Annals of Nuclear Energy 71 (2014) 427–435

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

Comparisons of prediction methods for peak cladding temperature and effective thermal conductivity in spent fuel assemblies of transportation/storage casks

Hyungjin Kim [a,*], Oh Joon Kwon [b], Gyeong-Uk Kang [a], Dong-Gyu Lee [c]

[a] *Korea Radioactive Waste Agency, 989-111, Daedeokdae-ro, Yuseong-gu, Daejeon, Republic of Korea*
[b] *Korea Advanced Institute of Science and Technology, 291 Daehak-ro, Yuseong-gu, Daejeon, Republic of Korea*
[c] *Korea Nuclear Engineering & Service Co., #402, Hyundai Plaza, 341-4 Jangdae-dong, Yuseong-gu, Daejeon, Republic of Korea*

ARTICLE INFO

Article history:
Received 10 February 2014
Received in revised form 3 April 2014
Accepted 5 April 2014
Available online 16 May 2014

Keywords:
Spent fuel
Two-region model
Wooton–Epstein correlation
Transportation/storage cask
Peak cladding temperature
Effective thermal conductivity

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. There are three models 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, and Wooton–Epstein correlation. The peak cladding temperatures of Babcock & Wilcox (B&W) 15 × 15 PWR spent fuel assembly under helium backfill gas were evaluated by using two-dimensional CFD simulation and compared with two models (Wooton–Epstein correlation, two-region model). The peak cladding temperature difference between the two-region model and CFD simulation ranges from −0.2 K to 9 K. Two-region model over-predicts the measured peak cladding temperature that performs in a spent fuel dry storage cask. Therefore the simulation could be used to calculate peak cladding temperature of spent fuel assemblies.

Application using CFD simulation was conducted to investigate the peak cladding temperature and effective thermal conductivity of spent fuel assembly used in Korea NPPs: 16 × 16 (CE type) and 17 × 17 (WH type) PWR spent fuel assembly. CFD simulation results are similar to each other, and the difference of temperature drop between the three arrays occurs slightly in all basket wall temperatures. The effective thermal conductivity calculated from the 16 × 16 PWR spent fuel assembly results was more conservative than those for the 17 × 17 array.

1. 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 from people during normal, off-normal and accident conditions.

Heat generated within the spent fuel assemblies makes the cask hotter than the cask's surroundings. To keep the integrity and retrievability of the spent fuel assembly, the cask of spent fuel transportation/storage must remain within the allowable cladding temperature of 673 K (400 °C). The allowable temperature limits the number and heat generation rate of the spent fuel assemblies that can be stored or transported in a cask.

To secure the safety of transportation/storage casks, thermal evaluation is accomplished, which meets the thermal performance requirements of US Government (2014), US NRC (2000), and US NRC (2009). Thermal evaluation considers normal, off-normal and accident conditions of transportation/storage.

The thermal evaluation of cask is especially difficult if the spent fuel assembly spacer grids 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 is carried out, the cask or canister and component inside the cask is modeled explicitly using three-dimensional models. The spent fuel assemblies are not modeled explicitly (i.e. fuel pellet and fuel cladding are not modeled

---

* Corresponding author. Tel.: +82 426015342.
E-mail address: hjkim@korad.or.kr (H. Kim).

http://dx.doi.org/10.1016/j.anucene.2014.04.004
0306-4549/

Nomenclature

Q	total assembly decay power
F_{peak}	axial power peaking factor
L_a	assembly active length
L_c	assembly cross-sectional circumferential length
S	assembly cross-sectional conduction factor (13.5738 for square, 12.8365 for hexagonal and 4.0 π for circular shape assemblies)
k_{gas}	fill gas conductivity
F_{cond}	conduction factor (interior)
$F_{\text{cond,w}}$	wall conduction factor
T_m	maximum fuel rod temperature
T_e	extrapolated fuel rod temperature (imaginary)
T_w	average enclosing wall temperature
C_{rad}	radiative heat transfer coefficient for the interior region
$C_{\text{rad,w,1}}$	first wall radiative heat transfer coefficient for the edge region
$C_{\text{rad,w,2}}$	second wall radiative heat transfer coefficient for the edge region
d	clad outside diameter of the fuel rod
p	rod-to-rod pitch
w	edge rod center-to-wall distance
f	edge-to-interior heat transfer ratio
q''	heat flux from spent fuel based on the basket inner surface heat transfer area (W/m^2)
T_{cl}	cladding surface temperature (K)
T_{ba}	basket surface temperature
ε_{cl}	cladding surface emissivity
ε_{ba}	basket surface emissivity
σ	Stefan–Boltzmann constant (W/m^2 K^4)
ΔT	cladding-to-basket wall temperature drop
T_o	center temperature (peak cladding)
T_s	surface temperature (basket wall)

separately on their own). But instead, they 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 (see Fig. 1). This method has been utilized by industrial 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 peak cladding temperatures of casks with reasonable accuracy and provides an uncomplicated method for determining transient behavior that will be experienced with storage.

To model spent fuel assembly as solids with homogeneous smeared, effective conductivities is needed. To determine the appropriate effective conductivity for PWR or BWR spent fuel assemblies, one needs to calculate the peak cladding temperature of the spent fuel assembly. This is because the peak cladding temperature is an important parameter that can affect the characteristics and behavior of the fuel cladding and the performance of the cask.

There are three methods available to estimate peak cladding temperatures inside a transportation/storage cask: two-region model, Wooton–Epstein correlation, and the effective thermal conductivity model.

Manteufel and Todreas (1994) developed a two-region model based on one-dimensional radiation and conduction heat transfer. The SF assembly is represented by two regions: an interior region characterized by an effective thermal conductivity (k_{eff}), and an edge region characterized by thermal conductance (h_{edge}). Two modes of heat transfer are considered in the interior region of the assembly (stagnant gas conduction and thermal radiation). However, this model neglects the possible effects of natural convection, the two dimensional heat transfer at the corners, and the unheated hollow tubes. The simulations using the two-region model were compared with the measurements performed in spent fuel transportation/storage casks. The results consistently over-predict the measured maximum cladding temperature. The two-region model has been used in the industry but is conservative about calculations used to design transportation/storage casks (FuelSolutions, 2007).

Wooton–Epstein correlation (Wooton and Epstein, 1963) is based on a set of experiments performed in 1963 for an array of rods (17 × 18) in air. It has historically been the primary tool of transportation/storage cask vendors because it simplifies the analysis and has been accepted by the Nuclear Regulatory Commission (NRC). In these models, the SF assemblies are modeled only as an edge heat flux to the basket structure without internal heat generation. Wooton–Epstein correlation was developed as an empirical fit to experimental data using single assembly array in air with assembly axial power distribution neglected. In spite of limitations, the Wooton–Epstein correlation has been shown to be conservative for the thermal evaluations of spent fuel in transportation/storage casks (Babcock and Wilcox Fuel Company, 1991).

The effective thermal conductivity (Bahney and Lotz, 1996) model was developed by Bahney and Lotz based on a finite element thermal analysis of various spent fuel assemblies with filled gas environments: helium, vacuum, nitrogen and argon. This model were developed assuming the basket walls surrounding the spent fuel assembly are at a uniform temperature. This is a reasonable approximation for assembles near the cask/canister center. Effective thermal conductivity model is similar to the lumped $k_{\text{eff}}/h_{\text{edge}}$ model. For finite element codes, there are effective thermal conductivity correlations for PWR (14 × 14, 17 × 17), BWR (9 × 9) assemblies under a different set of environments (helium, nitrogen and argon).

The peak cladding temperatures of spent fuel assemblies in a canister are also predicted by Computational Fluid Dynamics (CFD) (Gomez and Greiner, 2005). The comparison between the effective thermal conductivity model and CFD simulation is performed by using a FLUENT CFD package. A two-dimensional numerical simulation of heat transfer in a 7 × 7 BWR spent fuel assembly is performed under a helium or nitrogen environment for a range of assembly heat power and wall temperatures. For the helium environment, the temperature drop (the cladding-to-basket wall temperature drop, ΔT) calculated by CFD simulation at $T_w = 298$ K (25 °C) and 673 K (400 °C) are 14% and 40% higher than those predicted by the effective thermal conductivity model.

In this work, the peak cladding temperature was calculated by CFD simulation on a transverse cross section of spent fuel assembly, which is Babcock & Wilcox (B&W) 15 × 15 PWR assembly. The results of the peak cladding temperature and effective thermal conductivity using CFD simulation were compared with those of the two-region model and Wooton–Epstein correlation. Through the comparison, the difference between CFD simulation and two models were investigated. The peak cladding temperatures and effective thermal conductivity using CFD simulation were also calculated on 16 × 16 (CE type) and 17 × 17 (WH type) PWR spent fuel assemblies from Korea nuclear power plants (NPPs).