THREE-DIMENSIONAL CORE DESIGN OF A SUPER FAST REACTOR WITH A HIGH POWER DENSITY

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The SuperCritical Water-cooled Reactor (SCWR) pursues high power density to reduce its capital cost. The fast spectrum SCWR, called a super fast reactor, can be designed with a higher power density than thermal spectrum SCWR. The mechanism of increasing the average power density of the super fast reactor is studied theoretically and numerically. Some key parameters affecting the average power density, including fuel pin outer diameter, fuel pitch, power peaking factor, and the fraction of seed assemblies, are analyzed and optimized to achieve a more compact core. Based on those sensitivity analyses, a compact super fast reactor is successfully designed with an average power density of 294.8 W/cm^3. The core characteristics are analyzed by using three-dimensional neutronics/thermal-hydraulics coupling method. Numerical results show that all of the design criteria and goals are satisfied.

KEYWORDS : Super Fast Reactor, Core Design, Power Density

1. INTRODUCTION

The supercritical water-cooled reactor (SCWR), as the only water-cooled reactor concept among six nuclear energy systems that were selected as the Gen-IV reactors by Generation IV Forum, has been well developed worldwide [1-4]. The primary motivation for developing the SCWR is reducing capital cost in order to maintain the economic competitiveness of nuclear power plants against other power sources in the de-regulated electricity market. High economic competitiveness potentialities of the SCWR mainly come from its compact and simplified system, high thermal efficiency, and low amount of spent fuel. Many efforts have been made to enhance those properties. Among them, increasing the average power density is very effective for reducing the size of the reactor core and consequently reducing the sizes of the pressure vessel, containment, and reactor building.

The concept of fast spectrum SCWR, called a super fast reactor, is thus developed. As a moderator is not needed and fuel assembly can be designed in a tight lattice, the super fast reactor can be more compact than a thermal SCWR. In a past study [6], the conceptual design of a super fast reactor using MOX fuel and stainless steel cladding was successfully conducted with an average power density of 158.8W/cm^3. The core design was continuously improved to ensure that local void reactivity of all seed assemblies is negative throughout the cycle [7]. As high power density was not the design objective of those two designs, some margin may exist for increasing the power density.

The aim of this study is to pursue a high power density core design of the super fast reactor without violating any previously-given design criteria. The mechanism for increasing the average power density is theoretically analyzed from the definition of average power density. Then, core parameters affecting the power density are investigated. Some candidate cores are designed to perform the sensitivity analyses of those parameters on the average power density. Based on those sensitivity analyses, a high power density core is designed. Three-dimensional neutronics/thermal-hydraulics coupling method is used to evaluate the core performance in detail.

The remainder of this paper is as follows. Section 2 describes the design criteria and the reference core that are the design bases of this study. Section 3 analyzes the principle of increasing the average power density theoretically. Section 4 performs some sensitivity analyses of those parameters illustrated in Section 3. A final core design is optimized and evaluated by using three-dimensional neutronics/thermal-hydraulics coupling method in Section 5. Section 6 ends this paper with some conclusions.

2. DESIGN CRITERIA AND BASES

Core design is performed based on the reference core given by previous study [6] and the design criteria are kept the same as the reference core design; namely, no design criterion is violated and the improvements are realized by making use of the design margin and parameter optimization.

Design criteria and goals mainly include: 1) Maximum linear heat generation rate (MLHGR) should be less than 39kW/m.; 2) Maximum cladding surface temperature (MCST) should be less than 650 °C; 3) Buckling collapse and creep collapse of the fuel cladding, caused by the high coolant pressure, should be avoided; 4) Positive coolant density reactivity (negative void reactivity) should be achieved to ensure an inherent safety requirement of the water cooled reactor core; 5) Core power is around 700 MWe, which is especially suitable for a middle-scale electricity market; 6) The coolant outlet temperature should be higher than 500 °C, which corresponds to a thermal efficiency of 43.8%. All criteria given in this paper are under nominal conditions. Transient analysis is not included in this paper.

Main parameters of the reference core design are given in Table 1.

All core analyses are based on three-dimensional neutronics/thermal-hydraulics coupling calculation. Neutronics calculation is performed by using SRAC code [8], which was developed by the Japan Atomic Energy Agency. Thermal-hydraulics calculation is performed by using single channel analysis. Details about core analysis method can be found in the references [6].

Table 1. Main Characteristics of the Reference Core

R/Ns	Value
Core thermal power [MWt]	1650
Core height [cm]	300
Fuel rod diameter [mm]	7.0
Pitch to diameter ratio	1.16
Number of seed assemblies	126
Number of Blanket assemblies	73
Fissile Pu enrichment [wt%]	24.87
Coolant inlet/outlet temperature [°C]	280/503.7
Maximum cladding surface temperature[°C]	639.8
Average power density[W/cm^3]	158.8
Average linear heat rate[kW/m]	17.3
Maximum linear heat rate[kW/m]	35.9
Flow rate[kg/s]	850.0
Cycle length [EFPD]	380
Refueling scheme	3 batches
Coolant void reactivity[%dk/k] BOEC	-1.23
EOEC	-2.07

3. PRINCIPLE OF IMPROVING THE POWER DENSITY

The most limiting restriction of increasing the power density comes from the design criterion of the MLHGR, which is set to be less than 39kW/m. This criterion is relatively conservative compared with the past SFR design. Table 2 compares this criterion with the MLHGR of some typical SFRs [9].

Blanket assemblies are designed in the super fast reactor to convert fertile isotopes. Because the blanket assembly is loaded by the depleted UO_2 fuel discharged from the PWR, the enrichment of ^{235}U is as low as 0.2%. The power generated by the blanket assemblies at the beginning of the equivalent cycle (BOEC) is very low and can be ignored. As can be seen in the previous study, the MLHGR always appears at the BOEC. Thus, the following study mainly focuses on the status of the BOEC and regards the power generated by the blanket assemblies as negligible.

Based on the above model, the power density can be approximately calculated by

$$q_V = \frac{P_{tot}}{V_{tot}} = \frac{P_{tot}}{N_{pin} S_{cell} H \dfrac{N_{tot\_assem}}{N_{seed\_assem}}} \tag{1}$$

Where,

P_{tot} total thermal power

V_{tot} total core volume

N_{pin} total fuel pin number

S_{cell} area of fuel cell $(= \frac{\sqrt{3}}{2} P^2, P,$ fuel rod pitch$)$

H core active height

N_{tot_assem} total assembly number

N_{seed_assem} total seed assembly number

Areas of assembly ducts and gaps between assemblies are neglected because eq. (1) is just used to deduce those important parameters affecting the power density.

If the MLHGR is denoted by q_l^{max} and the power peaking factor is f, we can get

$$P_{tot} = N_{pin} \times H \times q_l^{max} / f \tag{2}$$

Table 2. Comparison of Linear Heat Generation Rate (kW/m)

	Peak Linear Power	Average Linear Power
JOYO	40	-
FFTF	42	24
MONJU	36	20
CRBRP	42	27
PHENIX	45	27
Super PHENIX	47	28
BN-600	53	36
SNR-2	42	-
Super fast reactor	39	17

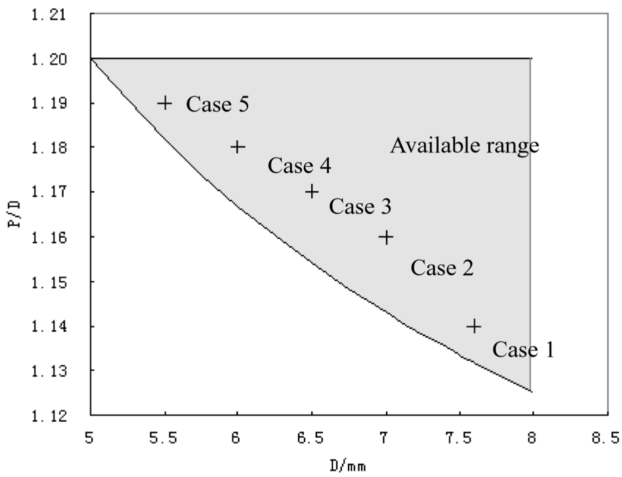

Fig. 1. Relationship between D and P/D

If we substitute eq. (2) into eq. (1), we get

$$q = \frac{q_l^{\max}}{S_{\text{cell}} f \frac{N_{\text{tot\_assem}}}{N_{\text{seed\_assem}}}} = \frac{q_l^{\max}}{\frac{\sqrt{3}}{2} P^2 f \frac{N_{\text{tot\_assem}}}{N_{\text{seed\_assem}}}} = \frac{q_l^{\max}}{\frac{\sqrt{3}}{2} (P/D \times D)^2 f \frac{N_{\text{tot\_assem}}}{N_{\text{seed\_assem}}}} \quad (3)$$

It is obvious that the power density is inversely proportional to square of P/D and D, so decreasing the fuel pin diameter or pitch is the most effective way to increase the average power density. The power density is also inversely proportional to f and $\frac{N_{\text{tot\_assem}}}{N_{\text{seed\_assem}}}$, which indicates that flattening the power distribution and increasing the fraction of seed assemblies are two other possible ways to increase the power density.

4. OPTIMIZATION OF FUEL PIN DIAMETER AND P/D

As discussed above£¨decreasing the pin diameter and *P/D* is very effective for improving the power density. However, there does exist low limitation on the diameter and *P/D* because the gap clearance between fuel pins should be large enough from thermal-hydraulic and mechanical considerations. According to the previous design experience of the reduced moderated water reactor (RMWR) core design [10], the minimum gap clearance should be kept larger than 1mm. That is:

$$(P/D - 1) \times D > 1\text{mm} \quad (4)$$

Eq. (4) indicates that decreasing *D* requires increasing *P/D*. In the meanwhile, however, the *P/D* ratio also has an upper boundary for achieving high coolant outlet temperature. As mentioned in the previous study [6], the coolant outlet temperature will decrease rapidly if the *P/D* exceeds 1.2 with a fuel pin diameter around 7mm. Considering the above limitations, we can draw the available design range of *D* and *P/D* in Fig. 1.

In order to quantitatively optimize the value of *D* and *P/D*, we set five cases with different *P/D* and *D* values within the available range as shown in Fig. 1. Yoo et. al. [11] designed a super fast reactor with a fuel pin diameter of 7.6mm and *P/D* of 1.14, which is labeled by Case 1 in Fig. 1. The fuel pin parameters given by the reference design [6] with a fuel pin diameter of 7.0mm and *P/D* of 1.16 is labeled by Case 2. Besides those two cases, three other cases are chosen to design the core and evaluate their characteristics. They are:

Case 3. *D*=6.5mm, *P/D*=1.17
Case 4. *D*=6.0mm, *P/D*=1.18
Case 5. *D*=5.5mm, *P/D*=1.19

Preliminary fuel and core designs are performed based on those three cases by using three-dimensional neutronics/thermal-hydraulics coupling method. The following sections introduce the fuel rod, seed assembly, and core configurations. Those important parameters are compared with the previous reference core designs.

4.1 Fuel Rod Configurations

Once the fuel rod outer diameter and *P/D* ratio are determined, other configurations of the fuel pin can be designed based on their corresponding design criteria. Cladding thickness is determined by two aspects. One is that the buckling collapse pressure should be less than 1/3 of strain stress of the stainless steel. The other is that the compressive to yield stress ratio should be less than 0.2. Ten percent of margin for corrosion is taken into account.

The core active height mainly depends on the design criterion of FIV, which can be simply written as,

$$\left(\frac{1}{2}\rho V^2\right)^{1.16} \mathrm{Re}^{0.25} < 2.0\times10^6 \text{ or } \frac{1}{2}\rho V^2 < 0.02\mathrm{MPa} \quad (5)$$

Those geometrical parameters for each case are summarized in Table 3. The fuel compositions of those five cases are different from each other because they are dependent on the power profile and cycle length requirements that will be considered in the core design.

4.2 Assembly Configurations

A super fast reactor consists of seed assemblies and blanket assemblies. The former are used to generate power and the latter are used to convert the fertile material. Three types of seed assemblies are designed based on those fuel rods of Case 3 to Case 5, respectively. The main parameters of those three cases are compared with previous designs in Table 4. Most of the configurations are kept the same for conservatism even though the dimensions are obviously decreased. The size of the blanket assembly is consequently reduced to match that of the seed assembly. The thicknesses of the ZrH layers in the blanket assemblies are optimized to achieve most negative overall and local void reactivity.

The geometrical structure of the assembly lattice is kept the same as the reference design, where fuel pins are

Table 3. Fuel Rod Configurations

Parameter	Case 1	Case 2	Case 3	Case 4	Case 5
Diameter [cm]	0.76	0.70	0.65	0.60	0.55
P/D	1.14	1.16	1.17	1.18	1.19
Gap clearance [mm]	1.064	1.120	1.105	1.080	1.045
Cladding thickness [cm]	0.043	0.043	0.42	0.41	0.040
Pellet cladding gap [cm]	0.010	0.004	0.003	0.003	0.003
Height [cm]	270	300	240	230	220

Table 4. Fuel Assembly Configurations

Parameter		Case 1	Case 2	Case 3	Case 4	Case 5
Seed assembly	No. of pins, total/fuel /tube	331/312/19	271/252/19	271/252/19	271/252/19	271/252/19
	Assembly pitch	16.58	14.182	13.3	12.45	11.56
	Assembly gap [cm]	0.2	0.2	0.2	0.2	0.2
	Duct thickness [cm]	0.2	0.2	0.2	0.2	0.2
Blanket assembly	No. of fuel pins	91	61	61	61	61
	ZrH layer thickness [cm]	1.3	1.2	0.9	0.83	0.77
	Duct thickness [cm]	2.4	2.1	2.0	1.92	1.74
	Duct gap	0.2	0.2	0.2	0.2	0.2

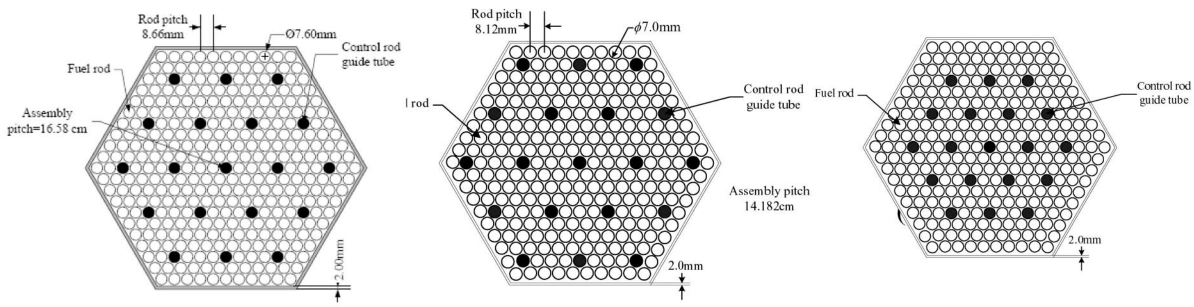

Fig. 2. Layouts of Seed Assemblies of Different Cases

arranged in a triangle lattice and 19 control rod guide tubes are put symmetrically into 3 circles. The difference lies on the number of fuel pins and positions of guide tubes, which are given in Fig. 2. Case 2 through Case 5 have only nine circles of fuel pins other than ten circles in Case 1 because Case 1 is designed with a power of 1000MWe, but Case 2 through Case 5 are designed with 700MWe of power. In the assembly layouts of Cases 3, 4, and 5, the guide tubes are moved to the inner region of the assembly. This improvement can reduce the radius of the guide tube grid spacer to improve the mechanical property of the assembly design.

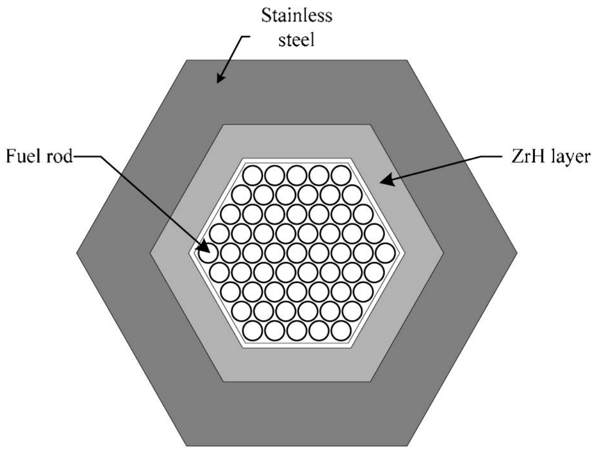

Fig. 3. Layout of Blanket Assembly

The layout of the blanket assembly is kept the same as the reference design, which is shown in Fig. 3.

4.3 Core Configurations

Core designs are performed based on those assembly configurations of Cases 3, 4, and 5. Three candidate cores are given and some important parameters are compared with the reference core designs in Table 5. As the heights of fuel rods are limited by the FIV constriction, we have to decrease the core active height for smaller fuel rod diameter designs. To keep the same power and average linear heat generation rate, the number of fuel rods has to

Table 5. Core Configurations

Parameter	Case 1	Case 2	Case 3	Case 4	Case 5
Core thermal power [MWt]	2358	1650	1960	2010	1800
Core height [cm]	270	300	240	230	220
Equivalent diameter [cm]	267	210	230	200	186
Number of seed assemblies	162	126	162	162	162
Number of blanket assemblies	73	73	73	73	73
Fissile Pu enrichment [wt%]	20.8	24.87	25.9	27.7	28.7
Fissile Pu inventory [t]	8.44	6.571	5.61	5.56	3.63
Heavy metal inventory [t]	40.58	26.42	24.4	20.1	14.9

Table 6. Comparison of Design Results

Calculated results		Case 1	Case 2	Case3	Case4	Case5
Coolant outlet temperature [°C]		503	501.5	502.96	501.84	497.58
Maximum cladding surface temperature [°C]		642.6	641.1	642.4	642.4	644.3
Cycle length [EFPD]		450	380	320	280	220
Average power density [W/cm^3]		156	158.8	226.0	265.5	301
Average linear heat rate [kW/m]		17	17.3	20	20.5	20
Maximum linear heat rate [kW/m]		38.9	35.9	38.5	38.6	38.9
Flow rate [kg/s]		1210	850.0	847.7	850.3	856.4
Average discharge burnup [MWd/kgHM]		68.3	69.3	68.9	69.3	69.8
Coolant void reactivity [%dk/k]	BOEC	-1.9	-1.23	-1.51	-0.23	-0.35
	EOEC	-1.8	-2.07	-1.20	-1.25	-1.39

be increased for smaller fuel rod designs. Therefore, the numbers of seed assemblies are increased from 126 to 162. This is also good for increase the fraction of seed assembly if the number of blanket assembly is kept the same.

Naturally, when the fuel rod diameter is reduced, the total volume and fuel inventory will be consequently reduced continuously from Case 1 to Case 5. As a smaller core has higher neutron leakage if the same reflector is used, the enrichment of fissile Pu has to be higher to achieve enough residual reactivity at the EOEC.

4.4 Design Results and Discussions

The performances of those three newly designed candidate cores are evaluated by using three-dimensional neutronics/thermal-hydraulics coupling calculation. Some main results are compared with two reference designs in Table 6. The average power densities are plotted in Fig. 4. From the above comparison, we can find that:

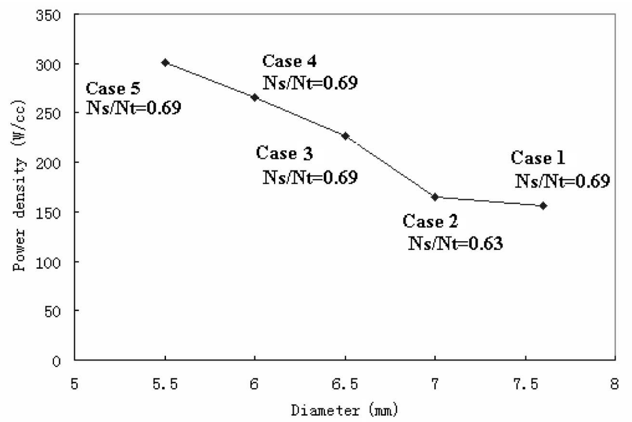

Fig. 4. Comparison of Power Density of Five Candidates

1. When the fuel pin diameter decreases, the power density increases almost linearly if the number fraction of seed assemblies is kept the same, and the cycle length decreases because the fuel inventory decreases and the discharge burnup is kept the same.
2. The number fraction of seed assemblies ($\frac{N_{tot\_assem}}{N_{seed\_assem}}$) also obviously affects the power density. Case 2 has a lower $\frac{N_{tot\_assem}}{N_{seed\_assem}}$, so its power density is lower.
3. All cases can achieve satisfying thermal-hydraulic results except Case 5, which has an outlet temperature less than 500 °C . This indicates that the minimum fuel pin diameter is around 5.5 mm in our design of a 700 MWe super fast reactor.

5. OPTIMIZATION OF CORE DESIGN OF CASE 5

The core design of Case 5 is taken as a base for the high power density core design. As can be seen from Table 6, the coolant outlet temperature of Case 5 is less than 500 °C. It is necessary to optimize the coolant flow pattern to increase the outlet temperature. Meanwhile, the power distribution can be flattened by adjusting the refueling scheme so that the average power density can be increased.

After carefully adjusting the flow pattern and loading scheme, we achieve a flow pattern as shown in Fig. 5 and a loading scheme as shown in Fig. 6. The values in Fig. 5 are the relative mass flux distribution of the core, where negative value stands for downward flow and positive value stands for upward flow. It is seen from Fig. 5 that all of the blanket assemblies are cooled by downward flow with low flow rate, the outmost seed assemblies are cooled by downward flow with high flow rate, and other seed assemblies are cooled by upward flow. The flow distribution can be realized by controlling the orifices located at the inlet of the assembly flow channels. The loading pattern shown in Fig. 6 is obtained by manually adjusting the core arrangement to achieve flat power distribution. Naturally,

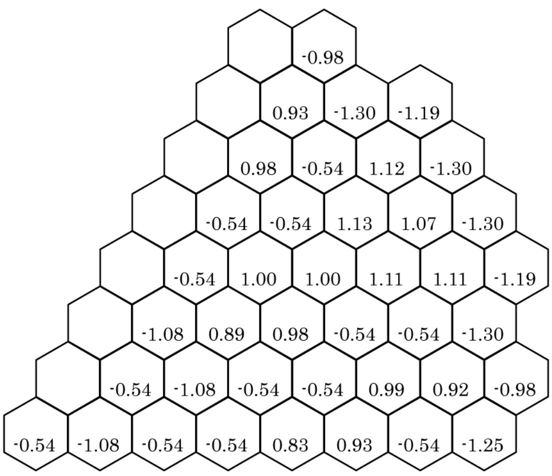

Fig. 5. Flow Pattern

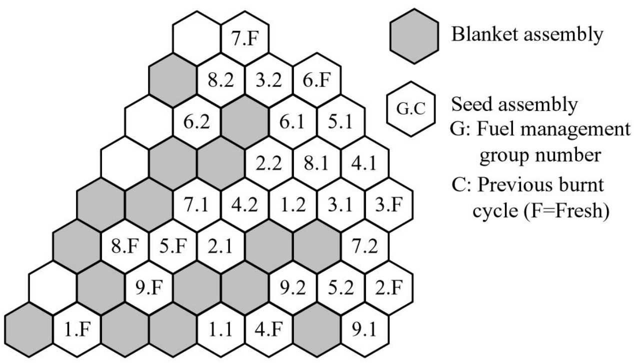

Fig. 6. Loading Pattern

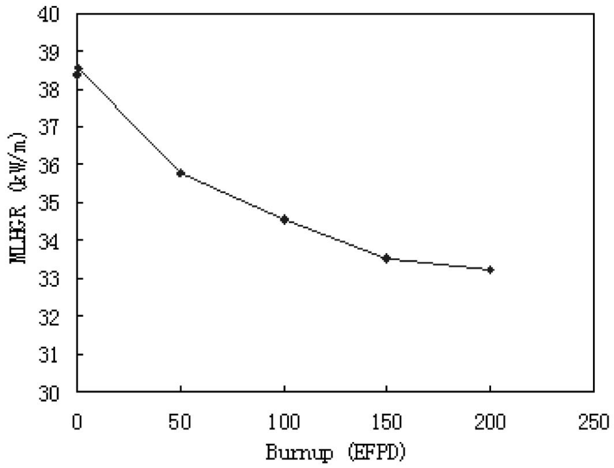

Fig. 7. Maximum Linear Heat Generation Rate

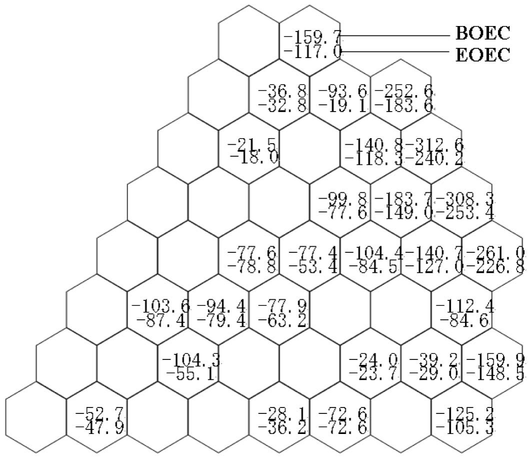

Fig. 9. Local Void Reactivity (BOEC and EOEC)

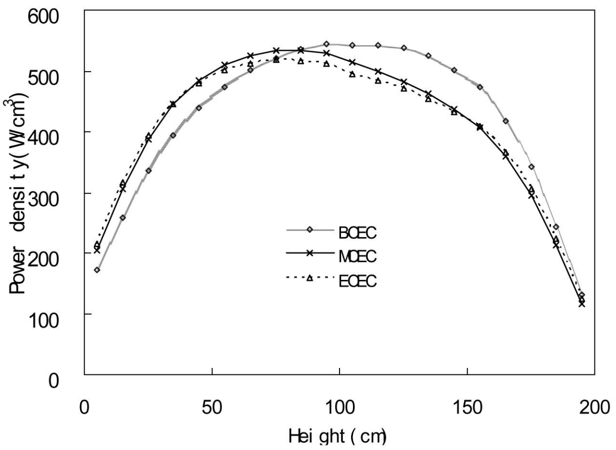

Fig. 8. Axial Average Power Distribution

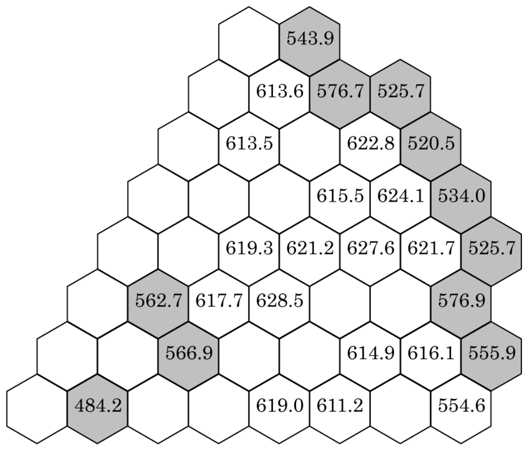

Fig. 10. Maximum Cladding Surface Temperature (ºC)

this loading pattern can be continuously improved by using some advanced optimization methods.

The goal of this study is to design a 700MWe super fast reactor, but from Table 5 we can see that Case 5 has a thermal power of 1800MWt, which means the electrical power is around 788MWe. Also, the core height is reduced to 200cm from the original 220cm. All of the other configurations are kept the same as those of Case 5.

After those modifications, the core characteristic is evaluated again by using three-dimensional neutronics/ thermal-hydraulics coupling calculation. The main calculated results are given and analyzed as the following. Figure 7 shows that the MLHGR decreases with burnup and the peak value appearing at the BOEC is well below 39kW/m, which was selected as one of the most important design criteria in the reference design. The axial power profiles given in Fig. 8 show that the axial power distribution does not change much from the BOEC to the EOEC and is almost kept unchanged from the MOEC to the EOEC. Negative local void reactivity is another important design criterion for the super fast reactor. The local void reactivity of each seed assembly is calculated by assuming the coolant of this assembly disappears. From the results given in Fig. 9, we can see all seed assemblies have negative local void reactivity at the BOEC and the EOEC. This is mainly thanks to the core arrangement optimized by the previous study [7].

In order to insure the MCST is kept below the design criterion, subchannel analysis was performed for each seed assembly. The theoretical model and correlation used in the subchannel analysis is the same as the reference core design [12]. The values shown in Fig. 10 are the MCSTs of all seed assemblies over the fuel cycle. We can see that the peaking MCST is 628.5 °C appearing in the middle region of the core.

Table 7 summarizes the main parameters and calculated results of the final core design. Even though most of the core characteristics are kept the same as the reference

Table 7. Summary of Main Parameters of Core Design

Parameter	
Diameter [cm]	0.55
P/D	1.19
Gap clearance [mm]	1.045
Cladding thickness [cm]	0.040
Pellet cladding gap [cm]	0.003
Height [cm]	200
Assembly pitch [cm]	11.561
No. of pins, total/fuel/tube	271/252/19
Core thermal power [MWt]	1602
Equivalent diameter [cm]	186
Number of seed assemblies	162
Number of blanket assemblies	73
Coolant outlet temperature [°C]	504.6
MCST [°C]	628.5
Average power density [W/cm^3]	294.8
Average discharge burnup [GWd/tHM]	69.4
Average fissile Pu enrichment	30.43
Coolant flow rate [kg/s]	820.5
Coolant void reactivity[%dk/k] BOEC/EOEC	-0.839/-1.712

core design, the average power density is successfully increased to 294.8 W/cm^3 from the original 158.8W/cm^3.

6. CONCLUSIONS

A high power density super fast reactor is designed in this study. First of all, the mechanism of improving the power density is analyzed theoretically. It is found that the fuel pin diameter, *P/D* value, fraction of the number of seed assemblies to the total number of the assemblies, and the power distribution are the main parameters affecting the power density. Then, some sensitivity analyses of those parameters are performed. According to the sensitivity analyses, some conclusions can be drawn as following.

1. Decreasing the fuel pin diameter is very effective to increase the power density. However, the fuel pin diameter has a lower limit because of mechanical reasons. In our particular design, the minimum diameter is determined to be 5.5 mm.
2. Increasing the volume fraction of seed assemblies can effectively increase the average power density.
3. The power distribution can be well controlled by adjusting the loading pattern, which is also very important for increasing the power density.
4. A core with a power density of 294.8w/cm^3 is successfully designed. Numerical results of three-dimensional neutronics/thermal-hydraulics coupling calculation show that all of the design goals and design criteria are satisfied. The average power density is increased by 86% compared to the reference core design, which means the size of the pressure vessel can be reduced dramatically. Consequently, the capital cost could be significantly reduced and the economical competitiveness of the super fast reactor could be significantly improved.

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