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Feasibility of using Gd_2O_3 particles in VVER-1000 fuel assembly for controlling excess reactivity

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Abstract

Neutronics feasibility of using Gd_2O_3 particles for controlling excess reactivity and pin power peaking factor of the VVER-1000 fuel assembly has been investigated. The motivation is that the use of Gd_2O_3 in form of micro-particles would increase the thermal conductivity of the Gd_2O_3 bearing fuel pellet which is one of the desirable characteristics for designing future high burnup fuel. Neutronics calculations have been conducted for the fuel assembly with the Gd_2O_3 particles distributed randomly using the Monte Carlo neutron transport MVP code. The results show that the Gd_2O_3 particles with the diameter of 60 μm could control the reactivity similarly to the homogeneous distribution of Gd_2O_3 with the same total amount. The power densities at the fuel rods with Gd_2O_3 particles increase by about 11%, leading to the decrease of the power peak and a slightly flatter power distribution. The power peak appears at the periphery fuel pins at the beginning of burnup which decreases slightly by 0.9%. Investigation has been performed to reduce the pin power peaking factor by increasing the number of Gd_2O_3-dispersed fuel rods and optimizing the particle diameter. The results show that by using 18 Gd_2O_3-dispersed fuel rods (instead of 12 Gd_2O_3-bearing fuel rods) with the same total amount of Gd_2O_3 and the particle diameter of 300 μm, similar reactivity curve can be obtained as the reference one while the pin power peaking factor at the beginning of burnup is decreased by about 5%.

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Keywords: Fuel assembly; VVER; Gd_2O_3 particle; reactivity; power distribution

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1. Introduction

In a light water reactor (LWR), burnable absorbers are usually used for controlling excess reactivity of the fresh fuel and the reactor core at the beginning of burnup stage, and flattening the power distribution to avoid an excessively high power peak at some fresh fuel assemblies. Integral burnable absorbers (IBAs) are the most common type in which burnable absorbing materials are integrated in a fuel assembly. The IBA is designed so that the reactivity of the fuel assembly remains relatively constant or slowly decrease in the early burnup stage until the IBA is almost depleted. This is to avoid a peak of reactivity during burnup, and consequently, avoid the appearance of a power peak during burnup. In the fuel assembly of VVER-1000 reactor, 12 gadolinium bearing fuel rods are loaded into a fresh fuel assembly to control the reactivity of the fuel assembly almost constant from the beginning of burnup to about 10-15 GWd/t. After this burnup level, the main absorbing isotopes are depleted completely and the reactivity decreases linearly with burnup similar to an assembly without gadolinium bearing rods. Gadolinia (Gd_2O_3) is one of the common burnable absorber materials to be used as the IBA in the fuel assembly of LWRs because of its high absorption cross section to neutrons in thermal energy range. In natural gadolinium, Gd^{155} and Gd^{157} are main absorbing isotopes which are about 30% of the natural isotropic compositions.

In conventional design, an amount of Gd_2O_3 within a few percent is mixed homogeneously with UO_2 fuel in several fuel rods of a fuel assembly. Since Gd_2O_3 has a smaller thermal conductivity than that of UO_2, one of the disadvantages is that the additional content of Gd_2O_3 leads to the decrease of the thermal conductivity of the fuel pellet [1]. For the purpose of the reduction of fuel costs, power upgrade and advanced fuel design with high burnup are desirable, which lead to the increase of the power density. Therefore, the increase of the thermal conductivity of the fuel pellets is one of the desirable characteristics. In order to avoid the problem of the decrease of the thermal conductivity due to the additional content of Gd_2O_3, the use of Gd_2O_3 in form of micro-particles in the UO_2 matrix could be a solution. It was reported that the thermal conductivity of Gd_2O_3-dispersed UO_2 fuel pellet is larger than that of $(U,Gd)O_2$ solid solutions with the same Gd_2O_3 content [3]. Iwasaki et al. [4] conducted experiments to investigate the effect of Gd_2O_3 dispersion on the thermal conductivity. The results showed that 10 wt% Gd_2O_3-dispersed UO_2 pellet with the diameter of the Gd_2O_3 particles of about 25-53 μm has the thermal conductivity of about 5.8-2.7 W/mK in the temperature range from 300 to 1273 K. This is larger than that of homogeneous mixed solid solutions (3.8 to 2.6 W/mK) with the same Gd_2O_3 content [4]. This means that the use of Gd_2O_3 particles could improve the thermal conductivity of Gd_2O_3-dispersed fuel pellets effectively. As mentioned in Ref. [4], the fabrication of the Gd_2O_3-dispersed fuel pellet would not be so complicated. It was processed similarly to the traditional fuel pellet with Gd_2O_3 powder. Gd_2O_3 particles are weighted and mixed with UO_2 powder in a mortar. The mixture was then pressed into a form of fuel pellet and sintered under a high pressure and high temperature condition.

In the present work, we aim at investigating, in neutronics point of view, the feasibility of using Gd_2O_3 particle type for reactivity controlling and the effect on the neutronics performance of the VVER-1000 fuel assembly. Spherical Gd_2O_3 particles were distributed randomly in the UO_2 matrix of fuel pellet instead of homogeneous distribution of Gd_2O_3 powder. The diameter of the Gd_2O_3 particles was determined for controlling the reactivity of the fuel assembly during burnup so that the target is to obtain the k_∞ curve similarly to that of the conventional fuel assembly. Comparison of the pin-wise power distribution between the new design and the conventional assembly has also been presented. In order to optimize the pin power peaking factor, a design of fuel assembly with 18 Gd_2O_3-dispersed fuel rods instead of 12 Gd_2O_3-bearing fuel rods of the reference design has been investigated. The locations of the 18 Gd_2O_3-dispersed fuel rods in the assembly and the diameter of the Gd_2O_3 particles were determined for obtaining the similar k_∞ curve but lower pin power peaking factor compared to the reference assembly.

2. Calculation models

Numerical calculations have been performed based on the low enriched UO_2 fuel assembly of the VVER-1000 reactor core using the Monte Carlo neutron transport MVP code and the JENDL-3.3 library [6,7]. The configuration and the detailed design parameters of the fuel assembly are displayed in Fig. 1 and Table 1 [5]. The assembly consists of 300 UO_2 fuel rods with the ^{235}U enrichment of 3.7 wt% and 12 Gd_2O_3 bearing fuel rods as shown in Fig. 1. In the numerical calculation model, spherical Gd_2O_3 particles are assumed to be distributed randomly in the UO_2

matrix of the fuel pellet. The statistical geometry (STG) model of the MVP code allows simulating the random distribution of the Gd_2O_3 particles. In the calculations, the history number of 25×10^6 is chosen to achieve the relative statistic error of the k_∞ within 0.01%. Calculations have been performed for two models of the fuel assembly: one with the homogeneous distribution of Gd_2O_3 powder in the UO_2 fuel pellet, and the other with the distribution of Gd_2O_3 particles.

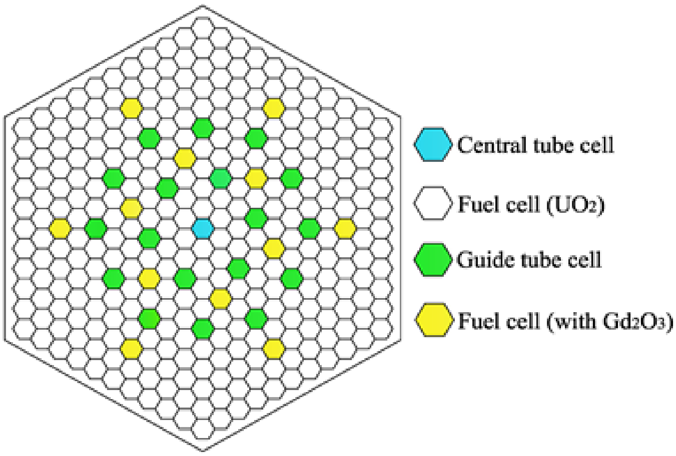

Fig. 1. Configuration of the VVER-1000 fuel assembly.

Table 1. Design parameters of the VVER-1000 fuel assembly.

Parameters	Unit	Value
Number of central tube	-	1
Number of guide tube	-	18
Number of fuel cell with Gd	-	12
Number of UO_2 fuel cell	-	300
Fuel cell inner radius	cm	0.3860
Fuel cell outter radius	cm	0.4582
Central tube cell inner radius	cm	0.5450
Central tube cell outter radius	cm	0.6323
Pin pitch	cm	1.2750
Fuel assembly pitch	cm	23.6
Non-fuel temperature	K	575.0
Fuel temperature	K	1027.0
^{235}U enrichment	wt%	3.7
Gd_2O_3 density	g/cm^3	7.4

3. Results and discussions

In the present work, we investigate the use of Gd_2O_3 particles instead of homogeneous distribution of Gd_2O_3 powder for the purpose of reactivity controlling and improving the thermal conductivity of the fuel pellets. The diameter of the Gd_2O_3 particles is determined so that the k_∞ of the fuel assembly is controlled similarly to that of the conventional design. In the conventional design with 12 Gd_2O_3-bearing rods, the k_∞ of the fuel assembly remains relatively constant from the beginning of burnup to about 10 GWd/t. After this burnup, most of the absorbing isotopes are completely depleted and the k_∞ decreases linearly similar to that of the fuel assembly without Gd_2O_3. Thus, in the first step of this design, we aim at obtaining a k_∞ curve as a function of burnup of the new fuel assembly similar to that of the reference design. The use of Gd_2O_3 particles for controlling the reactivity of a fuel pebble of a pebble bed reactor upto 60-100 GWd/t was investigated in previous works [8,9,10]. The radius of the particles of 820 or 950 μm was selected. The applicability of other absorbing materials was also investigated [9,11]. However, in the current design of the fuel assembly, we aim at controlling the reactivity upto 10 GWd/t, so that the radius of the particles could be predicted much smaller, and therefore, the self-shielding effect of the particles is also smaller.

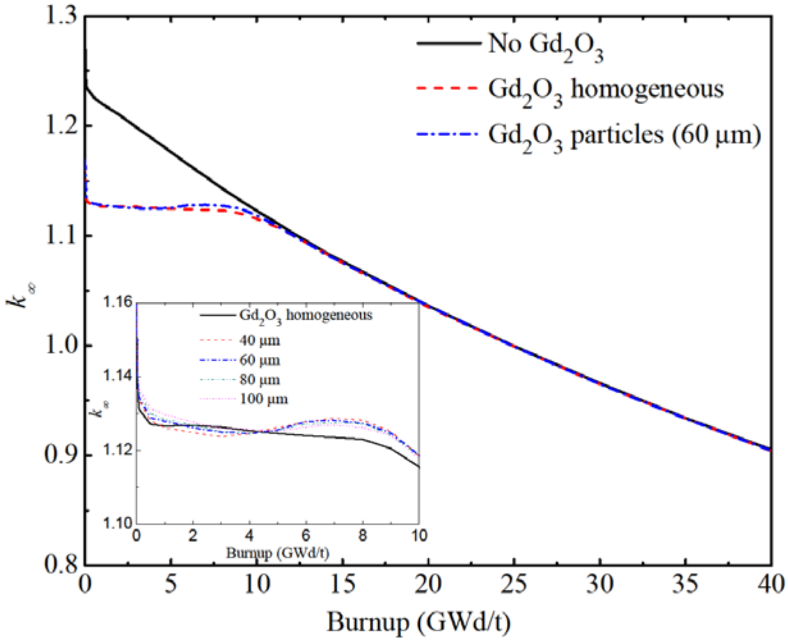

Fig. 2. The k_∞ as a function of burnup of the VVER-1000 fuel assembly.

In the calculation procedure, we assumed that the same amount of Gd_2O_3 is loaded into the fuel rod, i.e. 5% of volume, as in the conventional assembly. Then, a parametric survey was conducted to optimize the diameter of the Gd_2O_3 particles for reactivity control. Fig. 2 shows the effect of the diameter of the Gd_2O_3 particles on the reactivity curves of the fuel assembly in the burnup range from 0 to 10 GWd/t with the diameter varying from 40 to 100 μm. Since we aim at finding a reactivity curve close to the conventional one in this burnup range, the diameter of 60 μm was selected for further calculations to investigate the neutronics properties of the fuel assembly. Fig. 2 displays the k_∞ curve of the new fuel assembly with the Gd_2O_3 spherical particles having the diameter of 60 μm and the packing fraction of 5% (the volume ratio of the Gd_2O_3 particles and the matrix base in the STG model). It can be seen that this k_∞ curve is similar to that of the conventional design with homogeneous mixture of Gd_2O_3 during burnup. Other neutronics characteristics were also computed and compared to that of the conventional design.

Fig. 3 displays the pin-wise power distribution at the beginning of burnup (0 GWd/t) in the newly designed fuel assembly with the Gd_2O_3 particles in comparison with that of the conventional assembly. The figure shows the power in the 1/6th of the fuel assembly due to the symmetrical geometry. One can see that at the two Gd_2O_3-dispersed fuel rods, the relative power densities at 0 GWd/t increase about 11% compared to that of the reference design. At other fuel rods, the power densities decrease slightly within 0.9% in the outer fuel region and increase within 0.8% in the central region. As a result, the pin power peak which appears at the periphery fuel rod decreases by 0.9% (from 1.167 to 1.156). This means that by using the Gd_2O_3 particles, the pin-wise power distribution of the fuel assembly becomes slightly flatter. Since the Gd_2O_3 was designed to maintain the k_∞ relatively constant during the early burnup stage upto 10 GWd/t and avoid the reactivity peak during burnup, it is expected that the power peak at the beginning of burnup (0 GWd/t) is also the greatest power peak during the burnup.

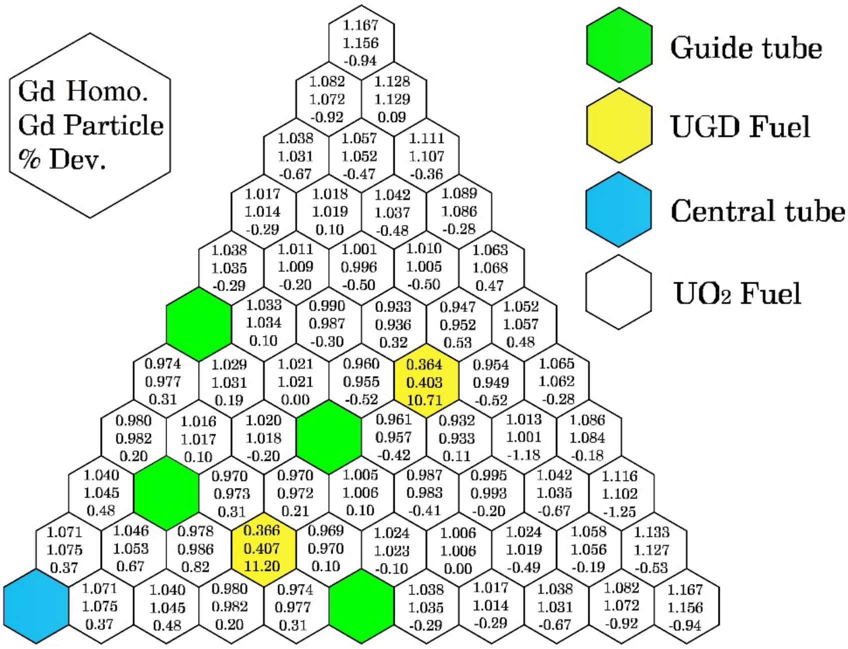

Fig. 3. Pin-wise power distribution of the VVER-1000 fuel assembly at 0 GWd/t in comparison with the reference design.

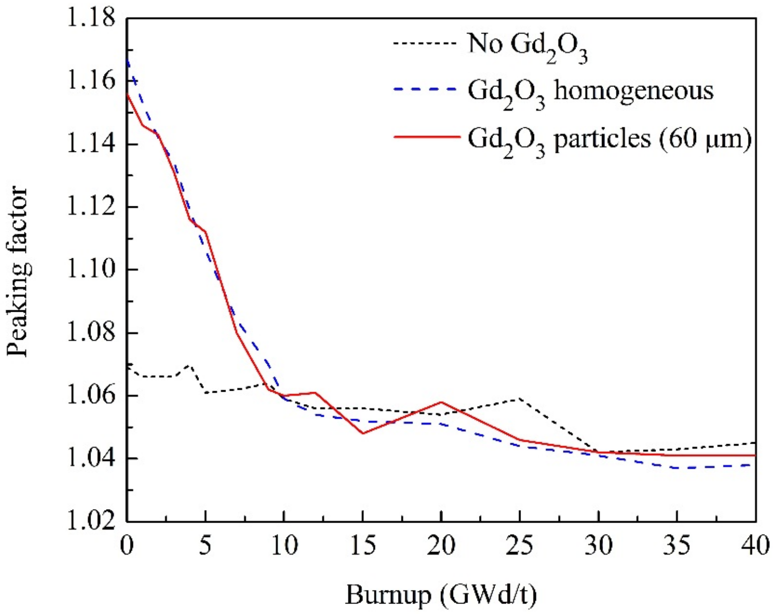

Fig. 4. Pin power peaking factor as a function of burnup of the VVER-1000 fuel assembly.

Fig. 4 depicts the pin power peaking factor as a function of burnup of the new fuel assembly in comparison with that of the conventional design (12 Gd_2O_3-bearing rods) and the fuel assembly without Gd_2O_3. In the fuel assembly without Gd_2O_3, the power distribution is flat with the power peaking factor of about 1.04-1.07. In the fuel assembly with Gd_2O_3, the power peaking factor is greater in the burnup range of 0-10 GWd/t with the highest power peak at 0 GWd/t. In this burnup stage, the Gd_2O_3 amount has effect on the reactivity. After this burnup level most of the absorbing isotopes are depleted, the power distribution becomes as flat as that of the assembly without Gd_2O_3. The peaking factor decreases with burnup and becomes slightly stable around the value of 1.040-1.060 after 10 GWd/t. By using the Gd_2O_3 particles instead the homogeneous Gd_2O_3 powder, the power peaking factor decreases slightly by about 0.9% at the beginning of burnup. Though this is not a remarkable decrease of the power peaking factor, the main merit achieved for the new fuel assembly with the Gd_2O_3 particles is the increase of the thermal conductivity of the fuel pellet compared to that of the conventional Gd_2O_3-bearing fuel pellet [4]. The results obtained in this preliminary investigation show that in the neutronics point of view it is feasible to use Gd_2O_3 particle type instead of powder in the UO_2 fuel pellet for excess reactivity controlling, while the main neutronics characteristics such as the reactivity and the power distribution during burnup could be obtained similarly to that of the conventional design.

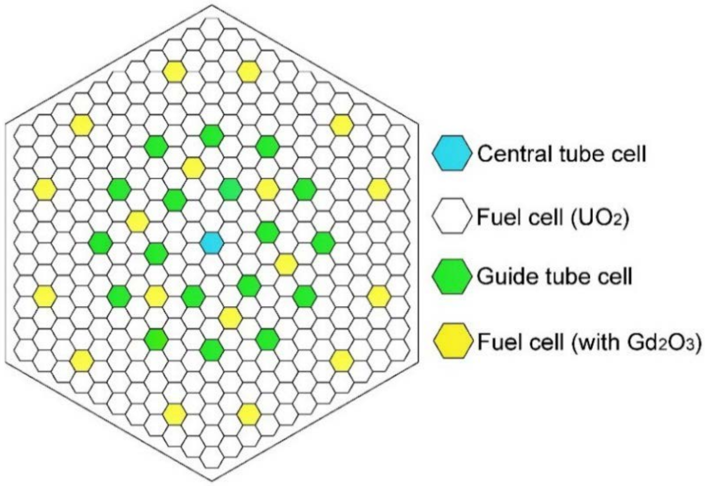

Fig. 5. Configuration of the VVER-1000 fuel assembly with 18 Gd_2O_3-dispersed fuel rods.

From the evolution of the power peaking factor with burnup as shown in Fig. 4, it is suggested that the further improvement should be conducted to flatten the power distribution and reduce the power peaking factor in the early burnup stage of the fuel assembly. Thus, investigation has been conducted to optimize the power peaking factor by increasing the number of Gd_2O_3-dispersed fuel rods and distributing them more evenly in the fuel assembly. A design with 18 Gd_2O_3- dispersed fuel rods (instead of 12 rods) has been considered. Optimization was performed to determine the diameter of the Gd_2O_3 particles in order to obtain the similar k_∞ curve during burnup. Fig. 5 shows the configuration of the new fuel assembly with 18 Gd_2O_3-dispersed fuel rods which was selected for further investigation of the Gd_2O_3 particle diameter. In this investigation we assumed that the total amount of Gd_2O_3 is remained the same in the fuel assembly. It means that the total amount of Gd_2O_3 in 12 rods of the reference design is now distributed equally to 18 rods. In this case, the packing fraction of the Gd_2O_3 particles is determined as 3.33% in volume. Fig. 6 displays the effect of the Gd_2O_3 particle diameter on the k_∞ curve of the new fuel assembly with 18 Gd_2O_3 fuel rods. The Gd_2O_3 particle diameter was investigated in the range of 200 to 360 μm and the value of 300 μm was selected. The k_∞ curve during burnup of the selected case is approximate that of the reference one (12 Gd_2O_3-bearing fuel rods with homogeneous distribution).

Fig. 7 depicts the evolution of the pin power peaking factor as a function of burnup of the new design with 18 Gd_2O_3-dispersed fuel rods. The pin power peaking factor of 1.10 appears at 0 GWd/t. Compared to the reference design and the new design with 12 Gd_2O_3 fuel rods, the k_∞ curves of the three cases are approximate. The power peaking factor of the new design with 18 Gd_2O_3-dispersed fuel rods is reduced by about 5%. The results indicates the neutronics feasibility of using Gd_2O_3 particle type instead of homogeneous distribution in the fuel rods for controlling the reactivity and flattening the power distribution. Further improvements of the design and investigation of thermal hydraulics properties of the newly designed fuel assembly using Gd_2O_3 particle type are desirable and are being conducted.

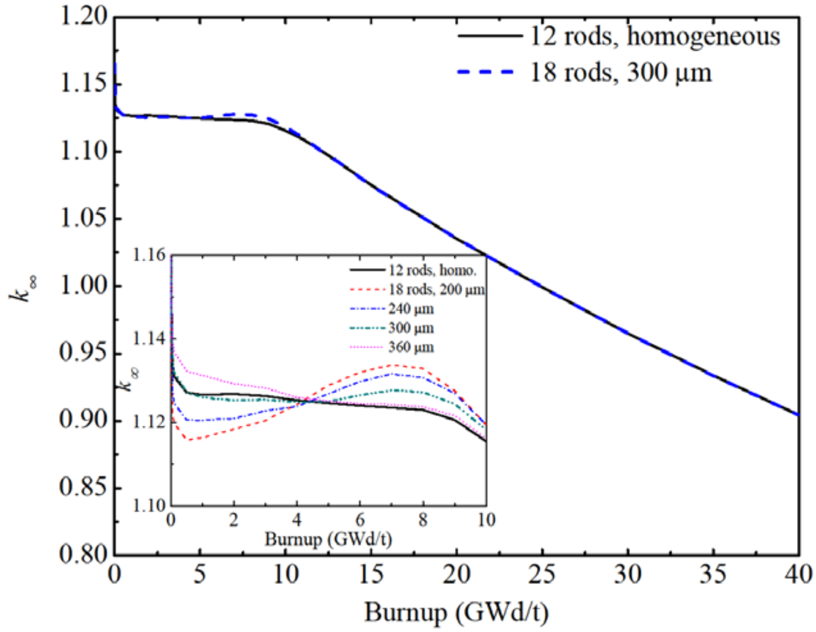

Fig. 6. The k_∞ as a function of burnup of the VVER-1000 fuel assembly with 18 Gd_2O_3–dispersed fuel rods.

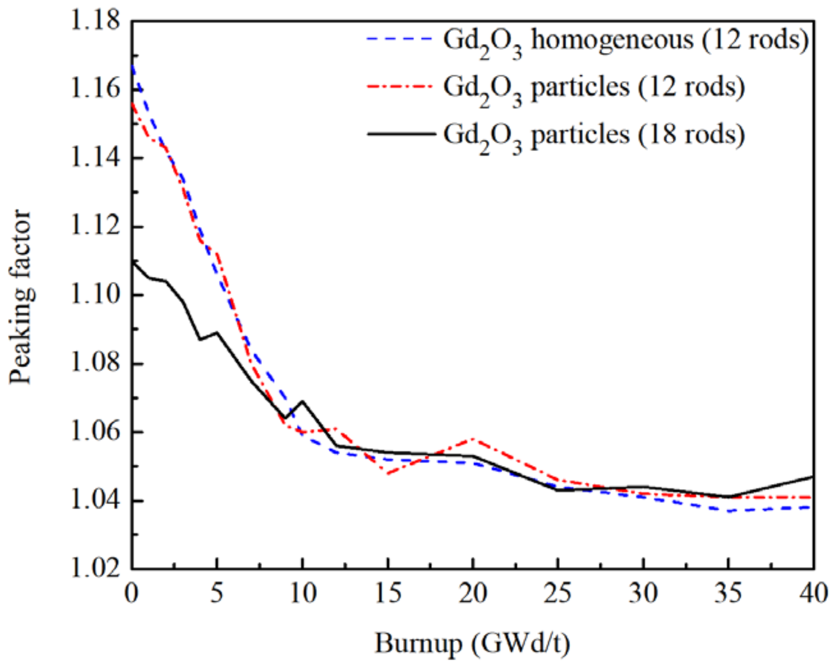

Fig. 7. Pin power peaking factor as a function of burnup of the VVER-1000 fuel assembly with 18 Gd_2O_3-dispersed fuel rods.

4. Conclusions

Investigation of the neutronics feasibility of using Gd_2O_3 particles in the UO_2 fuel pellet of the VVER-1000 fuel assembly has been conducted. The motivation is that the thermal conductivity of the Gd_2O_3-dispersed fuel pellet could be greater than that of the Gd_2O_3-bearing fuel pellet [4]. The results show that with the same content of 5% in volume, Gd_2O_3 particles with the diameter of 60 μm control reactivity similarly to the homogeneous distribution. The power density at the fuel pin with Gd_2O_3 particles increases by about 11% at the beginning of burnup which leads to the slight decrease of power peak and slightly flatter power distribution. The power peak appearing at the periphery pins at the beginning of burnup decreases by 0.9%. The results demonstrate that by loading the same amount of Gd_2O_3 but in form of particles with the diameter of 60 μm instead of the powder in the UO_2 fuel pellet, the neutronics properties of the new fuel assembly could be obtained similarly to that of the conventional design. Investigation has also been performed to reduce the pin power peaking factor by increasing the number of Gd_2O_3-dispersed fuel rods and optimizing the particle diameter. 18 Gd_2O_3-dispersed fuel rods (instead of 12 Gd_2O_3-bearing fuel rods) with the same total amount of Gd_2O_3 and the particle diameter of 300 μm were selected. The reactivity curve is obtained similarly to the reference one while the pin power peaking factor at the beginning of burnup is decreased by about 5%.

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