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Treatment of Control Rods in the Diffusion Nodal Calculation for the HTGR Cores

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I. INTRODUCTION

There is a strong need to model control rods accurately by capturing the transport effects in the diffusion theory for a high temperature gas cooled reactor (HTGR) core[1] as well as a light water reactor (LWR) core. The neutronic characteristics of control rods in the HTGR cores are quite different from those in the LWR cores. One of such characteristics comes from the fact that the control rods can be located in the graphite reflector in a HTGR core. The sharp flux gradient caused by the control rods in the reflector may increase the neutron leakage from the fuel region to the reflector region. The wide reactivity influence of a control rod due to a long neutron diffusion length provides another distinct characteristic of HTGR cores.

In previous studies[1,2], control rods in a HTGR core have been approximated roughly with a simple volume averaged homogenization of rodded calculational meshes, which produces large errors in estimating the control rod worth.

In this paper, an accurate control rod model for the HTGR was devised based on the equivalence theory[3] which has been successfully used in the analysis of control rods in the LWR core.

II. CONTROL ROD MODEL

By modifying the pebble-bed modular reactor (PBMR) core[4], a two-dimensional simplified spectral geometry as depicted in Figure 1 was constructed in order to derive our control rod model. Two HELIOS[5] lattice calculations with and without control rods were performed for this spectral geometry. The 190 energy group structure based on the ENDF/B-VI was used in the HELIOS calculations. It will be condensed into an 8 energy group structure for the subsequent diffusion core calculation.

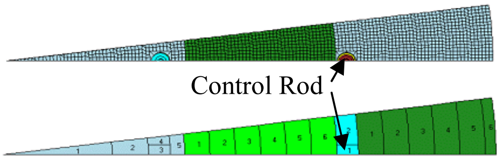

Fig. 1. A 2-D Spectral Geometry with Control Rods

For both the rodded and the unrodded cores, the parameters such as the homogenized cross sections and the discontinuity factors to be used in the diffusion core calculation can be obtained from the HELIOS calculations by applying the equivalence theory. For the LWR core analysis, the model which uses the equivalence theory parameters of the roddded core only for the control rod regions is widely used to simulate the rodded core. For the other regions in the rodded core, the parameters of the unrodded core are used in this model. This model is justified by the fact that the influence of a control rod is confined to within a very short distance from the control rod due to the short neutron diffusion length of the LWR core.

Prior to testing the applicability of this model to the HTGR cores, we equivalently transformed the original flux discontinuity equation across the left surface of the rodded mesh i in Figure 2

$$f^{r}_{Ri-1}\,\phi^{r}_{i-1} = f^{r}_{Li}\,\phi^{r}_{i} \tag{1}$$

into the following form:

$$f^{u}_{Ri-1}\,\phi^{r}_{i-1} = \frac{f^{u}_{Ri-1}}{f^{r}_{Ri-1}}\,f^{r}_{Li}\phi^{r}_{i} = f^{r*}_{Li}\,\phi^{r}_{i} \tag{2}$$

where u and r stand for the unrodded and rodded core conditions, respectively. A similar equation can also be derived for the right surface. This is to enable the use of the modified discontinuity factors only for the rodded mesh to reproduce the original rodded discontinuity condition.

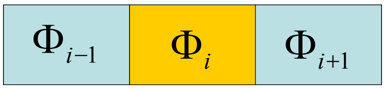

Fig. 2. Three-node configuration

First, we tried to apply the LWR model to simulate the rodded HTGR core, where all the regions maintain the cross sections and the discontinuity factors given at the rod-out state except for the control rod regions. As shown in Table I, the result indicates that the maximum error of the flux distribution and that of the multiplication factor are -1.42% and 0.55 %, respectively. Although they exhibit a slightly deviated flux and multiplication factor errors, the results are not satisfactory enough to estimate accurately the control rod worth in the HTGR analysis.

Table I. Results when the LWR model is applied.

Group	HELIOS		Diffusion Nodal	
	Flux at Fuel Region	Flux at Control Rod Region	Fuel Error (%)	Control Rod Error (%)
1	2.3571E+06	3.8574E+05	+0.82	-0.82
2	1.6494E+12	3.3393E+11	-0.22	-0.57
3	1.9498E+12	5.0462E+11	-0.46	-0.72
4	1.0824E+12	2.8514E+11	-0.55	-0.86
5	1.6121E+12	4.6125E+11	-1.27	-1.42
6	1.3191E+12	3.4881E+11	-0.33	-0.591
7	7.2364E+11	3.6252E+11	+0.37	-0.1.2
8	3.8735E+11	2.9525E+11	+0.50	0.01
k-eff	0.96503		0.97032 (0.55 %)	

To estimate the control rod worth more accurately, we tried some more cases which consider an additional inclusion of the different types of the rodded cross sections for the unrodded fuel regions. From the results of these tests, we found that the inclusion of the rodded scattering cross-sections for the fuel regions is much more crucial than the inclusion of any other type of cross sections. This is because the spectrum shift due to a control rod insertion in the reflector region may result in a big change in the neutron scattering pattern in the fuel region. By including the rodded scattering cross sections for the fuel regions, the accuracy in estimating the effective multiplication factor for the rodded core is significantly improved with a relative error of 0.01 %, as shown in Table II. It can be finally concluded that it is enough to use the rodded cross sections for the control rod regions and the rodded scattering cross sections for the fuel regions when estimating the control rod worth.

Table I. Results when the rodded fuel scattering cross sections are included additionally.

Group	HELIOS		Diffusion Nodal	
	Flux at Fuel Region	Flux at Control Rod Region	Fuel Error (%)	Control Rod Error (%)
1	2.3571E+06	3.8574E+05	1.31	-0.42
2	1.6494E+12	3.3393E+11	0.13	-0.22
3	1.9498E+12	5.0462E+11	0.03	-0.56
4	1.0824E+12	2.8514E+11	-0.02	-0.59
5	1.6121E+12	4.6125E+11	-0.05	-0.50
6	1.3191E+12	3.4881E+11	-0.04	0.46
7	7.2364E+11	3.6252E+11	0.00	0.86
8	3.8735E+11	2.9525E+11	0.05	1.06
k-eff	0.96503		0.96510 (0.01 %)	

III. CONCLUSION

A procedure for the analysis of control rods in the HTGR core was proposed based on the equivalence theory. In this procedure, a simple two-dimensional spectral geometry with control rods is used to derive the equivalence theory homogenized parameters such as the cross sections and the discontinuity factors. In spite of a very wide flux depression around an inserted control rod due to the long diffusion length of the HTGR core, the rodded core is simulated by a simple strategy by using the rodded homogenized parameters for the control rod regions and the rodded scattering cross section for the fuel regions.

This model when applied to the diffusion calculation was benchmarked against the reference HELIOS transport calculation. From the results, it can be concluded that this model is simple but accurate and practical in predicting the control rod worth and the rodded power distribution in the diffusion nodal calculation for the HTGR cores

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