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Heterogeneous Description of Fuel Assemblies for Correct Estimation of Control Rods Efficiency in BR-1200

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Abstract

This paper describes the development of full-scale models of the BR-1200 reactor for the MCU-FR code with a homogeneous and heterogeneous description of fuel assemblies' geometry. The correctness of the control rods efficiency calculation in a homogeneous model is analyzed. The control rods requiring heterogeneous modeling are defined.

Keywords: BR-1200, fast reactor, control rods, mixed nitride uranium-plutonium fuel, lead coolant, homogenous approximation.

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1. Introduction

BR–1200 – the power unit with lead-cooled fast reactor with mixed nitride uranium-plutonium fuel with a two-circuit scheme of removing heat to a turbine with supercritical steam parameters. The development of the reactor design is one of the directions for the implementation of the PROPYV project. The key requirement of the concept is exception of the most severe nuclear accidents mainly due to the properties and qualities of inherent natural safety in the neutron balance in the BR [1].

The purpose of this work is to verify the correctness of the control rods efficiency of the BR-1200 reactor using homogeneous fuel assembly (FA) models by detailed modeling of heterogeneous elements using the MCU-FR code [2]. The experience of fast reactors modeling is used in this work [3].

The class of the used model is benchmark with the prototype. A prototype of the real design of the BR-1200 reactor is modeled, which does not contain prepared cross sections. The concentration of nuclear nuclides approximately reflects the real compositions. Some characteristics are simplified in comparison with the prototype. The initial

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state is characterized by fully extracted control rods from the core. We considered 16 variants of the control rods positions in accordance with the project requirements.

2. Materials and Methods

The BR-1200 reactor model with the heat power of 2800 MW consists of 547 hexagonal cells arranged in accordance with the given map of the horizontal section of the model, which is divided into three sub-zones – central, intermediate and peripheral. Zones differ by height of the fuel part in the fuel assembly to equalize the radial distribution of the neutron flux and power density. Inside 85 cells of the central subzone are 72 fuel assemblies, 1 FA with emergency shutdown control rods, 6 FAs with reactivity compensation rods and 6 FAs with automatic control rods. Inside 240 cells of the central subzone are 186 fuel assemblies, 18 FAs with emergency protection rods, 30 FAs with reactivity compensation rods and 6 passive negative reactivity input devices. Inside the peripheral subzone are 222 fuel assemblies.

Each FA is described by a hexagonal cell of the BR-1200 reactor model in a homogeneous representation by MCU-FR code. Each cell is divided into vertical layers, which have homogeneous compositions. The core of the BR-1200 reactor is surrounded by 10 rows of steel reflector. The cross-section of the BR-1200 homogeneous model for the initial state, constructed by the MCU-FR visualizer, is shown in Fig. 1. In a homogeneous model the temperature of the fuel assemblies is assumed equal to the fuel temperature, and the reflector temperature is assumed to be equal to the temperature of constructional materials. At the stage of preparation of homogeneous and heterogeneous models of the BR-1200 reactor, taking into account the MCU-FR cross-section libraries used for calculations, the composition data in the benchmark are converted from natural materials to isotopic materials.

To verify the developed model, the volume of material zones is calculated using the program NCG2VTK that is a part of MCUOFFICE. NCG2VTK is a program designed to visualize the geometry and automatically calculate the volumes of registration areas.

Fuel rods, cladding and helium gap are described in detail in each hexagonal cell in the modeling of the BR-1200 in a heterogeneous representation by MCU-FR code. Examples of heterogeneous fuel assemblies in the MCU-FR are shown in Fig. 2. Control of the composition conformance of heterogeneous and homogeneous models taking into account the volume fractions of materials is carried out. The radial cross-section of the BR-1200 reactor homogeneous model for the initial state, constructed by the MCU-FR visualizer, is shown in Fig. 3.

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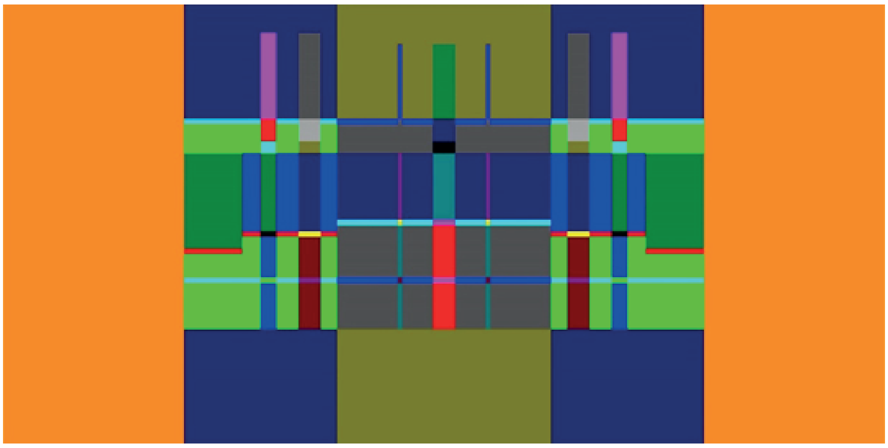

Figure 1: Vertical cross-section of a homogeneous model of BR–1200 reactor.

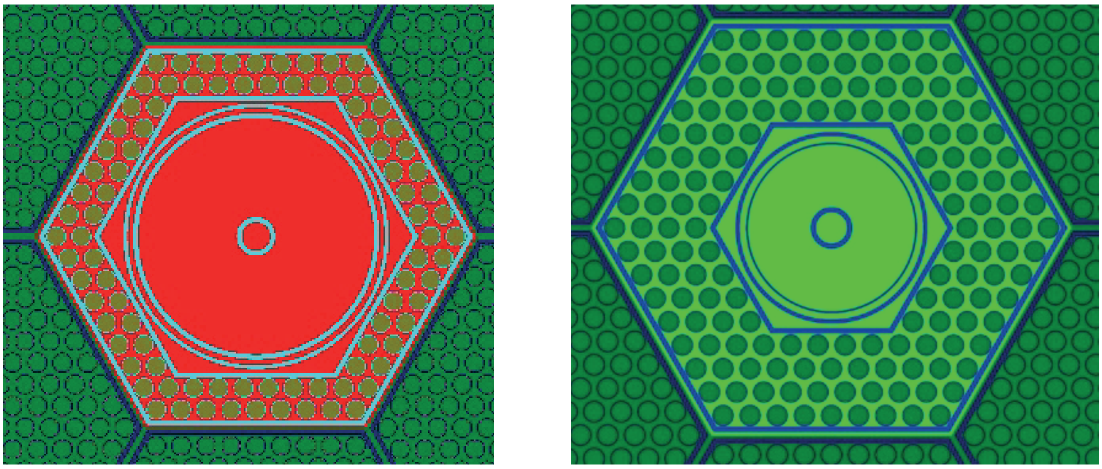

Figure 2: Heterogeneous fuel assembly models with control rods.

Table 1: The results of calculation of the BR-1200 reactor homogeneous model.

State No.	Keff	dKeff	Nhist, mill	t, min	Δρ	δΔρ	δΔρ,%
initial	0,99748	0,000019	960	4130	–	–	–
1	0,97067	0,00004	240	1117	2,77%	0,01%	0,5%
2	0,97146	0,00004	240	1281	2,69%	0,01%	0,5%
6	0,96757	0,00004	240	1144	3,10%	0,01%	0,5%
7	0,96796	0,00004	240	1180	3,06%	0,01%	0,5%
8	0,96976	0,00004	240	1220	2,87%	0,01%	0,5%
15	0,95541	0,00004	240	1195	4,41%	0,02%	0,4%
16	0,95540	0,00004	240	1330	4,42%	0,02%	0,3%

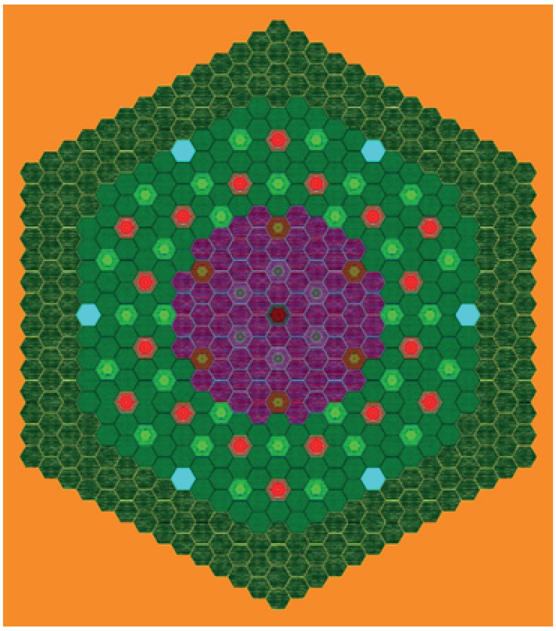

Figure 3: Horizontal cross-section of a heterogeneous model of BR–1200 reactor.

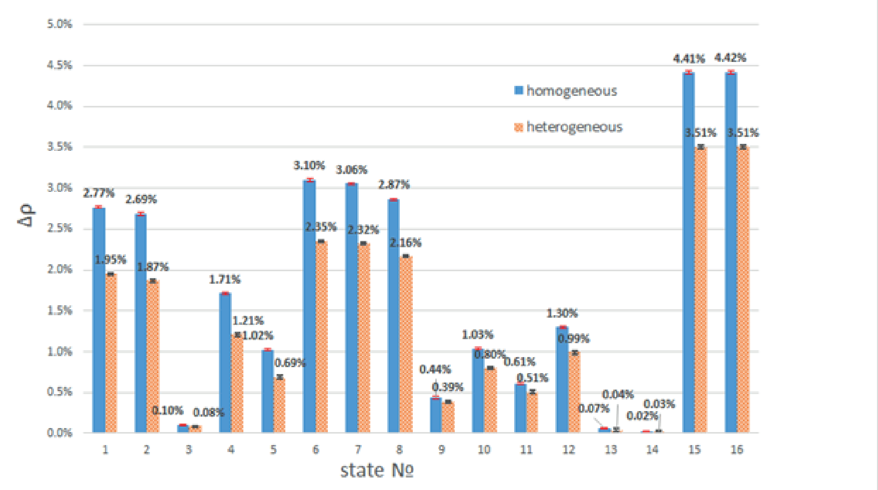

Figure 4: Functional Δρ for different states of homogeneous and heterogeneous models.

The main purpose of the benchmark is to determine the efficiency of the control rods for the normal operating mode of the BR-1200 reactor. In this work the initial state and 16 different states of the control rods position are considered:

1) 19 FAs with emergency protection are entered;

2) 18 FAs with emergency protection without the most effective one are entered;

3) 1 FA with emergency protection located in the central subzone is entered;

4) 12 FAs with emergency protection located in the intermediate subzone are entered;

5) 6 FAs with emergency protection located in the intermediate subzone are entered;

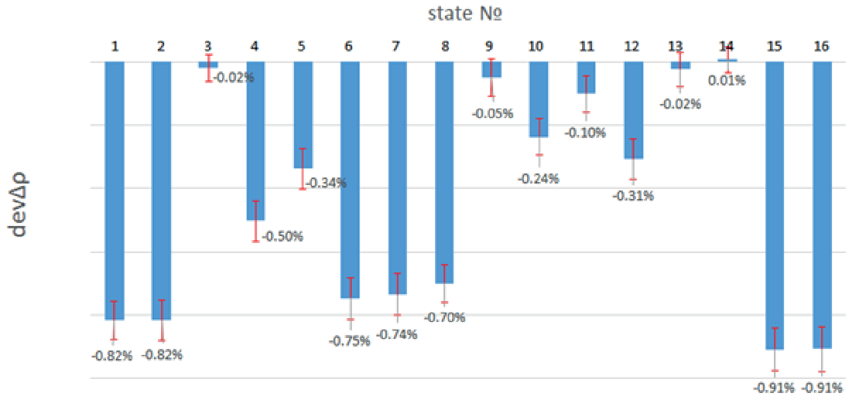

Figure 5: Deviation of the functional Δρ of the homogeneous model from the value for the heterogeneous model.

Table 2: The results of calculation of the BR-1200 reactor heterogeneous model.

State No.	Keff	dKeff	Nhist, mill	t, min	Δρ	δΔρ	δΔρ,%
initial	0,99786	0,00002	960	6267	–	–	–
1	0,97880	0,00004	240	1676	1,95%	0,01%	0,7%
2	0,97960	0,00005	240	1779	1,87%	0,02%	0,8%
6	0,97498	0,00005	240	1706	2,35%	0,02%	0,7%
7	0,97526	0,00005	240	1657	2,32%	0,02%	0,7%
8	0,97676	0,00004	240	1839	2,16%	0,01%	0,6%
15	0,96414	0,00005	240	1637	3,51%	0,02%	0,5%
16	0,96412	0,00005	240	1638	3,51%	0,02%	0,5%

6) 36 FAs with reactivity compensation are entered;

7) 35 FAs with reactivity compensation without the most effective one are entered;

8) 30 FAs with reactivity compensation located in the intermediate subzone are entered;

9) 6 FAs with reactivity compensation located in the central subzone are entered;

10) 12 FAs with reactivity compensation located in the intermediate subzone are entered;

11) 6 FAs with reactivity compensation located in the intermediate subzone are entered;

12) 12 FAs with reactivity compensation located in the intermediate subzone are entered;

13) 6 FAs with automatic control are entered;

14) 2 FAs with automatic control are entered;

15) 19 FAs with emergency protection and 36 reactivity compensation are entered;

16) all control rods are entered.

The functional characterizing the control rods efficiency is estimated for each state by the following formula:

$$\Delta\rho = \frac{1}{K^{i}_{\text{eff}}} - \frac{1}{K^{0}_{\text{eff}}}\% \tag{1}$$

where K^0_{eff} – the effective neutron multiplication factor in the initial state, K^i_{eff} – the effective neutron multiplication factor in the perturbed state.

We optimized the use of computer resources – the number of computational processors on which the calculation is performed. The main selection criteria are the calculation speed and the number of cores available on the cluster. The study of the dependence of the calculation time on the number of used computing cores was done. According to the received data it can be concluded that 64 cores are the most optimal number of computing cores for speed and availability. In each calculation, not less than 240 million stories were modeled on 4 nodes with 16 computational cores on the BASOV computing cluster of MEPhI.

The results of calculating each perturbed state in the homogeneous and heterogeneous reactor models describe the following quantities:

- dKeff – one standard deviation statistical error in the effective neutron multiplication factor;
- Nhist – number of histories;
- t – one-state calculation time;
- Δρ – functional characterizing the control rods efficiency, calculated by Eq. (1);
- δΔρ – absolute error of the functional Δρ;
- δΔρ – relative error of the functional Δρ in %.

To calculate the error of the functional, characterizing the control rods efficiency, we used the formula for indirect error calculations, taking into account the statistical error in the effective neutron multiplication factor:

$$\delta\Delta\rho = \sqrt{\left(\frac{dK_i}{K_i^{\,2}}\right)^2 + \left(\frac{dK_{initial}}{K_{initial}^{\,2}}\right)^2}, \tag{2}$$

where dK_i – absolute statistical error of the effective neutron multiplication factor in the i-th state (K_i) in the amount of three standard deviations, $dK_{initial}$ – absolute statistical error of the effective neutron multiplication factor in initial state in the amount of three standard deviations.

Calculations of the control rods efficiency of the BR-1200 reactor using the MCU-FR code were performed using two models: homogeneous and heterogeneous (only fuel parts of the fuel assemblies and the absorbing rods are described heterogeneously). The purpose of this analysis was to determine the effect of geometry simplifications on the results of the absorbing rods weight calculation. The following value was calculated for comparison of models:

$$\Delta K_{\mathrm{eff}}=K_{\mathrm{het}}-K_{\mathrm{hom}}, \tag{3}$$

where K_{het} and K_{hom} – effective neutron multiplication factor for heterogeneous and homogeneous models.

The following functional was used to determine the effect of homogenization on the control rods efficiency:

$$\mathrm{dev}\Delta\rho=\Delta\rho_{\mathrm{het}}-\Delta\rho_{\mathrm{hom}}, \tag{4}$$

where $\Delta\rho_{\mathrm{het}}$ and $\Delta\rho_{\mathrm{hom}}$ – functional, characterizing the control rods efficiency of heterogeneous and homogeneous models.

The following formula for the indirect calculation error was used (considering the absolute error of the functional):

$$\delta(dev\Delta\rho)=\sqrt{\left(\delta\Delta\rho_{\mathrm{het}}\right)^2+\left(\delta\Delta\rho_{\mathrm{hom}}\right)^2}, \tag{5}$$

where $\delta\Delta\rho_{\mathrm{het}}$ and $\delta\Delta\rho_{\mathrm{hom}}$ – absolute errors of the functional $\Delta\rho$ of heterogeneous and homogeneous models.

3. Results

The results of calculation of the effective neutron multiplication factor and the functionals for the homogeneous and heterogeneous models of the BR-1200 reactor using MCU-FR code for the initial state and 16 states of different control rods positions are obtained.

The results of calculation of the homogeneous and heterogeneous model of the BR-1200 reactor using the MCU-FR code for the initial state and some states of the various positions of the control rods are presented in Table 1 and Table 2.

From the results presented in Fig. 4 and Fig. 5 it can be concluded that in cases with the insertion of the large number of absorbing rods homogenization leads to increase of the absorbing rods weight by up to 0.91% in the value of the functional Δρ.

Some results required the improvement of statistics in order to reduce the statistical error (initial state, state No. 3, 13, 14).

4. Discussion

Analyzing the obtained results, it is possible to do some conclusions about the effectiveness of different groups of control rods in the BR-1200 reactor:

- States 3 (1 FA with emergency protection located in the central subzone), 13 (6 FAs with automatic control) and 14 (2 FAs with automatic control) are the least different from the initial state. In these states, the least number of absorbing rods are entered.
- States 15 (19 FAs with emergency protection and 36 FAs with reactivity compensation) and 16 (with all control rods) correspond to the largest input of negative reactivity. In these states, the greatest number of absorbing rods are entered.
- States 5 (6 FAs with emergency protection located in the intermediate subzone) and 10 (12 FAs with reactivity compensation located in the intermediate subzone) lead to practically the same value of negative reactivity, in spite of the fact that number of absorbing rods twice as large. Consequently, emergency protection elements are more effective for suppressing the reactivity.
- States 1 (19 FAs with emergency protection), 2 (18 FAs with emergency protection without the most effective one), 6 (36 FAs with reactivity compensation), 7 (35 FAs with reactivity compensation without the most effective) and 8 (30 FAs with reactivity compensation located in the intermediate subzone) are characterized by the insertion of about equal number of absorbing rods and approximately the same reactivity effect.

The difference in the effective neutron multiplication factor in the homogeneous and heterogeneous models has not exceed 1%. It must be noted that homogenization leads to a decrease in Keff in all cases. The smallest deviation is observed for the initial state, states 3, 13 and 14. The greatest deviation is observed for the states where a lot of absorbing rods have been introduced: states 1, 2, 6, 7, 8, 15 and 16.

The effect in Keff of the helium gap consideration between the cladding and the fuel does not exceed the value of the statistical error.

The calculation of the heterogeneous case requires around 30% more time than the calculation of the homogeneous case (with the same number of histories).

5. Conclusion

In this work BR-1200 reactor models with a homogeneous and heterogeneous description of the fuel assemblies for the MCU-FR code were developed. The 16 variants of models for determining the control rods efficiency were made.

The difference in the effective neutron multiplication factor in the homogeneous and heterogeneous models has not exceeded 1% for all states.

For all states the homogeneous model gives an underestimate of the effective multiplication factor in comparison with the heterogeneous.

The control rods requiring heterogeneous modeling were defined.

Acknowledgments

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