Core and Sub-channel Analysis of SCWR with Mixed Spectrum Core

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Abstract

The SCWR core concept SCWR-M is proposed based on a mixed spectrum and consists of a thermal zone and a fast zone. This core design combines the merits of both thermal and fast SCWR cores, and minimizes their shortcomings. In the thermal zone co-current flow mode is applied with an exit temperature slightly over the pseudo-critical point. The downward flow in the thermal fuel assembly will provide an effective cooling of the fuel rods. In the forthcoming fast zone, a sufficiently large negative coolant void reactivity coefficient and high conversion ratio can be achieved by the axial multi-layer arrangement of fuel rods. Due to the high coolant inlet temperature over the pseudo-critical point, the heat transfer deterioration phenomenon will be eliminated in this fast spectrum zone. And the low water density in the fast zone enables a hard neutron spectrum, also with a wide lattice structure, which minimizes the effect of non-uniformity of the circumferential heat transfer and reduces the cladding peak temperature.

The performance of the proposed core, including the neutron-physical and thermal-hydraulic behavior in sub-channel scale, is investigated with coupled neutron-physical/thermal-hydraulic simulation tools, which at the same time enables multi-scale analysis. During the coupling procedure, the thermal-hydraulic behavior is analyzed using a multi-channel code and the neutron-physical performance is computed with a 3-D diffusion code. Based on the core results, the pin-power reconstruction is carried out for each fuel assembly to predict the local pin-power distribution. Moreover, the sub-channel calculation is performed to obtain the thermal hydraulic parameters in each sub-channels and fuel rods. Based on the coupled analysis, measures to improve the performance of the SCWR-M core design are proposed and evaluated in this paper.

The results achieved in this paper have shown that the mixed spectrum SCWR core concept (SCWR-M) is feasible and promising. One reference SCWR-M design is proposed for future analysis.

Keywords*: SCWR (Super-Critical Water Cooled Reactor), core design, mixed spectrum, multi-physics coupling, multi-scale analysis*

1. Introduction

The supercritical pressure water cooled reactors (SCWR) offer high thermal efficiencies and considerable plant simplification and is considered as a logical extension of the existing water-cooled reactors[1]. In the last years, extensive R&D activities have been carried out covering various aspects of the SCWR development. Pre-conceptual core design is an important task among the R&D activities. For the time being, a large number of pre-conceptual designs of SCWR reactor cores have been proposed in the open literatures. Most of the concepts are based on thermal spectrum[2, 3]. Efforts were also made to design SCWR reactor cores with fast neutron spectrum[4].

Fast spectrum reactor cores proposed by Yoo[4] and Yang [5] consist of seed and blanket fuel. Fuel pins are tightly arranged inside fuel assemblies in a hexagonal lattice. The fast spectrum reactor enables higher fuel utilization and higher power density. However, the tight lattice will cause a strong non-uniformity of the circumferential distribution of heat transfer, and subsequently, the cladding surface temperature[5, 6]. Compared to the fast core design, the fuel assembly structure of a thermal reactor core is much more complicated[2, 3], mainly due to the introduction of additional moderator into the core or into the fuel assemblies. And hot-channel factor is another concern which should be taken into consideration in the thermal SCWR[7].

To avoid the serious problems in both mechanical design and safety features, and in the other hand to achieve a high temperature at the reactor exit, a mixed core design with multi-layer fuel assembly has been proposed by Cheng and Liu[7]. The core consists of two zones with different neutron spectrums, one with thermal and the other with fast spectrum. In the thermal zone co-current flow mode is applied with an exit temperature over the pseudo-critical point. The downward flow in the thermal fuel assembly will provide an effective cooling of the fuel rods. As a result, the cladding temperature will be kept at a low value. In the forthcoming fast zone a high exit temperature is achieved. Due to the high coolant inlet temperature over the pseudo-critical point, the heat transfer deterioration phenomenon will be eliminated in this upward flowing area. And the low density in the fast zone can provide a hard neutron spectrum with a wide lattice structure, which can mitigate the non-uniformity of the circumferential heat transfer at the cladding surface and ensure a big inventory of water in the core. Consequently, with a hard neutron spectrum and the multi-layer fuel assembly, a conversion ratio over 1.0 can be achieved.

Investigations are also carried out to perform core and sub-channel analysis. Recently, Waata et al. [8] developed a coupled simulation approach with MCNP and the sub-channel code STAFAS for a fuel assembly analysis. Although this gives detailed local characteristics of the fuel rods and sub-channels, application of the coupling procedure is restricted to one fuel assembly and requires extremely large computational efforts. The non-uniformity of the power and mass flow rate distribution over the reactor core is beyond consideration. This would lead to an underestimation of power generation in the hottest fuel assembly. Yamaji et al. [9] performed a pin-wise power reconstruction within fuel assemblies. Based on the pin-wise power distribution, sub-channel calculation is performed to obtain the detailed coolant and cladding temperatures of the sub-channels and the fuel rods. This approach requires a large amount of neutronic calculations to derive an accurate pin-wise power distribution in the assembly. Liu and Cheng evaluated the cladding peak temperature by a 3-D core coupling calculation[10]. In the first step, each fuel assembly is homogenized for the coupled core analysis of neutronics and thermal hydraulics. Based on the fuel assembly averaged parameters, several fuel assemblies with critical parameters, e.g. highest coolant temperature, are selected for further detailed investigations. In the second step, a coupled analysis of thermal-hydraulics in the sub-channel scale and neutron-physics in the pin-wise scale is then carried out for the selected critical fuel assemblies, in order to determine parameter distribution inside the fuel assembly. The fuel assembly averaged values, such as fuel assembly power, mass flux, and moderator flow rate, are taken from the coupling core calculation. However, in the second step, the reflective boundary condition is applied to the selected fuel assembly neutronic calculation, which will eliminate the non-uniform neutron flux distribution inside the fuel assemblies.

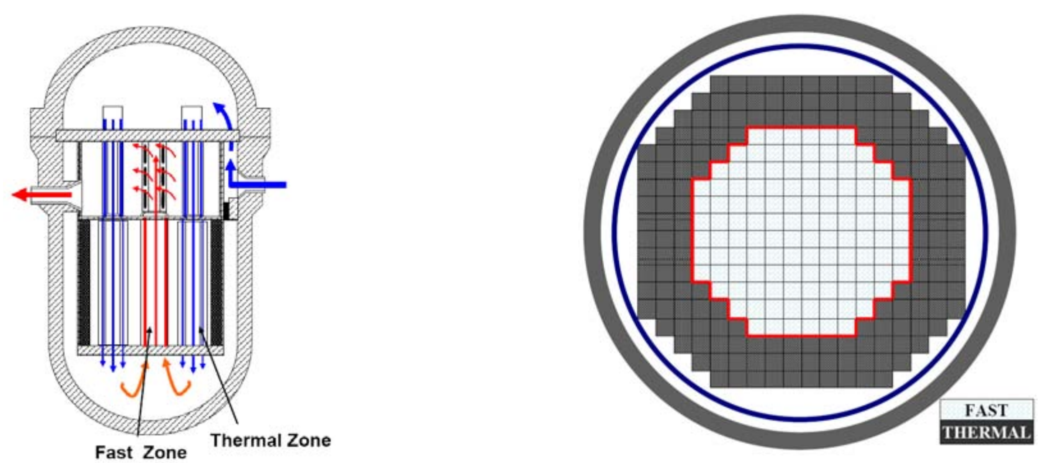
This paper will investigate the main features, including the sub-channel behavior, of the proposed core with 3-D coupled neutron-physical and thermal-hydraulic calculations. A detail discussion of the analysis code system will also be presented in this paper. According to the results obtained, it shows that the mixed spectrum SCWR concept (SCWR-M) is feasible and promising. One SCWR-M design will be recommended for the future study due to its better characteristics.

2. The mixed core design

Figure 1 shows schematically the geometrical arrangement of the proposed mixed core. There are totally 284 fuel assemblies in the core. To simplify the calculation process and to investigate the preliminary character of the mixed core, only the case with fresh fuels is considered in this study. The basic idea is to divide the core into two parts with different neutron spectrums. In the outer zone with 164 fuel assemblies, the neutron energy spectrum is similar to that of a thermal reactor. The inner zone with 120 fuel assemblies has fast neutron spectrum. The average linear power rate is 18 KW/m for both the thermal zone and the fast zone. The active height is 4.5 m for the thermal zone and 2.0 m for the fast zone. The average power density is 90.26 MW/m^3 including blanket fuel and the equivalent core diameter is 3.4m.

In the thermal zone, the co-current flow mode is applied to the fuel assembly. The cold water entering the pressure vessel goes upward to the upper dome and into both the moderator channels and the cooling channels of the thermal zone. In the thermal zone, 25% of the mass flow rate goes through the moderator channels. It exits the thermal zone in the lower plenum, from where it enters the fast zone of the reactor core (the inner zone in Figure 1a).

Table 1 summarizes some main parameters of the proposed mixed core. The water temperature at the inlet of the pressure vessel is 280°C and at the exit of the pressure vessel is 510°C. It is assumed that the water through the thermal zone is heated up to 385-400°C.



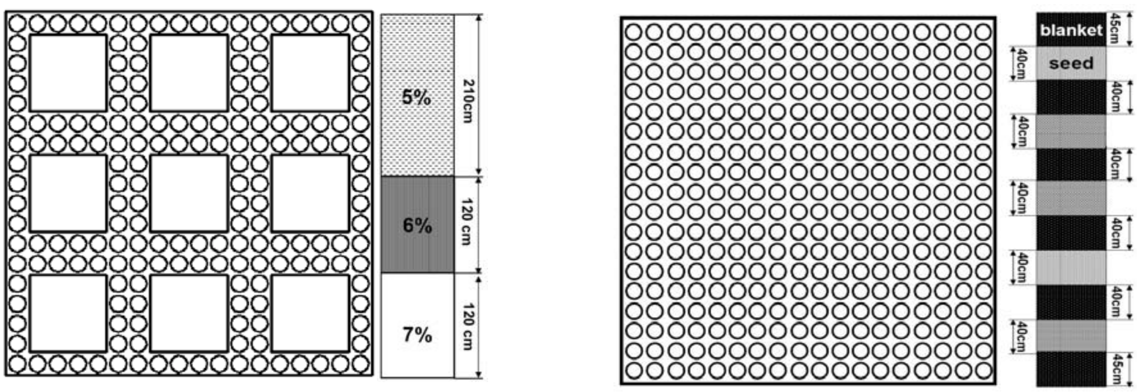
(a) Flow paths in the core (b) Fuel assembly arrangement in the core

Figure 1 Scheme of the SCWR-M core

The selection of the fuel assembly design is derived from an optimization work, which is performed by Yang [11]. For the thermal zone, the basic idea of the multi-layer concept is axially to divide the active length into several layers with different enrichment, schematically illustrated in Figure 2a. For the fast zone, in order to achieve negative void reactivity coefficients, the seed core is designed to be short to increase neutron leakage as schematically shown in Figure 2b. Axial blankets with depleted uranium are also introduced to increase the conversion ratio and to reduce the void reactivity coefficient. The seed and blanket materials are axially divided into 11 layers[11].

Table 1: Main parameters for the proposed SCWR-M

Design parameter	Thermal zone	Fast	Whole core
Thermal power (MW)	2400.0	1400.0	3800.0
Electrical power (MW)	–	–	1650.0
Core height (m)	4.5	2	–
Equivalent diameter (m)	3.4	2.14	3.4
No. of fuel assembly (-)	164	120	284
Fuel rod diameter (mm)	8.0	8.0	–
Pitch to diameter ratio (-)	1.20	1.20	–
Average power density	100.89	75.74	90.26
Flow rate (kg/s)	1927.0	1927.0	1927.0
Moderator fraction (%)	25.0	–	–
Fuel (-)	UO_2	MOX	–
Enrichment (%)	5.0;6.0;7.0	24.0	–



(a) Fuel assembly in the thermal zone (b) Fuel assembly in the fast zone

Figure 2: Reference fuel assembly structures of the thermal zone and the fast zone

3. Analysis methods

As indicated in Figure 3, the flow chart of core calculation is as follows: the preliminary design parameters (e.g. geometry of the fuel assembly, linear heat generation rate, mass flow distribution of coolant and moderator) are firstly set for the core calculation. The coupling method is based on the code developed by Liu and Cheng[12]. At the end of the burn-up calculation, the results will be compared to the design criteria, if the results meet all the design criteria, the calculation terminated; if not, the design parameters will be changed for another core calculation. However, the work of this paper only focuses on the preliminary analysis of an initial core without burn-up to achieve a basic understanding of the SCWR-M core.

At each burn-up point, the pin power reconstruction work will be carried out based on the nodal calculation results. And then, the sub-channel calculation is performed with the 3-D pin-power distribution in the assemblies. Therefore, a detail linear heat generation rate and thermal-hydraulic parameters (mass flux of each channel, cladding temperature on each rod pin) are obtained. The above procedures will be treated several times until satisfactory design parameters are achieved.

Macroscopic cross sections of seven groups (10.0 > group 1 > 1.353 > group 2> 9.118×10^{-3} > group 3> 4.8052×10^{-5} > group 4> 4.0×10^{-6} > group 5> 6.25×10^{-7} > group 6 > 1.0×10^{-7} > group 7 > 1.0×10^{-11}, unite: MeV) are selected for the neutronics calculation. The macroscopic cross sections are given as polynomial functions of the water density, effective fuel temperature and burn-up. The based macroscopic cross section and feedback coefficients are calculated by Dragon code [13]based on WIMS-D4 IAEA library.

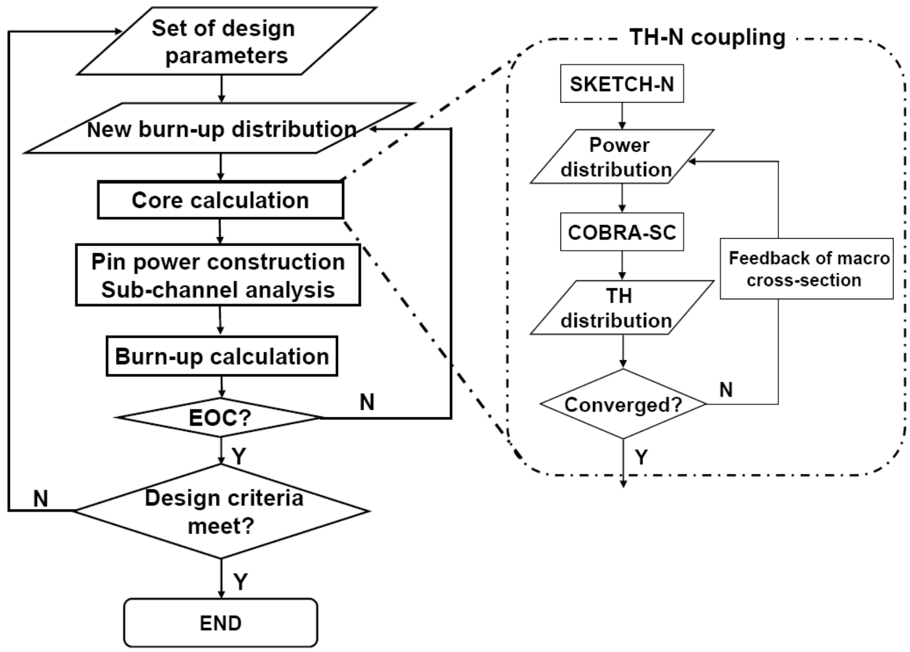


Figure 3 The core design and analysis flow chart

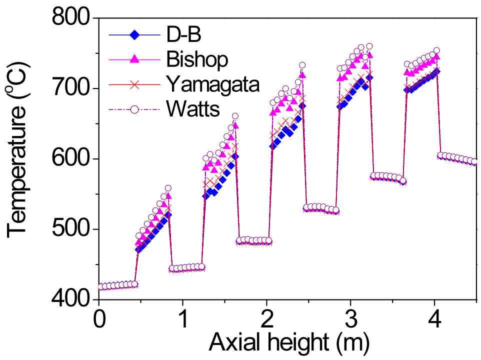
For the neutronics calculation, some validation work is performed by the MCNP code. The calculation area is illustrated in Figure 4: the inner 4 assemblies are fast fuel, whereas the other 12 assemblies are thermal fuel. The thermal and fast fuel assemblies' configuration are the same as the ones in Figure2. Figure 4 shows the assemblies power distribution and its errors between this coupling code system and MCNP. It indicates that the results are acceptable in the conceptual design of the SCWR.

1.173 2.4%	1.114 -1.3%	1.113 -1.2%	1.169 2.8%
1.119 -1.7%	0.598 0.3%	0.596 0.6%	1.107 -0.7%
1.116 -1.5%	0.601 0.2%	0.597 0.4%	1.109 -0.9%
1.180 1.8%	1.117 -1.6%	1.116 -1.5%	1.177 2.1%

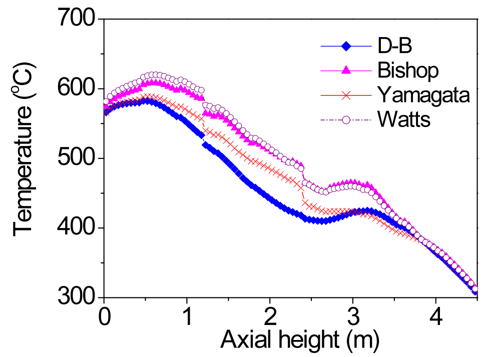
Figure 4 Power and error distribution in each FA (reference: MCNP results)

For the thermal hydraulic analysis, according to hydrodynamic conditions, several heat transfer correlations are selected for both fuel channels and moderator channels[6]. Figure 5 shows the calculated hot fuel rod cladding temperature for both fuel assemblies. Results are obtained using

Dittus-Boelter (D-B), Bishop, Yamagata and Watts correlations. The highest cladding temperature in fast and thermal fuel assemblies are predicted by Watts correlation. As a result, the Watts correlation is selected for the calculation of the heat transfer coefficient between the cladding and coolant.



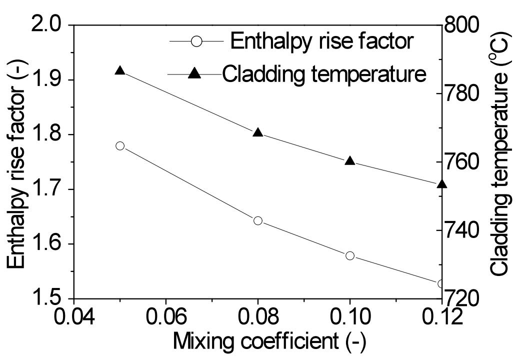
(a) Fast fuel assembly



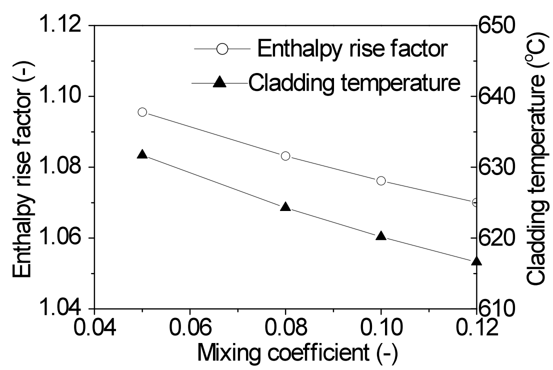
(b) Thermal fuel assembly

Figure 5 The cladding temperature distribution by various correlations

In the present analysis, the turbulent mixing coefficient between adjacent channels is varied in the range from 0.05 to 0.12, to investigate its effect on the calculated sub-channel parameters. Figure 6 presents the enthalpy rise factor and peak cladding temperature by various mixing coefficients (i.e. 0.05, 0.08, 0.10, 0.12). With an increase of the mixing coefficient, the enthalpy rise factor as well as cladding temperature can be reduced significantly for the fast assembly; whereas, this effect is not so obviously in the thermal assembly. For the further sub-channel analysis, the value of 0.10 is taken for the reference value of mixing coefficient.



(a) Fast fuel assembly



(b) Thermal fuel assembly

Figure 6 The hot channel enthalpy rise factor and cladding temperature vs. the mixing coefficient

4. Results of the reference core

4.1 Core results by fuel assembly homogenised

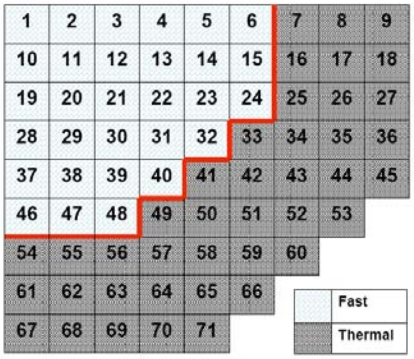


Figure 7 The arrangement of 1/4 core

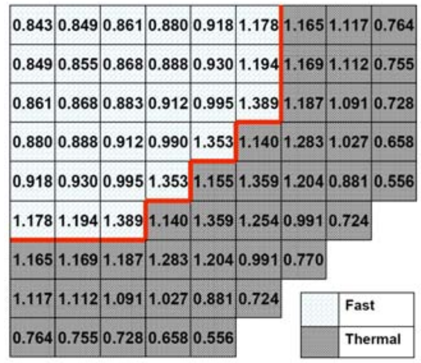


Figure 8 Radial power distribution of 1/4 core

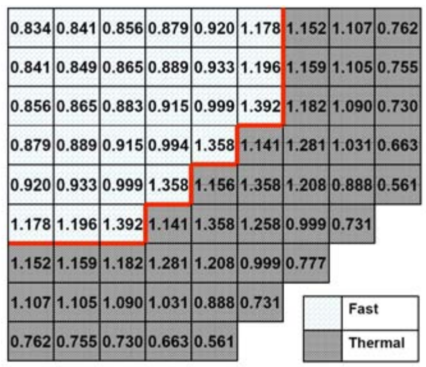


Figure 9 The relative flow rate distribution of 1/4 core

Figure 7 shows the identification numbers of the assemblies in the 1/4 core. It is assumed that the coolant flow rate in each fuel assembly can be adjusted by introducing inlet orifices. Figure 8 presents the radial power distribution of fuel assemblies in the 1/4 core. The relative power of the assemblies near the fast and thermal zone interface is much higher than the others due to the interference effect between the thermal and fast neutrons. Figure 9 shows the coolant flow rate distribution in the 1/4 core. The numbers present the relative coolant flow rate in each assembly. For the thermal zone, the moderator flow fraction is 25%. The coolant flow is assigned to match the power of each assembly to get a relatively uniform coolant outlet temperature of all the fuel assemblies. It should be noted that the relative power peak near to the fast and thermal zone interface is significantly large. As a result, the coolant flow rate in these fuel assemblies is increased in order to reduce the cladding temperature.

Table 2: the core results of the reference SCWR-M

Results	thermal zone	fast zone
Power fraction(-)	0.761	0.239
Inlet temperature (°C)	280.0	414.53
Outlet temperature (°C)	414.53	510.0
Maximum coolant temperature (°C) / fuel assembly No	483.33(FA7)	511.42(FA1)
Maximum moderator temperature (°C)/ fuel assembly No	370.66(FA71)	–
Maximum cladding temperature(°C)/fuel assembly No	536.66(FA42)	564.09(FA24)
Maximum fuel temperature (°C)/fuel assembly No	1718.95(FA42)	1156.32(FA5)
Whole core void reactivity (PCM)	-34892.0	

Table 2 summarized the core results of the reference SCWR-M. During the core calculation, one assembly is treated as one calculation node. As a result, table 2 can only present the average result of each fuel assemblies. At this calculation scale, the maximum cladding temperature is far away from the design limit [2], and the void reactivity of the whole core is negative to ensure the safety of the core.

4.2 Assembly results by sub-channel calculation

In the reference core design, the water density, power distributions are evaluated for homogenized fuel assemblies. In order to carryout the sub-channel analysis of the fuel assemblies in the reference core, the reconstructed pin-wise power distribution is obtained based on the nodal calculation results of each fuel assemblies.

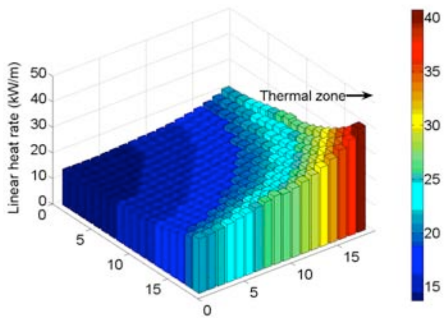


Figure 10 Pin-power distribution of the fuel assembly 24 (at the middle of the core)

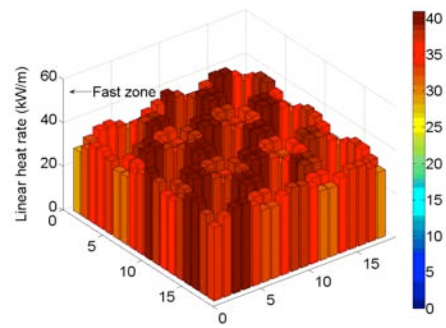


Figure 11 Pin-power distribution of the fuel assembly 42 (at the middle of the core)

Table 3:Sub-channel results of selected assembly

Results	thermal zone	fast zone
Maximum linear heat rate (kW/m)	27.9	40.8
Maximum coolant temperature (°C)	740.0	598.27
Hot channel enthalpy rise factor(-)	1.578	1.579
Maximum moderator temperature (°C)	370.63	-
Maximum cladding temperature (°C)	886.26	760.08
Maximum fuel temperature (°C)	1712.37	1887.23

Figure 10 and Figure 11 present the pin-wise power distribution of fast and thermal fuel assemblies in the middle of the core. The maximum linear heat rate of both fuel assemblies occurs at the interface of the thermal zone and fast zone. All the fuel assemblies are evaluated in the same way. The detail results of the worst fuel assembly are summarized in table 3. These results show that the peak cladding surface temperature of the sub-channel calculation is as large as 200°C higher than that evaluated by assembly homogenized method. This shows the importance of the sub-channel calculation. From the sub-channel calculation results, the cladding temperature is much higher than the design limit (650°C) [2]. Consequently, some improvements should be applied to the current SCWR-M design.

5. Improvement if the SCWR-M core

As discussed in chapter 4, the maximum cladding temperature is much higher than the design limit value. Considering the results and design parameters in the reference SCWR-M, the following 4 measures are introduced to improve the performance of the SCWR-M.

1) The fast and thermal zones are divided into 2 parts with different enrichments. As indicated in figure 12, the outer of the fast zone and the inner of the thermal zone have a lower enrichment fuel to flat the radial power distribution. This will also reduce the interaction effect between the thermal and fast zones.

2) Increase the mass flow rate in the fuel assemblies, which have higher power density and non-uniform pin-power distributions (such as the fuel assembly in the two zones interface), to lower the peak cladding temperature.

3) Reduce the moderator mass fraction from 25% to 20%, to provide a higher coolant mass flux to reduce the peak cladding temperature.

4) Enlarge the clearance of the peripheral fuel rod to 1.5mm, to provide a better coolability of the fuel rods near the assembly wall.

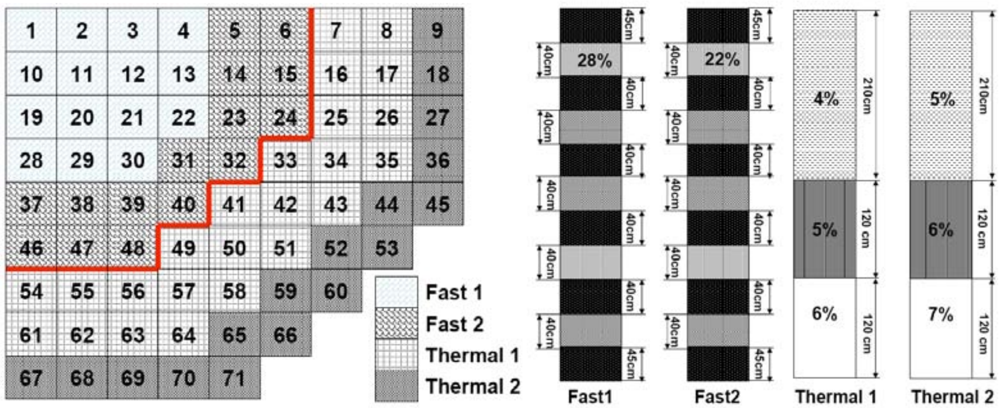


Figure 12 The arrangement of 1/4 improved core

5.1 Core and assembly results

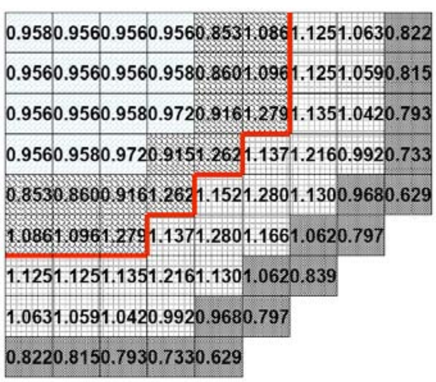


Figure 13 Radial power distribution of the core

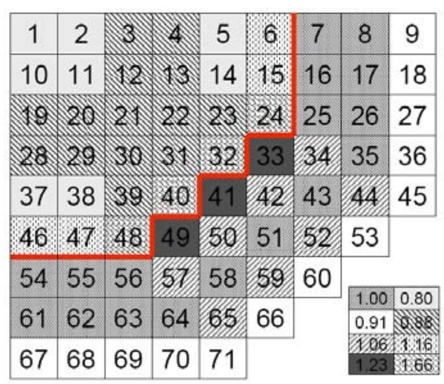


Figure 14 The relative flow rate distribution of 1/4 core

With the improved measures presented in previous chapter, figure 13 and figure 14 show the relative power and mass flow distribution in the 1/4 core. The mass flow fraction in the interface of the thermal and fast zones is much higher than the other fuel assembly.

Table 4 and table 5 summaries the core and sub-channel results of the improved SCWR-M core. For the assembly homogenised results, the cladding temperature is a little higher than the reference core. However, from the sub-channel calculation results point of view, the cladding temperature and other thermal-hydraulic parameter can be reduced significantly.

Table4: the core results of the improved SCWR-M

Results	thermal zone	fast zone
Power fraction(-)	0.730	0.270
Inlet temperature (°C)	280.0	407.7
Outlet temperature (°C)	407.7	510.0
Maximum coolant temperature (°C) / fuel assembly No	372.77(FA42)	-
Maximum moderator temperature (°C)/ fuel assembly No	525.25(FA42)	540.80 (FA1)
Maximum cladding temperature(°C)/fuel assembly No	604.84(FA42)	592.79(FA1)
Maximum fuel temperature (°C)/fuel assembly No	1696.22(FA42)	1168.25(FA24)
Whole core void reactivity (PCM)	-32569.1	

Table5: Sub-channel results of selected assembly

Results	thermal zone	fast zone
Maximum linear heat rate (kW/m)	39.07	39.08
Maximum coolant temperature (°C)	645.87	530.72
Hot channel enthalpy rise factor(-)	1.273	1.517
Maximum moderator temperature (°C)	366.38	-
Maximum cladding temperature (°C)	777.26	680.14
Maximum fuel temperature (°C)	1857.22	1942.06

6. Conclusion

The preliminary assessment of the mixed neutron spectrum SCWR core (SCWR-M) performance is carried out by a coupled neutron-physics/thermal-hydraulics approach with the emphasis on sub-channel behaviour. The results achieved in this paper have shown that the mixed spectrum SCWR core concept (SCWR-M) is feasible and promising. Some improvements are discussed and introduced to the current design. Finally, one SCWR-M design is proposed for future analysis.

7. Acknowledgments

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