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Calculation of the Effective Thermal Conductivity for PWR Spent Fuel Assembly

Sung-Hwan Chung, Kyoung-Myoung Chae, Byung-Il Choi and Heung-Young Lee

Nuclear Environment Technology Institute (NETEC), KHNP
P.O Box 149 Yuseong, Daejeon, Korea
E-mail: shchung@khnp.co.kr

Abstract

The spent fuel transport casks and spent fuel storage casks must be evaluated to dissipate the decay heat from spent fuel assemblies to the fuel basket and from the fuel basket to the outer cask surface. No active systems are required for removal and dissipation of the decay heat from spent fuel assemblies that is loaded within the casks. The fuel assemblies are very difficult to be modeled explicitly, i.e., fuel pellet, fuel cladding are not modeled separately on their own, but instead, they are available to be modeled as solids with homogeneous effective properties making no distinction between the different properties and heat transfer characteristics of cladding, pellet, spaces between rods, and gaps between pellet and cladding. This effective thermal property method will reduce analysis time and cost for thermal analysis of the cask. In this paper the effective thermal conductivity through a cross section of the fuel region of the fuel basket is calculated from a detailed two dimensional slice model of the traverse section of W.H 17x17 fuel assembly using FLUENT code based on the finite volume method. The effective thermal conductivity is found to model sufficiently the heat transfer by radiation and conduction between the fuel rods and between the fuel rods and the fuel basket in which the fuel assemblies reside, therefore this method could be applied to the thermal analyses of the transport casks and the storage casks.

Introduction

All transport casks and storage casks that contain spent nuclear fuel assemblies must be evaluated their expected normal operating temperatures and their responses to accident conditions in the related IAEA and domestic regulations[1][2][3]. That thermal capabilities of the casks comply with the regulatory requirements is typically demonstrated via calculations, although thermal properties of materials used in the casks are usually gathered from physical tests. Many times this is the case because determining thermal characteristic of the cask by testing must be accomplished using a full-size prototype cask. Thermal testing of a scale model cannot be used to accurately predict the response of the full-size cask because radiative, convective and conductive heat transfer do not scale linearly in space and time. Major thermal evaluation of the casks involves the conflict between passively removing radioactive decay heat from the cask while passively protecting the cask from external heat sources. The passive system that might be used to protect the containment system of the cask from overheating in an accident involving such as fire and explosion may exacerbate the difficulty of transferring the decay heat from the containment system to the cask surface and ultimately to the environment during normal operating conditions. An ideal passive thermal protection system of the cask is a thermodiode with a high heat conductance from the cask cavity to the outer cask surface and a high heat resistance the outer cask surface to the cask cavity.

The spent fuel transport casks and spent fuel storage casks must be evaluated to dissipate the decay heat from spent fuel assemblies to the fuel basket and from the fuel basket to the outer cask surface. No active systems are required for removal and dissipation of the decay heat from spent fuel assemblies that is loaded within the casks. The main mode of heat transfer between spent fuel assemblies and the fuel basket of the cask is via conduction and radiation. Where gaps between the fuel basket components exist, heat is transferred across the gaps via conduction through backfill medium of helium and radiation. Heat is transferred the gaps between the fuel basket and the inner surface of the cask body by radiation and conduction. Heat is transferred through the cask wall by conduction. Since the cask cavity within the fuel basket is highly compartmentalized, the effect of convection within the cask is not significant. The general arrangement of the KN-12 transport cask which consists cask body, bottom plate, neutron shielding, lid, and fuel basket as a typical cask model is shown in Fig. 1.

The spent fuel assembly consists of a large array of rods, typically arranged on a square layout, and each fuel consist fuel pellets, fuel claddings, gaps between fuel pellets and fuel claddings. The fuel assemblies are very difficult to be modeled explicitly, i.e., fuel pellet, fuel cladding are not modeled separately on their own, but instead, they are available to be modeled as solids with homogeneous effective properties making no distinction between the different properties and heat transfer characteristics of cladding, pellet, paces between rods, and gaps between pellet and cladding. This effective thermal property method will reduce analysis time and cost for thermal analysis of the cask.

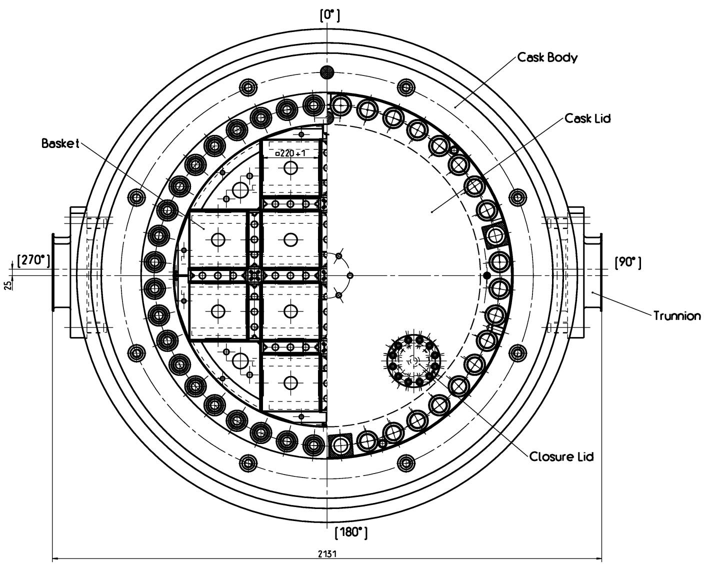


Fig.1 General Arrangement of the KN-12 spent fuel transport cask

In this paper the effective thermal conductivity through a cross section of the fuel region of the fuel basket is calculated from a detailed two dimensional slice model of the traverse section of W.H 17x17 fuel assembly. The analyses are carried out by FLUENT code, which is based on the finite volume method to solve general conservation equations for mass, momentum, energy etc. with discrete algebraic equations and is applied to a variety of fluid and thermal problems followed as natural convection, free jet flow, combustion, and participating radiation problems. The effective thermal conductivities calculated using FLUENT code are compared with the calculated results using NASTRAN code based on reference [4], and are found to be consistent, hence indicating that the methods and assumptions used are accurate.

Effective Thermal Conductivity Calculation

With the assumption of uniform heat generation within any given horizontal cross section of a fuel assembly, the combined thermal radiation and conduction heat transport effects is followed;

$$Q = Q_{cond} + Q_{rad} \qquad (1)$$

where, Q is assembly heat generation (W). Q_{cond} and Q_{rad} are energy transferred by conduction and radiation, respectively. In Equation (1), the first term on the right hand, Q_{cond} is $4pLk_e(T_{max} - T_s)$.

Replacing this term into Equation (1), it becomes;

$$Q - Q_{rad} = 4pLk_e(T_{max} - T_s) \quad (2)$$

Rearranging Equation (2) to k_e it is followed;

$$k_e = \frac{(Q - Q_{rad})/p}{4L(T_{max} - T_s)} = \frac{lQ}{4L(T_{max} - T_s)} \quad (3)$$

where, k_e and L effective thermal conductivity (W/mK) and assembly active length (m), respectively. And T_{max} and T_s are assembly center temperature(peak cladding K) and surface temperature (K), respectively. The l as a corrective factor is;

$$l = \frac{Q - Q_{rad}}{pQ} \quad (4)$$

The methodology adopted for simulating the traverse heat transfer characteristic through the fuel assemblies, and for calculating the temperatures in the fuel assemblies, is the effective thermal conductivity method as presented in Reference [4]. The method relies on using a detailed two dimensional model of a fuel assembly cross section to obtain the effective thermal conductivity of the fuel assembly using Equation (5), which is the analytical solution of the heat diffusion equation for a steady temperature in a rectangle generating heat;

$$k_e = \frac{Q}{4L(T_{max} - T_s)} \times 0.2497 \quad (5)$$

W.H 17x17 fuel assembly consists of 264 arrays of fuel rods, 24 guide tubes and 1 instrumentation tube, typically arranged on a square layout. And each fuel consist fuel pellets, fuel claddings, gaps between fuel pellets and fuel claddings. We considered that the fuel assembly region was filled with helium. Since every fuel rod in this array generates heat due to radioactive decay in the enclosed fuel pellets, there is a finite temperature difference required to transfer heat from the fuel rods to the periphery of fuel assembly. The heat is transferred by a combination of radiation exchange and conduction through helium in fuel basket. W.H 17x17 fuel assemblies are selected to calculate the effective thermal conductivity of the fuel region in the fuel basket.

The two dimensional analysis model of W.H 17x17 fuel assembly using FLUENT code, which is based on the finite volume method to solve general conservation equations for mass, momentum, energy etc. with discrete algebraic equations and is applied to a variety of fluid and thermal problems followed as natural convection, free jet flow, combustion, and participating radiation problems, is shown in Fig. 2. The analysis model consists of a quarter of W.H 17x17 fuel assembly using the symmetric geometry. The analysis model is consisted of 11924 nodes and 11696 two dimensional elements. The specification of W.H 17x17 fuel assembly is shown in Table 1. The material properties used in the analysis are provided in Table 2 to Table 5.

The extent of the analysis model represented the inner dimensions of the receptacle in which the fuel assembly resides. Fuel pellets, fuel claddings and the spaces between the fuel rods are fully modeled, using GAMBIT, which is a modeling package of FLUENT code. The space between the fuel rods is filled with helium. Because the gaps between the fuel pellets and their cladding are too small compared to the size of the fuel rod, they are neglected. These gaps are assumed to be filled with the fuel pellet material in the analysis model. In order to simulate radiation exchange between the fuel rods and between the fuel rods and the basket walls, the radiation model, Discrete Ordinates (DO) of FLUENT code is used

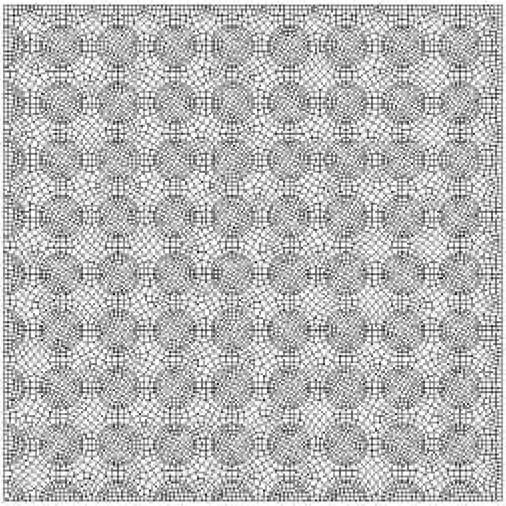


Fig.2 Two dimensional analysis model of fuel Assembly

Table 1 Specification of W.H 17x17 fuel assembly

Fuel assembly	maximum width	214.02 mm
	total length	4,102.92 mm
	Total weight	665.4 kg
Fuel rods	outer diameter	12.04 mm
	inner diameter	11.43 mm
	length	3,866.9 mm
	active length	3,657.6 mm

Table 2 Thermal properties of helium

Density (kg/m³) 0.15

Temperature (°C)	25.0	100.0	200.0	300.0	400.0
Conductivity (W/mK)	0.150	0.174	0.205	0.237	0.270
Specific Heat Capacity (J/kgK)	5200	5200	5200	5200	5200

Table 3 Thermal properties of stainless steel SA 240 Type 321

Density (kg/m³) 7920

Temperature (°C)	21.1	121.1	232.2	343.3	454.4	565.6	676.7	787.8
Conductivity (W/mK)	14.0	15.7	17.5	19.2	20.9	22.7	24.1	25.6
Specific heat capacity (J/kgK)	479.6	510.3	541.3	552.9	569.2	583.8	588.5	599.6

Table 4 Thermal properties of Uranium Dioxide

Density (kg/m³) 10400

Temperature (°C)	27.0	127.0	227.0	327.0	427.0	527.0	627.0	727.0
Conductivity (W/mK)	8.10	7.10	6.15	5.33	4.70	4.27	3.88	3.61
Specific Heat Capacity (J/kgK)	236.4	265.8	282.1	292.4	299.7	305.3	310.0	314.0

Table 5 Thermal properties of Zircaloy-4

Density (kg/m³) 6550

Temperature (°C)	100.0	200.0	300.0	400.0	500.0	600.0	700.0	800.0
Conductivity (W/mK)	13.6	14.3	15.2	16.4	18.0	20.1	22.5	25.2
Temperature (°C)	27.0	127.0	367.0	817.0	820.0	840.0	860.0	880.0
Specific Heat Capacity (J/kgK)	281.0	302.0	331.	375.0	502.0	590.0	615.0	719.0

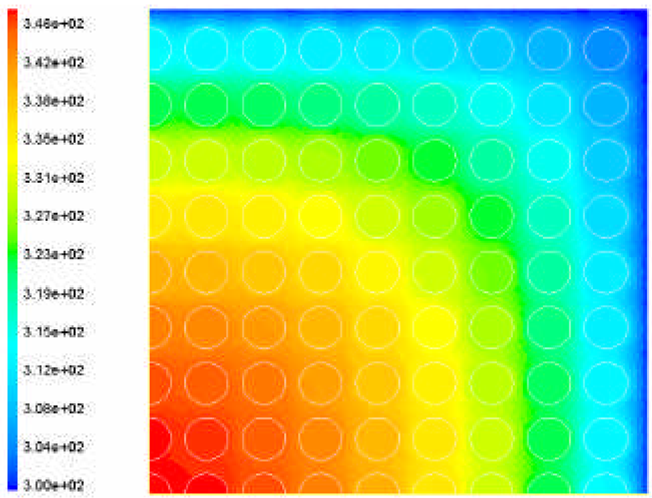
The effective thermal conductivities are calculated using same analysis model for the following cases;

CASE 1 : all tubes (24 guide tubes and 1 instrumentation tube) in W.H 17x17 fuel assembly are assumed to be fuel rods and have same size with fuel rods, and

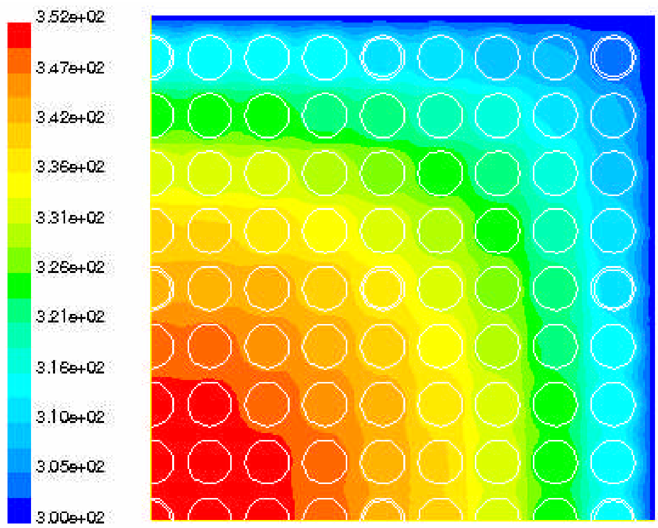
CASE 2 : all tubes (24 guide tubes and 1 instrumentation tube) are assumed to be same as real components and have same size with fuel rods.

Volumetric heat generation rate is calculated based on the cask heat load W.H 17x17 fuel assembly of 1.05kW and is applied to the elements representing fuel pellets. A constant temperature is applied to the boundaries of the analysis model. In order to obtain temperature dependent effective thermal conductivities, the analysis model is analyzed with the range of different boundary temperatures. The material properties at boundary temperature are applied to be constant in the analysis model. The surface emissivities of fuel claddings and fuel basket are applied for 0.8 and 0.36, respectively. For CASE 2, the emissivity of 0.36 is applied to the surfaces of 24 guide tubes and 1 instrumentation tube.

Temperature distributions of both cases in the cross section of the fuel assembly are shown in Fig. 3, when the constant temperature of 300K is applied to the boundaries of the analysis model. Maximum temperature is obtained in the center of the fuel assembly and about 346K for CASE 1 and about 352K for CASE 2. The temperature difference between the center and the wall boundary is about 46°C for CASE 1 and about 52°C for CASE 2. Temperatures of CASE 2 are higher than those of CASE 1. The results are summarized in the Table 6.



a. CASE 1



b. CASE 2

Fig.3 Temperature distribution in the cross section of the fuel assembly

Table 6 Effective conductivties

Temperature (K)	Effective conductivties			Effective conductivity difference	
	NASTRAN	CASE 1	CASE 2	NASTRAN – CASE 1	NASTRAN – CASE 2
300	0.389	0.372	0.344	0.017	0.045
400	0.528	0.511	0.477	0.017	0.051
500	0.713	0.720	0.656	-0.007	0.057
600	0.941	0.980	0.894	-0.039	0.047

Discussion

The heat from fuel pellets is transferred by conduction through fuel claddings and helium and by thermal radiation between fuel rods and between fuel rods and the wall of fuel basket. Since the calculated domain is horizontal cross section of a fuel assembly, the natural convection by buoyancy was not occurred in helium region.

Fig. 4 provides the calculate results of the effective thermal conductivities with the temperature range of the 300K to 600K. The results are compared to the calculated results using NASTRAN code, which is obtained for the thermal evaluation of the KN-12 transport cask. These results agree with NASTRAN results well. The results of CASE 1 are lower than NASTRAN in the range below about 500K and higher in the range over about 500K. But, the results of CASE 2 are lower than NASTRAN over all range. W.H 17x17 fuel assembly originally consists of 264 fuel rods, 24 guide tubes and 1 instrumentation tube, but CASE 1 assumes that 24 guide tubes and 1 instrumentation tube are fuel rods. This assumption of CASE 1 causes that the thermal conductivities of CASE 1 are higher than those of CASE 2 because the guide tubes of the fuel assembly act like thermal shields.

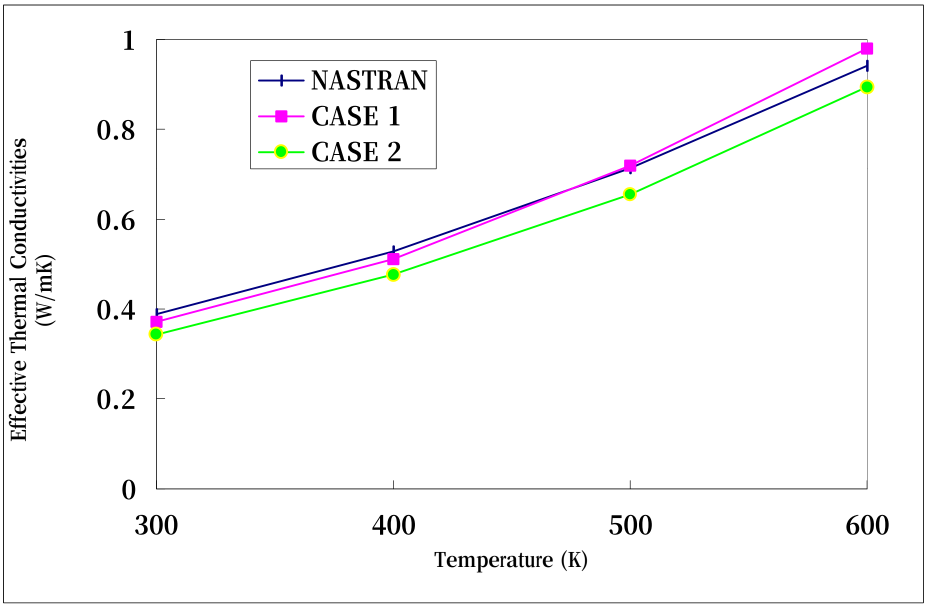


Fig. 4 Comparison of effective thermal conductivities of PWR fuel assemblies

For CASE 1, the relative error to NASTRAN is 4.3% at 300K. The conductivity difference between CASE 1 and NASTRAN is 0.017 W/mK. Maximum difference is 0.039 W/mK at 600K. For CASE 2, the relative error is 11.6% at 300K and the conductivity difference is 0.045 W/mK. Maximum difference is 0.057 W/mK at 500K. For both CASE 1 and CASE 2, the difference between maximum calculated temperature and boundary temperature is decreased with increasing boundary temperatures. The effective thermal conductivities increase as the temperature differences decrease. The relative error of CASE 2 is higher than CASE 1. But, the effective thermal conductivity curves of CASE 1 and NASTRAN cross at about 500K. For CASE 1, with increasing boundary temperatures, up to 500K the relative error decreases and over 500K increases. It is expected that the difference would be larger at higher temperature. The relative error of CASE 2 consistently decreases with increasing temperatures.

While the relative error of CASE 2 is higher than CASE 1, the curve trend of CASE 2 is more correspondent to NASTRAN. The differences of the effective thermal conductivities between CASE 2 and NASTRAN are nearly constant. As the results of CASE 2 are lower than NASTRAN and CASE 1 over all range, CASE 2 is more conservative than NASTRAN and CASE 1.

Conclusion

The effective thermal conductivity is found to model sufficiently the heat transfer by conduction and radiation between the fuel rods and between the fuel rods and the fuel basket in which the fuel assemblies reside. Therefore, the effective thermal conductivity method could be applied to the further thermal analyses of the transport casks and the storage casks.

References

[1] IAEA Safety Standards Series No.ST-1 "Regulation for the Safe Transport of Radioactive Material", 1996

[2] US NRC 10 CFR Part 71, "Packaging and Transportation of Radioactive Materials", 1996

[3] Korea Most Notice No.2001-23, "Regulation for Transportation and Packagings of Radioactive Material", 2001

[4] PT-361-G-A-R-002-REV-0, "CASTOR KN-12 Spent Nuclear Fuel Transport Cask Safety Analysis Report", KHNP, 2002