.7	278.1	279.6
Rod-72	214.6	265.3	266.7	268.1	269.4	270.9
Rod-40	199.1	245.6	246.8	248.1	249.4	250.7
Rod-08	169.4	208.5	208.5	210.4	211.4	212.4
Basket	130.4	150.5	150.7	150.9	151.1	151.3
Canister	48.4	52.7	52.7	52.7	52.7	52.7
Ambient	20.0	20.0	20.0	20.0	20.0	20.0

2.4. Comparison of thermal test and analysis results

Thermal test was performed to verify the reliability of the thermal analysis results. Fig. 2 shows the comparison of thermal test and analysis results. In the air environmental condition, the PCT was consistent within 1°C, and the maximum temperature difference of the fuel cladding was within 13°C. In the vacuum environment, a larger temperature difference was observed compared to the air environment, but the test and analysis results showed similar temperature distributions.



(a) Air environment (b) Vacuum condition

Fig. 2. Comparison of thermal test and analysis results.

3. Conclusions

At a vacuum pressure of 400 Pa, the thermal conductivity of air decreased by about 3%. Therefore, the thermal conductivity of air at atmospheric pressure can be used in the thermal analysis of the vacuum drying process. The analysis results according to the vacuum pressure showed that the natural convection effect was ignored at pressures below 10 kPa, and the canister temperatures were same. In a vacuum, radiation heat transfer was more dominant than heat conduction, so the effect of the thermal conductivity of air on the PCT was relatively small. The thermal test and analysis results showed similar temperature distribution, and the reliability of the thermal analysis results was confirmed.

Acknowledgement

This work was supported by the Institute for Korea Spent Nuclear Fuel(iKSNF) and National Research Foundation of Korea(NRF) grant funded by the Korea government (Ministry of Science and ICT, MSIT) (No. 2021M2E1A1085226)

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