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A New Radial Power Distribution Construction Model for Nuclear Fuel Performance Simulation Code FUPAC

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Abstract

Radial power distribution is important for temperature distribution calculations in fuel rod performance simulation code. In order to reconstruct the radial power profiles in one model for different types of fuel, such as UO_2, MOX, UO_2-Gd_2O_3, integral fuel burnable absorber(IFBA), etc., this paper proposes a new radial power distribution construction model. Compared with traditional radial power distribution interpolation method which is based on All Parameters Separated way (APS), the new RPD reconstruction method in this paper, called Partial Parameters Separated method (PPS), only use few transient parameters to construct the RPD by interpolation. PPS method has been used in fuel thermal-mechanical analysis code FUPAC. The numerical results show that PPS model can be used to reconstruct RPD for UO_2, UO_2-Gd_2O_3, IFBA fuel rods, and has an excellent precision. The PPS method, which not only can be used in current PWR's fuel, but also used in new type fuel, such as ATF, has a good validity and practicability.

Keywords: Nuclear reactor, fuel performance simulation, thermal mechanical analysis, neutronics, radial power distribution, PPS

1. Introduction

Neutronics simulation and thermal mechanical simulation should be coupled closely in nuclear fuel behavior simulation process. The fuel rod radial power distribution obtained from neutron transport calculations, determines the fuel rod temperature distribution. The burnup and neutron flux distribution in fuel rod affect the material radiation properties. The fuel rod temperature distribution obtained from thermal calculations affects the deformations of the fuel and the neutron cross section which affect the fuel rod radial power distribution in neutron transport calculations. The pellet and clad deformations, calculated by mechanical simulation, affect the radial power distribution and temperature distribution. If simulating the nuclear fuel rod behavior intuitively, neutron transport code and thermal mechanical code must be executed in a recursive manner, in which neutron transport code provides radial power distribution to thermal mechanical code and thermal mechanical code provides radii, pellet density and temperature distribution to neutron transport code. Because neutron transport calculations will require very long time, recursive simulation manner is not suitable for engineering application. Separating the neutron transport simulation and thermal mechanical simulation is classic method in current engineering codes.

There are two kinds of separating methods. The first method is simulating the neutron transport and depletion process with approximate method in thermal mechanical code. RADAR [1] model use differential equations for U-235 and Pu-239 to simulate the fissionable nuclides distribution, and use one group diffusion theory to get thermal neutron flux approximately. The cross sections used in RADAR model is provided by neutron transport code. Because RADAR model is not accurate for high burnup and MOX fuel due to that the buildup of higher Pu isotopes is not taken into account[2], the improvement model is proposed, such as TUBRNP [2], NEDAR [3], and model in Engine-B [4]. The advantage of this method is fast calculation speed. But the disadvantage of this method is: 1) the pellet temperature, density distribution and other parameters obtained in thermal mechanical analysis cannot affect the radial power distribution. 2) the approximate model should to be improved continuously to satisfy the new type of fuel, such as UO_2-Gd_2O_3, IFBA, .etc. For example, Frapcon-3.5[5] combine the TUBRNP model and interpolation method to treat UO_2-Gd_2O_3 fuel.

The second method is lookup tables model. A set of nuclear fuel rod radial power distributions with different parameters (such as fuel enrichment, burnup, pellet radius and so on) are calculated by neutron transport code and then the interpolation table is built. The real RPD used in thermal mechanical simulation is reconstructed by interpolation, according to the real local condition (such as fuel enrichment, burnup, pellet radius, pellet density distribution, and so on). Because all parameters, which affect the RPD, are used in the interpolation, this lookup tables method is called All Parameters Separated interpolation method (APS). The advantage of APS method is that neutron transport calculations are not needed in fuel thermal mechanical analysis process, once interpolation table was built. It is very convenience for fuel design engineer. But the interpolation table, created in APS method based UO_2 fuel, cannot be used in UO_2-Gd_2O_3, IFBA and other new type fuel rods. If an APS model is created for UO_2, UO_2-Gd_2O_3, MOX and IFBA simultaneously, the number of interpolation parameters, which affect the RPD, will be so large, that the neutron transport computing amount will be huge and the interpolation precision will not be high. Another way to treat different type fuels with lookup tables model is to develop different interpolation relationships for different fuel type. For example COPERNIC[6] code develops three interpolation relationships for UO_2, UO_2-Gd_2O_3, MOX respectively.

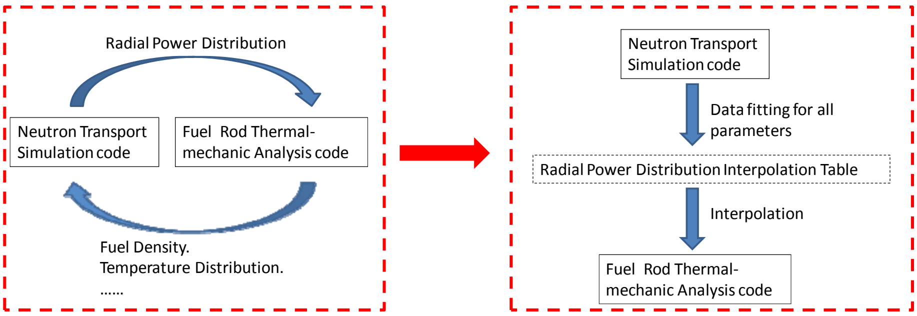

Figure1 Neutronics simulation and Thermal mechanical simulation couple relationship and APS separated ways

Based on APS method, this paper proposes a new RPD reconstructing method, which is called Partial Parameters Separated method (PPS). In PPS method, neutron transport calculations are needed before the thermal mechanical simulation for a new fuel rod type. But PPS method can be used for different kinds of fuel rod RPD reconstruction, and has a more wide application scope. In this paper, section 2 introduces the PPS method, and the RPD model in FUPAC code based on PPS is introduced in section 3. Numerical result is shown in section 4 and section 5 give the conclusion of this paper.

2. PPS Rod Radial Power Distribution Construction Method

In the neutronics simulation and thermal mechanical simulation separating manner for fuel behavior simulation, the key point is that real RPD can be reconstructed in fuel thermal mechanical analysis code. The model based on APS method for a type of fuel cannot be used for other type of fuel, because the key parameters to describe the new fuel's characteristic are not existed in interpolation table. PPS method can avoid this problem. The idea of PPS is that only partial parameters, which affect the RPD and vary in the fuel performance simulation process, are used to build the interpolation table and called transient parameters. Other parameters, called intrinsic parameters, represent the initial characteristic of fuel type, and are not in the interpolation table.

The transient parameters mainly include fuel burnup, pellet radius, coolant density, pellet density distribution, pellet temperature distribution, and so on. The intrinsic parameters mainly are initial ingredient and size, such as fuel enrichment, initial radius, initial ingredient distribution, and so on.

Before thermal mechanical simulation for a fuel rod, neutron transport calculations are needed to get the RPDs for different sets of transient parameters. Using the RPDs for different sets of transient parameters, interpolation table, in which transient parameters are interpolation variables, are built. And the real RPD for thermal mechanical calculations can be gotten by interpolation calculations, which uses local real transient parameters as interpolation variables.

In PPS method, the calculations amount is increased, because neutron transport calculations are needed. But neutron transport is not necessary for each fuel rod, but only for fuel rods with different intrinsic parameters. Fuel rods with same intrinsic parameters can share same RPD interpolation table. Generally, the number of fuel rod type in a nuclear reactor core is not very large. Thus, RPD interpolation tables for all kinds of fuel rods in a nuclear reactor core can be built through neutron transport calculations in advance. Thermal mechanical analysis for fuel rod can directly use the corresponding interpolation table. Comparing with APS, PPS method can be used for new type of fuels without model improvement.

The number of transient parameters is still large. If all transient parameters are interpolation variables in interpolation table, the RPD reconstructed model will be a high dimensional interpolation. The calculations amount is still large. In order to form an effective model based on PPS method, the key transient parameters, which affect the RPD greatly, should be selected as interpolation variables. And the other parameters, which affect the RPD weakly, can be neglected in PPS model.

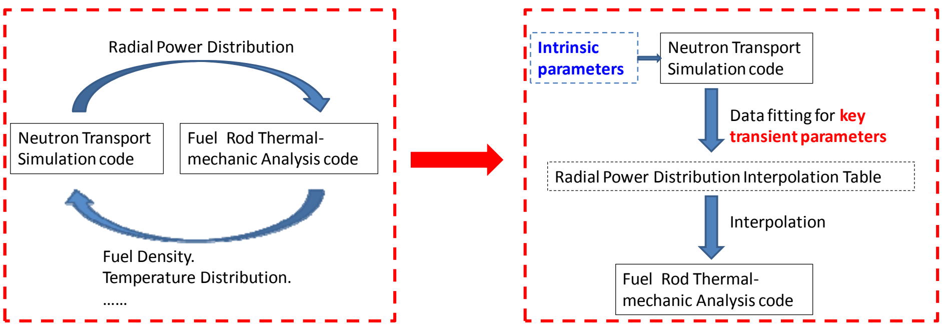

Figure 2 Neutronics simulation and Thermal mechanical simulation couple relationship and PPS separated ways

3. Rod Radial Power Distribution Construction model base on PPS

In order to select the key transient parameters in PPS method, sensitivity and uncertainty (S&U) are analysis in this chapter. In this paper, neutron transport code KYLIN-1[7] is used to do S&U analysis for PWR fuel rod. Two steps are included in the S&U analysis: 1) selecting the nominal values (shown in tab. 1) for all the transient parameters, and analysis the value variation range for each transient parameter; 2) changing one parameter's value and analysis the variation of RPD.

Table 1 nominal values for S&U analysis

index	parameter	value
1	Pellet radius (cm)	0.4096
2	Enrichment for U235 (%)	4.5
3	Content of Gd (%)	0
4	Thick of ZrB_2 on the pellet surface (cm)	0
5	p/d	1.32632
6	Burnup (MWD/TU)	60000
7	Coolant density (g/cm^3)	0.7046
8	Pellet density (g/cm^3)	10.42

3.1 S&U analysis for fuel pellet radius

Fuel pellet radius is mainly affected by thermal expansion and swelling. Thermal expansion is depended on temperature, the maximum value of which is melt point of pellet. The radius's maximum variation is 4.6% by thermal expansion and 4% by swelling. Finally, the maximum variation for pellet radius is not larger than 10%.

In this paper, 4% and 10% fuel pellet radius variation are selected to analyze the RPD variation. The result is shown in fig.4. The RPD is not very sensitive with radius and the uncertainty is small. In the PPS model, radius is neglected in interpolation table.

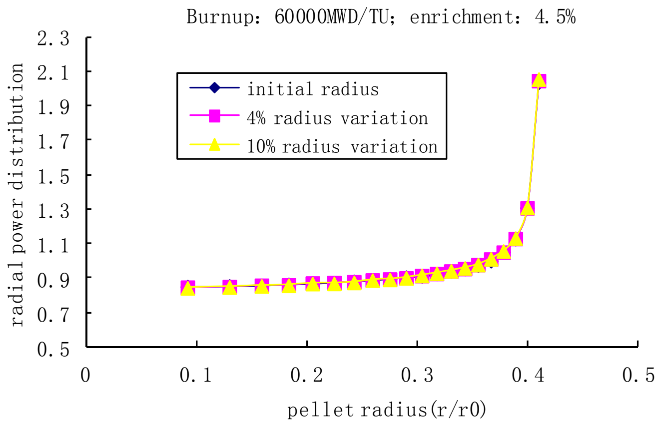

Figure 4 radial power distributions for different pellet radii

3.2 S&U analysis for coolant density

The coolant inlet and outlet temperature of nuclear reactor is 290℃ and 310℃. The pressure is 15.5MPa. The minimum and maximum coolant density is 0.6g/cm^3 and 0.8 g/cm^3. In this coolant density variation range, the RPD relative variation is less than 1%. In the PPS model, coolant density is neglected in interpolation table.

3.3 S&U analysis for fuel temperature

Fuel temperature is determined by power level. In this paper, the base linear power density is selected as 16.09kW/m. The variation range of linear power density for UO_2 and IFBA fuels is from 0.1 to 4 times the base value. And the variation range for UO_2-Gd_2O_3 is from 0.1 to 1.5 times the base value. Using the KYLIN-1 and FUPAC interlinked system, the final temperature distribution and RPD are gotten. The maximum relative variation of RPD is less than 1.8% for UO_2 and IFBA fuels. And the maximum relative variation of RPD is less than 1.3% for UO_2-Gd_2O_3 fuels. In this paper's PPS model, temperature is neglected due to the RPD uncertainty is small.

3.4 S&U analysis for burnup

The burnup varies large in the nuclear reactor. We compare the RPD at 10000MWD/TU and 50000MWD/TU. The maximum relative variation reaches 42%, according to the result shown in fig.5. In this paper, burnup is selected as an interpolation parameter.

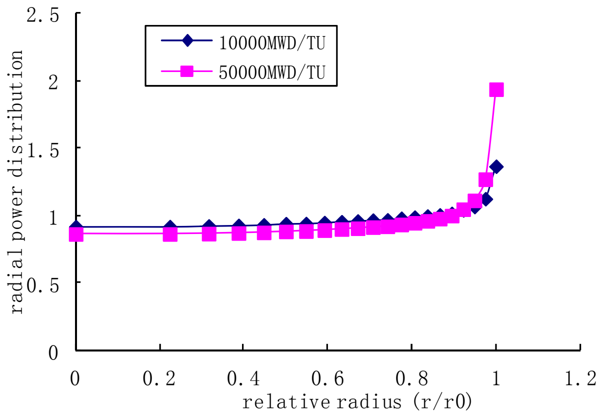

Figure 5 radial power distribution for different burnup

3.5 S&U analysis for pellet density distribution

Pellet density at different radius is different due to the different porosity and strain at different radius. We calculate the RPDs with a real fuel density distribution and flat fuel density distribution respectively, using KYLIN-1 code. The maximum relative error for two RPDs is 7.8%.

After data analysis, we find there is good relationship between power distribution and density distribution. Using the least square method, we get the relationship as follow.

$$f(i) = \left(\frac{\rho_i}{\bar{\rho}} \right)^{0.9} \bar{f}(i) \tag{1}$$

$f(i)$ is relative power value at radius i. $\overline{f}(i)$ is the power relative value calculated by flat density distribution. ρ_i is density relative value at radius i. And $\overline{\rho}$ is the average flat density.

The difference between RPD calculated by real pellet density distribution and RPD adjusted by eq.1 with RPD calculated by average flat pellet density distribution is less than 1%. Thus Eq.1 is accurate enough to recover the RPD. After test, Eq.1 also can be used for IFBA fuel rod.

For UO_2-Gd_2O_3, the relationship is :

$$f(i) = \left(\frac{\rho_i}{\overline{\rho}}\right)^{0.85} \overline{f}(i) \tag{2}$$

The difference between RPD calculated by real density distribution and RPD adjusted by eq.2 with RPD calculated by average flat density distribution is less than 1.2% for UO_2-Gd_2O_3.

According to Eq.1 or Eq.2, the average fuel density is a good interpolation variable, instead of pellet density distribution.

3.6 S&U analysis summary

According to S&U analysis results, burnup and pellet density distribution are the key parameters, which affect the RPD greatly. In this paper, burnup and average density are selected as the interpolation variables.

In this PPS model, KYLIN-1 code calculates the RPD at different burnup points and different average pellet densities. Then interpolation table, in which burnup and average pellet density are interpolation variables, is built. FUPAC, which is the fuel thermal-mechanic analysis code developed by NPIC, use the interpolation table to reconstruct the RPD with Eq.1 or Eq.2.

4. V&V for PPS Model

We compare the FUPAC calculation results with EMPA (Electron Probe Micro Analyses) test results [8] for UO_2 fuel. The test data is illustrated in tab.2. And the comparison results in Fig.6 and Fig.7 show that the FUPAC with PPS model can reconstruct the radial power distribution accurately.

QSII NPP's fuel rod[9] is simulated by FUPAC code. The fuel central temperature is compared with other analysis codes. The result in Fig.8 shows that PPS model has a good precision.

We use the method, that comparing the RPD reconstructed by PPS model with RPD calculated directly by neutron transport code KYLIN-1, to validate the PPS model used in FUPAC code for UO_2-Gd_2O_3 and IFBA fuel, because there is no test data for UO_2-Gd_2O_3 and IFBA fuel. Fig.9 is the result for UO_2-Gd_2O_3 fuel rod and Fig.10 is the results for IFBA fuel rod. The results show PPS model can reconstruct the RPD accurately. The maximum relative error is less than 1%.

Table 2 description of UO_2 fuel rod under EMPA test

Reactor name	Fuel rod	Cycle	Enrichment	Axial position	Local burnup

	index		(%)	(cm)	(MWD/TU)
CRUAS 2	5001	2	3.2	765	26200
GRAVELINES3+2	1067	3	4.5	2950	35400

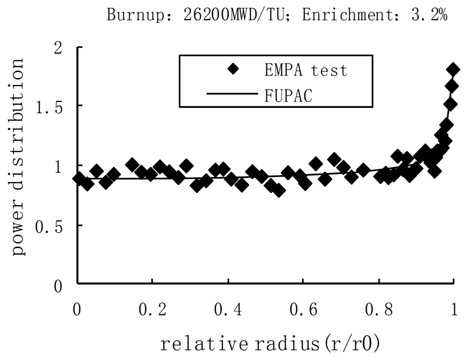

Figure 6 RPDs comparison for 3.2% UO_2 pellet

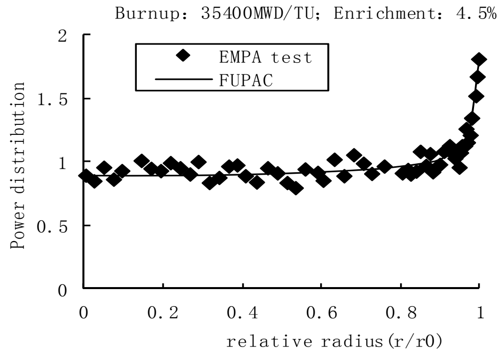

Figure 7 RPDs comparison for 4.5% UO_2 pellet

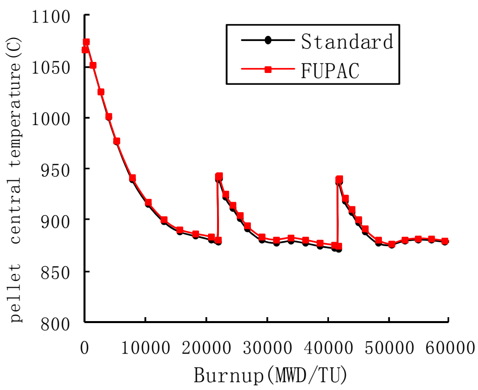

Figure 8 pellet central temperature comparison for UO_2 fuel

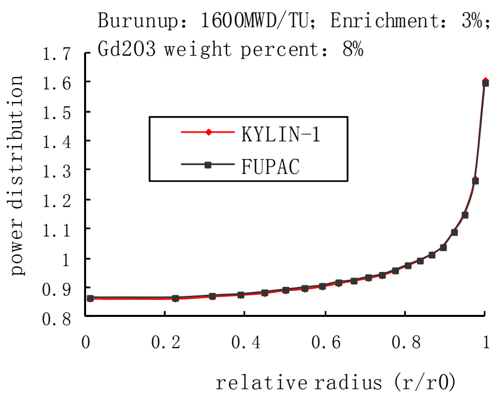

Figure 9 RPDs comparison for UO_2-Gd_2O_3 pellet

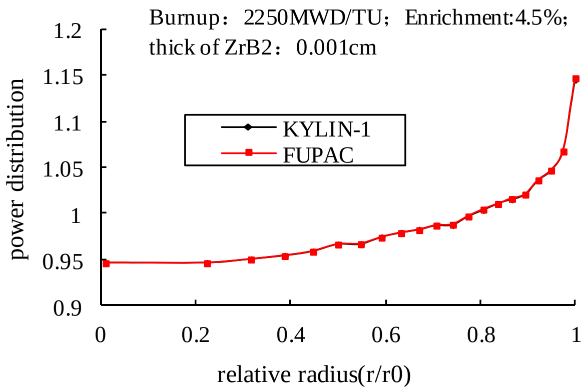

Figure 10 RPDs comparison for IFBA pellet

5. Conclusion

This paper proposes a new method called PPS to reconstruct the fuel radial power distribution for fuel thermal-mechanic analysis code. This method can be used to reconstruct RPD for UO_2-Gd_2O_3, IFBA fuel rods, for which traditional APS method cannot be used to reconstruct. The numerical results show that PPS model has an excellent precision. The PPS method, which not only can be used in PWR's fuel, but also used in new type fuel, such as ATF, has a good validity and practicability.

6. References

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