Comparisons of Peak Cladding Temperature and Effective Thermal Conductivity: CFD Simulation on PWR Spent Fuel Assemblies – 16278

Hyungjin Kim *, Gyeong-Uk Kang *, Chun-Hyung Cho *
* Korea Radioactive Waste Agency

ABSTRACT

When spent fuel assemblies from the reactor of nuclear power plants (NPPs) are transported or stored, the assemblies are exposed to a variety of environments that can affect the peak cladding temperature of spent fuel assemblies. There are four methods to calculate the peak cladding temperature of spent fuel assemblies in a cask: Manteufel and Todreas's two-region model, Bahney Lotz's effective thermal conductivity model, Wooton-Epstein correlation, and computational fluid dynamics (CFD) simulation. The CFD simulation based on the FLUENT code is used to calculate the peak cladding temperature and effective thermal conductivity of a spent fuel assemblies used in Republic of Korea NPPs: 14x14, 16x16 ACE7, 16x16 PLUS7 and 17x17 PWR spent fuel assemblies. The CFD simulation results show that the effective thermal conductivity of the 16x16 ACE7 was more conservative than those for the other assemblies. Therefore the effective thermal conductivity using 16x16 ACE7 is used for thermal evaluation of the KORAD's developing cask which can load 14x14, 16x16 ACE7, 16x16 PLUS7 and 17x17 spent fuel assembly.

INTRODUCTION

A transportation/storage cask contains spent fuel assemblies for pressurized water reactors (PWR) or boiling water reactors (BWR). The assembly consists of fuel rods, fuel, instrument and guide tubes, and channels that encircle the rod array. Before transportation and storage, the primary containment region is evacuated and filled with a backfill gas. The casks have been designed to provide confinement, shielding and criticality protection during normal, off-normal and accident conditions.

Heat generated within the spent fuel assemblies makes the cask hotter than the cask's surroundings. To maintain integrity and retrievability of the spent fuel assembly in the casks, the cladding temperature of spent fuel assemblies must remain below the allowable temperature of 673 K in accordance with requirements [1, 2, 3]. This allowable temperature limits the number and heat generation rate of the spent fuel assemblies that can be stored or transported in a cask.

Thermal evaluation of a cask using three-dimensional models is especially difficult if the spent fuel assemblies are modeled explicitly and included in the analysis. This method using explicitly spent fuel assemblies modeling is costly in time of setup and computational time and does not lend itself to parametric evaluation of cask design.
When the thermal evaluation on the cask is carried out, the cask or canister and components inside the cask are modeled explicitly using three-dimensional models. The spent fuel assemblies are not modeled explicitly (i.e. fuel pellet and fuel

cladding are not modeled separately on their own). Instead, these assembly elements are modeled as solids with homogenous "smeared" or "effective properties" making no distinction between the different properties and heat transfer characteristics of the cladding, pellet, spaces between rods, and gaps between pellets and claddings. This method has been utilized by industry and national laboratories which have been tasked by the Nuclear Regulatory Commission to verify vendor calculations for the storage and transportation casks. This solid method can predict the peak cladding temperatures of casks with reasonable accuracy and provides an uncomplicated method for determining transient behavior that will be experienced with storage [4, 5].

For the three-dimensional models of spent fuel assembly as solids with homogeneous smeared, the homogeneous spent fuel assembly needs the appropriate effective conductivity. To determine effective conductivity of three-dimensional models, first one calculates the peak cladding temperature on a transverse cross-section of spent fuel assembly according to the basket wall temperatures. Next, by using the peak cladding temperatures of the transverse cross-section, the effective thermal conductivity can be obtained.

There are four methods available to estimate peak cladding temperatures inside a transportation/storage cask: Two-region model, Wooton-Epstein correlation, the effective thermal conductivity model, and CFD simulation. Two-region model is based on one-dimensional radiation/conduction heat transfer, and arrays of rods (15x15, 8x8). Wooton-Epstein correlation is based on a set of experiments performed in 1963 for an array of rods (17x18). Also, the effective thermal conductivity model is based on arrays of rods (14x14, 17x17, 9x9). In addition, from investigating the results using two-region model, Wooton–Epstein correlation, and CFD simulations [6], the CFD simulation on a transverse cross-section of spent fuel assembly could be employed to calculate the peak cladding temperatures.

In this work, therefore the peak cladding temperature and effective thermal conductivity using CFD simulation were calculated on 14x14, 16x16 ACE7, 16x16 PLUS7 and 17x17 PWR spent fuel assemblies used in Republic of Korea nuclear power plants.

MODELING FOR PEAK CLADDING TEMPERATURE

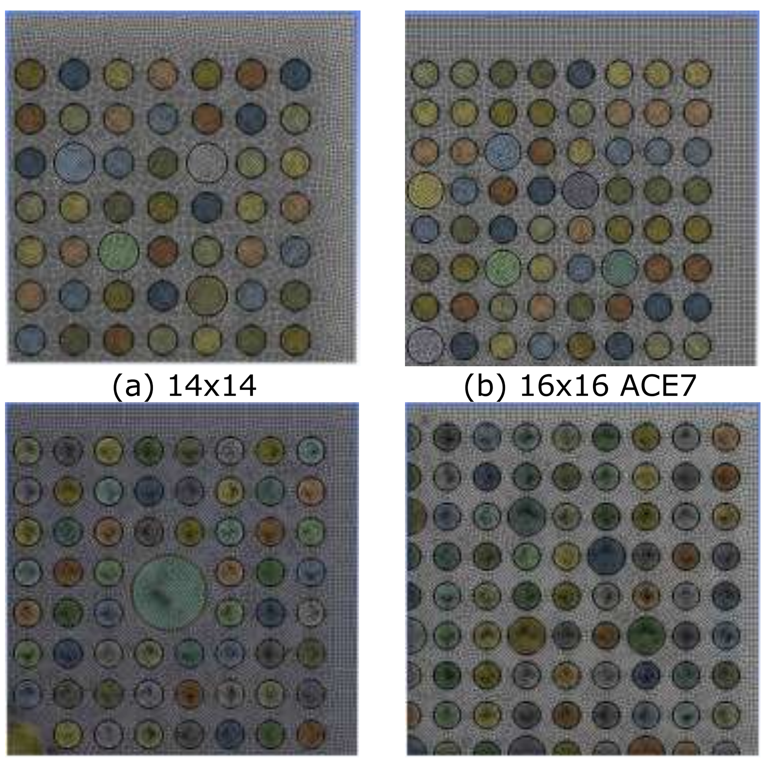
Under the same basket size, assembly heat load, and backfill gas, the 14x14 PWR spent fuel assembly was compared with 16x16 and 17x17 PWR spent fuel assembly to be stored in the KORAD's developing transportation/storage cask that can load both WH and CE type spent fuel.

We selected 14x14, 16x16(ACE7, Plus7) and 17X17 spent fuel types to calculate the peak cladding temperature and effective thermal conductivity. The assembly heat load is 796.2W. The assembly details used to model each assembly are given in Table 1.

Table 1. 14x14, 16x16 and 17x17 PWR assembly dimensions.

	14x14	16x16 (ACE7)	16x16 (PLUS7)	17x17
Number of rods	179	235	236	264
Number of guide tubes	16	21	5	25
Rod pitch	14.12 mm	12.32 mm	12.85mm	12.6 mm
UO2 pellet diameter	8.75 mm	7.84 mm	8.19 mm	7.84 mm
Cladding inner diameter	8.93 mm	8.00 mm	8.36 mm	8 mm
Cladding outer diameter	10.16 mm	9.14 mm	9.5 mm	9.14 mm
Guide tube inner diameter	12.5 mm	11.06 mm	22.86 mm	11.23 mm
Guide tube outer diameter	13.36 mm	11.96 mm	24.89 mm	12.04 mm
Active fuel length	3658 mm	3658 mm	3810 mm	3658 mm

Fig. 1 displays the two-dimensional CFD mesh model (FLUENT code) of each PWR assembly which, using symmetry, represents one quarter of an assembly. Assuming two planes of symmetry, the model includes the basket wall. The gap between fuel rod and fuel cladding is modeled. The resulting CFD models have over 28,000 elements.



(a) 14x14 (b) 16x16 ACE7

(c) 16x16 Plus7 (d) 17x17

Fig. 1. CFD model of PWR assemblies.

The thermal properties (specific heat and thermal conductivity) of helium, fuel cladding, guide tubes, and fuel rods are assumed with a temperature-dependent value [7]. The emissivity is 0.8 [8] for zircaloy (fuel cladding, guide tube) and 0.36 [9] for stainless steel (basket wall). The conduction and radiation temperature results were determined by solving a steady-state energy equation using a finite volume method with a second–order upwind discretization scheme. The convergence criteria check that the values for the residuals of the equations are 10^{-3} for the mass and momentum and 10^{-14} for the energy equation. Because the net heat transfer error should be very small, indicating an overall heat balance has been achieved, the value 10^{-14} for energy equation was selected.

Radiation model

The discrete ordinates (DO) radiation model was selected to solve the radiation of spent fuel assembly. The DO radiation model solves the radiative transfer equation (RTE) for a finite number of discrete solid angles, each associated with a vector direction fixed in the global Cartesian system (x, y, z). The fineness of the angular discretization is controlled by the user, which is analogous to choosing the number of rays for the discrete transfer radiation model (DTRM). The DO model does not perform ray tracing. Instead, the DO model uses a transport equation for radiation intensity in the spatial coordinates (x, y, z). The solution method is identical to that used for the fluid flow and energy equations.

The value of angular discretization and pixelation available in the discrete ordinates radiation model significantly affects the behavior of temperature. So, it is important for one to choose an adequate value of pixelation and discretization. The influence of these values according to a pixelation or discretization constant is identified in ANSYS [10] and US NRC [11]. The constants were determined to solve the spent fuel assembly: 3x3 for pixelation, 5x5 for discretization.

RESULTS AND DISCUSSION

Table 2 shows the peak cladding temperatures calculated from the CFD simulations for each assembly in a range of wall temperatures.

Table 2. Peak cladding temperatures, each PWR assembly under helium gas and an assembly heat load of 796.2W.

	Peak cladding temperatures (K)			
Basket wall temperature (K)	14x14	16x16 ACE7	16x16 PLUS7	17x17
300	352.6	351.8	342.7	340.7
400	437.9	438.3	431.2	430.3
500	527.6	528.2	522.9	522.7
600	620.2	620.9	617.1	617.3
700	715.1	715.8	712.8	713.3
800	811.8	812.5	810.1	810.7

Results for each assembly show the same general trend. Because the radiation heat transfer depends on the 4th power of temperature, there is less thermal resistance as the basket wall temperatures increases, and the temperature drop decreases at a higher temperature. The peak cladding temperature exceeding 673 K is produced with a high basket wall temperature (≥700 K). The temperature drop of 14x14, and 16x16 ACE7 assemblies is larger than that of 16x16 PLUS7, and 17x17.

The purpose of the effective thermal conductivity is to relate the temperature drop of a homogeneous heat generating square to the temperature drop across an actual assembly. Using the heat load and temperature drop obtained from the results of peak cladding temperatures, the effective thermal conductivity of the homogeneous heat-generating square can be calculated [12]. The effective thermal conductivity of each assembly is plotted in Fig. 2.

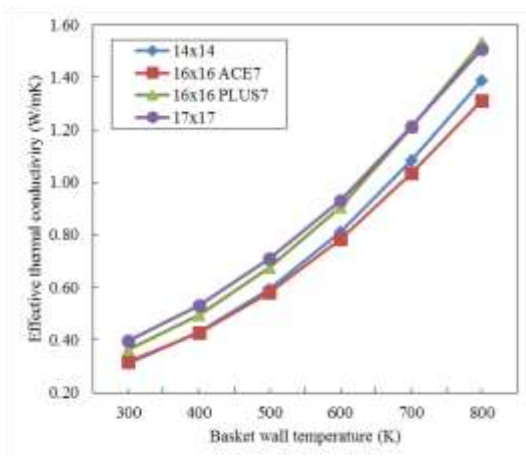
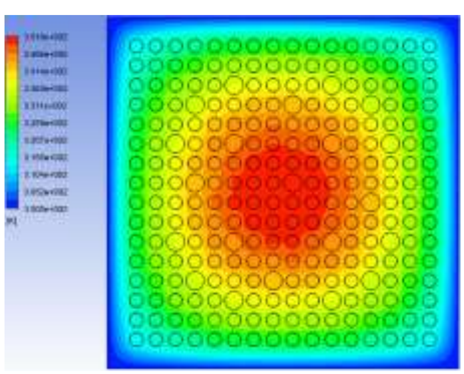
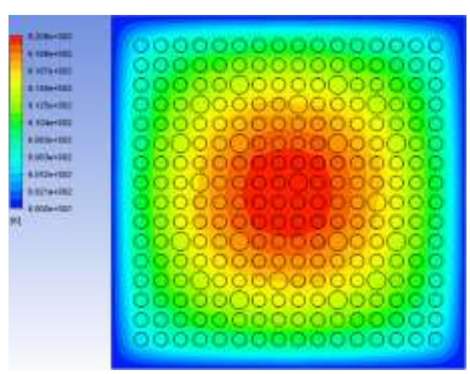


Fig. 2. The effective thermal conductivity of each spent fuel assembly for helium.

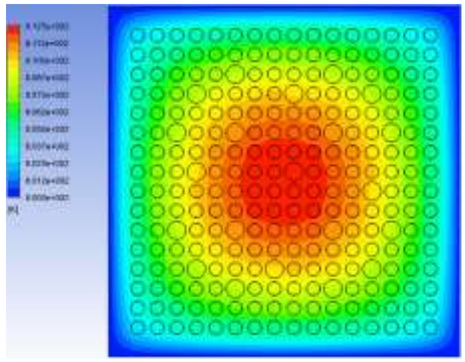
The values calculated from the 16x16 ACE7 PWR spent fuel assembly results are more conservative than those for the other assemblies for temperatures more than 500 K. For temperatures less than 500 K, the difference of values between 14x14 and 16x16 ACE7 is smaller.
Fig. 3 shows temperature distributions of 16x16 ACE7 with a basket wall temperature of 300 K, 600 K, and 800K.



(a) Basket wall temperature 300 K



(b) Basket wall temperature 600 K



(c) Basket wall temperature 800 K

Fig. 3. Temperature distribution of 16x16 ACE7 PWR spent fuel assembly.

CONCLUSIONS

Under the same basket size, assembly heat load and backfill gas, the 14x14 PWR spent fuel assembly was compared with 16x16 and 17x17 PWR spent fuel assemblies to be stored in the KORAD's developing cask.

With a helium backfill environment, the peak cladding temperature exceeds 673K with a high basket wall temperature (≥700 K). The temperature drop of 14x14, and 16x16 ACE7 is larger than that of 16x16 PLUS7, and 17x17. The effective thermal conductivity is highly basket wall temperature-dependent. The values of 14x14 are similar to those of 16x16 ACE7. The effective thermal conductivity of 17x17 and 16x16 PLUS7 showed the same trend. The values calculated from the 16x16 ACE7 PWR spent fuel assembly results are more conservative than those for the other assemblies for temperatures more than 500 K.

Therefore the effective thermal conductivity using 16x16 ACE7 is used for thermal evaluation of the KORAD's developing cask which can load 14x14, 16x16 ACE7, 16x16 PLUS7 and 17x17 spent fuel assembly.

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