Coupled Neutronics and Thermal–Hydraulics Analysis of Annular Fuel Assembly for SCWR

Chuanqi Zhao, Kunpeng Wang, Liangzhi Cao, Hongchun Wu and Youqi Zheng

Abstract During pre-conceptual design of supercritical water-cooled reactor (SCWR), assembly design is very important and affects core performance. Coupled neutronics and thermal–hydraulics analysis is required for dramatic changes of water density in SCWR. Annular fuel assembly is optimized from the point of view of neutronics and thermal–hydraulics performance using three-dimensional coupling code. Three-dimensional diffusion calculation for annular fuel assembly is carried out using FENNEL-N. Pin power distribution is obtained. With these power, SUBSC is used to perform sub-channel analysis. The effects of fuel rod distance and gap between fuel rods and assembly box on assembly performance are researched in the coupled analysis. Results have shown that increasing fuel rod distance and rod-to-box gap will increase k_{inf} and assembly power peaking factor. It is also shown in the results that heating heterogeneity of sub-channels plays a big role in assembly thermal performance and adding grid will flatten coolant outlet temperature as well as decrease maximum cladding surface temperature. Safety analysis of annular fuel assembly shows that the assembly is safe from the point of view of neutronics.

Keywords SCWR · Annular fuel assembly · Coupling calculation

1 Introduction

Supercritical light water reactor (SCWR) is a thermal reactor cooled and moderated by supercritical water [1]. Water does not exhibit a phase change from liquid to gas above 22.1 MPa. Therefore, the plant system is simpler and more compact than PWRs and BWRs without a dryer, water-steam separators, and recirculation pumps.

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The coolant outlet temperature is high because there is no limitation of saturation temperature at supercritical pressure. This results in high thermal efficiency, which is good not only for producing electricity but also for reducing the amount of spent fuel per generated watt of electricity.

In 2001, annular fuel is proposed by MIT to improve the power density of PWR [2, 3]. Annular fuel has many advantages over traditional solid fuel: Firstly, annular fuel has larger heat transfer area; thus, lower fuel temperature can be achieved which means more safety margin. Secondly, fission gas release at high burn-ups decreases as the fuel temperature decreases. Thirdly, the gap at both sides of fuel pellet provides more space for fuel swelling, and the probability of cladding damage decreases. Fourthly, annular fuel has larger rod diameter and it is helpful to avoid flow-induced vibration (FIV). Lastly, density of coolant in the center is large enough to provide sufficient moderation. In 2014, a pre-conceptual design of SCWR with annular fuel is proposed by Xi'an JiaoTong University [4]. In that design, the optimization is focused on core design. More optimization of fuel assembly should be carried out.

In this study, the annular fuel assembly is analyzed using three-dimensional neutronics and thermal–hydraulics coupling method. At first, the coupling code is developed. Traditional two-step method is used for neutronics calculation, and sub-channel method is introduced in thermal–hydraulics calculation. Then, optimization is performed using this code to improve the fuel assembly performance. At last, the safety of the fuel assembly is estimated from the viewpoint of neutronics.

2 Neutronics/Thermal–Hydraulics Coupling Code

2.1 Calculation Code

A three-dimensional coupling code for fuel assembly analysis is developed in this study. There are three modules in this code, including neutronics module FENNEL-N, sub-channel analysis module SUBCS, and the coupling module. The coupling flow chart is shown in Fig. 1.

FENNEL-N is based on two-step method which is wildly used in PWRs calculations. HELIOS is suitable to calculate complex geometry, and it is chosen to carry out fuel assembly calculation [5]. Macroscopic cross sections obtained in assembly calculation are fitting using Lilac code [6]. The diffusion code uses these fitting coefficients to get macroscopic cross sections for diffusion calculation. A three-dimensional code for hexagonal geometry, SIXTUS, is used as diffusion solver [7].

SUBSC is a sub-channel code for steady state single-phase flow calculation. Three-dimensional conduction model is introduced in fuel rod conduction calculation to get accurate fuel temperature distribution. SUBSC uses IAPWS-IF97 formulation to calculate water properties over supercritical pressure. Heat transfer

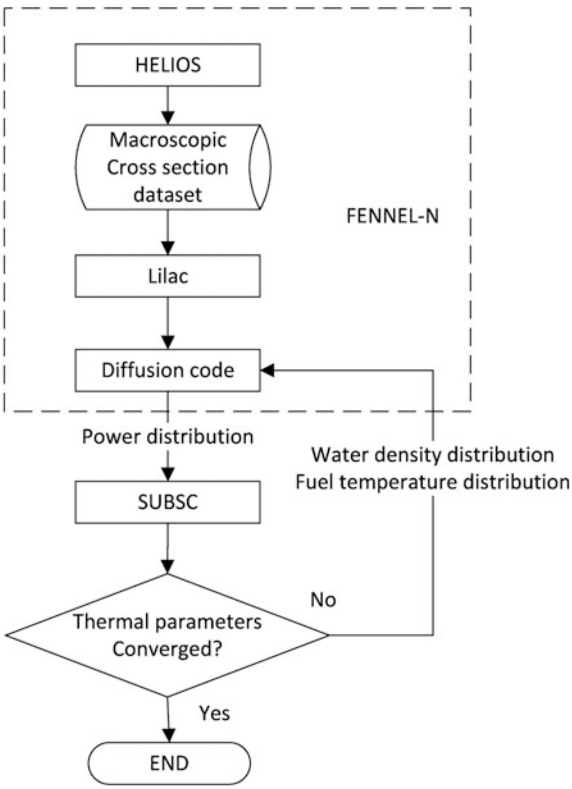


Fig. 1 Flow chart of coupling calculation

correlations will affect results, and the commonly used Bishop correlation [8] is chosen for supercritical water.

In the coupling calculation, FENNEL-N carries out the diffusion calculation based on initial water density and fuel temperature distribution. The three-dimensional power distribution can be obtained in diffusion calculation. This power is transferred to SUBSC for sub-channel calculation. SUBSC will provide new water density and fuel temperature distribution. If these thermal parameters are converged with the previous ones, the coupling calculation is finished. Otherwise new thermal parameters are used to update the macroscopic cross sections for next diffusion calculation. The data transmission between FENNEL-N and SUBSC is processed by coupling module.

2.2 *Calculation Model*

In neutronics calculation, a single fuel assembly with axial reflector at both top and bottom is calculated. Reflection and vacuum conditions are taken as radial and axial

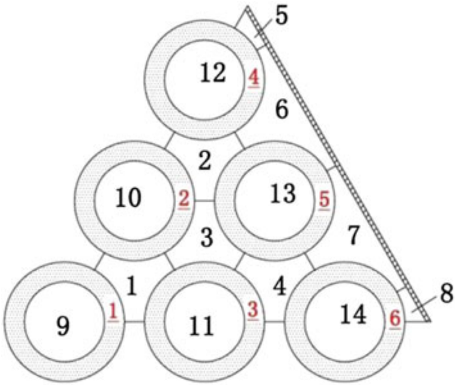


Fig. 2 Sub-channel Division of 1/6th assembly

boundary condition, respectively. Average linear power density of the *j*th layer Pjhome is obtained after three-dimensional diffusion calculation. With the results of HELIOS assembly calculation and fitting coefficient, the power form factor of the *i*th fuel rod at *j*th layer fijhete is calculated. The power distribution for each fuel rod in the fuel assembly can be calculated by Eq. (1).

$$P_{ij} = f_{ij}^{\text{hete}} \cdot P_j^{\text{homo}} \tag{1}$$

The sub-channel calculation is performed with the fuel rod power distribution. In annular fuel rod, the channel at the center is closed and it is called internal channel; channels among fuel rods are connected, and these are called external channel. Because of symmetrical geometry, one-sixth of the fuel assembly is calculated in sub-channel calculation as shown in Fig. 2. In Fig. 2, division and serial number of sub-channel are given. Besides, the serial number of fuel rod is given in red underlined number. The coolant flows into internal channels from the top to the bottom and flows upwards through the assembly in external channels. External sub-channels can be categorized into three groups. The first group is called center channel, including channels 1 and 4. The second group is called side channel, including channels 6 and 7. The last group is called corner channel, including channels 5 and 8. Water density distribution in each channel and each fuel rod temperature distribution can be obtained after sub-channel calculation. These parameters are used in FENNEL-N for next neutronics calculation.

3 Fuel Assembly Optimization

The hexagonal fuel assembly is shown in Fig. 3. The fuel assembly is consist of 19 fuel rods which are optimized in reference 4. In order to adjust coolant flow rate, closed fuel assembly is chosen in SCWR. The gap between adjacent fuel rods D_g and the gap between fuel rod and assembly boxes D_{box} will affect the neutronics

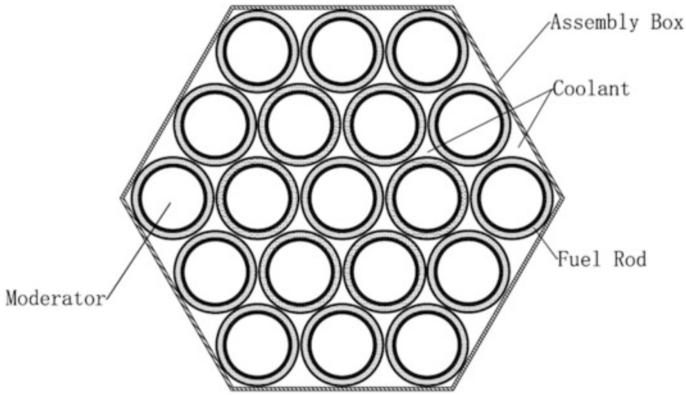


Fig. 3 Sketch of annular fuel assembly

and thermal–hydraulics performance. The coupled code is used to analyze the fuel assembly performance, and optimizations are done based on the analysis.

3.1 Neutronics Performance

In order to analyze neutronics performance of the fuel assembly, moderator density is set 600.0 kg m^{-3} and the coolant density is set 150.0 kg m^{-3}. HELIOS is used to calculate the change of k_{inf} with D_g and D_{box}. The results are shown in Fig. 4. It can be seen that k_{inf} increases with the increase in D_g and D_{box}. This is because there is more water in the fuel assembly with the increase in D_g and D_{box}, and more moderation is provided.

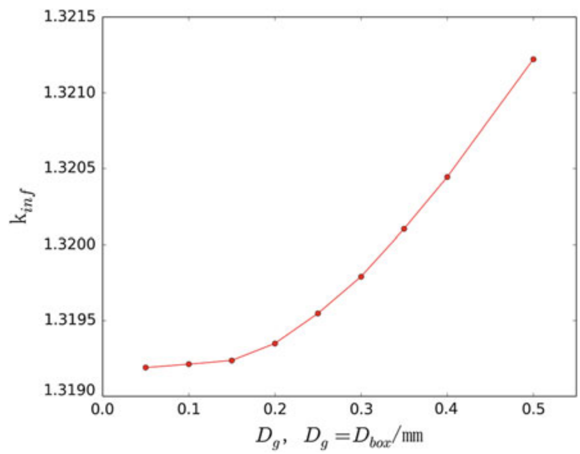
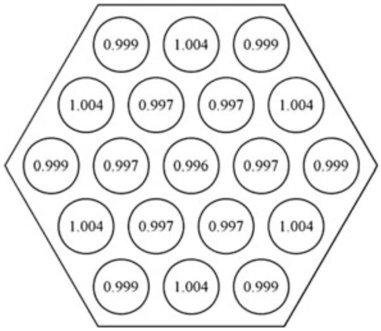
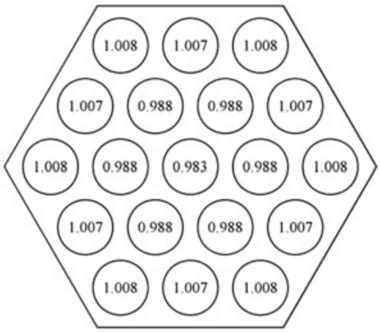


Fig. 4 Change curve of assembly k_{inf} with D_g and D_{box}

Fig. 5 Assembly relative power distribution. **a** $D_g = 0.05$ mm. **b** $D_g = 0.5$ mm



(a) D_g=0.05mm



(b) D_g=0.5mm

The power distribution inside the fuel assembly will also change with D_g and D_{box} (assuming $D_g = D_{box}$). The results show that the relative power peaking factor changes from 1.004 to 1.008 while D_g changes from 0.05 to 0.5 mm. Power distributions of $D_g = 0.05$ mm and $D_g = 0.5$ mm are shown in Fig. 5. In Fig. 5, the circle represents annular fuel rod and the number in it means relative power factor. The hexagon represents assembly box. It can be seen that the power of 6 fuel rods at the corner increases with increase in D_g. This is because there is more water in the corner with the increase of D_g and more moderation is provided. Figure 5 also shows that the relative power peaking factor is low for annular fuel assembly which is beneficial to decreasing the MCST.

3.2 *Thermal–Hydraulics Performance*

There are many aspects in thermal–hydraulics performance, such as axial water density distribution, fuel temperature distribution, cladding temperature distribution, flow distribution, and coolant outlet temperature distribution. Coolant outlet temperature distribution is important among them. Flat coolant outlet temperature is helpful to increase safety margin.

Coupled code is used to analyze the thermal–hydraulics performance. In the calculation, the coolant inlet temperature is 280 °C, and outlet temperature is 500 °C. The system pressure is 25 MPa.

The coupling calculation is carried out with different D_g and D_{box}. In order to analyze the results, a variable named peaking factor is defined as the ratio of maximum value to average value of one thermal parameter in external sub-channels. The peaking factor of coolant outlet temperature and coolant outlet flow rate is shown in Fig. 6. As shown in Fig. 6, the peaking factors of coolant outlet temperature and flow rate decrease with the increase in D_g and D_{box}. The Maximum cladding surface temperature (MCST) is also shown in Fig. 6. The MCST decreases with the increase in D_g and D_{box}.

In order to explain the result in Fig. 6, a variable named HA is declared to represent the heterogeneous of different sub-channel group. The HA can be calculated by Eq. (2).

$$HA = \frac{P_h}{A} \quad (2)$$

where, Ph—sub-channel heat perimeter/cm; A—sub-channel flow area/cm^2.

The change of sub-channel HAs and its ratios with D_g and D_{box} are shown in Fig. 7. When D_g and D_{box} increase, the HAs of three sub-channel groups decrease, which means different sub-channels are heated more evenly. With the mixture between sub-channels, the flow rate distribution and coolant outlet temperature are

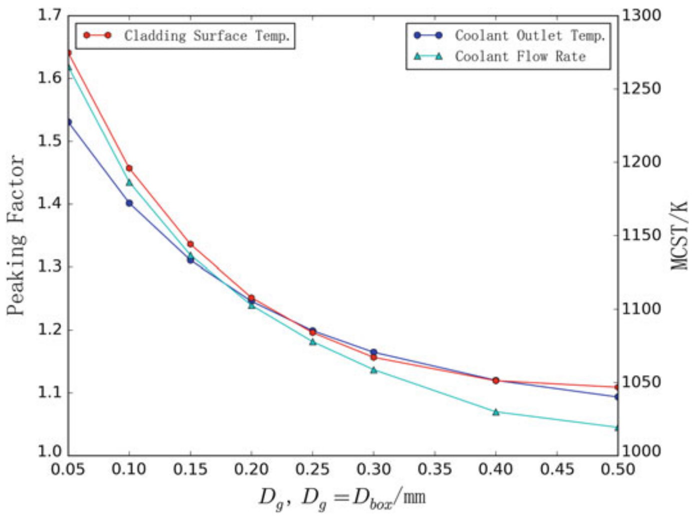


Fig. 6 Changing curve of peaking factor and MCST with D_g

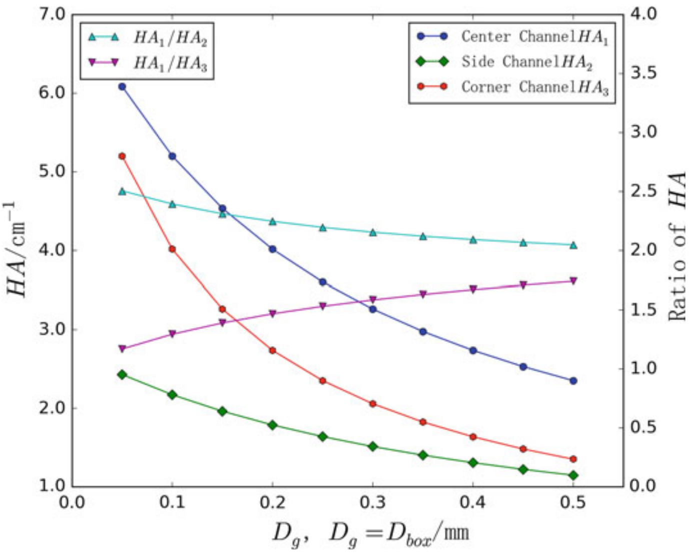


Fig. 7 Changing curve of sub-channel HA and ratios with D_g

more flat. It will cause the decrease in MCST, which is consistent with the result in Fig. 6.

As shown in Fig. 7, the HA ratio of different sub-channel group is high, which is not good for flat flow rate distribution. When $D_{\text{box}} = 0.5D_g$, the HA of corner channel and center channel is equal. The HA of side channel is always less than that of other two groups with increase in D_g. Therefore, increasing the HA of side channel will decrease the HA ratio and flatten flow rate distribution and outlet temperature distribution.

The HA of side channel can be increased by decreasing its flow area. There are two ways to decrease its flow area: structure inside the assembly box and spacer grid. Structure inside the assembly box will introduce more stainless steel which will absorb neutron. With spacer grid, the flow area can be changed by changing of mixing vane size. Using spacer grid makes less effect on neutronics performance because of less stainless steel.

When $D_{\text{box}} = 0.5D_g$, the HAs of center channel and side channel are made to be equal by adjusting mixing vane. There are 13 grids in axial direction. The first grid is 21.0 cm above the bottom, and grid space is 31.5 cm. The coupling calculation is carried out with 3 different D_g. The peaking factors of coolant outlet temperature and flow rate and MCST are shown in Table 1.

As shown in the table, the peaking factor of outlet temperature and flow rate and MCST decreases after adding spacer grid and mixing vane. When $D_g = 0.3$ cm, the MCST is lowest. MCST is higher when D_g is smaller. It is because sub-channel heterogeneity is larger and peaking factor is larger. MCST is higher when D_g is larger. It is because the coolant flow rate is low and the heat transfer coefficient is

Table 1 Assembly thermal performance with grid

D_g/cm	Center channel HA/cm^{-1}	Peaking factor		MCST/K
		Outlet temperature	Flow rate	
0.1	5.201	1.170	1.341	997.6
0.3	3.261	1.073	1.241	975.8
0.5	2.352	1.040	1.181	995.1

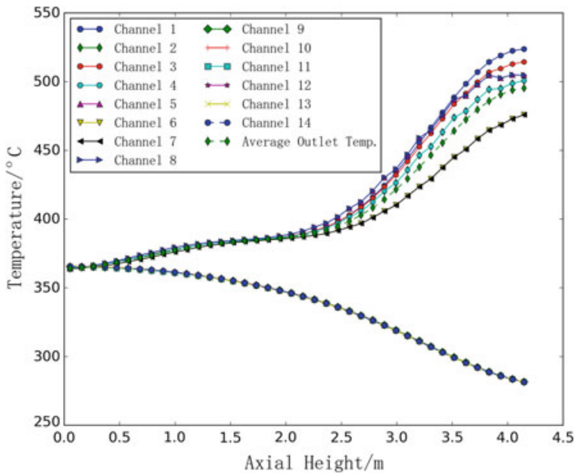


Fig. 8 Axial water temperature distribution of each sub-channel

low. The fuel assembly has better thermal–hydraulics performance when $D_g = 0.3$ cm.

It has been found that when HA ratio of center channel to side channel is equal to 1.2, peaking factor of outlet temperature and flow rate decreases to 1.037 and 1.193, respectively, and MCST decreases to 971.5 K. The axial distribution of coolant and moderator temperature is shown in Fig. 8. The coolant outlet temperature of channels 6 and 7 who have smaller HA is lower than the average value.

The MCST appears at fuel rod No. 4 and 6, the MCST is almost the same because of geometry symmetry. Taking fuel rod No. 4 as an example, the surface temperature of inner and outer cladding is shown in Fig. 9. The cladding temperature is different at different part of fuel rod facing different sub-channel. In Fig. 9, different fuel rod parts are distinguished by the sub-channel number which they are facing. The inner cladding surface temperature is low because of low moderator temperature. The change in external cladding surface temperature is mild because the coolant temperature is near pseudo-critical temperature and the heat transfer coefficient is high. The disturbance of cladding surface temperature is caused by spacer grid. The MCST appears at the top because of axial power distribution. The MCST will decrease after optimization of axial power distribution.

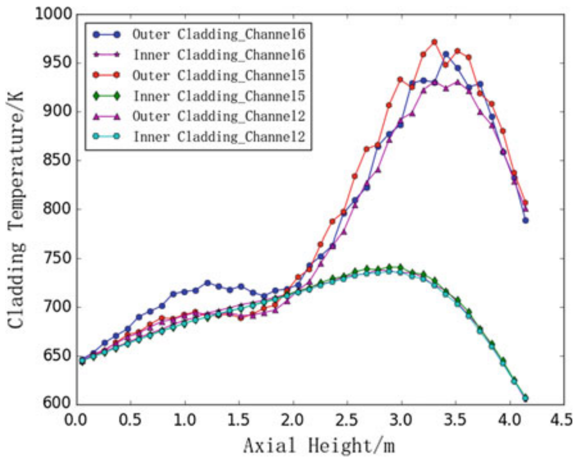


Fig. 9 Axial distribution of inside and outside cladding surface temperature

Table 2 Assembly design parameters

Parameters	Values
Distance between fuel rods D_g/cm	0.30
Distance between fuel rod and assembly box D_{box}/cm	0.15
Number of spacer grid	13
Grid spacing/cm	31.5
Assembly box thickness/mm	1.0

The design of assembly box is referred to HPLWR [9]. The material is stainless steel SS316L, and the thickness is 1.0 mm. Design parameters of the annular fuel assembly is shown in Table 2.

4 Assembly Safety

In order to ensure the assembly and core safety, negative void reactivity effect and negative Doppler reactivity coefficient is required.

By increasing void fraction, void reactivity effects for a fuel assembly change as shown in Fig. 10. It decreases as void fraction and burn-up increase and keeps negative.

The Doppler reactivity coefficient is calculated for a typical fuel assembly at the reference fuel temperature of 1000 K. The change in Doppler reactivity coefficient with burn-ups is shown in Fig. 11. The Doppler reactivity coefficient decreases with increase of burn-up and keeps negative.

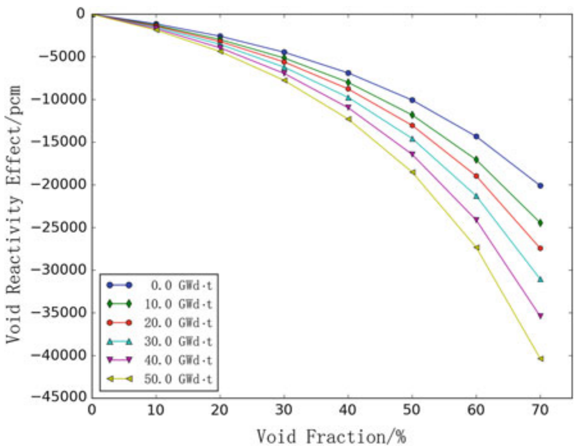


Fig. 10 Changing curves of void effect with void fraction at different burn-ups

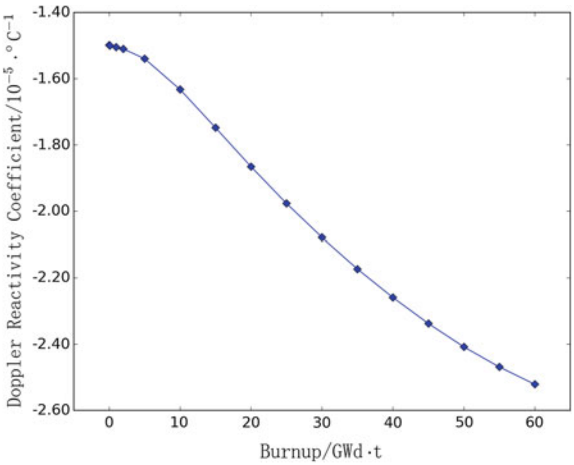


Fig. 11 Changing curve of fuel temperature coefficient with burn-ups

5 Conclusions

Neutronics and thermal–hydraulics performance of annular fuel is analyzed and optimized using three-dimensional coupling code in this study. The results show that increasing of fuel rod gap and gap between fuel rod and assembly box increases increase k_{inf} but it almost does not affect fine power distribution. The heterogeneity of sub-channels causes ununiformed coolant outlet temperature and flow rate, and it makes the MCST higher. The MCST decreases by adding spacer grid. The safety analysis shows that the assembly has negative void reactivity effect and negative Doppler reactivity coefficient; thus, it is safe from the viewpoint of neutronics.

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