ANALYSIS OF THE IMPACT OF COOLANT DENSITY VARIATIONS IN THE HIGH EFFICIENCY CHANNEL OF A PRESSURE TUBE SUPER CRITICAL WATER REACTOR

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Abstract

The Pressure Tube (PT) Supercritical Water Reactor (SCWR) is based on a light water coolant operating at pressures above the thermodynamic critical pressure; a separate low temperature and low pressure moderator. The coolant density changes by an order of magnitude depending on its local enthalpy in the porous ceramic insulator tube. This causes significant changes in the neutron transport characteristics, axially and radially, in the fuel channel. This work performs lattice physics calculations for a 78-element Pu-Th fuel at zero burnup and examines the effect of assumptions related to coolant density in the radial direction of a HEC, using the neutron transport code WIMS-AECL.

1. Introduction

A Pressure Tube type Super Critical Water Reactor (PT-SCWR) is a reactor design based on a light water coolant operating above its thermodynamic critical point of 22.1 MPa and 647 K. This allows for a very high thermodynamic efficiency and a direct coolant cycle [1].Atomic Energy of Canada Limited (AECL®) has collaborated with Natural Resources Canada (NRCan) and the Natural Sciences and Engineering Research Council (NSERC) to develop a pre-conceptual design of the PT-SCWR. This design is light-water cooled, with a heavy water moderator and operates using a batch fuelled Plutonium/Thoriumcycle. The design employs a High Efficiency Channel (HEC) concept with an outer pressure tube in direct contact with the moderator and a ceramic Yttria-Stabilized Zirconia (YSZ) insulator to provide thermal insulation of the PT from the high temperature coolant. The porousinsulator region provides the necessary thermal isolation between the high temperature coolant and low temperature moderator, eliminating the need for a separate calandria tube.The proposed insulator has a volumetric porosity of 76%[2].The reference model is summarized in Table 1 below.

Table 1 Reference Model Properties of PT-SCWR [5]

Region	Material	Geometry	
Centre Pin	10wt% Y2O3 in ZrO2	2.82 cm radius	
Fuel Ring 1 (15 pins)	13wt% PuO2 in ThO2	0.62 cm radius	3.66 cm pitch
Fuel Ring 2 (21 pins)	13wt% PuO2 in ThO2	0.62 cm radius	5.11 cm pitch
Fuel Ring 3 (x pins)	13wt% PuO2 in ThO2	0.35 cm radius	6.30 cm pitch
Cladding	310SS	0.06 cm thick	On Fuel + Centre Pins
Liner Tube	310SS, 70% Porosity	6.80 cm inner radius	6.85 cm outer radius
Insulator Region	Yttria Stabilized Zirconia 76% Porosity	6.85 cm inner radius	7.85 cm outer radius
Pressure Tube	Excel Alloy	7.85 cm inner radius	9.05 cm outer radius
Moderator	0.167% H2O in D2O		25 cm pitch

The reference fuel for the PT-SCWR pre-conceptual design is a 78-element bundlewith a 25 cm lattice pitch, fueled with a homogenous reference composition of 13 wt% PuO_2 in ThO_2 [3]. The thorium is Th-232; the plutonium isotopics are described in[3], sample SF97-4.The properties of water at it reaches the supercritical phase vary significantly at 25 MPaover the relevant temperatures, as shown in Figure 1[3]. Light water is a very strong neutron moderator and absorber. This large potential change in coolant density has a strong effect on the neutron transport characteristics in the fuel channel. The insulator region maintains the temperature gradient between the hot inner coolant region and the pressure tube, which is in contact with the cooler heavy water moderator. The inner coolant temperature gradient ranges from 625 K to 880 K, with the moderator at 342 K. The purpose of this work is to study the effects of modelling assumptions in the insulator region on the neutron physics of the PT-SCWR lattice cell.

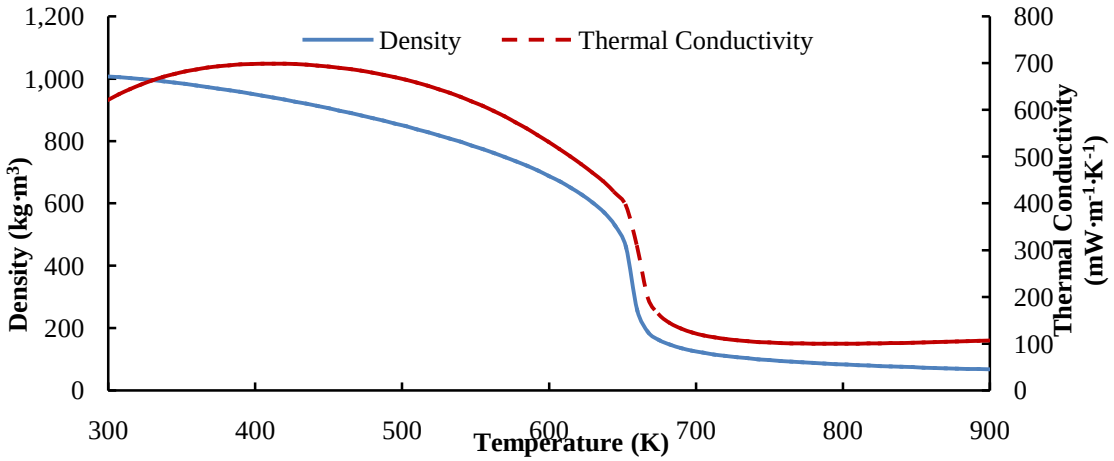

Figure 1 Light water density and Thermal Conductivity vs. Temperature at 25 MPa

2. Methodology

The PT-SCWR lattice cell is modeledusing WIMS-AECL Version 3.1.2.1. WIMS-AECL is a two-dimensional neutron transport code typically used for reactor lattice cell calculations in both steady state and slowly time-variant systems [4]. Nuclear data was taken from the E70ACR library included with the release of WIMS-AECL, based on data from the ENDF/B-VII nuclear data library [5].

For the reference model in this work, the density of the water in the insulator region is assumed to be the same density as the coolant averaged density at each axial location. The reference model addresses the change in temperature in the insulator region, but does not modify the density of the water within the insulator which would occur due to the temperature change. To account for axial effects, this model must be evaluated at several sections along the length of thechannel. In particular the changes in coolant properties in thepseudocritical transition must be considered. Due to the large changes in the coolant properties and material temperatures throughout the channel (Figure 2), the two-dimensional lattice cell isevaluated at five equally spaced axial locations. These five positions are considered to be sufficiently descriptive of the average neutronics of the HEC[2].Table 2 summarizes the boundary conditions used[2,3].

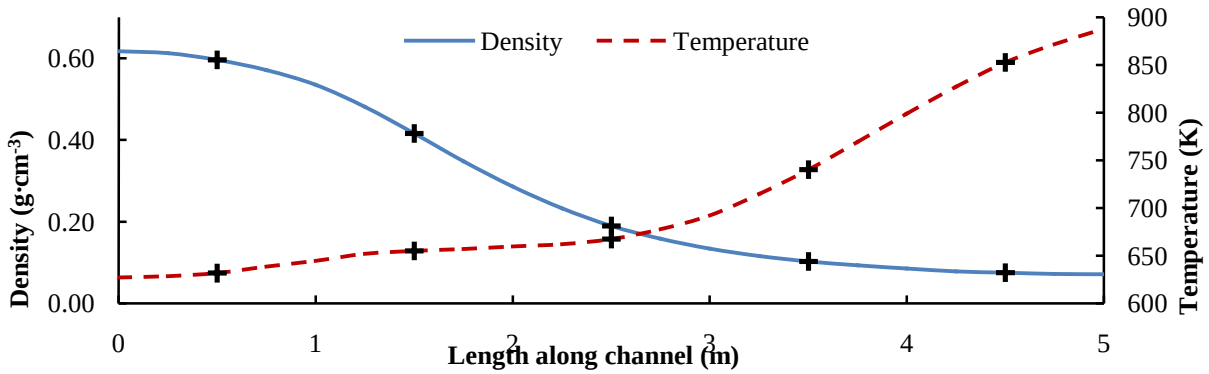

Figure 2Coolant properties along length of PT-SCWR Channel

Table 2 Temperature Boundary Conditions[3]

Boundary Condition	Channel Position 0.5m	Channel Position 1.5m	Channel Position 2.5m	Channel Position 3.5m	Channel Position 4.5m
Coolant/Liner Tube (K)	632.35	656.3	675.27	774.05	881.45
Pressure Tube Inner Surface (K)	477.55	485.51	491.82	524.65	560.35

In order to calculate thermal profile withinthe insulator regionat each of the 5 axial locations, a number of assumptions of the properties of the insulator are needed. The insulator region is treated as a two-dimensional cylindrical region, with boundary conditions matching the inner coolant temperature and outer moderator temperature of the reference model. The governing equation for radial heat conduction at a given axial location is:

$$\frac{\partial}{\partial r}\left(rK(T)\frac{\partial T}{\partial r}\right) = 0 \quad (1)$$

If the thermal conductivity of the insulator and water is assumed to be constant,the temperature distribution in this two-dimensional cylindrical insulator region is a logarithmic curve, with constant selected to match the boundary conditions.This logarithmic temperature distribution ignores the very strong temperature dependence of the thermal conductivity near the pseudo critical temperature, which mustbe included in determining the temperature distribution within the insulator region.

The thermal conductivity of water is obtainedfrommini REFPROP based on the NIST database Version 9.1 at 25 MPa[6]. The exact solution to equation 1 with the thermal conductivity of water alone is determined using FlexPDE 5.0[7].

The total thermal conductivity of the YSZ composite material is alsoa function of temperature. The model of Woodside allows calculation of the effective thermal conductivity of a porous mixture of a solid and gas as a function of the effective porosity and the thermal conductivities and densities of the constituents[8].The work of Schlichting, Padture and Klemens presents information needed for an interpolation between the values for the YSZ used in this model[9]. This information, combined with the varying thermal conductivity of waterare used as input for the model of Woodside and evaluated at 76 per cent porosity. This results in an evaluation of the

effective thermal conductivity of the porous mixture of YSZ and water as a function of temperature.The resulting thermal conductivity curve for the mixtureis shown in Figure 3.

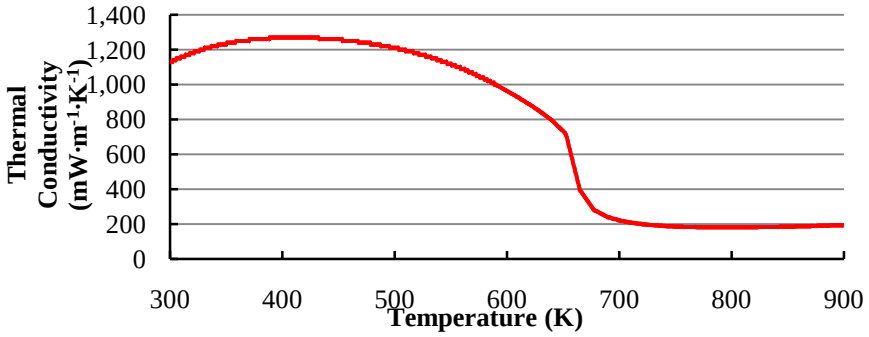

Figure 3 Calculated Thermal Conductivity of Porous Insulator Region

Spatial discretization is necessary for input into the WIMS-AECL model.When subdividing the insulator region, the total mass of water in each subdivision must be conserved.To assess the sensitivity of the methodology to discretization, three models of insulator are used: i) 3-subregions with constant densityii) 3 subregions and iii) a model with 10 subregions.

Thedifferent models used arereferred to as Logarithmic T (with constant k), k(Water) and k(Water-YSZ). Each model also has a variation in the subregions, referred to as i)_, ii) and iii).

3. Results

The modified insulator treatment differs heavily from the reference model, in all of the various treatments.Table 3 contains the average positive reactivity (k-infinity), for the basic three subregion model for each model.The voided case for the Coolant Density Reactivity (CDR) is calculated by fully voiding the coolant in the channel, liner tube and porous YSZ.

Table 3 Average Positive Reactivity (ii- 3 subregions)

Model	$k_{infinity}$	CDR (mk)
Reference Model	1.26521	2.16
LogarithmicT (constant k)	1.27285	-2.58
k(Water)	1.27403	-3.31
k(Water-YSZ)	1.27412	-3.37

All of the models explored increase the average $k_{infinity}$ of the reactor relative to the reference model. The data is an unweighted average from the five equally spaced slices of the channel. The $k_{infinity}$ values show a large change between the models that account for density gradients in the insulator and the reference case. The effect of including the thermal conductivity of the YSZ to the thermal conductivity of the insulator region calculation has a very small effect on the $k_{infinity}$ value (Figure 4). The most significant finding is the role of insulator density modelling is related to the strong influence on CDR. Notably, the increase in the overall average reactivity changes the estimated CDR from a positive to a negative value.The $k_{infinity}$ of each model has a strong dependence on the axial position since as the coolant water is heated by the fuel, the temperature inside the insulator region increases, reducing the density of the water within the region.

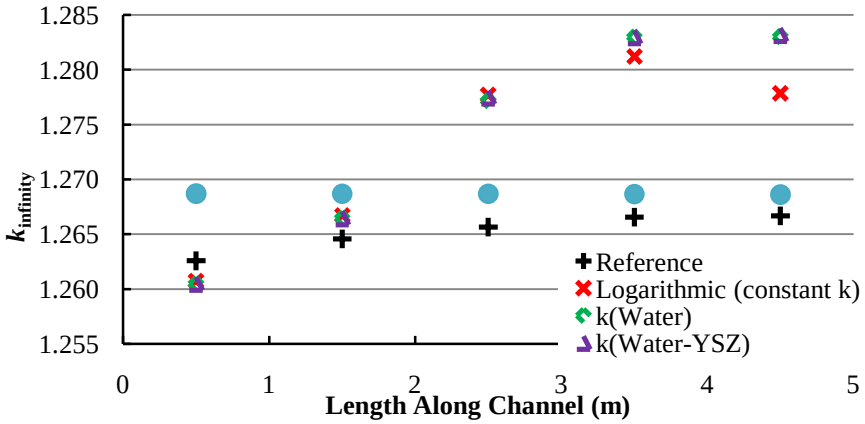

Figure 4Model ii)$k_{infinity}$at zero burnup, along the channel (ii- 3 subregions)

The $k_{infinity}$of the lattice cell increases with the distance from the coolant inlet. In the k(water) model, the $k_{infinity}$ is 14 mk higher at the outlet of the channel than at the inlet. This 14 mk change can have large effects on the characteristics and axialpower profile of the reactor.

The effect of changing the number of subregions within the insulator region was also studied. The effect of moving from one to three to ten regions has a differing magnitude depending on the axial position being studied, ranging from roughly 1.9 mk (in all 4 types of thermal conductivity assumed) to 0.15 mk. This effect is relatively small compared to other factors involved in the simulations. The channel average reactivity is affected by less than 0.6 mk in all 4 cases.The number of subregions used in the analysis provides a significant effect on the calculated $k_{infinity}$. Depending on the position in the channel, the $k_{infinity}$ can change over 3 mk. Figure 5demonstrates the dependence on axial position.

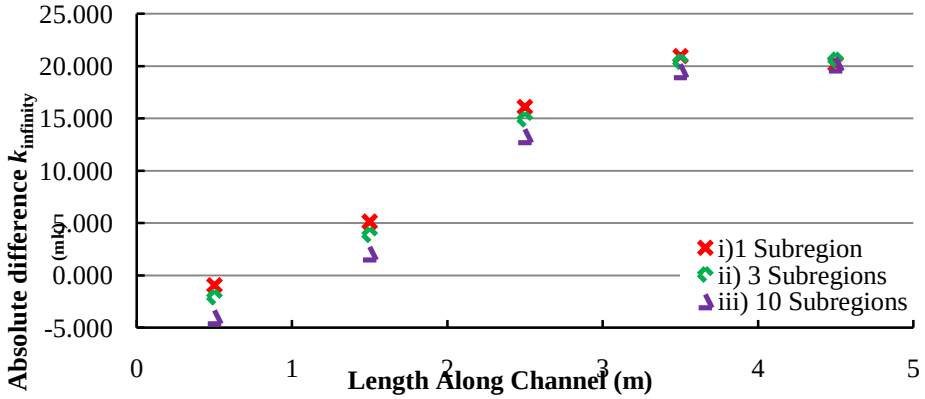

Figure 5 Absolute difference in mk from Reference Model of k(Water-YSR)

The k(water) and k(Water-YZR) models provide similar results. This is predictable, given the similar shape of the thermal conductivity curves. The thermal conductivity of water is dominating the overall thermal conductivity of the highly porous (76% porous) YSZ insulator, resulting in only minor differences in the temperature distribution between the two models.

4. Conclusions

The coolant density in the insulator has a strong effect on the neutronics of the PT-SCWR lattice cell studied and has been shown to be important for physics calculations. Determining the density profile of the light water within the YSZ insulator region is an important component of determining the neutronic properties of the PT-SCWR. The models explored can change the reactivity of the system by 5.5 mk over the entire channel, with local effects as much as 10.1 mk. Furthermore the effect of insulator thermal modelling varies along the axis of the channels, largely as a result of the large change in coolant temperature.

5. References

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