Physical Analysis of Control Rod Structure in Pressurized Water Reactor

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Abstract

Reactivity control is an important field of reactor research, and control rod is one of main way of reactivity control. Currently, in order to improve the safety of some new reactors, boric acid is eliminated as a means of reactivity regulation, and the loss of controlled reactivity is compensated by increasing the reactivity value of control rods. The reactivity value of control rod is related to its size and structure. In this paper, the reactivity value of cylindrical control rod and cross shaped control rod in PWR is calculated by using a Monte Carlo code, and the influence of two kinds of control rods on the core reactivity under the same volume and the same neutron irradiation area, and the relationship between the geometry size of cross shaped control rods and the core reactivity are analyzed. The results show that the reactivity value of control rod is directly proportional to its volume and neutron irradiation area; with the same volume of control material, the reactivity value of cross shaped control rod is higher; with the same neutron irradiation area, the reactivity value of cylindrical control rod is higher; when the reactivity value is the same, the volume of cross shaped control rod is smaller, about 75% of the volume of cylindrical control rod, which provides a new idea for the study of reactivity control scheme without boric acid.

Keywords: *Pressurized water reactor, BEAVRS2.0, fuel assembly, control rod, reactivity, cross shaped control rod*

I. Introduction

The main reactivity control modes for the reactor include: control rod, boric acid and combustible poison rod [1-3]. Since high-concentration boric acid has a positive temperature coefficient [4,5], it may affect the inherent safety of the reactor. In the design of some new reactor types, reactivity control method replacing boric acid regulation is studied [6]; the combustible poison rod is arranged at the beginning of its life. The reactivity value changes with fuel consumption and cannot be adjusted manually [7]. The control rod provides an important means to adjust the reactivity in the reactor [8]. Made of materials that strongly absorb neutrons (B4C, Ag-In-Cd, etc.), it has advantages such as fast reactivity, precise reactivity control, reliable operation, and flexible use.

The shape and size of control rods differ greatly in different reactor design schemes. For the most common light water reactors, there are mainly two types of rods: cylindrical control rod and cross shaped control rod. Cylindrical control rods are basically used in pressurized water reactors, which are inserted into guide pipe channels in fuel assemblies; cross shaped control rods are mainly used in boiling water reactors and are arranged in the water gap between four adjacent fuel assemblies [9]. At present, cross shaped control rod layout schemes are also used in some new reactor designs, such as the supercritical water-cooled reactor CSR1000 [10], and the special power experimental reactor SPERT III E-Core [11]. In the existing control rod design schemes, the cross shaped control rod is mainly arranged in the gap of the fuel assembly. This paper proposes a scheme of arranging the cross shaped control rod in the fuel assembly guide tube, and compares it with the cylindrical control rod to explore a new scheme for the subsequent design of fuel assembly in the new reactor type. The calculation mainly analyzes the impact of control rod structure and size changes on the reactivity of the reactor core, while adaptability adjustments to the fuel assembly for this purpose are not considered for the time being.

II. Theoretical Analysis

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The control rod is an important component for emergency control and power regulation in the reactor, which is mainly used to control the reactivity changes owing to the following factors:

(1) Doppler effect of fuel;

(2) The temperature effect and void effect of the moderator;

(3) Transient xenon effect;

(4) Boron dilution effect;

(5) Depth of hot shutdown.

When the core has no control rods, the neutron single-group diffusion equation [12] is:

$$\nabla \cdot D\nabla\phi - \Sigma_a\phi + \frac{1}{k}\nu\Sigma_f\phi = 0 \quad (1)$$

Where, D is the diffusion coefficient, ϕ is the neutron flux density, Σ_a is the neutron absorption cross section, Σ_f is the neutron fission cross section, k is the multiplication coefficient, and ν is the average number of fission neutrons. After insertion of the control rod, the macroscopic absorption cross section changes from Σ_a to $\Sigma_a' = \Sigma_a + \delta\Sigma_a$, and the meaning of $\delta\Sigma_a$ is as follows:

$$\delta\Sigma_a = \begin{cases} \Sigma_{a,p}, & 0 \le z \le Z, 0 < r \le a \\ 0 \end{cases} \quad (2)$$

Where, $\Sigma_{a,p}$ is the control rod absorption section against the neutron, Z is the longitudinal height of the control rod, and a is the radial length of the control rod. Hence, the single group equation of neutron flux density is:

$$\nabla \cdot D\nabla\phi' - (\Sigma_a + \delta\Sigma_a)\phi' + \frac{1}{k+\delta k}\nu\Sigma_f\phi' = 0 \quad (3)$$

δk is the multiplication coefficient perturbation due to the insertion of the control rod. Subtract the integral of formula 1 from formula 3. Then, according to $\Delta\rho = \delta\left(\frac{k-1}{k}\right)$, there is:

$$\Delta\rho = \frac{-\int_{V_P}\delta\Sigma_a\phi'\phi dV}{\int_V \nu\Sigma_f\phi'\phi dV} \approx -\frac{\Sigma_{a,p}\int_{V_P}\phi^2 dV}{\int_V \nu\Sigma_f\phi^2 dV} \quad (4)$$

Where, $\Delta\rho$ is the change in core reactivity, $\Sigma_{a,p}$ is the macroscopic cross section of neutron absorption in the control rod, V_P is the neutron absorber volume of the control rod, and V is the volume of the core active area. According to the above formula, under constant core structure and neutron flux density, the change in reactor core reactivity is inversely proportional to the control rod volume.

III. Calculation Model

In this paper, based on the description of the reactor core-related parameters in the BEAVRS2.0 (Benchmark for Evaluation And Validation of Reactor Simulation) benchmark [13], a calculation model is established for the fuel assembly with cylindrical control rods. The fuel elements in the assembly are arranged in 17×17 distribution. Each assembly contains 264 fuel rods, instrument tubes used for in-core measurement at the assembly center, and 24

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symmetrically distributed control rod guide tubes. The relevant parameters are shown in Table 1. The fuel rod structure and control rod structure are shown in Fig 1 and 2. The central area of the fuel rod is UO_2 fuel, the outer layer is covered by zirconium cladding, and the gap between the cladding and the fuel is filled with helium. The control rod is placed in the guide tube, the outer layer is a stainless steel cladding, and the central area is a neutron absorber (Ag-In-Cd). The gap between the neutron absorber and the cladding is also filled with helium.

Table 1 Fuel assembly parameters

Parameter	Value	Parameter	Value
Fuel assembly pitch /cm	21.50364	Guide tube outer diameter/cm	1.20396
Fuel rod bundle distribution	17 × 17	Guide tube material	Zirconium alloy
Fuel assembly height /cm	365.76	Number of instrument tubes	1
Fuel rod bundle pitch /cm	1.25984	Instrument tube outer diameter/cm	1.203 96
Fuel rod fuel area diameter/cm	0.78436	Instrument tube inner diameter/cm	0.87376
Fuel rod cladding thickness/cm	0.05715	Control rod absorber diameter/cm	0.76454
Fuel rod outer diameter/cm	0.9144	Control rod cladding thickness/cm	0.09779
Fuel pellet material	UO_2	Outer diameter of control rod cladding/cm	0.96774
Fuel rod cladding material	Zirconium alloy	Control rod material	Ag(80%)-In(15%) -Cd(5%)
Fuel enrichment degree	3%	Control rod cladding material	SS304
Number of guide tubes	24	Air gap material	Helium
Guide tube inner diameter/cm	1.12268	Number of control rod bundles	24

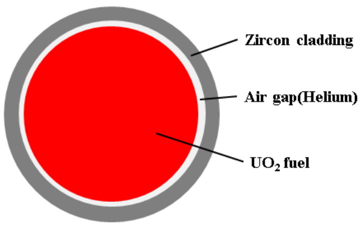

Fig 1: Fuel rod structure

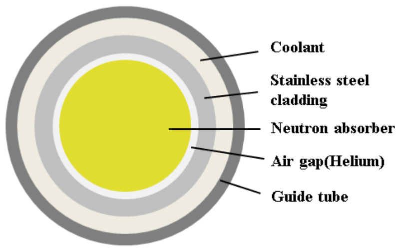

Fig 2: Cylindrical control rod structure

The cross shaped control rod structure is the same as the cylindrical control rod except that the neutron absorber in the center has a different shape, as shown in Fig 3. The geometric parameters of the cross shaped control rod include blade width *a* and shaft length *b*. The control rod shape is determined by assuming the relationship between the cylindrical control rod and the cross shaped control rod as well as the relationship between *a* and *b*.

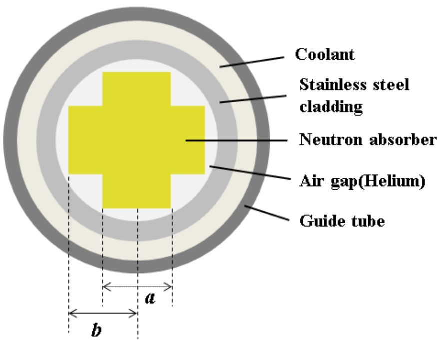

Fig 2: Cross shaped control rod structure

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IV. Control Rod Reactivity Analysis

This section mainly analyzes the impact of the volume and neutron irradiation area of the cylindrical control rod and the cross shaped control rod on the reactor core reactivity. The size of the control rod guide tube remains unchanged, while impact of the change in the gap between the control rod and the guide tube on the reactor core is ignored. In order to accurately calculate the impact of control rod geometry and size changes on the reactor core reactivity, Monte Carlo method was used for analysis.

4.1 Reactivity analysis of control rod with equal volume

The volume of the cylindrical control rod is $\pi r^2 h$, and the volume of the cross shaped control rod is $(4ab - a^2)h$. It is assumed that the cylindrical control rod and the cross shaped control rod have equal volume, that is, $\pi r^2 h = (4ab - a^2)h$. Furthermore, assume that the axis length b of the cross shaped control rod is equal to the blade width a, $b = a$. Then, the relationship between the radius r of the cylindrical control rod and the axis length b of the cross shaped control rod is:

$$b = \sqrt{\frac{\pi r^2}{3}} \tag{5}$$

The radius r of the cylindrical control rod has a value range of [0.35 cm, 0.45 cm]. Assume that the initial fission source is located in the center of the fuel assembly and the source intensity is 20000. Calculate the change of the reactor core effective multiplication coefficient K_{eff} under the 500-generation neutron cycle. The final calculation results are shown in Table 2.

Table 2 K_{eff} for different control rod volumes

Volume/cm^3	Effective multiplication coefficient K_{eff}	
	Cylindrical control rod	Cross shaped control rod
0.38485	1.09648$\pm$0.00040	1.05451$\pm$0.00022
0.43008	1.07988$\pm$0.00040	1.03615$\pm$0.00023
0.45908	1.07161$\pm$0.00037	1.02526$\pm$0.00022
0.47784	1.06442$\pm$0.00022	1.01851$\pm$0.00021
0.52810	1.04835$\pm$0.00039	1.00131$\pm$0.00023
0.58089	1.03271$\pm$0.00035	0.98344$\pm$0.00022
0.63617	1.01825$\pm$0.00038	0.96689$\pm$0.00023

According to the relationship between the reactivity ρ and the effective multiplication coefficient K_{eff},

$$\rho = \frac{K_{eff} - 1}{K_{eff}} \tag{6}$$

The relationship between the volume of the cylindrical control rod and the cross shaped control rod and the core reactivity is established, as shown in Fig 4.

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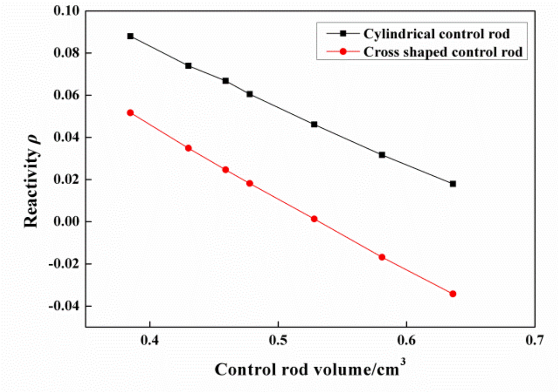

Fig 3: Effect of control rod volume on reactivity

It can be seen from the figure that regardless of cylindrical control rod or cross shaped control rod, its volume is inversely proportional to the change in reactor core reactivity, which is consistent with the theory. However, under the same volume, cross shaped control rod has greater reactivity value, and as the volume increases, there is greater increment in the reactivity value. Analysis of the surface area of the two control rods reveals that:

$$\begin{cases} S_{cylinder} = 2\pi rh \\ S_{cross} = 8bh \end{cases} \tag{7}$$

Where, $S_{cylinder}$ is the surface area of the cylindrical control rod, S_{cross} is the surface area of the cross shaped control rod, and h is the control rod height. According to formulas 4-5, there is

$$S_{cross} = 8\sqrt{\frac{\pi}{3}}rh \approx 8.19rh > S_{cylinder} \tag{8}$$

The above formula shows that the cross shaped control rod has bigger surface area under the same volume, which means that the cross shaped control rod in the reactor core has larger contact surface with the neutron, and it is easier to interact with the neutron.

4.2 Reactivity analysis of control rod with equal neutron irradiation area

The analysis in the previous section shows that the reactivity value of the control rod is not only related to the volume, but also to its area. It is assumed that the cylindrical control rod and the cross shaped control rod have equal side area. That is, the neutron irradiation area of the sub-absorber is equal, and the relationship between axis length b and blade width a of the cross shaped control rod is $b = 1.5a$. The two control rods have equal neutron irradiation areas. That is, their bottom surface circumferences are equal. The bottom surface of the cylindrical control rod is round, and its circumference is $2\pi r$. According to the geometric relationship, the bottom circumference of the cross-shaped control rod is irrelevant with blade width a, which is always $8b$. The relationship between the radius r of the cylindrical control rod and the axis length b of the cross shaped control rod is:

$$b = \frac{\pi r}{4} \tag{9}$$

The radius r of the cylindrical control rod has a value range between [0.35cm, 0.53cm]. The material and neutron source parameters of the control rod are consistent with those in Section 3.1. The calculation results are shown in Table 3.

Table 3 K_{eff} under different neutron irradiation area

Neutron	Effective multiplication coefficient K_{eff}

irradiation area/cm^2	Cylindrical control rod	Cross shaped control rod
804.348	1.09648±0.00040	1.15915±0.00032
850.311	1.07988±0.00040	1.14661±0.00034
896.274	1.06442±0.00022	1.13268±0.00036
942.237	1.04835±0.00039	1.11886±0.00037
988.199	1.03271±0.00035	1.10492±0.00038
1034.162	1.01825±0.00038	1.09197±0.00038
1080.125	1.00278±0.00038	1.07814±0.00044
1126.088	0.98810±0.00043	1.06566±0.00038
1172.050	0.97465±0.00039	1.05311±0.00035
1218.013	0.95865±0.00038	1.04005±0.00040

The relationship between reactor core reactivity and neutron irradiation area of the cylindrical control rod and the cross shaped control rod is shown in Fig 5.

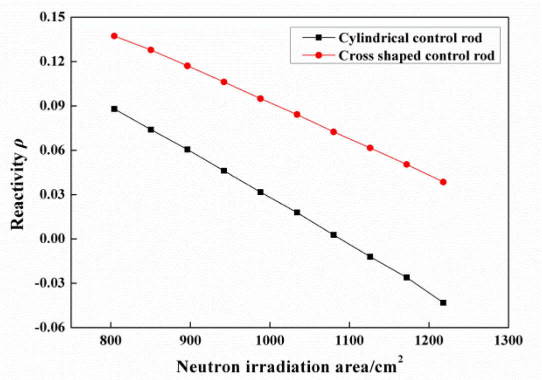

Fig 4: Effect of control rod neutron irradiation area on reactivity

It can be seen from the figure that regardless of cylindrical control rod or cross shaped control rod, the neutron irradiation area is inversely proportional to the reactor core reactivity. Under larger action area between the control rod and the neutron, the control rod has greater neutron absorption capacity, and the core reactivity decreases as the neutron flux density decreases. Under the same area, the cylindrical control rod has a stronger absorption capacity against neutrons. When analyzing the size of the two, there is:

$$\begin{cases} V_{cylinder} = \pi r^2 h \\ V_{cross} = (4ab - a^2)h \end{cases} \tag{10}$$

Where, $V_{cylinder}$ is the volume of the cylindrical control rod, V_{cross} is the volume of the cross shaped control rod, and h is the control rod height. According to formula 8, there is:

$$V_{cross} = \frac{3\pi^2}{16} r^2 h \approx 0.589\pi r^2 h < V_{cylinder} \tag{11}$$

Under the same neutron irradiation area, the cylindrical control rod has a larger volume, which means that neutrons enter the control rod absorber and are more likely to be absorbed by the cylindrical control rod, while the neutrons in the cross shaped control rod are more likely to escape from the control rod area.

4.3 Reactivity analysis of cross shaped control rod

The axial length *b* and leaf width *a* of the cross shaped control rod are geometric parameters describing the control

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rod shape. The shape of the cross shaped control rod can be determined by determining the dimension of *b* and *a*. This section analyzes the relationship between reactivity and neutron irradiation area of cylindrical control rod with a radius of *r*=0.38227cm and leaf width *a* of cross shaped control rod. Since the area is constant, the axial length *b* is a certain value, and *a* has a value range of [0.1*b*, 2*b*], and the shape changes as shown in Figure 6.

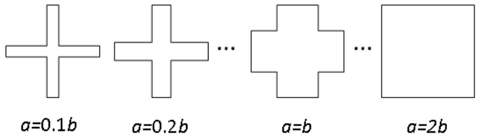

Fig 5: Geometric change of cruciform control rod

The calculation result is shown in Fig 7:

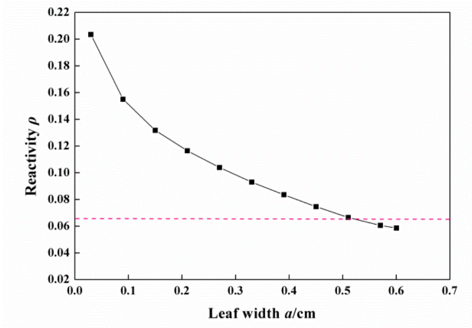

Fig 6: Relationship between reactivity and geometric parameters of cross shaped control rods

As the width *a* of the cross shaped control rod increases, the reactor core reactivity decreases. That is, the reactivity value of the control rod increases. Moreover, when *a* tends to 0, its reactivity value changes the most, and as *a* continues to increase, its reactivity value increment gradually tends to be flat. The red dashed line in the figure shows the reactivity of a cylindrical control rod with equal neutron irradiation area when it is inserted into the reactor core. When *a*=0.52cm, the cross shaped control rod and the cylindrical control rod have equal reactivity value. The cross shaped control rod shape at this time is shown in Fig 8. Its shape is quite close to a square control rod. The circumscribed radius of the cross shaped control rod is 0.39699cm, which is larger than the 0.38227cm radius of the cylindrical control rod. If the size of the control rod guide tube remains unchanged, the gap between the cross shaped control rod and the guide tube becomes smaller, which may affect the drop time of the control rod. If we exclude the impact of the control rod movement, the volume of the cross shaped control rod is 77% that of the cylindrical control rod, so a quarter of the neutron absorber material can be saved.

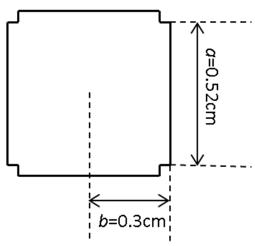

Fig 7: Shape of cross control rod

V. Conclusion

Based on the existing control rod shape design, this paper proposes a scheme of placing the cross shaped control rod in the pressurized water reactor fuel assembly, and analytically compares it with the cylindrical control rod.

The reactivity changes in the reactor core of the cylindrical control rod and the cross shaped control rod are calculated separately under the conditions of equal volume and equal neutron irradiation area. Moreover, the impact of the geometric parameters of the cross shaped control rod on the reactivity is analyzed. The conclusions are drawn as follows:

(1) Under the same volume, the reactivity value of the cross shaped control rod is higher, and under the same neutron irradiation area, the reactivity value of the cylindrical control rod is higher;

(2) Under the same reactivity value, the volume of the cross shaped control rod is about 75% that of the cylindrical control rod.
If we exclude the impact of the control rod structure change on the control rod action, the use of cross shaped control rod can compensate for the controlled reactivity loss caused by the cancellation of boric acid adjustment, which can provide a new idea for the design of reactivity control scheme. However, this paper only makes a preliminary study, and it’s necessary to consider the thermal hydraulic, fuel consumption and other factors for further analysis.

References

[1] A. Hussain, X. Cao, “Reactivity control technique for a pressurized water reactor with an inventive TRISO fuel particle composition,” Progress in Nuclear Energy, vol. 51, no. 6-7, pp. 742-745, 2009.

[2] H. Guo, L. Buiron, P. Sciora, et al., “Optimization of reactivity control in a small modular sodium-cooled fast reactor,” Nuclear Engineering and Technology, vol. 52, no. 7, pp. 1367-1379, 2020.

[3] S. Atkinson, D. Litskevich, B. Merk B, “Variable Reactivity Control in Small Modular High Temperature Reactors Using Moderation Manipulation Techniques,” Energies, vol. 11, no. 7, 2018.

[4] O. Icelli, S. Erzeneoglu, R. Boncukcuoglu, “Experimental studies on measurements of mass attenuation coefficients of boric acid at different concentration,” Annals of Nuclear Energy, vol. 31, no. 1, pp. 97-106, 2004.

[5] A.I. Al-Shamayleh, D.A. Solovyov, A.A, et al., “Determining the critical concentration of boric acid and the time of its onset when reaching to minimum controllable power for VVER,” Journal of Physics Conference Series, vol. 1689, pp. 012041, 2020.

[6] B.Y. Xia, P. Yang, L.J. Wang, et al., “Study on reactivity control method for supercritical water-cooled reactor CSR1000,” Nuclear Power Engineering, vol. 34, no. 1, pp. 26-30, 2013.

[7] J.A. Renier, “Development of Improved Burnable Poisons for Commercial Nuclear Power Reactors,” office of scientific & technical information technical reports, 2002.

[8] T. Mina, A. Lashkari, M.S. Fa Rhad, et al., “Neutronic analysis of control rod effect on safety parameters in Tehran Research Reactor,” Nuclear Engineering and Technology, vol. 50, pp. 1017-1023, 2018.

[9] S. Schunert, Y. Wang, J. Ortensi, V. Laboure, et al., “Control rod treatment for FEM based radiation transport methods,” Annals of Nuclear Energy, vol. 127, pp. 293-302, 2019.

[10] B.Y. Xia, P. Yang, L.J. Wang, et al., “Study on Reactivity Control Method for Supercritical Water-Cooled Reactor CSR1000,” Nuclear Power Engineering, vol. 01, no. 1, pp. 26-26, 2013.

[11] L. Cao, A. Gerlach, Y. Xu, et al., “Neutronics modeling of the SPERT III E-Core critical experiments with MPACT and KENO,” Annals of Nuclear Energy, vol. 80, pp. 207-218, 2015.

[12] Z.S. Xie, H.C. Wu, S.H. Zhang, “Physical analysis of nuclear reactor. Beijing: China Atomic Energy Press,” ISBN7-5022-1061-X, 2004.

[13] N. Horelik, B. Herman, M. Ellis, et al., “Benchmark for evaluation and validation of reactor simulation (BEAVRS). Version 2.0.1,” Massachusetts Institute of Technology: MIT Computational Reactor Physics Group, 2017.

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