OPTIMISATION OF CANFLEX-SCWR BUNDLE THROUGH SUBCHANNEL ANALYSIS

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Abstract

A subchannel code ATHAS has been developed to analyze the behavior of CANFLEX®1 bundle. The code includes a relatively large number of correlations for heat transfer, hydraulics resistance, mixing calculations as options and hence is applicable for detailed sensitivity analyses. CANFLEX bundle is appropriate for use in the CANDU®2-SCWR with radial power uniform distribution. The PCST is much lower than the design limit of cladding surface temperature 850°C. The optimization design is preliminary performed, the results show that the bundle can be optimized with modification of geometry and vertical arrangement, the coolant and cladding temperature distribution is more uniform than those before modification and the highest cladding temperature can be reduced to 727°C. The gap effect on heat transfer is also discussed. The gap effect in optimized bundle seems can be neglected.

1. Introduction

The super-critical water-cooled reactor (SCWR) is essentially a pressurized water reactor operating above the thermodynamic critical point of water (T_c=647.1K, P_c=22.06 MPa). It is considered as one of the most promising Generation IV reactors because of its simplicity, high thermal efficiency, and nearly fifty years of industrial experience from thermal-power stations with a SCW cycle [1]. Evolving from the existing designs, there are currently two types of SCWR concepts: (a) a large reactor pressure vessel containing the reactor core heat source, analogous to conventional PWRs and BWRs, and (b) distributed pressure tubes or channels containing fuel bundles, analogous to conventional CANDU and RBMK nuclear reactors. The design of CANDU SCWR aims at cost reduction and improved safety, as compared to the existing fleet of CANDU reactors.

A relatively large amount of researches in Japan and European Union have been focusing on the pressure-vessel type of SCWR design. Oka [2] summarized design concepts of SCWR and proposed the concept of once-through cycle, supercritical pressure, light-water-cooled reactors [3], [4]. Heusener et al. [5] proposed a different conceptual design of the SCWR. Both concepts of Oka and Heusener are thermal reactors, Yoo et al. [6] introduced a separate concept based on the fast reactor design. Russia and Canada have been focusing on the pressure-tube design of the SCWR [7]. The pressure-tube design eliminates the need of a thick wall vessel. In principle, this design has the key features for improving safety and

[1] CANFLEX – CANDU Flexible (a registered trademark of AECL and Korea Atomic Energy Research Institutes).
[2] CANDU – Canada Deuterium Uranium (a registered trademark of AECL).

performance: passive heat removal, multi-pass reactor flow, flexible fuelling strategy, and flat power and temperature distributions in the core.

Since supercritical pressure water is single phase over all operation temperatures, there is no phenomenon associated with burnout or dryout along the fuel rod, unlike in current light water reactors. For this reason, peak cladding surface temperature (PCST) has been a crucial design criterion rather than Departure from Nucleate Boiling Ratio (DNBR) or Critical Power Ratio (CPR) to avoid cladding overheating over the fuel lifetime. Cladding surface temperature distribution is normally dependent on the flow distribution in subchannels and radial power distribution. The flow distribution in SCWR is much different from subcritical water-cooled reactors due to the characteristics of the supercritical water thermo-physical properties and the subchannel heterogeneity will exist. These factors have a strong impact on the PCST and consequently the operation performance. The flexibility of the CANDU fuel design allows the implementation of different fuel configurations and changing the fuel geometry to maximize the fuel performance. The objective of this paper is to present the result of the optimisation of the conceptual CANDU-SCWR fuel design through the subchannel analysis.

2. Subchannel Analysis Code ATHAS

The subchannel code 'ATHAS' has been developed at the Xi'an Jiaotong University (XJTU) with the support of AECL [8]. Figure 1 illustrates the evaluation scheme of the code. After initialising all parameters, the code reads in the subchannel configuration of the bundle, initial and boundary conditions (i.e., pressure, mass flow rate, coolant inlet temperature, and power), and power distributions. The calculation starts with the "outer iteration" to solve the momentum, mass, and energy equations based on assumed flows in all subchannels. Separate iterations are required to solve the mass and energy equations (referred as the "continuity iteration in Figure 1). The outer iteration is considered complete after both the axial flow and energy convergences have been achieved. Calculated results are provided and the calculation terminates in steady-state analyses or proceeds to the next time step in transient analyses.

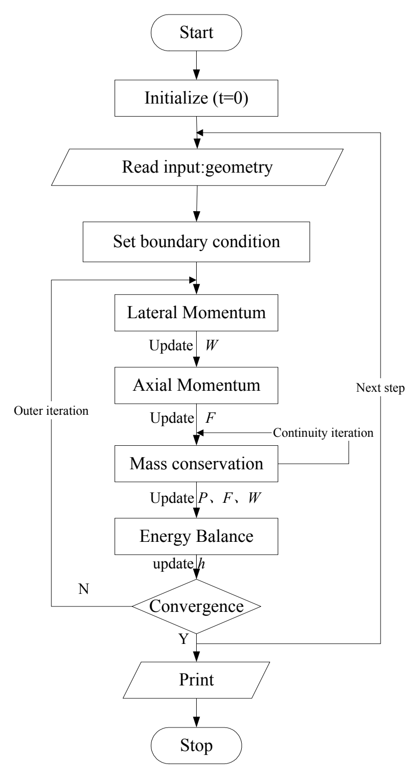

Figure 1 Evaluation Scheme of ATHAS Subchannel Code.

The code has been developed on the basis of mass, energy, and momentum (lateral and axial directions) conservative equations. Besides, closure relationships are required to facilitate the calculations. These relationships capture the heat transfer and hydraulic resistance between the supercritical fluid and cladding surfaces, and turbulent mixing between subchannels.

The validation of ATHAS code has been carried out by Shan et al [10] after comparing some existing subchannel codes for supercritical condition, such as STARS (Japanese code), STAFAS (German code), VIPRE-W (USA code), the results showed good agreement with those codes for different SCWR types.

3. Subchannel Analysis of A CANFLEX Bundle

The preliminary design of the CANDU SCWR fuel has been initiated, but the bundle geometry and fuel composition have not been established. Therefore, the current CANLFLEX bundle has been adopted to facilitate the current analysis.

3.1 Fuel Assembly Configuration

Figure 2 illustrates the CANFLEX bundle configuration including the rod and subchannel identifications. The rods are arranged in 4 rings. Elements in outer two rings have an outer diameter of 11.52 mm and those in the inner ring and the centre rod are 13.53 mm. The inner diameter of the pressure tube is 104.1 mm. Table 1 lists dimensions of the bundle and the calculated flow area.

Table 1 Fuel Geometry Parameters

Parameters	Values
Element diameter	13.53/11.52 mm
Element length	643.9 cm
Element heated length	643.9 cm
Pressure-tube diameter	104.1 mm
Overall flow area	37.09 cm^2

The following assumptions have been implemented to facilitate the analysis:

- No segmentation (i.e., the heated length of the element is the same as the overall length).
- Impact of appendages on heat transfer is neglected.
- Symmetric cosine axial-power profile (the coolant has less effect on the neutronics due to coolant bi-directional flow in adjacent bundles and separation of coolant and moderator).

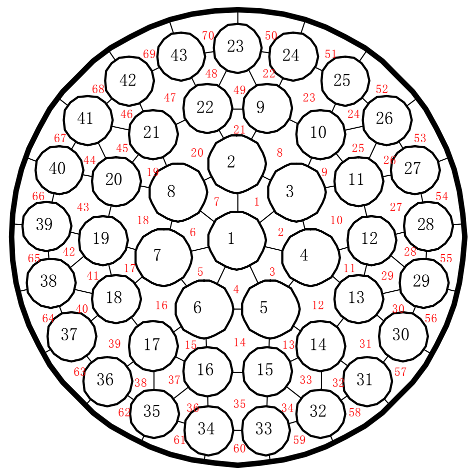

Figure 2 Subchannel Identification in a CANFLEX fuel bundle.

- Uniform radial power profile. This assumption is due to lack of detail neutronic design of SCWR.

Table 2 lists flow conditions employed in the current analysis. These flow conditions have been introduced to test the code and differ from those proposed for the CANDU-SCWR [7]. Relevant flow conditions will be applied in subsequent phases.

Table 2 Reactor operation parameters in Current Analysis

Parameters	Values
Coolant inlet pressure	25 MPa
Coolant inlet temperature	350°C
Coolant exit temperature	625°C
Limit of cladding temperature[7]	850°C

3.2 Reference Case

A reference case has been established to analyse subchannel characteristics of the CANFLEX bundle under supercritical flow conditions. It is based on the following empirical equations options:

- Heat transfer correlation: Bishop 1964 correlation,
- Turbulent mixing model: Rowe and Angle model for the gap-to-diameter ratio of 0.149,
- Flow resistance equation: Blasius equation.

A sensitivity study of heat-transfer correlations, turbulent mixing models, and flow resistance equations on peak cladding surface temperature predictions has been examined [9].

Figure 3 illustrates the coolant temperature and maximum cladding-temperature distributions at the outlet of the fuel bundle. The location of maximum cladding temperature, however, is just after the axially central position (due to the non-uniform axial power profile). The highest coolant temperature is 692.56°C at Subchannel 35, while the lowest is 538.74°C at both Subchannel 55 and 65. Temperature gradients have been observed between top and bottom elements, and side elements. Circumferential temperature distributions are relatively small at rods in the inner and middle rings, but increase at outer-ring rods. Temperature differences at outer-ring rods are due to the assumed cold pressure-tube temperature, reducing the coolant temperature in subchannels.

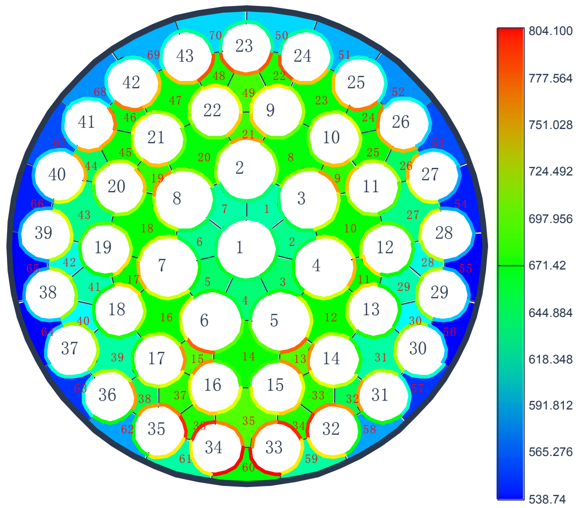

Figure 3 Distributions of Maximum Cladding Surface Temperatures and Outlet Coolant temperature.

Figure 4 shows axial variations of predicted mass flux at various subchannels along the bundle. The variation of mass flux in subchannels at each node is attributed to differences in hydraulic diameters. The axial mass-flux variation is relatively drastic in these subchannels. This is attributed to the drastic variations of density and viscosity leading to sharp changes in pressure drop as the bulk temperature in the subchannel reaches the pseudo-critical temperature. The mass flux redistributes after the pseudo-critical point when the bulk-temperature difference increases.

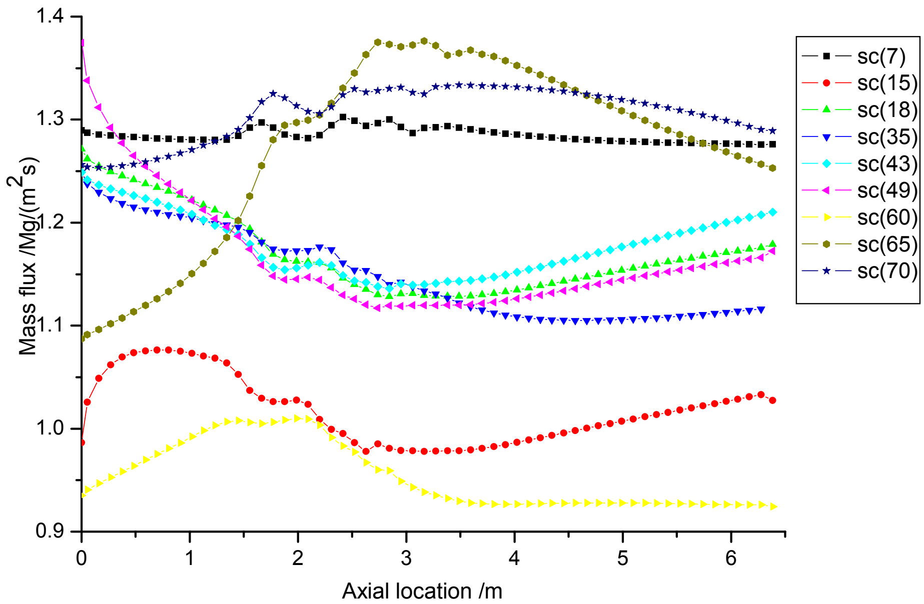

Figure 4 Subchannel Coolant Mass Flux Distribution along Axial Nodes.

Figure 5 shows the coolant temperature distribution of typical subchannels along the axial nodes. The subchannel temperature distribution is almost uniform prior to the pseudo-critical temperature. Beyond this point, the temperature difference between the cool and hot subchannels increases reaching a maximum of 153.82°C.

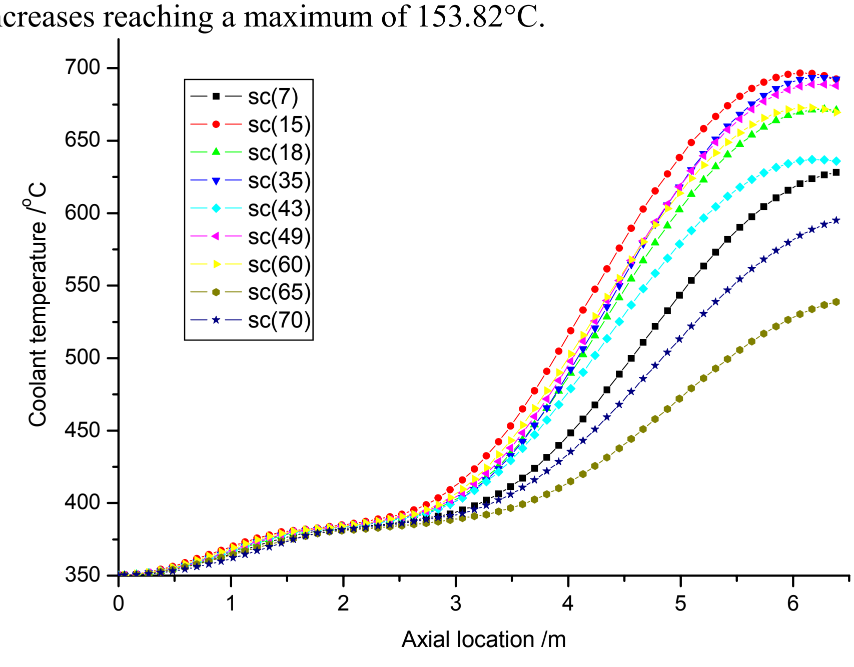

Figure 5 Subchannel Coolant Temperature Distribution Along Axial Nodes.

Figure 6 illustrates cladding-surface-temperature distributions at typical subchannels along the bundle. The surface temperature increases generally along the bundle, reaching a maximum at locations close to the downstream end, and decreases afterward. This maximum temperature location corresponds mainly to the power and flow variations. The maximum predicted surface temperature is 804.1°C at Rod 33 facing Subchannel 60. These rods are located in the outer ring of the bundle (where the local power is the highest) while the Subchannel 60 has a relative higher temperature than other channels.

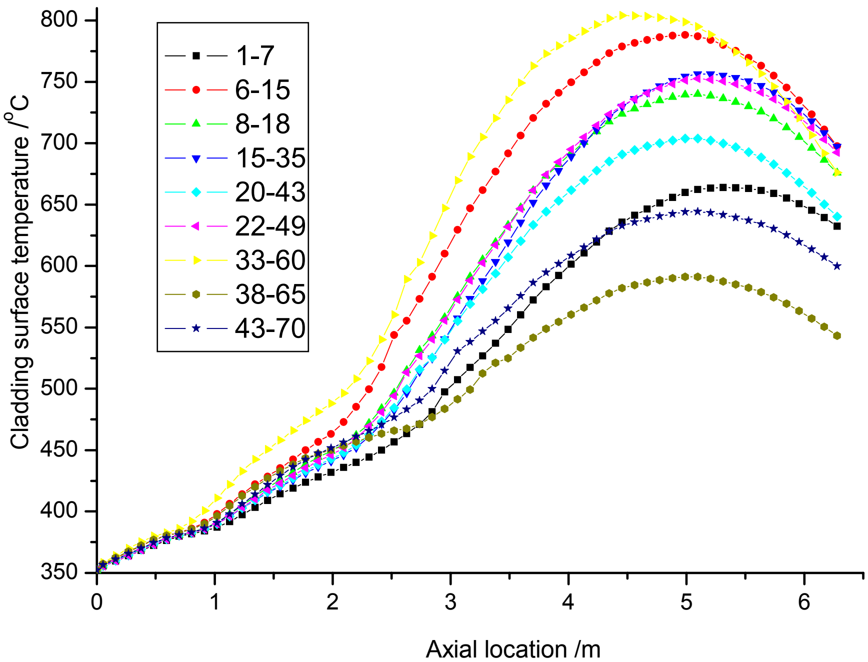

Figure 6 Cladding Surface Temperature of Typical Locations along Axial Nodes (1-7 denotes the fragment of rod 1 that facing subchannel 7)

3.3 Fuel-Design Optimisation

The analysis showed that the CANFLEX bundle is an appropriate fuel design for the CANDU SCWR (with the peak cladding surface temperature of 804°C meeting the criteria of 850°C). However, the coolant flow and temperature distributions are not uniform in all subchannels of the bundle. Differences between the maximum and minimum coolant temperatures at the outlet and between the maximum and minimum cladding temperatures at the peak power location are 153.82°C and 221.1°C, respectively. An optimization of the fuel geometry is attempted to improve the uniformities of coolant flow, coolant temperature, and cladding temperature in the bundle.

Neglecting the inter-channel mass and heat transfers, heat balance in a subchannel can be expressed as

$$\frac{P_h}{A} q'' = G \frac{\Delta h}{z} \tag{1}$$

The right hand side of Eq. (1) represents the energy transferred to coolant. In the left hand side of Eq. (1), the heat flux is constant regardless of radial fuel pin locations for the uniform radial power distribution and constant fuel rod diameter size over the fuel assembly. This implies that that the ratio of heated perimeter to flow area is a parameter representing the degree of coolant channel heterogeneity within a fuel assembly. This ratio indicates the amount of heat transferred through the fuel-cladding surface to neighboring subchannels and signifies the channel heterogeneity together with the hydraulic diameter. If the ratios in some subchannels differ strongly from those of other subchannels, the non-uniformity of coolant enthalpy distribution would increase within an assembly.

Two aspects of fuel-design optimization have been examined to improve uniformities of coolant temperature and cladding-temperature distributions. One of these aspects introduces a change in channel orientation from horizontal to vertical (this is hypothetical as the current conceptual design maintains the horizontal fuel channel). This change would eliminate the buoyancy effect (i.e., between top and bottom elements in a horizontal channel) and the coolant temperature and cladding-temperature gradients across the bundle. The other aspect focuses on optimization of the pitch-circle diameters of element rings to achieve similar heated perimeter to flow-area ratios.

Table 3 compares pitch-circle diameters of element rings between the reference and optimized SCWR fuel designs. The optimized pitch-circle diameters have been obtained to achieve similar ratios of heated perimeter to flow area in subchannels through the geometry calculation using the subchannel code.

Table 3 Optimization of Pitch Circle Diameters of Element Ring

Ring	Pitch Circle Diameter (cm)	
	Reference	Optimized
1	0	0
2	3.485	3.48
3	6.179	6.26
4	8.808	8.97

Figure 7 illustrates the coolant temperature and cladding-temperature distributions at the maximum-cladding temperature location of the optimized fuel design in a vertical channel. Both distributions are more uniform for the vertical optimized design than the horizontal reference design. Differences between the maximum and minimum coolant temperatures and between the maximum and minimum cladding temperatures have been reduced to 20.34°C and 64.2°C, respectively (compared to 153.82°C and 221.1°C for the horizontal reference design). Table 4 summaries differences in coolant temperature and cladding surface temperature between the horizontal reference and vertical optimized designs. The maximum coolant temperature and cladding temperature have been reduced by about 56°C and 77°C, respectively, for the vertical optimized design.

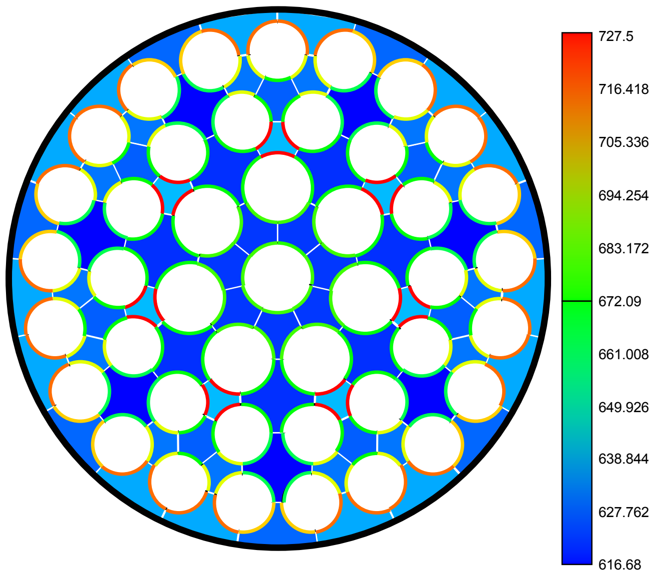

Figure 7 Distributions of Maximum Cladding Surface Temperatures and Outlet Coolant temperature after optimization

Table 4 Comparison of Coolant and Cladding Temperatures between Reference and Optimized Fuel Designs

Item	Reference	Optimized	Difference
Highest coolant temperature, °C	692.56	637.02	55.54
Lowest coolant temperature, °C	538.7	616.68	-77.98
Highest cladding temperature, °C	804.1	727.5	76.6
Lowest cladding temperature, °C	582	663.3	-81.3

One of the potential concerns for the optimized fuel design is the reduction in gap size between some elements. The subchannel analysis accounts mainly for a global change in subchannel size, but is not capable to include the gap-size effect on supercritical heat transfer. A separate study has been performed to examine the gap-size effect on azimuthal cladding temperature distribution using a computational fluid dynamic (CFD) tool [10]. The analysis showed that:

- The cladding temperature at surfaces facing the gap is higher than those facing the subchannel. This difference is attributed to poor heat transfer capability in triangle and square channels. The square array of element is worse because of relative smaller gap size.
- The highest temperature was observed at the triangular subchannel between connected triangular and square subchannels with the same pitch. Temperature at the gap is lower than at the subchannel due to the strong cross flow at the gap enhancing the heat transfer.

These observations identified a stronger gap size effect for square subchannels than triangular subchannels. Figure 7 shows the highest cladding temperature occurring at triangular subchannels between the intermediate and inner rings (mainly due to the small flow area), where the pitch-to-diameter ratio is about 1.2. A previous calculation has indicated almost uniform circumferential temperature distribution for rods with pitch-to-diameter ratio of 1.14 [10]. Therefore, the gap size effect on local heat transfer is not dominant in these subchannels of the optimized design (i.e., with pitch-to-diameter ratio of 1.2).

The effect of gap size on heat transfer at gaps between connected square and triangle subchannels is generally small due to the strong cross flow. Table 5 list the gap-size change for eight gap types in the reference and optimized designs. The cladding temperature difference between surfaces at the gap and at the subchannel is about 60°C for the pitch-to-diameter ratio of 1.1, if the cladding azimuthal conduction model is included [11]. The difference is anticipated to be smaller for pitch-to-diameter ratios greater than 1.1 (e.g., the pitch-to-diameter ratio is 1.21 for the gap type No. 5 in Table 5). On the other hand, assuming the gap effect is dominant, the cladding temperature at the gap is about 731°C (i.e., 671°C+ 60°C) and remains much lower than the limiting criteria.

Table 5 Gap size modification list

Type No	Rod-Rod	Reference	Optimized	Gap type
1	23-pressure tube	0.224	0.144	Square-Square
2	23-24	0.160	0.184	Square-Triangle
3	22-23	0.400	0.441	Triangle-Triangle
4	9-22	0.222	0.24	Triangle-Triangle
5	9-10	0.222	0.24	Square-Square
6	2-9	0.191	0.232	Square-Triangle
7	2-3	0.159	0.156	Square-Triangle
8	1-2	0.389	0.387	Triangle-Triangle

4. Conclusion

The subchannel code "ATHAS" has been applied in the optimisation of the CANFLEX bundle for the CANDU-SCWR. It includes a relatively large number of correlations for heat transfer, hydraulics resistance, mixing calculations as options and hence is applicable for detailed sensitivity analyses. In addition, an azimuthal conduction model has been implemented to establish the fuel temperature.

A CANFLEX bundle having a symmetric-cosine axial power profile and a uniform radial power profile has been applied to examine the optimisation feasibility. The reference design has been shown appropriate for use in the CANDU-SCWR with horizontal fuel channels. The predicted PCST is much lower than the design limit of 850°C. However, a cladding temperature gradient has been observed between top and bottom elements in the bundle and a non-uniform coolant temperature distribution in various subchannels.

The fuel-channel orientation has been changed from horizontal to vertical to eliminate the top-to-bottom cladding temperature gradient in the bundle. In addition, the pitch-circle diameters of element rings are optimised to improve the uniformity of coolant temperature distribution in various subchannels. These changes have led to more uniform coolant and cladding temperature distribution than the reference design. The maximum cladding temperature in the optimised design has been reduced to 727°C, as compared to 804°C in the reference design.

The optimisation of pitch-circle diameters has reduced some gaps between elements and between element and pressure tube. The impact of the gap-size reduction on heat transfer has been examined and is generally small.

5. Acknowledgments

The authors would like to express their appreciation to Atomic Energy of Canada Limited and Xi'an Jiaotong University for their financial support.

6. References

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