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Gap Material and Radial Geometry Modeling Dependency on a T/H Analysis in a Channel of CANDU6 Reactor

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1. Introduction

There is a gap between pressure tube and calandria tube which insulates the primary heat transport system from the moderator system. The gap is filled with CO_2 gas and has specific velocity and pressure. This Annulus Gas System (AGS) is grouped to include several channels.

But the CUPID [1] code which is developed in Korea Atomic Energy Research Institute (KAERI) doesn't have the CO_2 properties which are necessary for the T/H analysis. Instead of the CO_2 properties, we can choose 8 alternative materials such as helium, hydrogen, nitrogen, krypton, xenon, air, argon and sf6 [2].

In this research, sensitivity on choosing different gap material will be cleared. Actual CANDU6 channel has radial regions such as fuel, coolant, pressure tube, gap and calandria tube. Thus, not only flow directional heat transport but also radial heat transport occurs in a real channel. Moveover, gas in the gap will transport some energy through gas flow direction.

The amount of heat transport through primary coolant, gas and radial direction to moderator will be discussed. Also, T/H result change will be analyzed when we omit pressure tube, gap and calandria tube by simplifying the radial modeling.

By the way, only Q7 channel is analyzed and parameters related with T/H referred to those of Q7 position in this study for pressure tube deformation analysis which will be conducted later.

2. Problem Description

If the radial structures such as pressure tube, gap and calandria tube are not modeled, 100% heat transport will be done through axial direction which is direction of main fluid. To do that, we need to prepare both geometries for the CUPID code running. As already mentioned in the introduction section, gas between pressure tube and calandria tube can play a role for radial heat transport. To see dependency of the gap material, 8 materials including air were tested mainly on heat transport ratios for axial main heat transport, axial gas heat transport and radial heat transport through pressure tube wall, gas and calandria tube wall.

2.1 Geometry Condition

To describe exact geometry of a channel in the CANDU6 reactor, radial structures such as pressure tube, gap region and calandria tube should be included in the modeling. But due to increase in geometrical complexity and thus problem difficulty as well as increase in the number of mesh, we were curious what will happen when those radial structures are omitted. By the way, we have known information about radial heat transfer to the moderator tank through pressure tube wall, gas region and calandria tube wall. It is known as maximum 5% among heat produced by fuel rod. Thus, sometimes it is neglected for several T/H codes for CANDU6 code. In this study, we will see what happens when those structures are not depicted in regard to several parameters such as bundle-wise fluid temperature, void fraction, equilibrium quality, mixture enthalpy and so on, quantitatively.

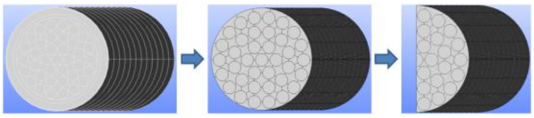

Fig. 1. Changes in Modeling of PHWR Channel

As shown in Fig. 1, full geometry from the Salome software was tested initially, and then the model changed by deleting pressure tube, gas region and calandria wall. Finally, by using symmetry on y-z plane (x=0), half of the geometry is used which allowed us to save calculation time and reduce complexity. Although pressure tube deformation occurs as operation time goes on, the geometry changes due to the aging effect is not considered in this study. Thus, straight pipe-like geometry will be dealt with.

2.2 Boundary & Initial Conditions

Boundary conditions for inlet, outlet and y-z plane should be retained for different geometries and gas materials. Typical CANDU6 values were taken for this study as shown in Table I.

Table I: Problem Description

	Initial Value	Inlet Condition	Outlet Condition
Pressure (Pa)	11.4E6		10.0E6
Liquid Temperature (K)	535.61		N/A
Void Fraction	0.0		N/A
NCG Quality	0.0		0.0
Velocity	8.3229		N/A

(m/s)		

As mentioned in previous section (Section 2.1), aging effect is not considered in this study. Thus, changes in T/H conditions including inlet & outlet header pressures are not reflected in Table I and this study.

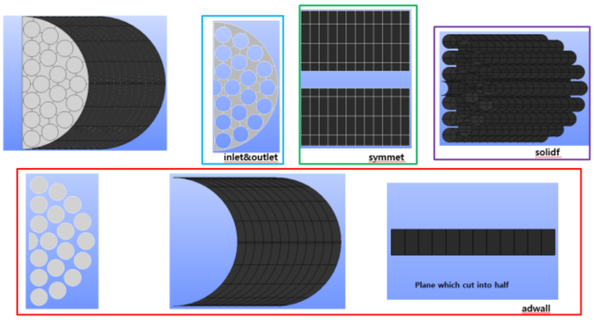

Fig. 2. Boundary conditions for a channel analysis

As shown in Fig. 2, boundary conditions for surfaces are described. We have inlet and outlet for top and bottom sides of pressure tube along z-axis, adiabatic conditions for top and bottom sides for fuel, pressure tube wall and plane which cut center rod, symmetry boundary condition on plane which cut pressure tube and conduction plane for fuel and fluid interface, which is called as name of 'solidf' in CUPID simulation.

Not only boundary condition but also heat condition should be imposed when we have power in fuel rods. To simplify conditions, consine power shape for axial direction is assumed and ring-wise radial power distribution is assumed as shown in Fig.3 and Table II.

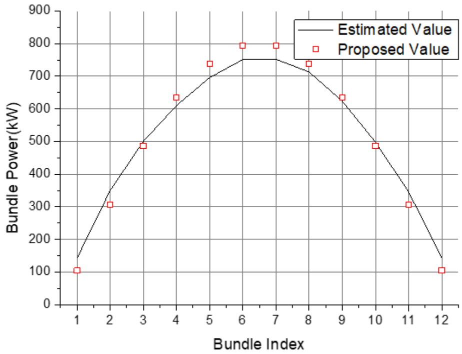

Fig. 3. Bundle-wise power difference between proposed and estimated values

Table II: Ring-wise Power Distribution inside of a Bundle at Average Exit Burnup

Element Ring	Number of Elements	Element Power		Percent Power	
		Nor. To Bundle Avg.	Nor. To Outer Element	Per Element	Per Ring
Outer	18	1.120	1.000	3.026	54.46
Intermediate	12	0.9254	0.8266	2.501	30.01
Inner	6	0.8247	0.7367	2.229	13.37
Center	1	0.7843	0.7006	2.120	2.120

2.3 Material Properties and Assumptions

In this study, fuel region is simplified as one integrated region which originally consisted of fuel pellet, gap and cladding. Because of too much complexity on geometry, mentioned details are omitted to simplify the geometry, model and to reduce the number of grid. Instead of depicting all details, volume weighted properties are used as shown in Table II and III.

Table III: Heat Capacity after Volume Weighted Average

Region Name		Pellet	Gap	Cladding	Merged Material
Volume Fraction		0.88	0.03	0.09	1.00
Material		UO_2	He	Zr	UO_2+He+Zr
Temperature (K)		Thermal Conductivity (w/mK)			
1	273.15	7.3	0.151	13.6	7.7
2	373.15	7.3		14.1	7.7
3	473.15	6.7		14.8	7.2
4	573.15	5.8		15.8	6.6
5	673.14	5.1		16.9	6.1
6	773.15	4.6		18.1	5.7
7	873.15	4.2		19.5	5.5
8	973.15	3.8		21.1	5.3
9	1073.15	3.5		22.8	5.2
10	1173.15	3.3		24.6	5.1
11	1273.15	3.1		26.8	5.2
12	1373.15	2.9		29.2	5.2
13	1473.15	2.8		31.7	5.3
14	1573.15	2.6		34.4	5.5
15	1673.15	2.5		37.3	5.6
16	1773.15	2.5		40.4	5.9

Table IV: Conductivity after Volume Weighted Average

Region Name		Pellet	Gap	Cladding	Merged Material
Volume Fraction		0.88	0.03	0.09	1.00
Material		UO_2	He	Zr	UO_2+He+Zr
Temperature (K)		Heat Capacity (J/m^3K)			
1	273.15	2.43E+06	927.3	1.88E+06	2.306E+06
2	373.15	3.01E+06		2.08E+06	2.838E+06
3	473.15	3.17E+06		2.21E+06	2.987E+06
4	573.15	3.24E+06		2.29E+06	3.055E+06
5	673.14	3.24E+06		2.38E+06	3.070E+06
6	773.15	3.31E+06		2.38E+06	3.124E+06
7	873.15	3.31E+06		3.63E+06	3.245E+06
8	973.15	3.32E+06		4.46E+06	3.327E+06
9	1073.15	3.33E+06		4.95E+06	3.379E+06
10	1173.15	3.34E+06		5.12E+06	3.401E+06
11	1273.15	3.34E+06		4.95E+06	3.393E+06
12	1373.15	3.35E+06		4.46E+06	3.354E+06

13	1473.15	3.35E+06	3.36E+06	3.256E+06
14	1573.15	3.36E+06	2.38E+06	3.174E+06
15	1673.15	4.12E+06	2.38E+06	3.841E+06

Although we know materials which were used to make components in a channel, those were changed slightly due to CUPID code capability. Real and simulation materials are shown in Table IV.

Table V: Structural Material, Temperature and Specification of Q7 Channel

Region Boundary	Specification (cm)	Reference/CUPID Material	Reference/CUPID Initial Temp. (K)
Fuel Radius	0.64808	UO$_2$, He, Zr4/ UO$_2$+He+Zr4 Volume Weighted	960.15/535.61
Pressure Tube Inside Radius	5.1689	D$_2$O(99% purity)/D$_2$O only	561.15/535.61
Pressure Tube Outside Radius	5.6032	Zr-Nb/Stainless Steel	561.15/342.15
Calandria Tube Inside Radius	6.4478	CO$_2$/Air	451.65/451.65
Calandria Tube Outside Radius	6.5875	Zr-2/Stainless Steel	342.15/342.15
Bundle Length	49.53	N/A	N/A
Number of Bundles	12	N/A	N/A

Although air is used for gap material by default, various options were possible for gap material such as helium, hydrogen, nitrogen, krypton, xenon, argon and sf6. Important properties for those materials are listed in Table VI.

Table VI: Material Properties in CUPID NCG List

Symbol (Atomic Number)	M. P. (℃)	B. P (℃)	Density (g/L)	k (w/mK)	C (j/molK)
He(2)	-272	-269	0.1786	0.1513	20.78
H(1)	-259	-253	0.0899	0.1805	28.84
N(7)	-210	-196	1.251	25.83	29.12
Kr(36)	-157	-153	3.749	0.0094	20.79
Xe(54)	-112	-108	5.984	0.0057	20.79
Air(N/A)	192	-194	1.225	0.025	29.07
Ar(18)	-189	-186	1.784	0.0177	20.79
SF6(N/A)	-78	-78	1.87	0.0166	51.07

3. Numerical Results

Even though we have a variety of T/H results through this study, the most important thing is amount of heat transport depends on gap material. Thus mixture enthalpy difference between inlet and outlet multiplied by mass flow is calculated for both primary heat transport system and annulus gas system. Each power is divided by the channel total power so that we can know the fraction of energy transported by each fluid as shown in Table VII.

Table VII: Energy Transportation Fraction by Different Regions

	Gap Material	PHTS (%)	AGS (%)	MODER-ATOR (%)
1	Helium	93.4	0.2	6.4
2	Hydrogen	93.5	0.1	6.4
3	Nitrogen	93.1	1.4	5.5
4	Krypton	92.5	4.2	3.3
5	Xenon	92.1	6.6	1.3
6	Air	93.1	1.5	5.5
7	Argon	93.0	1.5	5.0
8	SF6	92.0	2.0	0.8

It was revealed that amount of heat transport by primary heat transport system is not sensitive depend on the gap material while amount of heat transport by AGS or moderator is relatively sensitive depend on gap material (Heat transportation by PHTS ranges from 92.0%-minimum to 93.5%-maximum). From this fact, it can be approximated that using air instead of CO$_2$ which is used in real AGS will not be a matter so that justification of result from simulations using air is possible for later research.

Another issue arose in regard to geometry simplification case. What happens we omit pressure tube, gas gap and calandria wall is that small but clear changes can be observed. By eliminating the 3 regions, more energy will be retained in the PHTS so that fluid temperature will rise. For this reason, fluid density and mixture mass drop and pressure increases due to more void fraction.

In fact, motivation of this study is to do analysis of pressure tube deformation effect. Because it is well known that pressure tube deformation reduces critical channel power (CCP) significantly, 3 parameters such as pressure, mass flux, equilibrium quality are main concerns for a critical heat flux (CHF) point of view as shown in Fig. 4~6.

Though difference between results of full and simplified geometries is marginal, its amount is not negligible at the same time. Especially, it seems that mass flux and equilibrium quality difference will have more impact on CHF prediction (currently table type CHF prediction is usually used for CCP calculation).

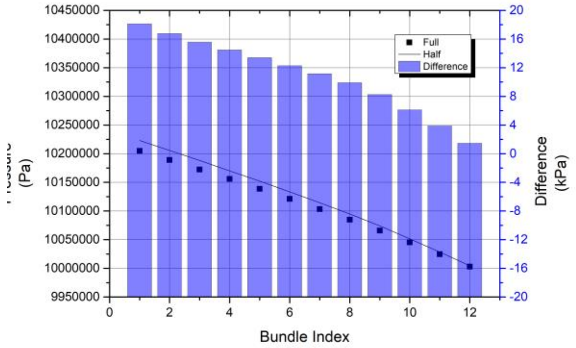

Fig. 4. Bundle-wise Pressure for Full and Simplified Geometries

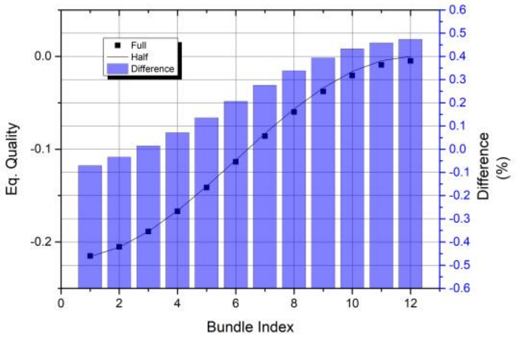

Fig. 5. Bundle-wise Equilibrium Quality for Full and Simplified Geometries

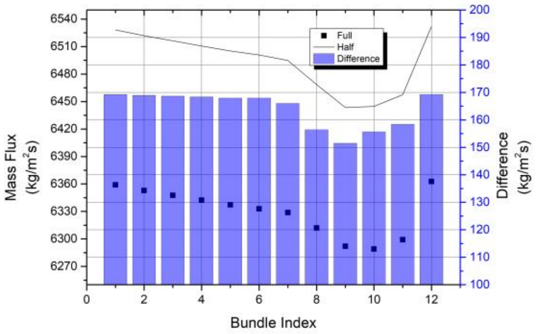

Fig. 6. Bundle-wise Mass Flux for Full and Simplified Geometries

4. Conclusions

In this study, two major subject were dealt with. One is gap material dependency on a channel analysis. Another is geometry simplification (omit pressure tube, gap and calandria tube) effect. At the end we found that gap material impact of amount of heat transportation by PHTS is negligible. In addition, because we have mass flux and equilibrium quality difference when we omit the three regions, it is better to include the three regions as many as possible for precise CCP prediction. Because we will get higher equilibrium quality and lower mass flux when we neglect pressure tube, gap and calandria tube, we will have lower CCP. Thus omitting the three regions will give us conservative result for channel safety margin point of view.

REFERENCES

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[2] H. Y. Yoon et al., CUPID CODE MANUAL VOLUME II: User’s Manual, KAERI/TR-4404, 2011.