PROPOSAL OF HETEROGENEOUS GFR CONTROL ROD DESIGN

Lenka Dujčíková[1], Branislav Vrban[1], Jakub Lüley[1], Štefan Čerba[1], Ján Haščík[1]

[1] *Institute of nuclear and physical engineering, Slovak University of Technology*
E-mail: xdujcikova@stuba.sk

Received 30 April 2014; accepted 12 May 2014

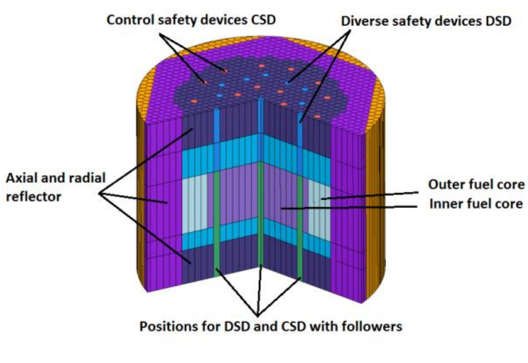
1. Introduction

Gas-cooled fast reactor represents a conceptual pin type design with thermal power of 2400 MW_{th}. GFR is a fast neutron spectrum system, which implies several advantages suchas uranium utilization and waste minimization in terms of use of spent fuel from light water reactors. Plutonium production in active core during operation is sufficient for neutron balance in terms of sustainability. Considering active core without blanket, proliferation risk is minimized. High outlet temperature of coolant (850 °C) allows high thermal cycle efficiency at the level of 48 % [1] and provides a possibility of industrial use of the generated heat

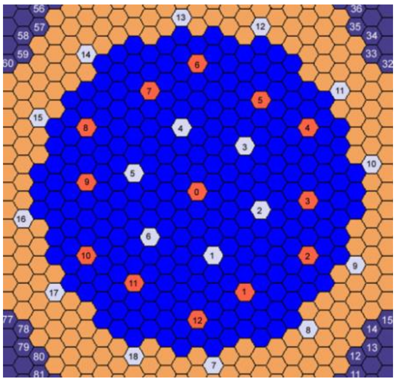
2. Computational tool and model specification

The KENO VI module is a Monte Carlo code which provides a steady-state criticality calculation of three-dimensional systems. The Monte Carlo approach is a statistical method where the expected behavior of neutrons in a system is estimated by simulating the lives of large number of individual neutrons. Using random numbers, the computer can generate a random history for the life of each neutron. [2]

For the purpose of calculations, three-dimensional hexagonal model of GFR was developed using the KENO VI. Model consists of active core, radial and axial reflector and safety rods system. Active core is divided into two parts - inner and outer core.



a)



b)

Fig.1: *a) 3D cross-sectional view of GFR model [3] b) positions of DSD and CSD in AC [3]*

The fuel pin consists of uranium plutonium carbide (UPuC) .The PuC volume fraction in inner core reaches 14.2 % and in outer core 17.6 %. Active core is surrounded by six rings of homogeneous radial Zr_3Si_2 reflector and by 1 m high axial reflector of the same structure placed above and below the gas plenum. The control rod system is composed of 13 diverse safety devices (DSD) and 18 control safety devices (CSD) with same material composition and structure. Homogeneous composition is given by Tab. 1. Positions of CSD and DSD in active core (AC) is shown in Fig. 1 b.

Tab. 1.*Homogeneous composition of DSD and CSD devices*

Component	Material	Volume fraction [%]
Absorber	B_4C	30.26
Cladding	SiC fibered	10.85
Coolant	He	40.57
Construction material	AIM1 stainless steal	11.22

3. Homogeneous control rod worth

Control rod worthrepresents the change in reactivity caused by its insertion in position z in active core. Using monoenergetic diffusion approach, equation for control rod worth is obtained from perturbation theory

$$\rho(z) = \rho(H)\frac{z}{H_e}\left(1 - \frac{\sin\frac{2\pi z}{H_e}}{\frac{2\pi z}{H_e}}\right), \tag{1}$$

where H_e stands for extrapolated height of active core.

Equation (1) is called integral characteristic of control rod and graphically, it gives the increasing S curve.[4]

At first, the homogeneous control rod worth was investigated.The reactivity worth was calculated for two selected positions DSD0 and DSD7. Reasonfor DSD0 selection was the position in the axis of active core. In case of DSD7, effect of interference between assemblies is minimized, due to the distance between DSD7 and other subassemblies (S/A). Integral characteristics were calculated for both safety devices.In both cases,theoretical integral characteristic was also calculated using the equation (1).

Integral characteristics of DSD0 and DSD7 devices are shown in Fig. 2. Asexpected, both characteristics are S curve shaped. To fit the results a third degree polynomial was used for KENO calculation characteristic.differences between theoretical and KENO calculation characteristic arisefrom use of monoenergetic diffusion approach in equation (1). Calculated DSD0 worth is -293.79 ± 17.76 pcm and DSD7 worth is -317.051 ± 19.31 pcm. Uncertainty values were obtained using uncertainties propagation law.

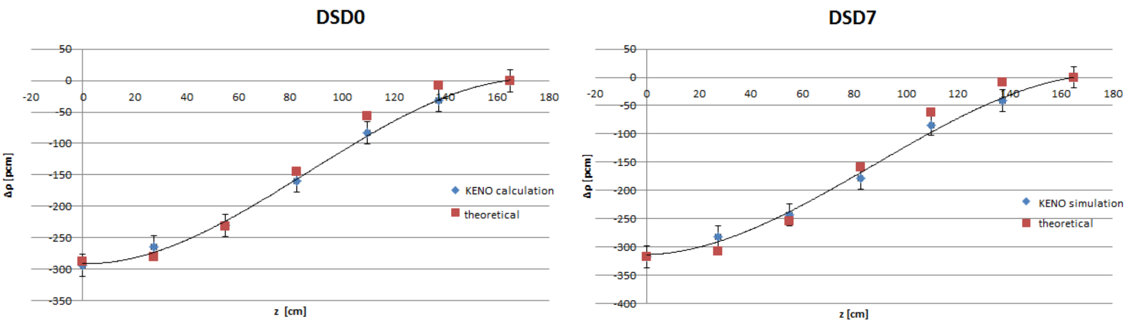


Fig.2: *Integral characteristics of DSD0 and DSD7*

5. Proposal of heterogeneous GFR control rod design

The main purpose of this study is a proposal of heterogeneous control rod (CR) design. The investigation of absorber pin radius, number of pins and radial distribution of pins in CR will be provided. Heterogeneous CR worth should be equivalent to homogeneous CR worth value defined in GoFastR project by CEA. In investigated designs of heterogeneous CR, components volume fractions and control rod radius r_i = 8.9145 cm are maintained.

In CR design, optimal pin radius is an important consideration. If the pin radius is too large, the absorber material is not utilized in the most effective way, due to self-shielding effect. For ^{10}B atoms in central part of the pin, the probability for neutron capture is small due to limitedneutron free path in material. On the basis of previous KENO calculation, neutron free pathvalue of 2-3 cm was founded. Therefore, absorber pin radius should not be greater than 1 cm.

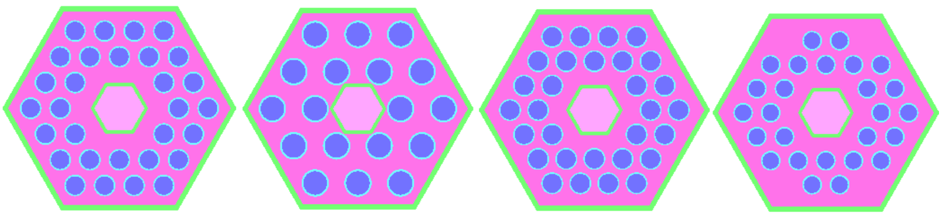
Next step is the definition of number of absorber pins in control assembly. If we consider constant assembly dimensions and absorber volume fraction, number of pins with desired radius could be calculated by

$$\boldsymbol{N} = \frac{f V_{SA}}{V_p}. \tag{2}$$

In equation (2), f is absorber volume fraction, V_{SA} is volume of S/A and V_p is volume of single absorber pin. If the number of pins is determined, cladding thickness could be calculatedbased on theknown SiC volume fraction. The thickness of S/Awrapper was also calculated from known material volume fraction and S/A dimensions.Rod follower was included in CRdesign. On the basis of previous considerations, 4 heterogeneous CRdesign were founded.The wrapper thickness and the rod follower dimensions are same in each case. Radius of rod follower r=1.9 cm was calculated. Thickness of outer assembly wrapper is 0.45 cm. Parameters of individual designs are shown in Tab. 2. Radial assembly cross sections are shown in the Fig. 3.

Tab. 2. *Parameters of individual designs*

	Design 1	Design 2	Design 3	Design 4
Pin radius [cm]	0.811	1.0511	0.85	0.92
Number of pins	30	18	30	26
Pin pitch [cm]	1.3	1.9	1.25	1.25
Pin cladding thickness [cm]	0.14	0.17	0.125	0.14



a) b) c) d)

Fig.3: *Radial cross sections a) design 1 b) design 2 c) design 3 d) design 4*

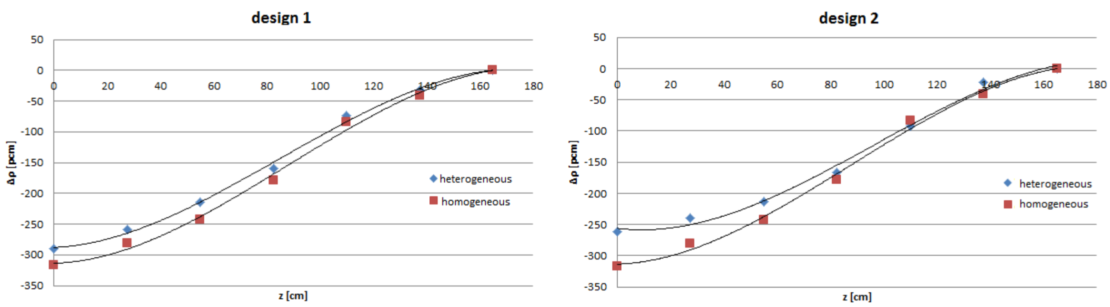


Fig.4: *Integral characteristics of individual heterogeneous designs 1 and 2*

Integral characteristic was calculated for each heterogeneous design. Position DSD7 was selected for this analysis. Integral characteristics of heterogeneous designs are shown in the Fig. 4 and 5. For each design, integral characteristic of homogeneous CR was also plotted. As can be seen in the Fig.4, heterogeneous CR worth is always lower than homogeneous CR worth. In the case of design 4, integral characteristic is in good compliance with homogeneous characteristic. Accordingly, the value of CR worth is the highest for design 4.

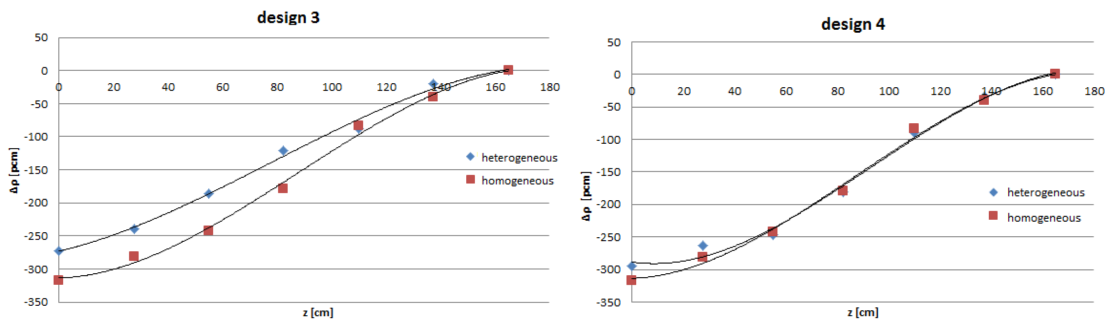


Fig.5: *Integral characteristics of individual heterogeneous designs 3 and 4*

6. The main results

Values of heterogeneous CR worths are shown in Tab. 3.

Tab.3: *Comparison of CR worth for individual designs*

Design 1	r = 0.81 cm	-290.179 ± 17.17 pcm
Design 2	r = 1.05 cm	-261.027 ± 19.28 pcm
Design 3	r =0.85 cm	-271.956 ± 17.74 pcm
Design 4	r =0.92 cm	-294.979± 18.62 pcm
Homogeneous CR		-317.051 ± 19.31 pcm

7. Conclusion

Control rod worth is the lowest for design with the largest absorber pin radius. This result is consistent with our assumption about self-shielding. If pin radius decreases, CR worth increases. Worth of design 4 is the closest to worth of homogeneous CR, although pin radius is larger than in design 1 and 3. In this case, effect of shielding between absorber pins is significant. Design 4 contains less pins than design 1 and 3. For that reason, absorber pins at the central part of S/A are utilized in more effective way. Design 4 seems to be optimal heterogeneous control rod design among all of our investigated designs.

It should be noted, that boron burn up and thermal-hydraulics aspects were not considered in this study.

Acknowledgement

This study was supported by the Slovak Research Development Agency No. APVV-0123-12. Authors would like to thank to all GoFastR project participants for valuable advice.

References:

[1] Brunel L., Chauvin N., Mizuno T., Pouchon M.A., Somers F.:*GFR Fuel and Other Core Materials*, GIF Symposium, Paris, France, 2009

[2] *SCALE: Comprenhensive Modeling and Simulation Suite for Nuclear safety Analysis and design*, ORNL/TM-2005/39, Oak Ridge National Laboratory, USA, 2011

[3] Vrban, B. and others: *Investigation of the coupled reactivity effects of the movable reflector and safety control rods*, EFR conference, Paris, 2013

[4] Reuss P.: *Neutron physics*, ISBN: 978-2-7598-0041-4, EDP Sciences, France, 2008