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Re-evaluation of the Fuel Temperature Coefficient of CANDU 6

Yonghee Kim* and Donny Hartanto
Korea Advanced Institute of Science and Technology
373-1 Kusong-dong, Yusong-gu
Daejeon, Korea, 305-701
Corresponding author: yongheekim@kaist.ac.kr

1. Introduction

The evaluation of the fuel temperature reactivity coefficient (FTC) is important as it is one of the important safety parameters in the nuclear reactor. Recently, in CANDU 6 reactor, the FTC at equilibrium core is calculated to be slightly positive in the vicinity of the fuel operating temperature (960.16 K) as shown in Figure 1. The result in Fig. 1 was calculated for Wolseong Unit #1 by the diffusion code RFSP-IST. Based on deterministic analyses of CANDU fuel lattice, Ref 2 indicates that the positive FTC was mainly ascribed to the upscattering by oxygen in fuel and the thermal fission resonance of Pu-239.

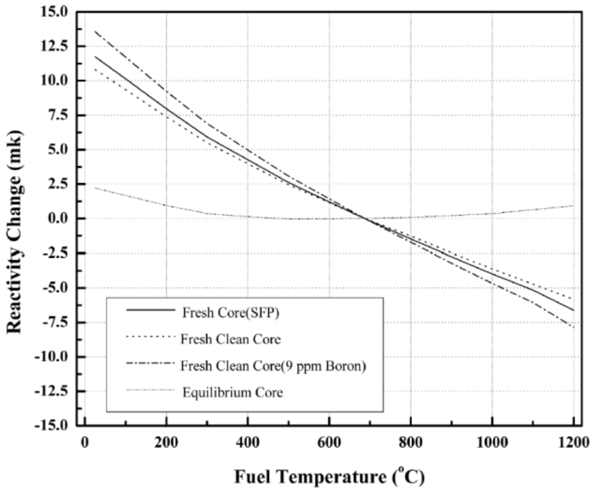

Figure 1. Reactivity change due to instantaneous change in fuel temperature [1]

In this study, the FTC of CANDU 6 reactor was re-evaluated by analyzing the FTC of the standard CANDU fuel lattice with the continuous-energy Monte Carlo code MCNPX [3]. In most deterministic and stochastic codes, the scattering kernel is based on an unphysical assumption that the target is at rest. In MCNPX, the problem was solved by implementing the Doppler Broadened Rejection Correction (DBRC) [4] kernel. It was reported that the fuel Doppler effect is noticeably enhanced by accounting for the target motion. In this work, the modified MCNPX, called MCNPX-DBRC was used.

2. Doppler Broadened Rejection Correction

When dealing with neutron scattering in most of the well-known codes, the temperature of the interacting heavy nuclide is set arbitrarily to zero. This leads to inconsistency between the loss and production terms of the very basic transport equation [4]. The DBRC method is proposed to deal with this problem. It is a statistical approach which is based on the use of a complementary rejection technique [4]. In this method, a modification of the probability density function is necessary. The probability function is used by MCNPX to simulate the target velocity V and the angle between neutron and target μ_t. With the corrected probability density function, MCNPX is able to include the effect of the energy dependence of the cross sections on the scattering kernel.

The corrected probability function can be written as:

$$P(V,\mu_t) \rightarrow a)\ \left\{\frac{\sigma_s(E_r,0)}{\sigma_s^{max}(E_\xi,0)}\right\}\ b)\ \left\{\frac{v_r}{v+V}\right\}$$

$$c)\ \left\{\frac{2\beta^4V^3e^{-\beta^2V^3}+(\beta v\sqrt{\pi}/2)(4\beta^3/\sqrt{\pi})V^2e^{-\beta^2V^3}}{1+\beta v\sqrt{\pi}/2}\right\} \qquad (1)$$

where $\beta=\left(\frac{A_m}{2k_BT}\right)^{1/2}$, v is the neutron speed, V is the speed of the target and neutron speed v_r is relative velocity to the target at rest.

The brackets a) and b) represent the two constraints in the chosen value of V and μ_t in the bracket c). The ratio of $\frac{v_r}{v+V}$ cannot exceed unity and a rejection technique is applied in MCNPX. If a random number between 0 and 1 is less than $\frac{v_r}{v+V}$, the choice of the target velocity V and μ_t (which defines v_r) is accepted. The choice of the target velocity V is performed by sampling a specific velocity for the target nucleus out of a Maxwell-Boltzmann distribution. The term in a) expressed by the ratio of two cross sections is always below unity and it is the missing term added. This term introduces correctly the Doppler broadening of the scattering kernel [4].

3. CANDU Model Problem

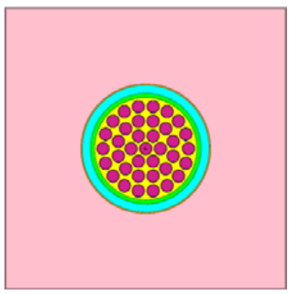

Figure 2. The standard CANDU fuel lattice

A standard CANDU fuel lattice was modeled and analyzed in this work. The standard fuel bundle consists of 37 fuel rods. The fuel bundle is loaded into a pressure tube and a Calandria tube surrounds the pressure tube that physically separates the moderator from the coolant. Heavy water is used for both coolant and moderator. Each fuel rod has radius of 0.64808cm and the cladding thickness is 0.4038mm. The fuel pitch is 28.575cm. The linear power is 12.939kW/cm. Figure 2 shows the standard CANDU fuel lattice model.

4. Results and Discussion

The CANDU fuel lattice was depleted up to 230 days or 7.5 GWd/MTHM by using MCNPX-DBRC based on the ENDF/B-VII library. The result of the depletion is shown in Fig. 3. In order to simulate the equilibrium core conditions, the fuel lattice is often analyzed at the mid-burnup. In typical CANDU core, the mid-burnup usually corresponds to 3.6 GWD/MTHM. In this work, for a conservative evaluation, the FTC is calculated at a slightly higher burnup of 3.9 GWd/MTHM.

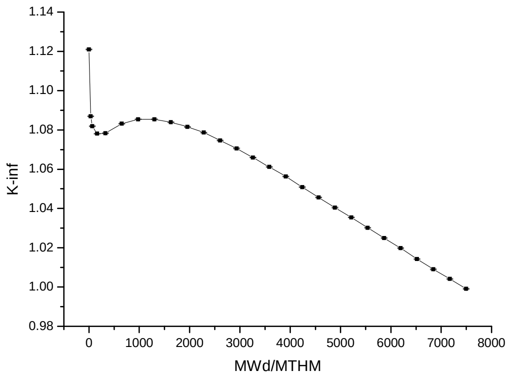

Figure 3. The multiplication factor vs. burnup

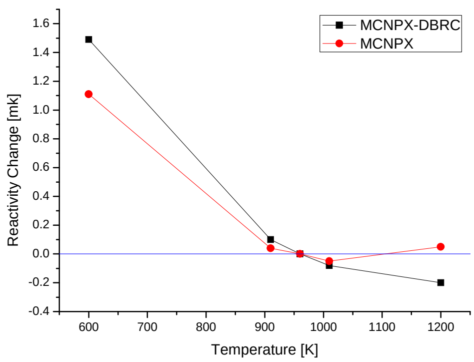

Figure 4. The reactivity change as function of fuel temperature

Figure 4 provides the result of the reactivity change as a function of the fuel temperature. In the MCNPX calculations, the uncertainty of the k-inf value is only ±0.00001. It is clearly observed that the DBRC scheme provides a slightly negative FTC up to 1200 K, while the FTC turns out to be slightly positive above ~1000 K with the original MCNPX. It should be noted that the Doppler broadening is noticeably enhanced by taking into account the target (U-238) motion. Table I shows the FTC values evaluated by using MCNPX in the vicinity of the average fuel temperature at full power condition, i.e., 960 K.

Table I. Comparison of FTC evaluated by MCNPX with and without DBRC kernel

ΔT	Without DBRC	With DBRC
-50 K	-0.07166 ± 0.0283	-0.17931 ± 0.0283
+50 K	-0.08958 ± 0.0283	-0.14347 ± 0.0283

For a comparison purpose, similar analyses were also performed with McCARD [5], in which thermal motion of the heavy metals such as U is not accounted for, and the result are summarized in Table II. Table II compares the FTC values obtained at the mid-burnup with several nuclear data libraries. From Table I and II, one can clearly notes that the DBRC scheme significantly enhance the Doppler broadening effect and makes the FTC more negative.

Table II. Comparison of FTC evaluated for several nuclear libraries

ΔT	ENDF/B-VI	ENDF/B-VII	JENDL4.0
-50 K	-0.07380 ± 0.0283	-0.10976 ± 0.0283	-0.10945 ± 0.0283
+50 K	-0.01845 ± 0.0283	-0.07318 ± 0.0283	0.00000 ± 0.0283

5. Conclusions

For an accurate evaluation of the FTC of CANDU, the thermal motion of the heavy atoms, particularly U-238, should be correctly considered. Based on the corrected MCNPX results, it is very likely that the FTC of CANDU 6 is slightly negative up to 1100~1200 K. The current lattice code for CANDU design needs to be re-evaluated in terms of the FTC.

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