SUBCHANNEL AND RADIATION HEAT TRANSFER ANALYSIS OF 54-ELEMENT CANDU-SCWR BUNDLE

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Abstract

In order to improve the fuel utilization for the CANFLEX-ACR-based bundle under SCWR conditions, a significantly different design with 54-element, has been proposed by Boczar et al. on the CCSC-2010 conference. Their calculation illustrates that the reactor physics feasibility of this design. The present paper analyzed its thermal-hydraulics performance with ATHAS code and CATHENA code. The results show that (1) the proposed bundle can meet the thermal hydraulics criteria well at both BOC and EOC; (2) the bundle can remove 2% full power only through radiation heat transfer to passive moderator.

1. Introduction

The Supercritical Water Reactor (SCWR), which has a simpler and more compact system, achieves a higher thermal efficiency compared to currently existing LWRs and HWRs, and uses the experiences from commercial supercritical fossil-fired power plant, has been selected as one of the 6 candidates of 4th generation nuclear power plant.

The CANDU system projected for the longer-term (2025–2060)[1] is a Supercritical Water Reactor (SCWR) system that offers advantages in the areas of sustainability, economics, safety and reliability and proliferation resistance. The SCWR CANDU concept is being developed for several applications, such as hydrogen production, steam applications such as extraction of oil from oil sands, process heat, desalination, etc.

The key component required for CANDU-SCWR is the high efficiency channel (HEC). As currently envisaged, the HEC design combines both the calandria and pressure tubes into a single tube insulated on the inside by a suitable insulator. This channel design ensures that the operating temperature is close to that of the moderator. An alternate design employs a re-entrant flow path which ensures that the PT operates at a temperature close to the inlet temperature. In both designs, the PT surface temperature is low enough to allow the use of conventional zirconium-based alloys.

It is well known that the decay heat can be discharged to the large passive heat sinks, such as a separate low temperature and low pressure moderator via radiation and natural convective heat transfer during a LOCA+ECCS unavailable accident in the CANDU serial design, which has always been a great advantage for CANDU reactors. The improved channel design allows the use of a passive system to cool the moderator with significant enhancement to the moderator role as a passive safety system.

In order to improve the fuel utilization for the CANFLEX-ACR-based bundle under SCWR conditions, a significantly different design with 54-element, has been proposed by Boczar et al.[2] on the CCSC-2010 conference. Their calculation illustrates that the reactor physics feasibility of this design, while its thermal-hydraulics capability remains unknown, such as peak cladding temperature, radiation heat transfer capability under LOCA+NO ECCS.

The major concerns of this study are: (1) Subchannel analysis of new designed bundle (hot channel and average channel) to make sure the peak cladding temperature is below the limiting criteria at BOC and EOC condition; (2) at certain decay heat power levels, what the maximum cladding temperature could be, in case that in late phase of LOCA+ECCS unavailable accident; (3) effect of insulator conductivity, natural circulation heat transfer coefficient of moderator on the radiation heat transfer.

2. Bundle description

The modified bundle design has 54 fuel elements, a fuel bundle radius of 6.4 cm (vs 5.0 cm with CANFLEX-ACR), and a large centre pin to displace coolant. Figure 1 shows the REC design, which is very similar in design to the HEC design, differing by the presence of a small coolant annulus (nominally 3 mm thick) adjacent to the pressure tube in the REC design,

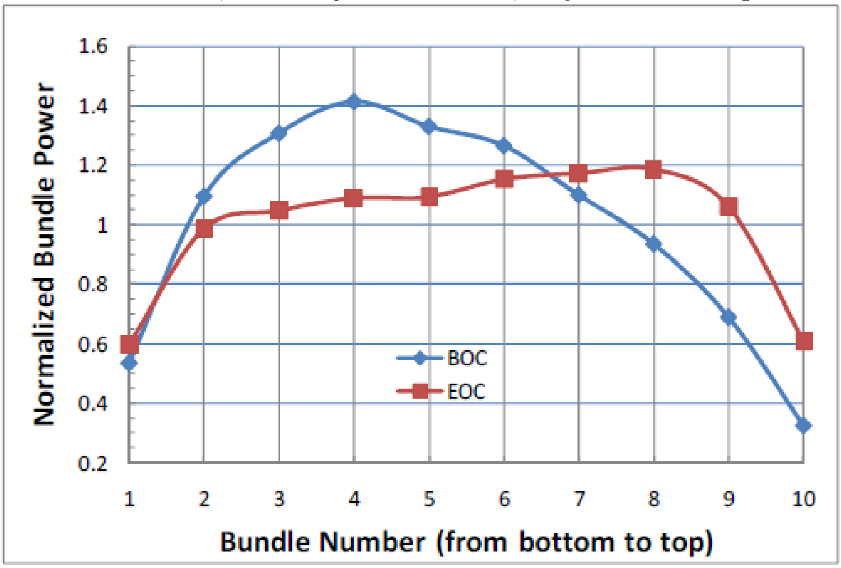

Figure 2 RFSP-calculated normalized bundle power for the channel with maximum channel power

Table 1 lists the important parameters of this kind of bundle. In this study, the HEC design is selected. Table 2 lists flow conditions employed in the current analysis. The channel power is also listed in the table. The axial power distribution (at BOC and EOC) is shown in Figure 2.

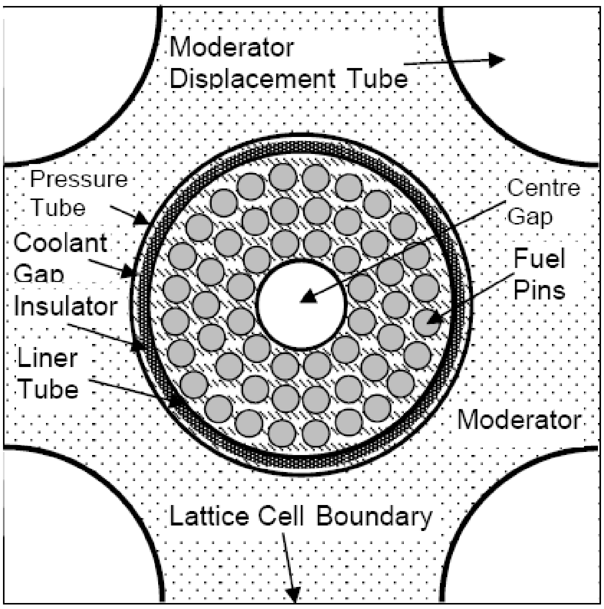

Figure 1 Schematic of the modified REC design

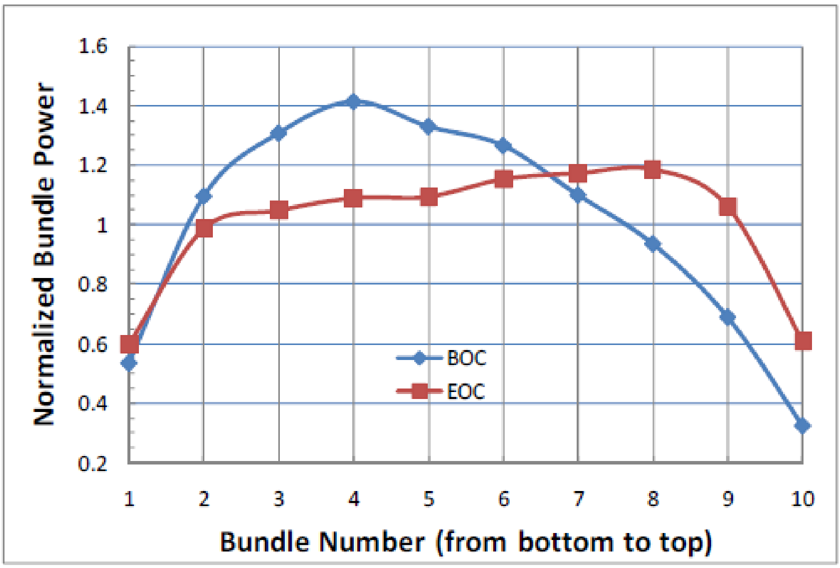

Figure 2 RFSP-calculated normalized bundle power for the channel with maximum channel power

Table 1 Specifications of the lattice parameters for the reference REC design with a larger fuel bundle size and moderator displacement tubes

Parameter	Value
Lattice Pitch	27 cm
Elements per bundle	55
Elements in rings 1, 2, 3	12, 18, 24
Pitch circle radius, ring 1	2.88 cm

Pitch circle radius, ring 2	4.33 cm
Pitch circle radius, ring 3	5.80 cm
Radius of central pin	1.9 cm
Outer radius of central pin cladding	2.0 cm
Radius of pins in ring 1, 2 and 3	0.61 cm
Outer radius of ring 1, 2 and 3 pin	0.64 cm
Liner Tube inner radius	6.8 cm
Bundle length	49.5 cm
Liner Tube thickness	0.1 cm
Insulator inner radius	6.9 cm
Insulator thickness	0.5 cm
Outer coolant layer thickness	0.3 cm
Pressure tube inner radius	7.7 cm
Pressure tube thickness	0.9 cm
Moderator displacement tube inner	7.12 cm
Moderator displacement tube	0.08 cm

Table 2 Reactor operation parameters

Parameters	Values
Coolant inlet pressure	25 MPa
Coolant inlet temperature	350 °C
Coolant exit temperature	625 °C
Average coolant mass flux	671.81kg/(m^2·s)
Channel power	8.467 MW

3. Subchannel analysis

ATHAS code[3] is selected as subchannel analysis tool. The ATHAS code is applicable for transient and steady state calculations derived from basic transient conservative equations. Due to the lack of relevant experimental data for subchannel parameters, a literature survey of heat transfer, hydraulic resistance, and turbulent mixing at supercritical pressures has been performed to compile applicable correlations for implementation into the code. In addition, a 3-D heat conduction model has been implemented to establish the cladding temperature. The code has been verified with other subchannel codes (such as STAFAS, modified VIPRE), and applied to analyzed the CANFLEX bundle at supercritical condition.

A calculation case has been established to analyze the subchannel characteristics of the 54-rod CANDU bundle under supercritical conditions. It is based on the following options: (1) Heat transfer correlation: Jackson correlation[4], (2) Turbulent mixing model: Rowe and Angle model [5] for the gap-to-diameter ratio of 0.149, (3) Flow resistance correlation: Blasius equation[6], (4) 3-D heat conduction is considered in the calculation of cladding temperature.

Table 3 illustrates the thermalhydraulics result of hot channel and average channel. The peak channel power factor is 1.19 at BOC and 1.15 at EOC[2]. The mass flux of hot channel is assumed to be ideally increased to meet the inlet/outlet coolant temperature. It can be seen that the peak cladding temperature for all cases (normalized and hot channel; BOC and EOC) are all well under the limiting criteria. The peak temperature at EOC is larger than that at BOC is because of axial power profile. The power profile is more flatten at EOC than at BOC, so the power is much larger in the outlet half region.

Table 3 Comparison of normalized and hot channel bundle

Peak cladding temperature, °C	BOC, normalized	753
	EOC, normalized	800
	BOC, hot channel	761
	EOC, hot channel	808
Outlet coolant temperature difference between maximum and minimum temperature, °C	BOC, normalized	46
	EOC, normalized	50
	BOC, hot channel	49
	EOC, hot channel	48

4. Radiation heat transfer

In the study, radiation heat transfer analysis of this new concept has been carried out with CATHENA code [7].

Assumptions of the key model parameters are given in

Table 4.

Table 4 Key parameters and boundary conditions

Outside of pressure tube	Heat transfer coefficient 600 W/m²/°C	
	Temperature 80 °C	
Inside of centre pin	Thermally insulated	
Rated power	2540 MW	
Decay Heat	1%, 2% and 3% of rated power, respectively	
Surface emissivity	Liner tube	0.34

	Center pin	0.34
	Fuel pin	0.8

As shown in the above table, the moderator temperature is set to 80 °C, and the inside of center pin is set as thermally insulated because all the coolant in the system is supposed to have evacuated completely.

4.1 View Factor Matrix model description

CATHENA GEOFAC code [8] has been applied to generate the View Factor Matrix of the model. The View Factor Matrix, as shown in the Figure 3, is generated in such a way that all the symmetric conditions can be met: the liner tube and insulator and center pin are divided circumferentially into 24 and 12 sectors, respectively, and every sector faces one fuel pin, while all the fuel pins are divided into 6 sectors, one of which faces the center of the bundle accurately.

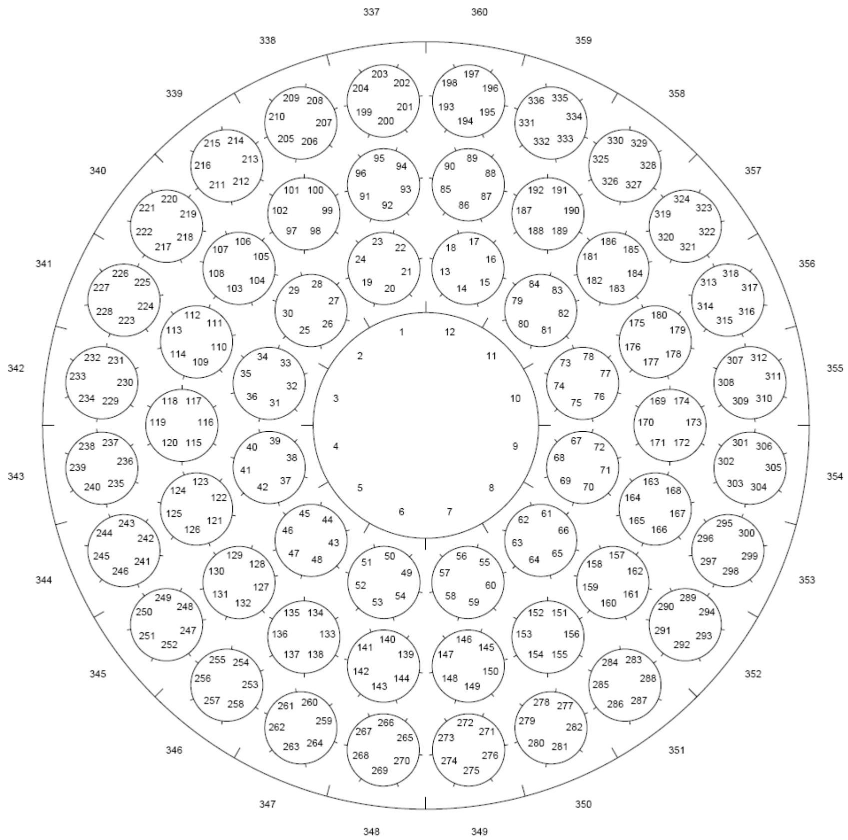

Figure 3 View Factor Matrix generated with GEOFAC

Generally speaking, more sectors the model is divided into, the more precise the prediction of the temperature distribution would be, while the increase of the sector numbers would also increase the complexity of the analysis. Thus, we have generated the View Factor Matrix as mentioned above.

Axial power distribution has not been considered in our model, because the CATHENA code is not capable to carry out such 3-D-radiation calculations, and no axial conduction is assumed.

4.2 Results analysis

A CATHENA model for a post-blowdown fuel channel analysis has been developed.

The reference case is defined as: (1) power level: 2%; (2) conductivity of insulator: 2 W/(m°C); (3) heat transfer coefficient: 600 W/(m^2°C). The reasons of selecting those data are (1) According to Torgerson's result [1], the conductivity o insulator should be larger than 2 W/(m°C) to ensure the capability of radiation heat transfer; (2) the range of the heat transfer coefficient of natural circulation with water is 200-1000 W/(m2°C)[9].

Different cases are also analyzed as sensitivity analysis, such as different conductivity of insulator (1, 2, 3 W/(m°C)), different heat transfer coefficient of natural circulation (200,600,1000 W/(m2°C)) , and different power level(1%, 2% and 3%).

The temperature distributions and maximum cladding temperature are our main concern, which may determine the feasibility of radiation heat transfer from bundle to moderator. Different stainless steel has different melting point, normally 1399 ~ 1455 °C, so the limiting criteria should be about 1350°C.

4.2.1 Analysis of reference case

The cladding temperature is the most important parameter we need to focus on. Table 5 shows the cladding temperature in each ring. Because sector 2 is the innermost sector and sector 5 is outmost sector (as shown Figure 4), so the cladding temperature at sector 2 is highest and that at sector 5 is lowest. The highest temperature is 1391°C, which occurs at sector 2 in ring 1.

The highest temperature is slightly higher than limiting criteria, however, the calculation is based on the conservative assumption, that is only radiation heat transfer is considered, and the natural convective heat transfer with steam is ignored. So the highest temperature will be acceptable if natural convection is considered.

Table 5 Result of reference case

Sector	Center rod	Ring 1	Ring 2	Ring3
1	1383	1387	1333	1215
2	1383	1391	1349	1239
3	1383	1386	1332	1213
4	1383	1368	1284	1135

5	1383	1362	1270	1108
6	1383	1368	1284	1136

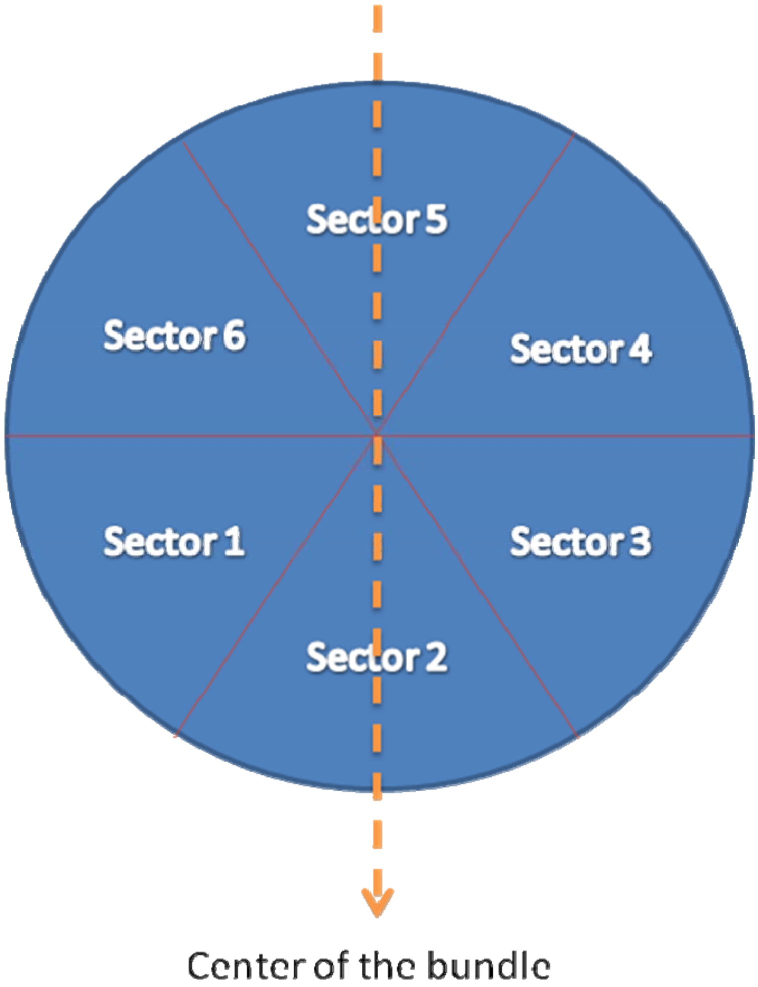

Figure 4 Illustration of sectors

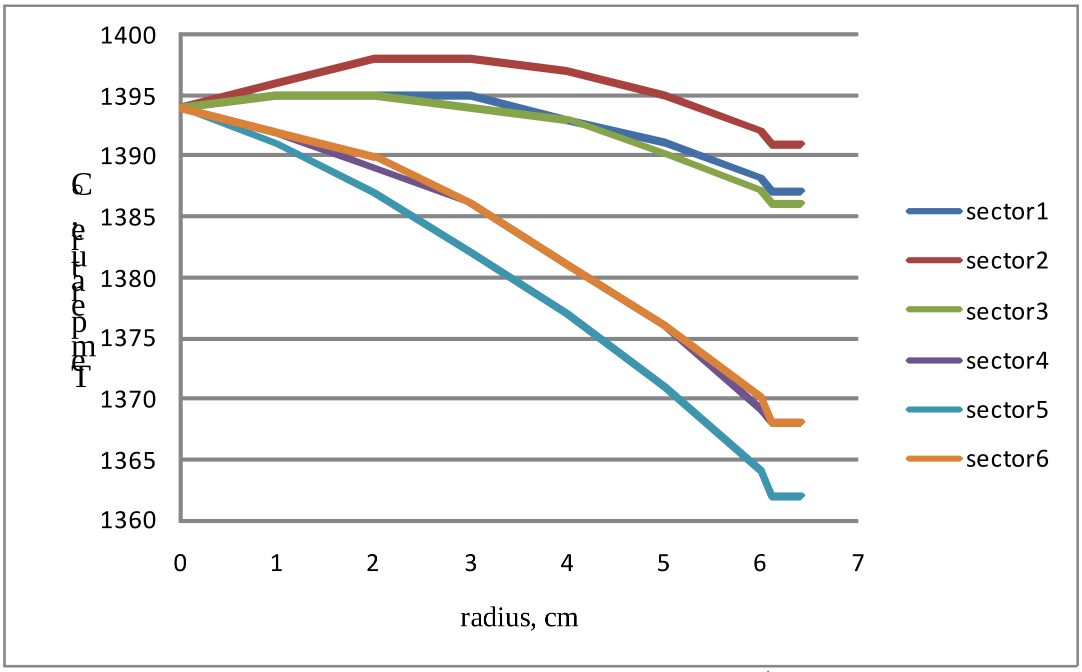

Figure 5 Temperature distribution of the 1st ring pins

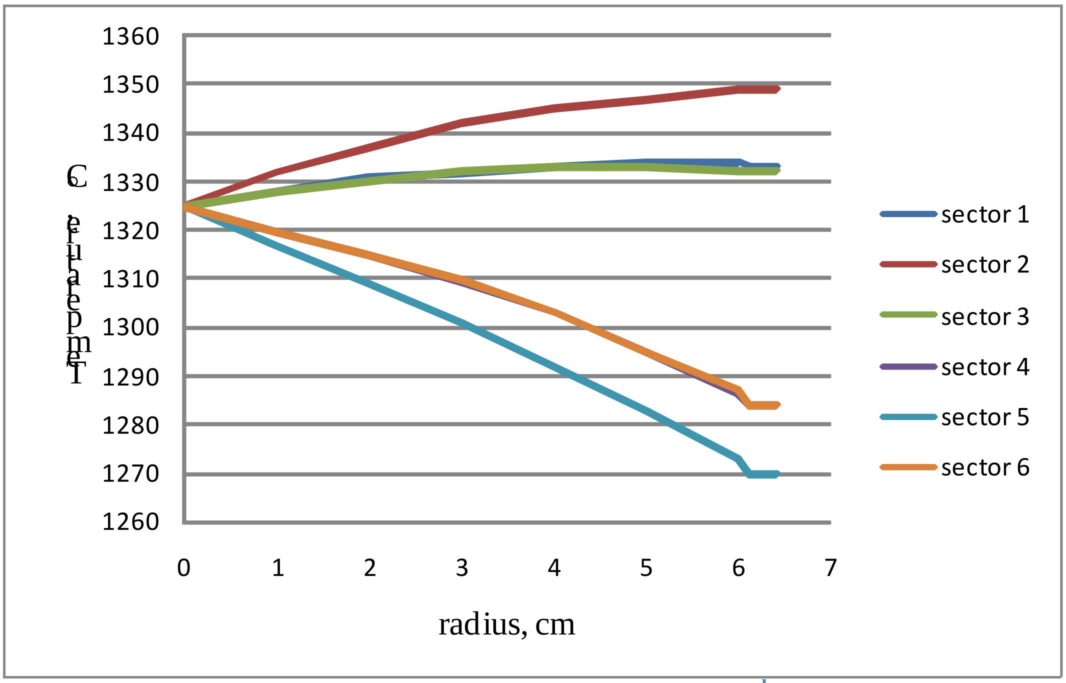

Figure 6 Temperature distribution of the 2nd ring pins

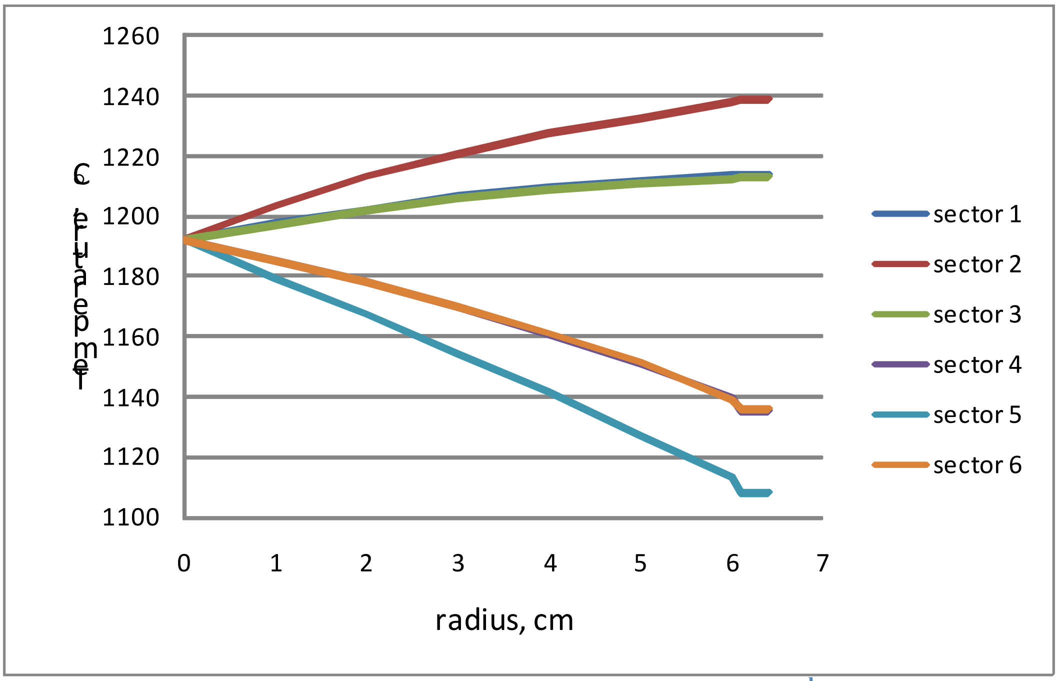

Figure 7 Temperature distribution of the 3rd ring pins

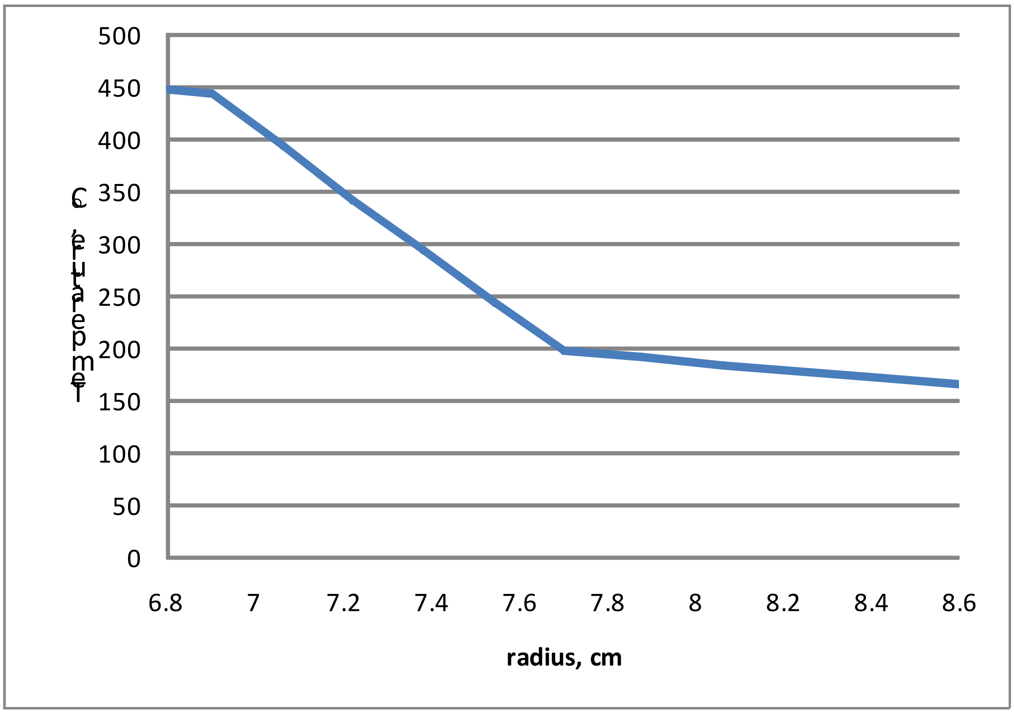

Figure 8 Temperature distributions of the liner/insulator/pressure tube

Figure 5 to Figure 8 show the fuel temperature distribution in different ring and liner/ insulator/ pressure tube. The radial temperature distribution is not similar to traditional distribution, which is because of highly non-uniform cladding circumferential temperature. As shown in Fig.6, the cladding temperature of the sectors of 1, 2 and 3 is much higher than fuel temperature, which means that there exists strong circumferential conduction in those elements. The highest fuel temperature is 1398°C, which is much lower than the melting point.

4.2.2 Effect of Power

Table 6 shows the cladding temperature profile in different sectors of ring 1 under 3 different power level (1%, 2% and 3%), the calculation keeps the insulator conductivity and heat transfer coefficient constant, which are same as reference case.

The highest temperature will be as high as 1600°C, which is not acceptable for stainless steel, so it can be concluded that this new design can not remove 3% full power only with radiation heat transfer.

Table 6 the cladding temperature profile in different sectors of ring 1 under 3 different power level

Sector	1%	2%	3%
1	1073	1387	1619
2	1076	1391	1624
3	1073	1386	1617
4	1063	1368	1592
5	1060	1362	1585
6	1063	1368	1592

4.2.3 Effect of insulator conductivity

Table 7 shows the cladding temperature profile in different sectors of ring 1 with 3 different insulator conductivities (1, 2 and 3 W/m °C), the calculation keeps the power level and heat transfer coefficient constant, which are same as reference case.

The results show that the conductivity will not have very large influence on cladding temperature. The highest temperature will be as high as 1432°C, which is acceptable if the natural convective heat transfer of steam is considered.

Table 7 cladding temperature profile in different sectors of ring 1 under 3 different insulator conductivities

Sector	K=1	K=2	K=3
1	1428	1387	1379
2	1432	1391	1384
3	1427	1386	1378
4	1409	1368	1360
5	1403	1362	1354
6	1409	1368	1360

4.2.4 Effect of natural circulation heat transfer coefficient

Table 8 shows the cladding temperature profile in different sectors of ring 1 under 3 different heat transfer coefficient (200, 600 and 1000 W/m^2 °C), the calculation keeps the power level and insulator conductivity constant, which are same as reference case.

The results show that the heat transfer coefficient will not have very large influence on cladding temperature. The highest temperature will be as high as 1416°C, which is acceptable if the natural convective heat transfer of steam is considered.

Table 8 cladding temperature profile in different sectors of ring 1 under 3 different heat transfer coefficient

Sector	h=200	h=600	h=1000
1	1412	1387	1383
2	1416	1391	1388
3	1411	1386	1382
4	1393	1368	1364
5	1387	1362	1358
6	1393	1368	1364

5. Conclusion

The thermal-hydraulics performance is analysed with subchannel analysis code ATHAS and safety analysis code CATHENA.

The results show that

(1) The proposed bundle can meet the thermal hydraulics criteria well at both BOC and EOC. For BOC, the maximum cladding temperature of hot channel is 761 °C. For EOC, the maximum cladding temperature of hot channel is 808°C. The peak temperature at EOC is larger than that at BOC is because of axial power profile. The power profile is more flatten at EOC than at BOC, so the power is much larger in the outlet half region.

(2) A radiation heat transfer capability of 54-element CANDU-SCWR bundle was analysed with conservative assumption of ignoring natural convective heat transfer of superheated steam. The design can remove about 2% full power to moderator with radiation heat transfer; Power level has large influence on peak cladding temperature, it is hard to remove 3% full power to moderator with radiation heat transfer; The effect of insulator conductivity and heat transfer coefficient is not very large.

6. REFERENCE

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