Inter-Comparison of Doppler Reactivity Coefficients for LWR UO_2 and MOX Cells

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ABSTRACT

A detailed inter-comparison has been performed for the Doppler reactivity coefficient of UO_2 and MOX fueled light water reactor (LWR) cells between Osaka University and CEA-Cadarache.

The Monte-Carlo code MVP with the JENDL-3.2 library and the deterministic code APOLLO2 with the CEA93 library processed from the JEF-2.2 file were used. The effect of the spatial distribution of temperature and self-shielding within a fuel rod has been studied. For the UO_2 cell, the Doppler reactivity coefficients calculated by the two codes agree each other within 3%. The neglect of the temperature distribution leads to 7% ± 2% and 11% overestimation for MVP and APOLLO2, respectively.

For the MOX cell, the Doppler reactivity coefficient calculated by MVP differs from that of APOLLO2 by only 3%. However, if one uses the volume-averaged temperature, the results differ by 8%. The effect of temperature distribution for the Doppler reactivity is 6% for MVP and 11% for APOLLO2. This disagreement is investigated through the neutron balance analysis and the reaction rate differences.

1. INTRODUCTION

The effect of spatial distribution of fuel temperature and self-shielding on the Doppler reactivity coefficient has been investigated by many researchers[<1>-<6>].

In this study, a detailed comparison is done through an international Benchmark using the deterministic codes and the Monte-Carlo code. The continuous-energy Monte-Carlo code MVP[<7>] was used as a reference calculation. As the deterministic calculation, the APOLLO2[<8>] code was used.

The APOLLO2 code utilizes the 172-energy group CEA93 library processed from the JEF2.2 File[9] ; resonance absorption calculations are based on the probability table method[10],[11] and the background matrix space-dependent formalism[12]. The MVP code utilizes the JENDL 3.2 library[13]. These calculations are consistent because both calculations use the same ^{238}U resonance parameters[14].

The calculations were performed for two Doppler cases: Case 1 with temperature distribution, and Case 2 with uniform volume averaged temperature. The fuel region is divided into 10 equi-volume regions. The radial temperature profile inside the PWR fuel pellet was defined through METEOR thermo-mechanical calculations at P = 140 W/cm and P = 208 W/cm (the corresponding average fuel temperatures are 780.3 K and 863.5 K).

2. BENCHMARK RESULTS

2.1 K_{inf} and the Doppler reactivity coefficient

Table 1 compares the k_{inf} values and the Doppler reactivity coefficients calculated by the MVP and APOLLO2 codes for the UO_2 and MOX cells.

Concerning the UO_2 fuel, the k_{inf} values calculated by the two codes are in good agreement, but the Doppler reactivity coefficient obtained using the actual temperature distribution is smaller than that calculated for the volume averaged temperature case by 7(+/-2)% for MVP and 12% for APOLLO2. This difference is significant for the Doppler reactivity coefficient and beyond the target accuracy. If we use the constant effective temperature defined by Rowlands[15], the difference with respect to the distributed temperature case becomes acceptable.

For the MOX cell, due to the Pu240 component, the Doppler reactivity coefficients are larger than those for the UO_2 cell, respectively 19% and 26% in MVP and APOLLO2 calculations. It is seen that the Doppler reactivity coefficient calculated by MVP is smaller than the APOLLO2 results. Furthermore if one neglects the temperature distribution, the Doppler reactivity coefficient is increased by 6(+/-3)% in MVP instead of 11% in APOLLO-2. When using the constant temperature, the difference between the two codes on Doppler reactivity coefficient increases up to 0.27 pcm/°C ; this disagreement is quite unacceptable.

In APOLLO2 the standard calculation route uses a flat effective temperature[16]; therefore the space-dependent self-shielding is accounted in each fuel ring through the Background Matrix formalism (a generalization of the homogeneous effective cross section method and the Equivalence theorem). The APOLLO2 reference calculation with radial temperature profile is more complex, using a multiband method and crossed probability tables $p(\sigma_k^{T1},\sigma_m^{T2})$.

Table 1. Comparison of k_{inf} and Doppler Reactivity Coefficient for PWR UO_2 and MOX Cells

	The accuracy Method		UO_2		MOX	
			Temperature Distribution	Average Temperature	Temperature Distribution	Average Temperature
k_{inf}	140 W/cm	MVP	1.2315 (0.0029%)*	1.2313 (0.0029%)	1.1386 (0.0039%)	1.1383 (0.0039%)
		APOLLO2	1.2307	1.2301	1.1366	1.1359
	208 W/cm	MVP	1.2288 (0.0029%)*	1.2284 (0.0029%)	1.1357 (0.0039%)	1.1351 (0.0039%)
		APOLLO2	1.2281	1.2271	1.1335	1.1325
Doppler Coefficient (pcm/℃)		MVP	-2.63 (1.9%)**	-2.80 (1.8%)	-3.12 (2.1%)	-3.32 (2.0%)
		APOLLO2	-2.55	-2.84	-3.23	-3.59

* Standard deviation (%Δk). ** Relative standard deviation in %.

2.2 **Analysis**

In order to explain this APOLLO2/MVP discrepancy in UO_2 and MOX fuel, we have compared the change of capture reaction rate of each heavy nuclide due to the increase 140→208W/cm of the linear heat rate (the reaction rates were normalized in both codes to a unit neutron source).

Table 2. Total ^{238}U capture rates for UO_2 cell

		Average Temperature	Temperature Distribution	Difference
140W/cm	MVP	0.23745 (0.01%)	0.23729 (0.01%)	-1.6E-04
	APOLLO2	0.23825	0.23784	-4.1E-04
208W/cm	MVP	0.23935 (0.01%)	0.23908 (0.01%)	-2.7E-04
	APOLLO2	0.24016	0.23954	-6.2E-04
Difference	MVP	1.90E-03	1.79E-03	-1.1E-04
	APOLLO2	1.91E-03	1.70E-03	-2.1E-04

Table 3. Total capture rates of the heavy nuclide for MOX cell

(a) ^{238}U

		Average Temperature	Temperature Distribution	Difference
140W/cm	MVP	0.19631 (0.01%)	0.19613 (0.01%)	-1.8E-04
	APOLLO2	0.19810	0.19767	-4.3E-04
208W/cm	MVP	0.19827 (0.01%)	0.19796 (0.01%)	-3.1E-04
	APOLLO2	0.20020	0.19951	-6.9E-04
Difference	MVP	1.96E-03	1.83E-03	-1.3E-04
	APOLLO2	2.10E-03	1.84E-03	-2.6E-04

(b) ^{239}Pu

		Average Temperature	Temperature Distribution	Difference
140W/cm	MVP	0.15010 (0.01%)	0.15007 (0.01%)	-3E-05
	APOLLO2	0.15067	0.15068	1E-05
208W/cm	MVP	0.15022 (0.01%)	0.15022 (0.01%)	0
	APOLLO2	0.15080	0.15081	1E-05
Difference	MVP	1.20E-04	1.50E-04	3E-05
	APOLLO2	1.30E-04	1.30E-04	0

(b) ^{240}Pu

		Average Temperature	Temperature Distribution	Difference
140W/cm	MVP	0.11581 (0.02%)	0.11569 (0.02%)	-1.2E-04
	APOLLO2	0.11365	0.11355	-1.0E-04
208W/cm	MVP	0.11612 (0.02%)	0.11600 (0.02%)	-1.2E-04
	APOLLO2	0.11403	0.11392	-1.1E-04
Difference	MVP	3.1E-04	3.1E-04	0
	APOLLO2	3.8E-04	3.7E-04	-1E-05

Table 2 shows the ^{238}U capture rates for the UO_2 cell. The ^{238}U capture rate difference between the

two linear heat rates is 190 and 191 pcm for MVP and APOLLO2, respectively. This good agreement leads to similar Doppler reactivity coefficient when using the volume-averaged temperature as shown in Table 1. When considering the temperature distribution, the ^{238}U capture rate increase with temperature is larger for MVP than for APOLLO2 by about 5%. So the Doppler reactivity coefficient by MVP is larger than the results of APOLLO2.

Table 3 shows the ^{238}U, ^{239}Pu, ^{240}Pu capture rates for the MOX cell. We see that the ^{239}Pu and ^{240}Pu have smaller contribution to the change of capture rate than ^{238}U. Moreover the change of the capture rate due to the temperature distribution is large for ^{238}U, smaller for ^{240}Pu and negligible for ^{239}Pu. When taking the effect of temperature distribution into account, the ^{238}U capture rate modification linked to Doppler broadening decreases by 7% for MVP and by 12% for APOLLO2. This relative difference corresponds to the Doppler reactivity difference between the cases with and without temperature distribution in Table 1.

Let us consider the physical reason why the Doppler reactivity coefficient for the case with temperature distribution is smaller than that with average temperature. Doppler worth is proportional to the change of absorption rates, mainly of ^{238}U, ^{239}Pu and ^{240}Pu. The temperature distribution is quite parabolic, and the temperature difference between the two linear heat rates is large at the rod center, and small at the rod periphery. Therefore, Doppler broadening and the difference of capture rates between the two linear heat rates becomes small at the rod periphery and large at the rod center compared to the uniform temperature case. Thus the Doppler reactivity coefficient is dependent on these effects, and the influence of the rod periphery is stronger than the rod center in almost resonance due to weak self-shielding in the periphery. So the temperature distribution decreases the Doppler reactivity coefficient.

We can now consider why APOLLO2 has a larger effect of temperature distribution than MVP. Figures 1 and 2 show the difference of the ^{238}U capture rate between the two linear heat rates for the UO_2 and MOX cells, respectively. It is seen that the effect of the temperature distribution is different at each resonance.

In MVP, at the 60th group (454.0eV-677.3eV), the effect of the temperature distribution increases the difference of the ^{238}U capture rates for the UO_2 cell and is negligible for the MOX cell. This trend is not consistent with APOLLO2. Furthermore, the increase of the ^{238}U capture rate difference for the temperature distribution case is not seen below 100eV, where opposite trend is seen. When considering the temperature distribution, the increase of the ^{238}U capture rate becomes large around the rod center compared to the decrease of the capture rate around the periphery. So, total ^{238}U capture rate becomes large. However, in APOLLO2, the ^{238}U capture rate is decreased at the 60th group both for UO_2 and MOX cells. At the 69th group (55.6eV-67.9eV), the opposite trend is seen between MVP and APOLLO2, when considering the temperature distribution for UO_2 and MOX cells. At the 75th group (33.72eV-37.27eV), for the UO_2 cell, the result of the ^{238}U capture rate difference is not

consistent between MVP and APOLLO2. These phenomenon can be attributed to the complicated behavior of the difference of the ^{238}U capture rate between two linear heat rates at each region for APOLLO2. Figure 3 shows that the results of MVP are smooth, but those of APOLLO2 express some ragged trends in regard to the temperature distribution calculation.

3. CONCLUSION

This study made sure how much error the volume averaged temperature calculation had. According to the reference calculation, the continuous-energy Monte-Carlo code MVP, neglecting temperature distribution in the fuel rod increased Doppler reactivity coefficient by 7(+/-2)% for the UO_2 cell and 6(+/-3)% for the MOX cell. The APOLLO2 deterministic calculation predicts a temperature profile effect which amounts to 11%. The reason of this MVP/APOLLO2 discrepancy was in ^{238}U capture rates mainly. Though the situation was complicated very much at each resonance, the volume averaged temperature increased the difference of ^{238}U capture rates between the two linear heat rates more in APOLLO2 than in MVP. Furthermore, for small resonances, including the temperature distribution could increase the difference of ^{238}U capture rates since Doppler broadening was larger in the rod center than in the rod periphery due to a weak self-shielding, but this phenomenon did not appear in APOLLO2.

This disagreement on “radial temperature profile effect” between the APOLLO2 reference route and the MVP continuous-energy Monte Carlo calculation could point out the weakness of the full correlation assumption used in the crossed probability tables implemented in the deterministic code.

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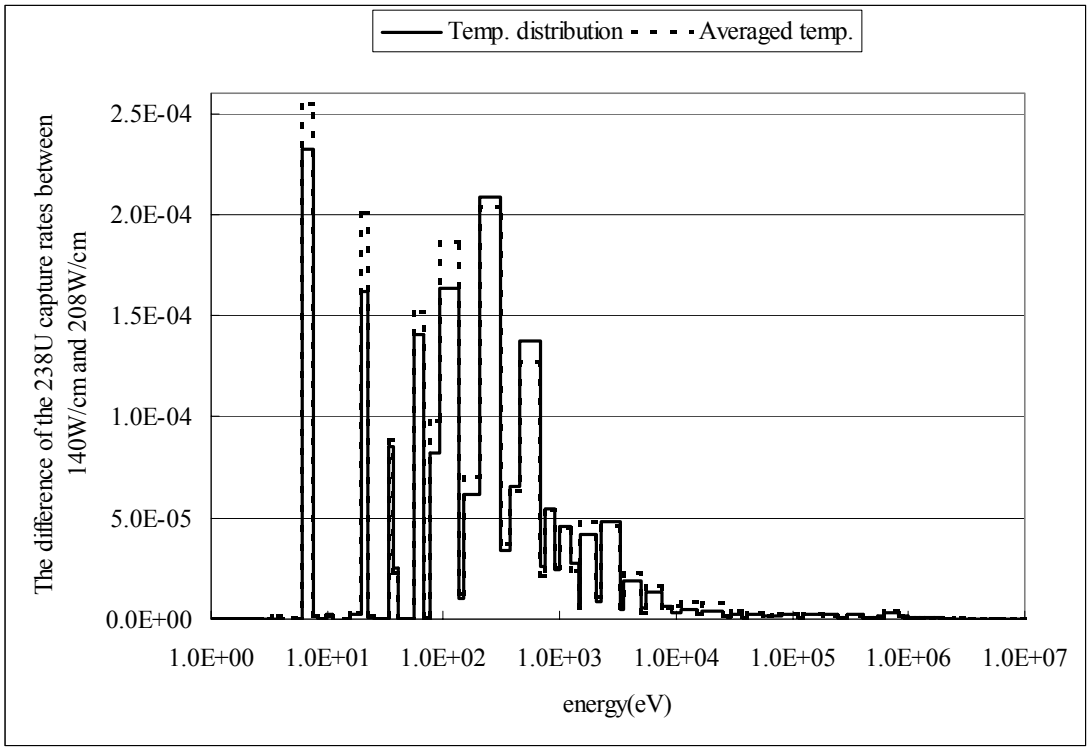
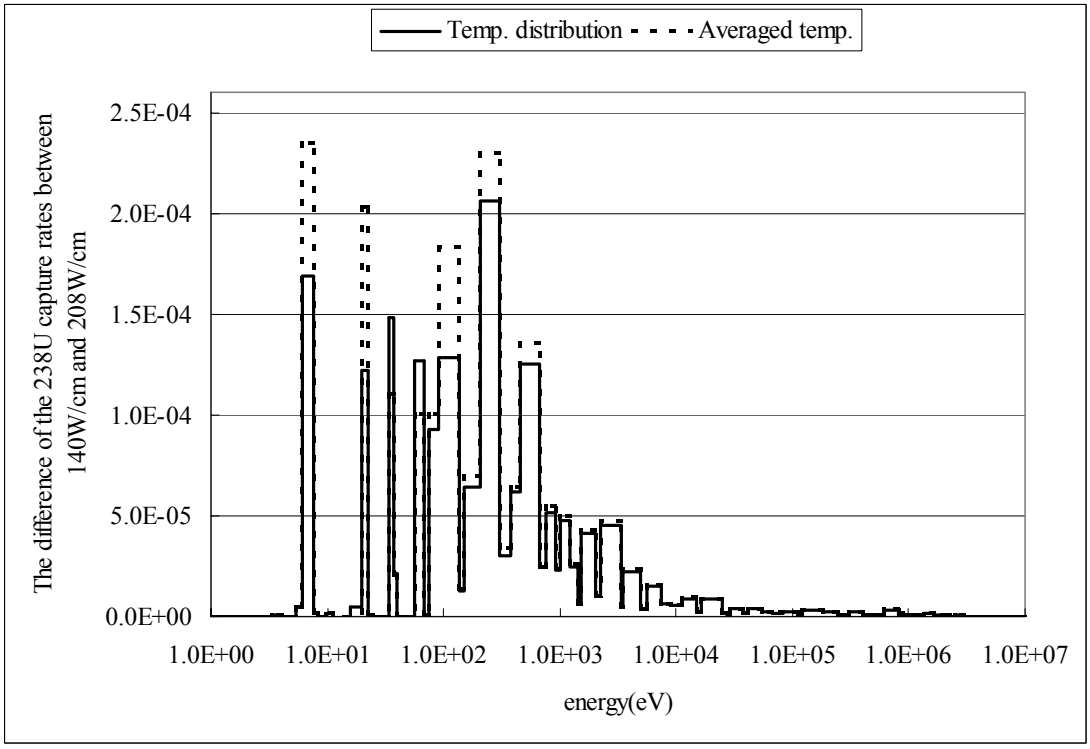
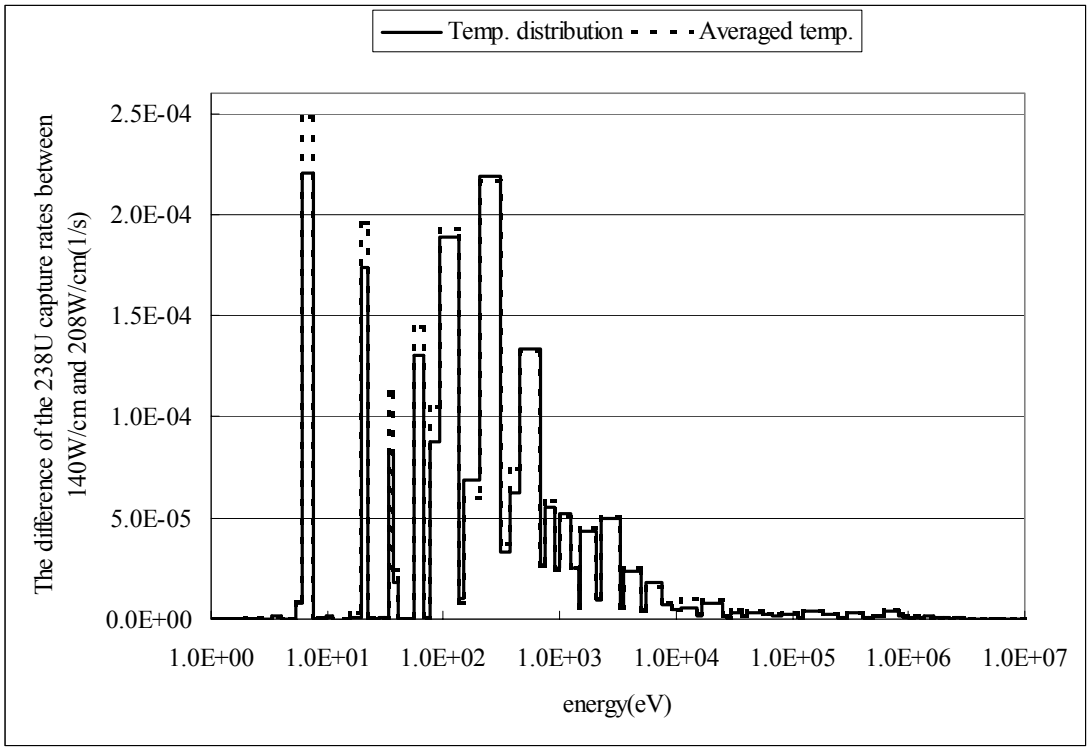


(a) MVP for UO2 cell

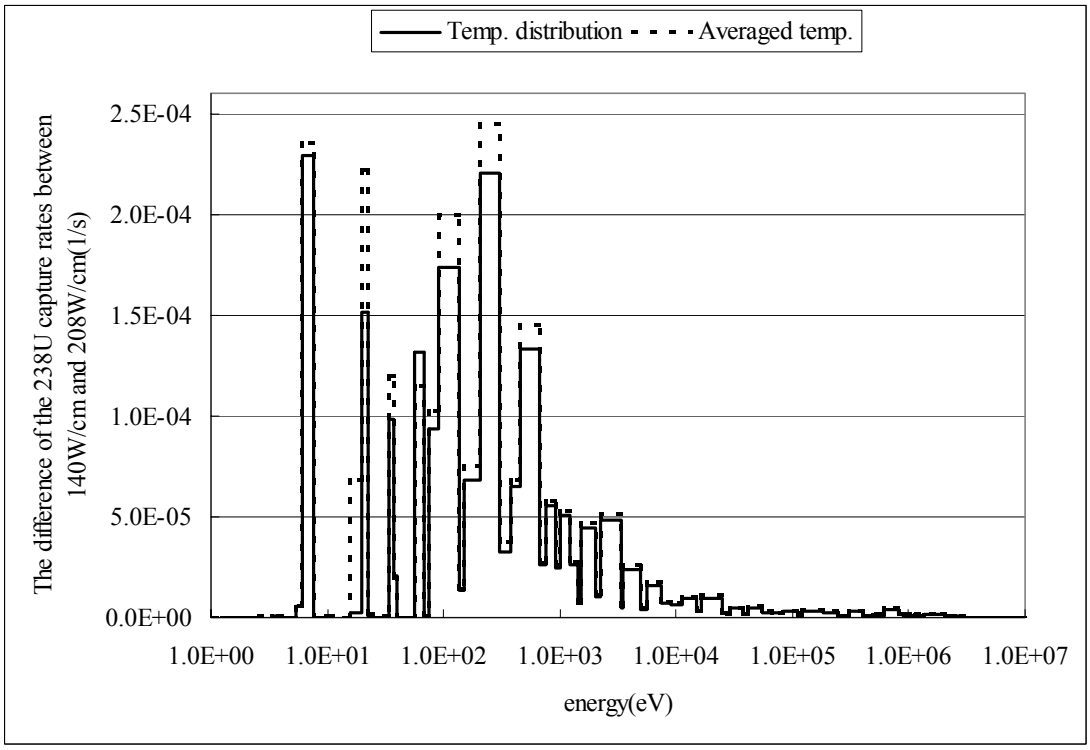


(b) APOLLO2 for UO2 cell

Figure 1. The difference of the ^{238}U capture rates between 140W/cm and 208W/cm for the UO_2 cell

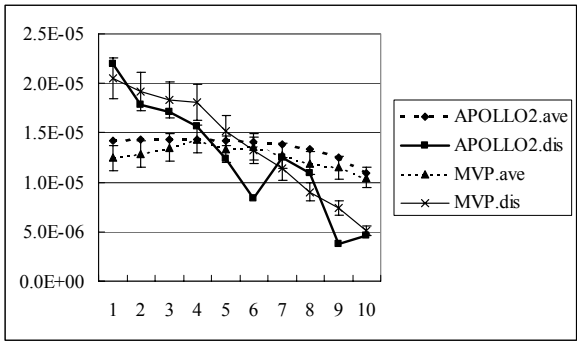


(c) MVP for MOX cell

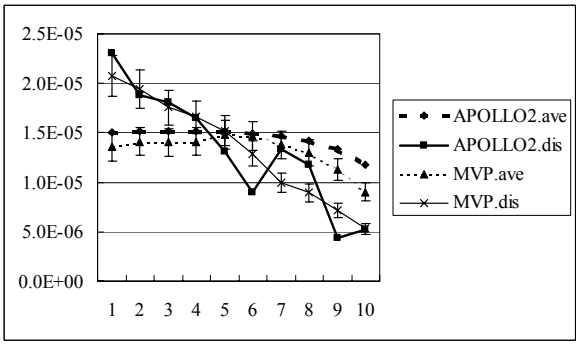


(d) APOLLO2 for MOX cell

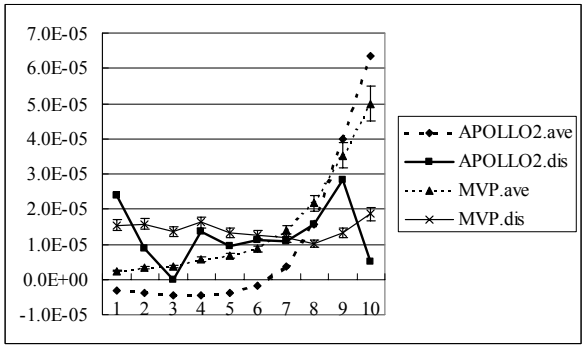
Figure 2. The difference of the ^{238}U capture rates between 140W/cm and 208W/cm for the MOX cell



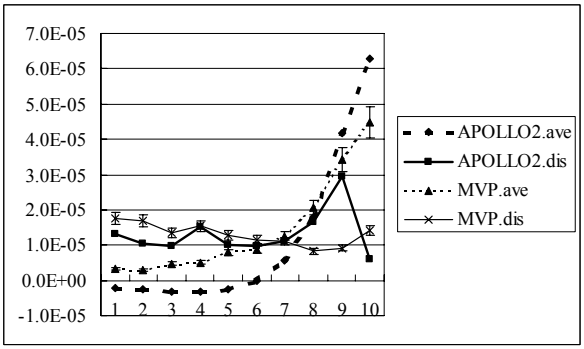
(a) 60th group for the UO_2 cell



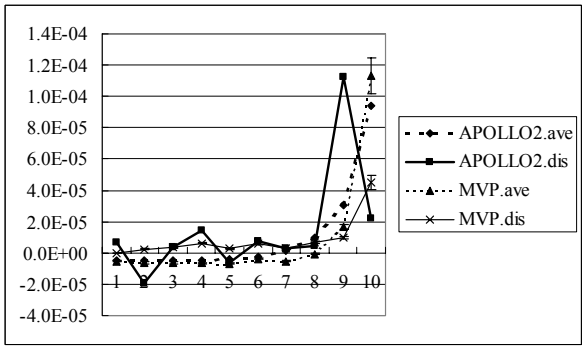
(b) 60th group for the MOX cell



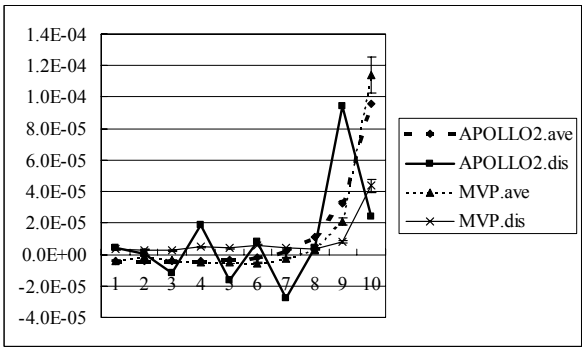
(c) 69th group for the UO_2 cell



(d) 69th group for the MOX cell



(e) 75th group for the UO_2 cell



(f) 75th group for the MOX cell

Figure 3. The difference of the ^{238}U capture rates between 140W/cm and 208W/cm at each region