Analysis the Response Function of the HTR Ex-core Neutron Detectors in Different Core Status

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Abstract – Modular high temperature gas cooled reactor HTR-PM demonstration plant, designed by INET, Tsinghua University, is being built in Shidao Bay, Shandong province, China. HTR-PM adopts pebble bed concept. The harmonic synthesis method has been developed to reconstruct the power distributions on HTR-PM. The method based on the assumption that the neutron detector readings are mainly determined by the status of the core through the power distribution, and the response functions changed little when the status of the core changed. To verify the assumption, the influence factors to the ex-core neutron detectors are calculated in this paper, including the control rod position and the temperature of the core. The results shows that when the status of the core changed, the power distribution changed more remarkable than the response function, but the detector readings could change about 5% because of the response function changing.

I. INTRODUCTION

HTR-PM (High-Temperature gas-cooled Reactor-Pebble-bed Module) demonstration plant [1,2] is designed by Institute of Nuclear and New Energy Technology (INET), Tsinghua University, is being built in Shidao Bay, Shandong province, China.

It is important to monitor the reactor condition during operation. There are many systems are developed to monitor the status of the core, such as BEACON, GARDEL for Pressurized Water Reactor (PWR) [3-6], and other systems for other type of reactors [7]. For HTR there are many differences compared to PWRs. For PWRs, there are channels for neutron detectors in some of the fuel assemblies, so the power distribution can be reconstructed from the readings of these in-core detectors. However, there is no in-core detector in HTR-PM, and the power distribution is supposed not to be measured before. So it is really difficult and challenging to reconstruct the power distribution for HTR-PM. Previous researches proposed to reconstruct the power distribution based on the only information from the ex-core detectors [8-11].

One method to reconstruct the power distribution from ex-core detector is harmonic synthesis method [8-11]. This method assumes that the power distribution in real operation conditions can be considered as a linear combination of a harmonic set in mathematics, and it is verified by numerical calculations that for most status of the core, the in-core power distribution could be reconstructed by only several number of harmonics with an acceptable accuracy. So the power distribution could be reconstructed by several detectors using this idea. The method will be introduced in section III. In these method, response function is the connection between power distribution and the detector readings. The performance of the response function is very important, which will be explained in section III too.

In this paper, response function and the detector readings in different core status will be calculated, and the result will be showed in section IV.

II. THE HTR MODEL

The calculation model mainly refers to the layout of the HTR-PM reactor with some simplification,
which has a cylindrical active zone of 11m height and 1.5m radius. The core parameters are based on the equilibrium core calculated by VSOP software. Outside the active zone is the graphite reflector, and the neutron detectors located in the cavity concrete about 3m away from the active zone. Between the core and the neutron detectors, there are not only reflectors, but also gap, structural materials and control rod. That leads difficulties to the neutron calculations in these area. Figure 1 presents the vertical section of the simplified HTR calculation model.

![Figure 1. Vertical section of HTR calculation model](image)

There are 4 sets of the neutron detectors in azimuthal direction, and has 8 control rods arranged around the active zone. Figure 2 presents the horizontal section of HTR calculation model.

![Figure 2. Horizontal section of HTR calculation model](image)

In this paper, calculations were done in 2-dimensional and 3-dimensional model. The calculations of 2-dimensional model was showed in Figure 2. For the symmetry of the model, calculations were made in 1/8 of the model.

III. RECONSTRUCT METHODS

In first part of this section, several reconstruct methods were described, especially the harmonic synthesis method which are used to reconstruct the power distributions in HTR. In second part of this section, the importance of the response function were explained.

III.A. Harmonic Method

Harmonic synthesis method provides one solution to reconstruct the power distribution from the ex-core neutron detectors. The main idea of the harmonic synthesis method is to use the linear combination of characteristic distributions to reconstruct the power distribution (Eq.1). The fitting coefficients can be calculated from the readings of ex-core neutron detectors. In this paper, the characteristic distributions of the harmonic synthesis method are the harmonics of K eigenvalues problems of neutron diffusion. The harmonic set is calculated by modified version CITATION [12], a neutron diffusion program which is improved to calculate the harmonic set of K characteristic values and eigen-functions (distributions) [8]. In this method, the number of the harmonics can be used reconstructing the power distributions is equal to or less than the number of the independent ex-core detectors. In former studies, there are only four detectors in different height concerned independent, and this is the biggest limitation of this method on current arrangement of the detectors.

\[
p_{real} \approx \sum_{i=0}^{N-1} a_i p_i
\]  

(1)

In order to use higher order harmonics to describe the power distribution more accurately, the harmonics grouping method was developed [9]. The harmonics grouping method groups harmonics together according to the correlation coefficient of the fitting coefficients for different status of the core (Eq.2) and make these harmonics into several characteristic distributions (Eq.3). At last, the in-core power distribution could be described by the linear combination of the characteristic distributions (Eq.4). A characteristic distribution can contain informations of several high order harmonics, and four neutron detectors can determine four coefficients of the characteristic distributions, so this method can describe the in-core power distribution more accurately using the same number of detectors.

\[
d_{i,j} = \frac{c_i^T c_j}{\sqrt{(c_i^T c_i)(c_j^T c_j)}}
\]  

(2)
\[ f_i = \sum_{n=1}^{N_t} \frac{d_{1,n}}{|d_{1,n}|} \left| \mathbf{c}_n \right| \mathbf{p}_n \]  
\[ p_{\text{real}} \approx \sum_{i=1}^{N} a_i f_i \]

Nevertheless, there is still limitation to the number of harmonics to reconstruct the in-core power distribution, because the number of harmonics is limited, only the correlation coefficient larger than the threshold can be put in the same group. To use more harmonics to describe the in-core power distribution, harmonics’ coefficients polynomial expansion method was developed [9-10]. This method treated the coefficients of every harmonic as a polynomial function of the position of the control rod (Eq.5), so it can search for the position of the control rod by nonlinear method and use the position of the control rod to calculate the in-core power distribution. Once the position of the control rod is determined, the in-core power distribution can be calculated by Eq.7. This method can use harmonics as many as needed. For this method, only the position of the control rod need to be monitored. In theory, four detectors is enough to get the control rod position, and then get the power distribution of the core.

\[ p_{\text{real}} \approx \sum_{i=0}^{N-1} a_i \mathbf{p}_i = \sum_{i=0}^{L} a_i(h) \mathbf{p}_i \]
\[ a_i(h) \approx \sum_{l=0}^{L} d_{i,l} h^l \]
\[ p_{\text{real}} = \sum_{l=0}^{N-1} \sum_{l=0}^{L} d_{i,l} h^l \mathbf{p}_i = \sum_{l=0}^{L} f_i h^l \]
\[ f_i = \sum_{l=0}^{N-1} d_{i,l} \mathbf{p}_i \]

For application, the readings of the harmonics should be calculated before. Basically, the readings of the detector could be calculated by Eq.9. But if calculating the detector readings through Eq.9, one transport calculation should be done for each harmonics distribution, and this cost a lot of time.

\[ R_m = \int_{\gamma} \int_{\Omega} \int_{\Omega} \phi(\vec{r}, E, \vec{E}) \Sigma_{a,m} * \delta(\vec{r} - \vec{r}_m) d\vec{r} dE d\Omega \]

For the linearity of the transport equation, the detector reading could be regarded as the sum of readings which each fission source caused. Therefore, the response function were defined as Eq.10. \( R_m \) is the reading of detector, \( P(\vec{r}) \) is the distribution of the fission power (fission source), and \( r_m(\vec{r}) \) is the response function.

\[ R_m = \int_{\gamma} P(\vec{r}) * r_m(\vec{r}) d\vec{r} \]

Eq.10 shows that \( r_m(\vec{r}) \) is the connection between the fission source and the detector reading. If the response function is calculated, the readings of the detector could be calculated by Eq.10. Although the calculation of the response function also use the transport equation, but for each detector, it need only one transport calculation, the number of transport calculations are much less.

The transport equation is a linear equation when the cross section of the model is constant. But when the reactor operating, the cross section of the reactor isn’t constant. The performance of the response function should be studied for different core conditions. If the response function is not sensitive to the cross section changing caused by the control rod movement or the temperature change, the method will work well. If not, the method will need some correction. So the performance of the response function is very important.

IV. RESPONSE FUNCTION PERFORMANCE

In this section, calculations will be done in 2-dimensional and 3-dimensional model, for different core status. For HTR adopt online refueling, the material of active zone is stable in equilibrium core, the burnup will not influence the response function. So in this paper, only the influence from reactor temperature and the control rod position are surveyed.

IV.A. Influence by the Reactor Temperature

The reactor temperature could influence the cross section, and then influence the response function. In this paper, response function was calculated in different reactor temperature. The 2-dimensional result was shown in Figure 3 and Figure 4. The
calculation was be done by SN2D. The two response function was 100°C upper than nomal operation temperature and 100°C lower than nomal operation temperature respectively. Figure 5 shows the deviation of the two results. That shows the response function is nearly same in the area near the outside of the active zone, and the response function in these area is most important. Because the response function is much larger than that in the center of the core. The average deviation of the two response function is about 0.2366% for the temperature changed 200°C. The result means that the temperature has nearly no influence to the response function.

The 3-dimensional calculations also shows the same results, which showed by . . . A1-A4 is four detectors in different height, and in same azimuthal. The results is agreed to the 2-dimensional results.

<table>
<thead>
<tr>
<th></th>
<th>+100°C</th>
<th>-100°C</th>
<th>Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>0.29454</td>
<td>0.29414</td>
<td>0.138%</td>
</tr>
<tr>
<td>A2</td>
<td>0.57877</td>
<td>0.57770</td>
<td>0.184%</td>
</tr>
<tr>
<td>A3</td>
<td>0.60938</td>
<td>0.60823</td>
<td>0.190%</td>
</tr>
<tr>
<td>A4</td>
<td>0.38114</td>
<td>0.38050</td>
<td>0.169%</td>
</tr>
</tbody>
</table>

Table 1. Results of 3-dimensional calculation

IV.B. Influence by the Control Rod

When reactor operating, the control rod influence the cross section a lot in the position of control rod. For the position of the control rod and the neutron detector, the control rod might has influence to the response function, and the influence must be analyzed in detail.

The result of the 2-dimensional calculation was shown by Figure 6 and Figure 7. The two response functions with control rod and without control rod are presented respectively. Figure 6 and Figure 7 shows that in 2-dimensional calculation the response function has a 50% distinction mainly in the area near the control rod. But the average distinction is about 18.54%.
In 3-dimensional calculation, the readings of the four detectors are showed in . , has a distinction less than 4.14% to the readings calculated using the response function with no control rod. When the control rod moved from top (0cm) to 650cm, the readings of the A1 detector changed more than 50% comparing with the initial one, but the changes influence by the response function is only 4.147%, which is much less than the influence by the change of fission source.

Based on the 2-dimensional and 3-dimensional calculation, the deviation of the detector readings with and without control rod is not large. The variation of the detector readings mainly caused by the fission source changed, and only a little variation is caused by the response function changed.

V. CONCLUSIONS

In this paper, the response functions for difference core conditions were calculated and analyzed. The result shows that the reactor temperature has nearly no influence to the response functions, but the control rod has a little influence to response functions.

Based on the analysis, the deviation of the response function with and without control rod caused a little change of the detector readings. The readings mostly determined by the fission source, and the response function only need a little adjustment. How to adjust the response function is the work for next step.

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