MODELLING OF CANDU-SCWR UNIT CELL WITH DRAGON: FROM CARTESIAN TO HEXAGONAL GEOMETRY

N. Bejaoui and G. Marleau
Institute of Nuclear Engineering,
École Polytechnique de Montréal, Québec, Canada
najoua.bejaoui@polymtl.ca, guy.marleau@polymtl.ca

Abstract

A new hexagonal model of the Canadian supercritical water-cooled reactor unit cell geometry is compared with the Cartesian model in DRAGON. This hexagonal model is considered for a compact core since further savings in the construction costs can be achieved by a reduction in the heavy water inventory in the core while still satisfying the constraints on the mechanical size of the pressure tube header. In our study, we investigate two options: using a reduced lattice pitch while preserving the same pressure tube; and increasing the outer radius of the pressure tube while using an hexagonal cell that has the same 2-D volume as the original Cartesian model.

Preliminary results indicate that the effective multiplication factor of the equivalent hexagonal unit cell is slightly lower than of the original Cartesian cell (0.15 mk). Reducing the lattice pitch of the hexagonal cell to that of the Cartesian cell decreases further the reactivity (20 mk) but reduces the moderator volume by more than 20 %. Other options for reducing the moderator volume that consists in increasing the outer radius of the pressure tube are analyzed, including replacing the moderator by super critical light water coolant or other structure material.

Keywords: Compact hexagonal reactor, Hexagonal cell geometry, Canadian-SCWR

Introduction

A large number of researchers from the Generation IV International Forum (GIF) community are currently working on various types of supercritical water-cooled reactors (SCWR) [1]. Both pressure vessel and pressure tube SCWR concepts are being explored. In Canada, the CANDU-SCWR is seen as a logical evolution of current CANDU designs. The preliminary concept uses a calandria vessel containing the low-pressure moderator and five meters long fuel channels. This concept uses off-power batch refuelling, and to simplify the fuelling process, the reactor core is oriented vertically [2]. Another feature of this concept is that the coolant is forced vertically downwards; that is, the coolant enters the fuel channels at the top and exits at the bottom of the core.

Most CANDU-SCWR concepts proposed to date are such that the vertical fuel channels are positioned in a Cartesian lattice with a lattice pitch of 25 cm. In this paper we introduce a new conceptual design where the fuel is arranged in an hexagonal pattern. In such a geometry, the heavy water moderator is distributed more uniformly around the fuel leading to a more optimal use of the moderator. Moreover, it also provides the designer the option to reduce the lattice pitch, while preserving the same mechanical constraints on coolant headers spacing, thereby reducing the dimensions of the reactor and its heavy water inventory. Because hexagonal lattices are more compact than Cartesian lattices, there is also the possibility to increase the dimensions of the fuel channel while preserving the fuel to moderator volume ratio of the Cartesian lattice.

Here, we assess the neutronic characteristics of several hexagonal CANDU-SCWR lattices using the cell calculation code DRAGON [3] and compare their properties with the conventional Cartesian unit cell. We analyze both a compact (hexagonal lattice pitch identical to the Cartesian case) and several variations of the reference hexagonal cell (fuel to moderator ratio preserved) and compare the effective multiplication constant, coolant void reactivity (CVR) and exit burnups of each type of cell with the reference calculation.

In Section 1 of this paper, we describe the Canadian-SCWR reference lattice. The hexagonal cell models we will consider are presented in Section 2. In section 3, following a brief discussion of the DRAGON modeling options considered, we present and discuss the results we obtained for the different models proposed. Finally, in Section 4, we conclude.

1. Unit cell specifications and DRAGON simulations

1.1 Geometry and material used

The bundle, shown in Figure 1, has two concentric fuel rings, each with 31 elements composed of mixtures of thorium and plutonium dioxide. The fuel elements are all clad in 0.6 mm thick zirconium-modified 310 stainless steel. The central flow tube is a solid tube of zirconium-modified stainless steel (the same material as the fuel sheaths and inner liner) which prevents mixing of the downward flowing coolant with the upward flowing coolant. An insulating layer may be required for the central flow tube in order to prevent heat transfer to the downward flowing coolant, however, this option is not investigated in this work. Detailed bundle specifications are listed in Table 1 as described in [7].

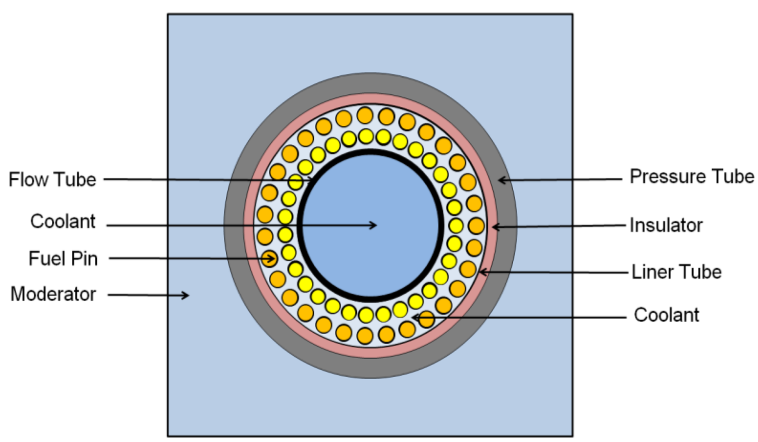

Figure 1 Cross-sectional view of the 62-element Canadian-SCWR fuel bundle design

Component	Dimension	Material	Composition (Wt%)	Density (g/cm^3)
Central coolant	4.45 cm radius	Light water	100% H2O	0.59254
Flow tube	4.45 cm inner radius 0.1 cm thik	Zr-mod SS	C:0.034; Si:0.51; Mn:0.74; P:0.016;S:0.0020;Ni:20.82; Cr:25.04; Fe:51.738;Mo:0.51:Zr:0.59	7.90
Inner pins (31)	0.415 cm radius 5.30 cm radius No displacement angle	15 wt% PuO2/ThO2	Pu:13.23;Th:74.70;O:12.07	9.91
Outer pins (31)	0.465 cm radius 6.55 cm radius No displacement angle	12 wt% PuO2/ThO2	Pu:10.59;Th:77.34O:12.08	9.87
Cladding	0.06 cm thik	Zr-mod SS	As above	7.90
Coolant	n/a	Light water	100% H2O	variable
Linner tube	7.20 cm IR 0.05 cm thik	Zr-mod SS	As above	7.90
Insulator	7.25 cm IR 0.55 cm thik	Zirconia (ZrO2)	Zr:66.63; Y:7.87;O:25.5	5.83
Outer tube	7.80 cm IR 0.05 cm thik	Excel (Zirconium Alloy)	Sn:3.5;Mo:0.8;Nb:0.8;Zr:94.9	6.52
Pressure tube	7.85 cm IR 1.2 cm thik	Excel (Zirconium Alloy)	Sn:3.5;Mo:0.8;Nb:0.8;Zr:94.9	6.52
Moderator	25 cm square lattice pitch	D2O	99.833%D2O;0.167%H2O	1.0851
Na	Na	Rg-Pu	Pu-238:2.75;Pu-239:51.96; Pu-240:22.96;Pu-241:15.23; Pu-249:7.10	

Table 1 SCWR 62-element fuel bundle and channel specifications

1.2 Depletion calculation parameters

In this study, the temperatures of the moderator, coolant and fuel are respectively 300 K, 600 K and 900 K. For the evolution calculations, the power density is constant at 45.99 MW/t. These calculations are performed up to 1200 days by increasing time intervals from 1 day at the beginning of the cycle to 200 days at the end of the cycle.

2. Simulation Strategy for the hexagonal Cell

The differences between the Cartesian and hexagonal cell models are illustrated in Figure 2. Here we assume that for structural reason, the outer diameter of the mechanical structure required to bolt the header to the pressure tube is $s = 1$ cm smaller than the Cartesian lattice pitch (L = 25 cm), namely 24 cm. Assuming that the outer radius of the pressure tube is 9.05 cm, this means that the thickness of this structure is $t = 2.95$ cm. This assumed thickness is considered as the main constraint on the dimensions on the lattice cell. The lattice pitch variations of the hexagonal models we will investigate are the following:

1. Reference hexagonal cell (CASE 1) similar to the Cartesian model.

   Here we select a lattice pitch that preserves the moderator volume V_m

$$V_m = L^2 - \pi r^2 = 367.6957 \text{ cm}^2$$

   In this case, each sides of the hexagon will be given by

$$h_{max} = L\sqrt{2/3\sqrt{3}} = 15.51 \text{ cm}$$

   and has an equivalent hexagonal lattice pitch of

$$L_{max} = \sqrt{3}h_{min} = L\sqrt{2/\sqrt{3}} = 26.8642 \text{ cm}$$

2. Compact hexagonal cell (CASE 2) with a lattice pitch identical to the Cartesian lattice pitch.

   In this case, each sides of the hexagon will be given by

$$h_{min} = L/\sqrt{3} = 14.4338 \text{ cm}$$

   the volume of the moderator being reduced to

$$V_m = \sqrt{3}\,L^2/2 - \pi r^2 = 283.9616 \text{ cm}^2$$

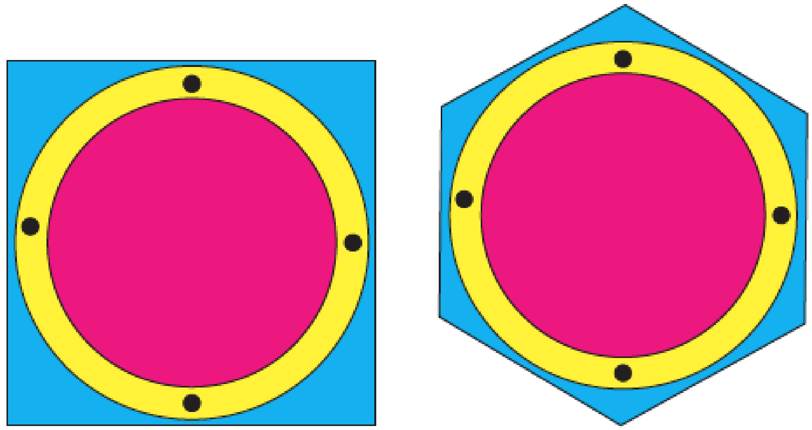

Figure 2 Cartesian (left) and hexagonal (right) cell models where the region inside the pressure tube is indicated in pink and the mechanical structure required to bolt the header to the reactor is indicated in yellow

As the reference hexagonal cell has a larger lattice pitch than the Cartesian cell, one can still maintain the same distance between the mechanical structures required to bolt the header while increasing the outer radius of the pressure tube to $r_{PT} = (L_{max} - s)/2 - t = 9.9821$ cm, thus decreasing the volume of moderator to $V_m = 311.96$ cm^2.

Several options can then be considered:

1. CASE 3 consist in increasing the outer radius of the pressure tube to 9.9821 cm while preserving it thickness and that of the liner and insulator. Here the fuel bundle and the central coolant region are not changed.
2. CASE 4 is similar to 1, but the fuel pins are also moved towards the exterior (same central coolant region).
3. CASE 5 is similar to 2 but the central coolant region is also expanded.
4. CASE 6 is similar to 1 but increase the thickness of the pressure tube.
5. CASE 7 is similar to 1 but increase the thickness of the insulator.

3. Results and discussion

For the cell calculations, the analysis is performed using the EXCELT: tracking module of DRAGON. In all cases, the collision probability (CP) method is used to solve the neutron transport equation. Only infinite multiplication constant problems (without neutron leakage) are considered. The 69 groups microscopic cross sections library selected for our calculations is the "iaea" WIMS-D4 library from WLUP [5].

Since we are using the CP approximation, one must select carefully the spatial mesh discretization (radial and Cartesian and hexagonal) in order to ensure constant sources over spatial regions of the geometry. On the other hand it is generally possible to use a simplified version of this geometry for the resonance self-shielding calculation [6].

This study is divided into two parts. First, we study the impact on lattice properties of geometry changes made to the fuel channel. Next, the effect of the burnup on k_{eff} and the fuel cycle time are examined and the results are compared to the prior Cartesian reference concept.

3.1 Impact on Lattice Physics of Changes to the Channel Options

The various results presented in this section were investigated for fresh fuel via DRAGON calculations of k_{eff}. Here, $k_{\text{eff}}^{\text{cooled}}$ corresponds to cell calculations performed with the coolant at the reference density and temperature. The $k_{\text{eff}}^{\text{external void}}$ and $k_{\text{eff}}^{\text{total void}}$ correspond respectively to cell calculations with the external coolant (coolant around the fuel pins only) absent and for total coolant voiding (central coolant pin also voided). Results for k_{eff} are presented in Table 2 for the Cartesian and the reference hexagonal cells. One will also find in this table the coolant void reactivities (mk) $\text{CVR}^{\text{external}}$ and $\text{CVR}^{\text{total}}$ defined respectively as

$$\text{CVR}^{\text{external}} = 1000\left(\frac{1}{k_{\text{eff}}^{\text{cooled}}} - \frac{1}{k_{\text{eff}}^{\text{external void}}}\right)$$
$$\text{CVR}^{\text{total}} = 1000\left(\frac{1}{k_{\text{eff}}^{\text{cooled}}} - \frac{1}{k_{\text{eff}}^{\text{total void}}}\right)$$

As one can see, the differences between the Cartesian model and the reference hexagonal model (CASE 1) are very small (maximum difference of 0.15 mk). One can also observe that the CVR's are slightly larger for the case where the Cartesian geometry is considered. This may be explained by a combination of the fact that for the hexagonal geometry neutron slowing down is expected to be slightly more efficient (more uniform distribution of moderator around the fuel) and the use of approximate boundary reflection conditions in these calculations (white boundary conditions) that have for effect to redistribute uniformly the neutron entering the cell after reflection. As a result, the hexagonal reference model shows good overall agreements with the reference Cartesian model because the fuel and moderation properties are nearly identical although the geometries are different.

	Cartesian model	**Reference hexagonal model (CASE 1)**
$k_{\text{eff}}^{\text{cooled}}$	1.29488	1.29473
$\Delta k_{\text{eff}}^{\text{cooled}}$	-	0.15
$k_{\text{eff}}^{\text{external void}}$	1.30154	1.30124
$\text{CVR}^{\text{external}}$ (mk)	3.95	3.86
$k_{\text{eff}}^{\text{total void}}$	1.27248	1.27202
$\text{CVR}^{\text{total}}$ (mk)	-13.60	-13.79

Table 2 k_{eff} and CVR comparison for the Cartesian and reference hexagonal unit cell

Table 3 shows a comparison of the multiplication factors and CVRs obtained from the different hexagonal unit cell models presented in Section 2, namely CASE 1 to CASE 7.

The first observation is that the compact model (CASE 2) gives a k_{eff} that is 20 mk lower than the reference case (CASE 1). This observation can be explained by the changes in the level of neutron slowing down in the moderator region: the volume of the moderator in CASE 2 is reduced by 20% compared to the volume of the moderator in CASE 1, therefore leading to a lower multiplication factor. In addition, $\mathrm{CVR}^{\mathrm{external}}$ is now negative due to this decrease in neutron moderation.

Increasing the outer radius of the pressure tube in CASE 3, leads to the decrease of k_{eff} and shifts the CVR in the negative direction comparing to those of the CASE 1. Both of these results are a consequence of replacing part of the moderator volume by the coolant between the fuel pins; thus decreasing the reactivity and leading to a negative contribution to CVR when the moderation is lost. The CVR can therefore be "tuned" or shifted by varying the moderator volume, which can be achieved by changing the outer radius of the pressure tube in CASE 1. An increase in the outer radius of the pressure tube will shift the CVR in the negative direction, while a decrease in the outer radius of the pressure tube will shift the CVR in the positive direction.

	CASE 1	CASE 2	CASE 3	CASE 4	CASE 5	CASE 6	CASE 7
$k_{\mathrm{eff}}^{\mathrm{cooled}}$	1.29473	1.27170	1.27905	1.27673	1.26785	1.24033	1.25670
$\Delta k_{\mathrm{eff}}^{\mathrm{cooled}}$	-	23.04	15.69	18.00	26.88	54.41	38.03
$k_{\mathrm{eff}}^{\mathrm{external\ void}}$	1.30124	1.26859	1.26722	1.26659	1.26613	1.23747	1.25647
$\mathrm{CVR}^{\mathrm{external}}$ (mk)	3.86	-1.92	-7.30	-6.28	-1.07	-1.86	-0.15
$k_{\mathrm{eff}}^{\mathrm{total\ void}}$	1.27202	1.21427	1.21714	1.21488	1.21337	1.17702	1.20525
$\mathrm{CVR}^{\mathrm{total}}$ (mk)	-13.79	-37.19	-39.76	-39.88	-35.41	-43.37	-33.97

Table 3 Changes to the hexagonal unit cell options

Looking at CASE 2 and CASE 3, we observe that the k_{eff} increases by increasing the outer radius of the pressure tube therefore replacing the heavy water moderator by more efficient super critical light water coolant.

Increasing the outer radius of the pressure tube and spreading the fuel pins towards the exterior (CASE 4) results in a decrease in the overall k_{eff} as compared to CASE 3, an increase in $\mathrm{CVR}^{\mathrm{external}}$ but a decrease in the $\mathrm{CVR}^{\mathrm{total}}$. Both of these results are a consequence of decreased moderation for the neutrons reaching the fuel pins since the effect of moderation by the central coolant region will remain about the same while parasitic absorption by light water will increase.

Increasing the dimensions of the central coolant region (CASE 5) from CASE 4 leads to a further decrease in the k_{eff} and an increase in the CVRs. This is a consequence of minimizing the coolant volume between the fuel rings that also acts as a moderator.

Increasing the insulator (CASE 6) and the pressure tube thickness (CASE 7) globally decreases the moderator volume inside the fuel channel, but also increases the amount of material between the fuel and moderator. The net result is a decrease in k_{eff}, due to an increase in the parasitic absorption.

3.2 Burnup results

Figure 3 illustrates the behaviour of k_{eff} as a function of time. In the case of the reference Cartesian and hexagonal models, k_{eff} drops below 1 approximately after 925 days, while for CASE 2, CASE 3 and CASE 4, the fuel cycle is somewhat shorter (875 days). The shortest fuel cycle of 825 days is observed for CASE 3. The behaviour of k_{eff} is approximately the same for all the geometry configurations. However, CASE 3, which is initially more reactive than CASE 2 and CASE 4, becomes less reactive towards the end of irradiation, namely after 600 days. All these major differences between Cartesian and the other four cases can be explained in part by differences in moderation and in another part by different fuel consumption during irradiation due to the different flux spectrum seen by the fuel.

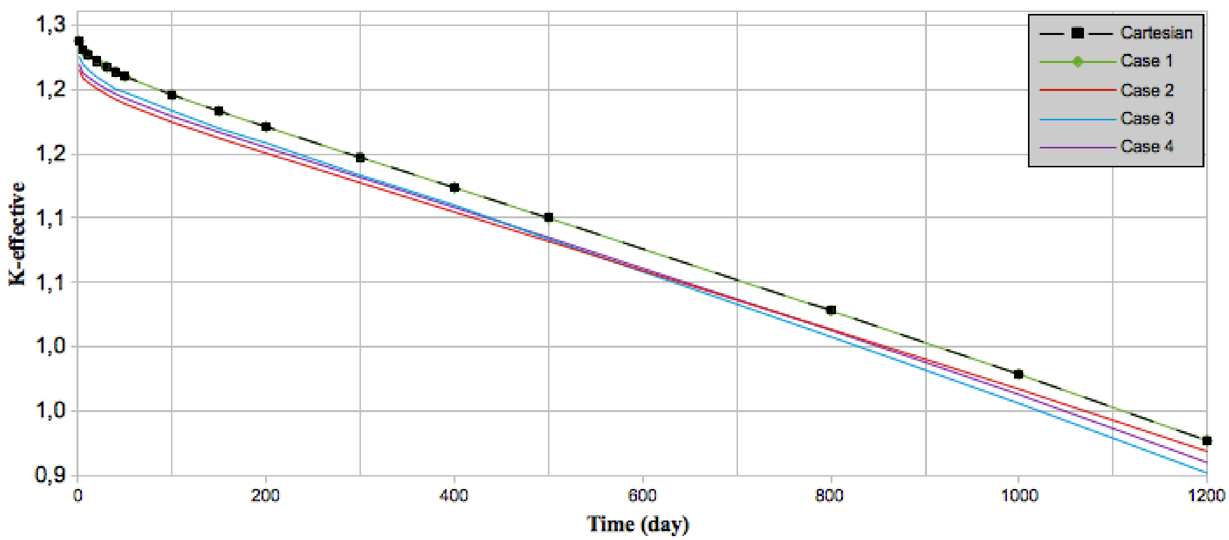

Figure 3 k_{eff} as a function of burnup time for different unit cell models

4. Conclusion and future work

In this paper, a novel hexagonal unit cell model for SCWR is introduced. The neutronic characteristics of this fuel lattice have been investigated and compared with the conventional Cartesian model. The results of these comparisons show that:

1. The reference Cartesian and hexagonal unit cells have nearly identical multiplication factors and coolant void reactivities. Indeed, a difference in k_{eff} of only 0.15 mk is observed. Consequently, the effect of the geometry on unit cell calculations is very small when the same moderator volumes are considered.
2. Significant differences were found in k_{eff} values between the reference and the compact hexagonal unit cell model when compared. This is due to the fact that the moderator volume is reduced by 20%. To compensate for this loss of moderator, we have enlarged the outer radius of the pressure tube to have more coolant between fuel rings that also acts as a moderator. Consequently, we have increased the k_{eff} from 1.27170 to 1.27905 (7.3 mk increase). We have also enlarged the central coolant region but in this case, the k_{eff} decreased from 1.27170 to 1.26785 (-3.9 mk). As a result, increasing the dimensions of the central coolant pin is not appropriate if one wants to increase the k_{eff} of the compact unit cell, nor is increasing the pressure tube and insulator thickness.
3. The compact unit cell model has a shorter fuel cycle than the reference model. These differences may be explained by different flux spectrum distribution in the fuel as well as starting from a lower initial k_{eff}.

Finally, a further step using different coolant and pressure tube properties would be to test and optimize the compact unit cell k_{eff}, CVR and fuel cycle. Work along these lines is in progress.

5. Acknowledgments

One of the authors (N.B.) wishes to express her recognition to Mission Universitaire de Tunisie à Montréal for its financial support. This work was also supported, in part, by the NSERC/NRCan/AECL Generation IV Energy Technologies Program.

6. References

[1] U.S. DOE Nuclear Energy Research Advisory Committee, Generation IV International Forum, "A technology roadmap for Generation IV Nuclear Energy Systems", GIF-00200, 2002, http://gif.inel.gov/roadmap/pdfs/gen_iv_roadmap.pdf.

[2] M. Yetisir, W. Diamond, L.K.H. Leung, D. Martin and R. Duffey, "Conceptual Mechanical Design for a Pressure-Tube Type Supercritical Water Cooled Reactor," The 5th International Symposium on Supercritical Water-Cooled Reactors, Vancouver, British Columbia, Canada, March 13-16 (2011).

[3] G. Marleau, R. Roy and A. Hébert, "A User Guide for DRAGON 3.06," Institute of Nuclear Engineering, École Polytechnique de Montréal, Montréal, Québec, Canada, Technical report IGE-174 Rev. 8 (2009).

[4] E. Varin, A. Hébert, R. Roy and J. Koclas, A user's guide for DONJON. Institut de génie nucléaire, École Polytechnique de Montréal, Report IGE-208 Rev. 3 (2003).

[5] WIMS Library Update Project, "WLUP Libraries (Wimslib subdirectory),"

http://www-nds.iaea.org/wimsd/downloads.htm (2008).

[6] A. Hébert, "Applied Reactor Physics", Presses internationales Polytechnique, Montréal, Québec, Canada, pp. 207-282 (2009).

[7] J. Pencer, D. Watts and al, "Core Neutronics for the Canadian SCWR Conceptual Design," The 6th International Symposium on Supercritical Water-Cooled Reactors, Shenzhen, Guangdong, China, March 03-07, (2013).