A MECHANISITIC MODEL FOR PRESSURE TUBE-CALANDRIA TUBE THERMAL CONTACT CONDUCTANCE FOR A PRESSURE TUBE BALLOONING EVENT

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Abstract

During an event resulting in loss of cooling ability to the fuel such as a critical break large Loss of Coolant Accident (LOCA), pressure tubes in a CANDU® reactor could undergo ballooning deformation resulting in physical contact between the pressure tube (PT) and its surrounding calandria tube (CT). Thermal contact conductance between the two tubes plays a major role in whether CHF occurs on the outside of the calandria tube. A mechanistic model for contact conductance under transient contact pressure is developed. The resulting contact conductance transient is then compared to experimental data obtained in a graphite heater fuel channel deformation experiment. It is shown that a sustained high level of PT-CT contact conductance is not consistent with the results obtained through the developed mechanistic model.

1. Introduction

CANDU reactors are of the heavy water pressure tube type. The core consists of several hundred horizontal fuel channels surrounded by a heavy water moderator. Fuel channels consist of a Zircaloy-2.5%Nb pressure tube enclosed within a Zircaloy-2 calandria tube. There is an annulus gas gap between the pressure tube and the calandria tube. Under extreme accident conditions such as a critical break LOCA, the pressure tube may deform. If the fuel channel remains pressurized, the hot pressure tube can balloon into contact with the calandria tube.

Thermal contact conductance between pressure tube and calandria tube must be understood as it is a key factor in studying fuel channel integrity. Once PT-CT contact occurs, heat is transferred from the hot pressure tube to the relatively cool calandria tube. The heat flux to the calandria tube is a function of the temperatures of the two tubes as well as the thermal contact conductance between them. For high heat flux levels the calandria tube temperature can increase enough for film boiling to occur on the outer surface. Film boiling will severely limit heat transfer to the moderator and cause overheating of the calandria tube which could lead to fuel channel failure. It is therefore important to understand the mechanisms involved in thermal contact conductance and to study the transient behaviour of contact conductance during a PT-CT contact event.

This paper presents a new approach to calculating the contact conductance transient during the initial contact and post-contact phases of a postulated critical break loss of coolant accident. The contact pressure at the interface between the tubes is a critical parameter in determining the thermal contact conductance. An iterative method is used to solve for creep strain in the pressure tube and calandria tube which determines the interfacial pressure. A modern correlation

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for contact conductance is then applied. The results show an initially high contact conductance in the initial contact phase. This is followed by a rapid decrease in conductance across the interface. These results are due to the interfacial pressure being high at initial contact. As the pressure tube transfers heat to the calandria tube and cools down, thermal expansion of calandria tube and thermal contraction of the pressure tube causes the conductance to rapidly decrease. This is known as the post-contact phase.

2. Modelling Methodology

Following PT-CT contact, a heat pathway is established from the fuel to the moderator. The incident heat flux on the pressure tube is from the fuel. The main thermal conductance restrictions are at the PT-CT interface and at the calandria tube-moderator interface. However, the heat transfer coefficient for pool boiling convective heat transfer from the calandria tube is 10-50 kW/m^2/°C [1], which is significantly higher than the PT-CT contact conductance. Another conduction resistance in the heat pathway is conduction through the pressure tube and calandria tube material itself.

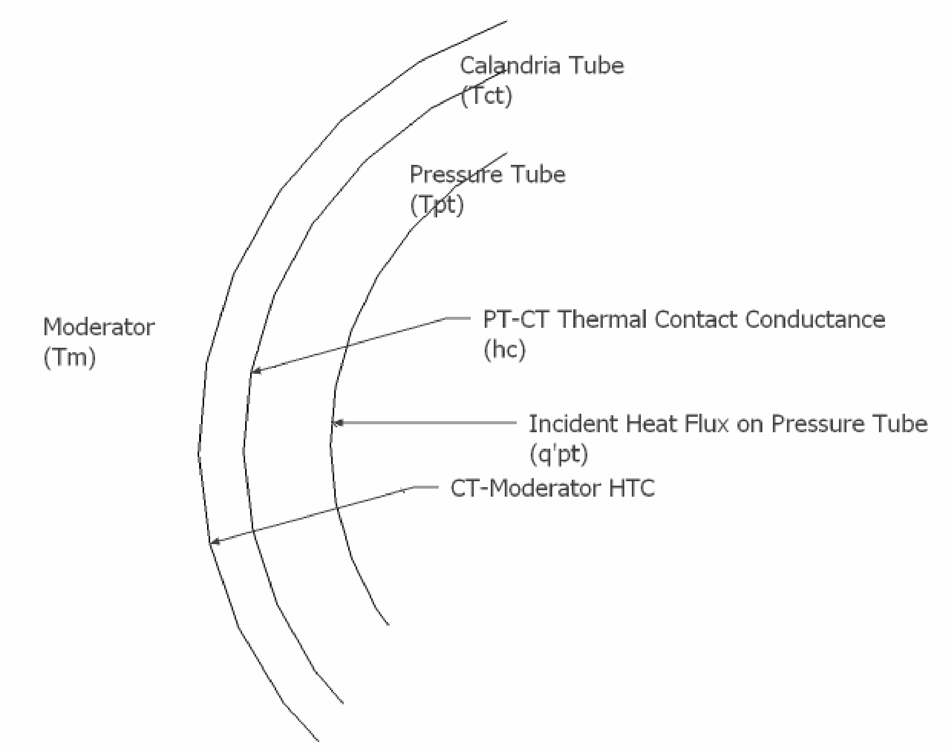

Figure 1 Pressure tube in contact with calandria tube

Assumptions:

- Pressure tube creep is uniform in the radial and azimuthal directions
- There is no strain in the axial direction
- Once PT-CT contact is made both tubes experience the same creep strain rate
- At initial contact, contact pressure increases to its maximum rapidly
- Radiation heat transfer is negligible

2.1 Contact conductance theory

When two solid surfaces come into contact, microscopic contact areas and gap areas are formed. This is because real surfaces are not perfectly smooth and microscopic surface asperities are present. Since perfect contact between two surfaces is not possible, thermal conductance between solid surfaces is dependant on the actual contact area.

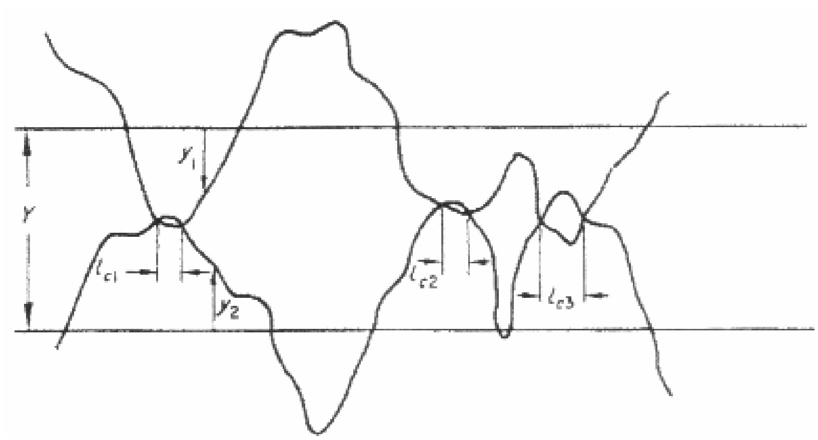

Figure 2 Ref. [2] Example of microscopic regions of solid contact and gaps in two contact surfaces

If areas of solid contact and gaps are thought of as each having their own contact resistance, they can be summed like parallel resistors;

$$h = h_c + h_g \qquad (1)$$

The total contact conductance is the sum of conductance across solid contact areas and conductance across gas gap areas. Each term can be calculated separately to determine the total contact conductance. For the case studied in this paper, both modes of heat transfer are similar in magnitude and both play an important role in determining the overall heat transfer.

Heat transfer by means of radiation between the two surfaces may also be included in Equation (1), but for the purposes of this paper it is assumed to be negligible. Calculation of the radiative heat transfer coefficient [7] for the case of two concentric tubes gives a maximum value approximately three orders of magnitude less than the values of solid and gas gap conductance. This is consistent with observations from experimental results where CT temperature does not increase significantly prior to contact.

2.1.1 Key parameters

The ratio of contact pressure to surface material hardness is a key parameter for determining solid contact area. This is because the total solid conductance is proportional to the total area of the solid contact regions. As interfacial pressure is increased, the contacting surfaces get pressed together with greater force resulting in a higher value of solid conductance.

Surface roughness is also a key parameter. Finer surface finishes (smaller surface asperities), result in higher values of conductance. This is due to roughness effects on mean plane separation, which increases gas gap conductance for a finer surface finish. Also, smaller roughness values result in the presence of more contact points for a greater solid contact area.

Mean plane separation, represented as Y in figure 2, is the main parameter influencing conduction through the gas gap regions. It is assumed that the gap area is too small for convective heat transfer; therefore the gas gap conductance is inversely proportional to the mean plane separation of the two surfaces.

2.2 Yovanovich Model

The model proposed by Yovanovich [6] provides a good estimate of contact conductance for macroscopically conforming rough surfaces. It was chosen over other models, such as the Ross-Stoute model because of its ability to calculate mean plane separation. This is important because for PT-CT contact solid and gas gap conductivity are of comparable magnitude. Models such as Ross-Stoute (developed for fuel-cladding interface) only provide a rough estimate of the gas gap conductance. This is acceptable for some scenarios where the gas gap conductance is significantly smaller than the solid conductance. Lemczyk and Yovanovich [3] have shown that the Yovanovich [6] model accurately determines contact conductance for the case of compound cylinders; a similar geometry to PT-CT contact.

The Yovanovich model:

$$h_c = 1.25\frac{k_s m}{\sigma}\left(\frac{P}{H}\right)^{0.95}, h_g = \frac{k_g}{Y + \alpha_a \beta \Lambda} \tag{2}$$

The key parameters as discussed in section 3.1.1 including the contact pressure/surface hardness ratio and the mean plane separation are present in the Yovanovich model. This model includes the addition of empirically determined terms. The gas gap conductivity now takes gas temperature and molecular movement into account.

The mean plane separation is defined as;

$$Y = 1.184\sigma\left[-\ln\left(\frac{3.132P}{H}\right)\right]^{0.547} \tag{3}$$

This is an approximation to the complimentary error function which is derived from the assumption that the height of surface asperities follows a Gaussian distribution.

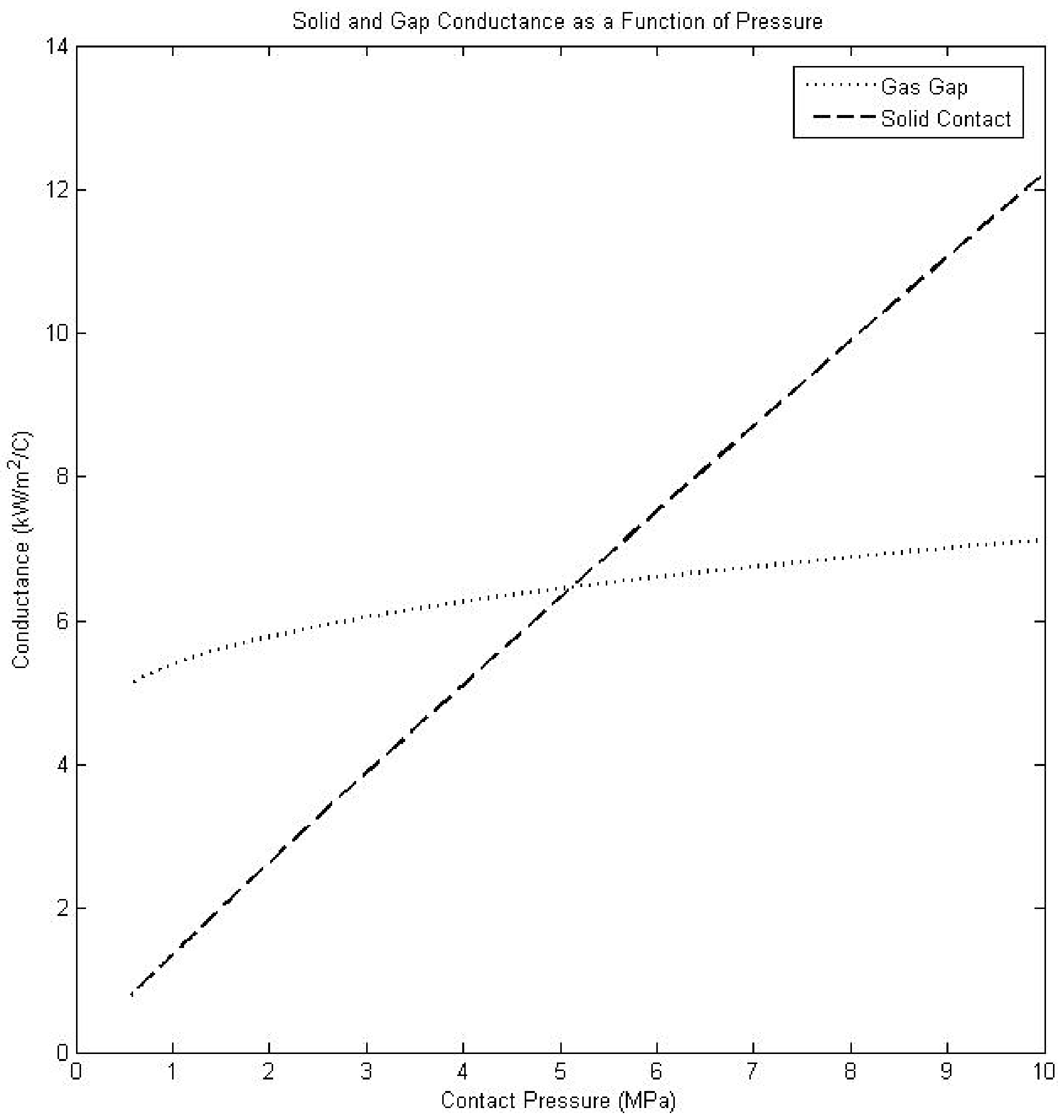

Figure 3 Gap and solid conductance calculated from the Yovanovich model [6] as a function of contact pressure

As seen in figure 3, the solid contact conductance has an almost linear relationship with respect to contact pressure. The gas gap conductance also increases with contact pressure. This is due to a smaller value of mean plane separation at higher contact pressures.

2.3 Code Structure/Implementation

A computer code was developed to compute the transient heatup and contact of a pressure tube and calandria tube. In the code, three separate but dependant variables are solved simultaneously. The variables are: creep strain, contact conductance, and PT/CT temperature. Contact pressure between the two tubes is solved by simultaneously matching the creep strains in the two tubes, given the internal driving pressure in the PT and external pressure outside the CT.

2.3.1 Creep Strain

In the pre-contact phase, before PT/CT contact is made, the pressure tube is heated up and undergoes ballooning deformation. The Shewfelt [5] correlation for Zr-2.5%Nb pressure tubes is used to determine the creep strain of the pressure tube:

$$\dot{\varepsilon}_{pt} = 5.7x10^{7}\,\sigma_{pt}^{1.8}\exp\left(-29200/T_p\right) \tag{4}$$

In the post-contact phase, when the pressure tube creep strain is sufficiently high that PT/CT contact occurs, it is assumed that the PT creep strain rate is equal to the CT creep strain rate. The Shewfelt correlation for Zr-2 calandria tubes [4] is used.

CT – Dislocation creep (coupled equations)

$$\dot{\varepsilon}_{d} = 22000\left(\sigma_{ct}-\sigma_{i}\right)^{5.1}\exp\left(-34500/T_c\right) \tag{5}$$

Where,

$$\sigma_i(t) = 1.4 + \int_0^t \left[110\dot{\varepsilon}_d - 3.5x10^{10}\,\sigma_i^{1.8}\exp\left(-34500/T_c\right)\right]dt \tag{6}$$

CT – Grain Boundary sliding

$$\dot{\varepsilon}_{gb} = 140\sigma_{ct}^{1.3}\exp\left(-19000/T_c\right) \tag{7}$$

Where the total CT creep strain rate is:

$$\dot{\varepsilon}_{ct} = \dot{\varepsilon}_{gb} + \dot{\varepsilon}_{d} \tag{8}$$

The CT equations in conjunction with the PT equation for creep strain rate are used together to iteratively solve for the contact pressure between the two tubes. This is accomplished by using relations to define radial stress in the CT and PT from the forces acting on the tubes.

$$\sigma_{PT} = \frac{(P_{\text{int}}-P_i)r_{PT}}{\tau_{PT}} \qquad \sigma_{CT} = \frac{(P_i-P_{ext})r_{CT}}{\tau_{CT}} \tag{9}$$

2.3.2 Contact Conductance

Before PT/CT contact is made, there is still a small amount of heat transfer to the calandria tube due to conduction through the carbon dioxide annulus gas. This is approximated by the following equation:

$$h_g = \frac{k_g}{\delta} \tag{10}$$

Where, δ is the separation distance between PT outer surface and CT inner surface. After contact, the Yovanovich correlation from section 2.2 is used to determine the contact conductance.

2.3.3 Temperature

For both pre and post contact phases the following, coupled differential equations are solved simultaneously to determine the temperatures of the PT and CT.

$$m'_{pt} c_{ppt} \frac{dT_{pt}}{dt} = q'_{pt} - h'_{eff}\left(T_{pt} - T_c\right) \tag{11}$$

$$m'_c c_{pc} \frac{dT_c}{dt} = h'_{eff}\left(T_{pt} - T_c\right) - h'_{conv}\left(T_c - T_l\right) \tag{12}$$

In the pre-contact phase the heat transfer to the calandria tube is small. Therefore this phase is known as the “pressure tube heat up phase” as no significant increase in calandria tube temperature is seen as PT temperature rises.

3. Results

Two examples of results obtained can be seen in figures 4 and 5. Figure 4 represents a case where no film boiling is observed. This is established by fixing the pool boiling convective heat transfer coefficient between the calandria tube and the moderator at 50 kW/m^2/°C. This falls within the expectable range for natural convection heat transfer [1]. The incident heat flux on the pressure tube was 25 kW/m. A table including other property values used in the model can be found in the appendix.

During the heatup phase, the pressure tube heats up approximately linearly. When contact is made, there is a sharp decrease in temperature as heat is transferred from PT to moderator via the calandria tube. CT temperature does not rise significantly because no nucleate boiling or dryout occurs on the CT surface, this results in no CT creep strain deformation. PT-CT contact conductance is high at initial contact, (approximately 11 kW/m^2/°C) when contact pressure is at its highest. This value quickly decreases as the pressure tube temperature decreases. The steady state value settles to approximately 5 kW/m^2/°C.

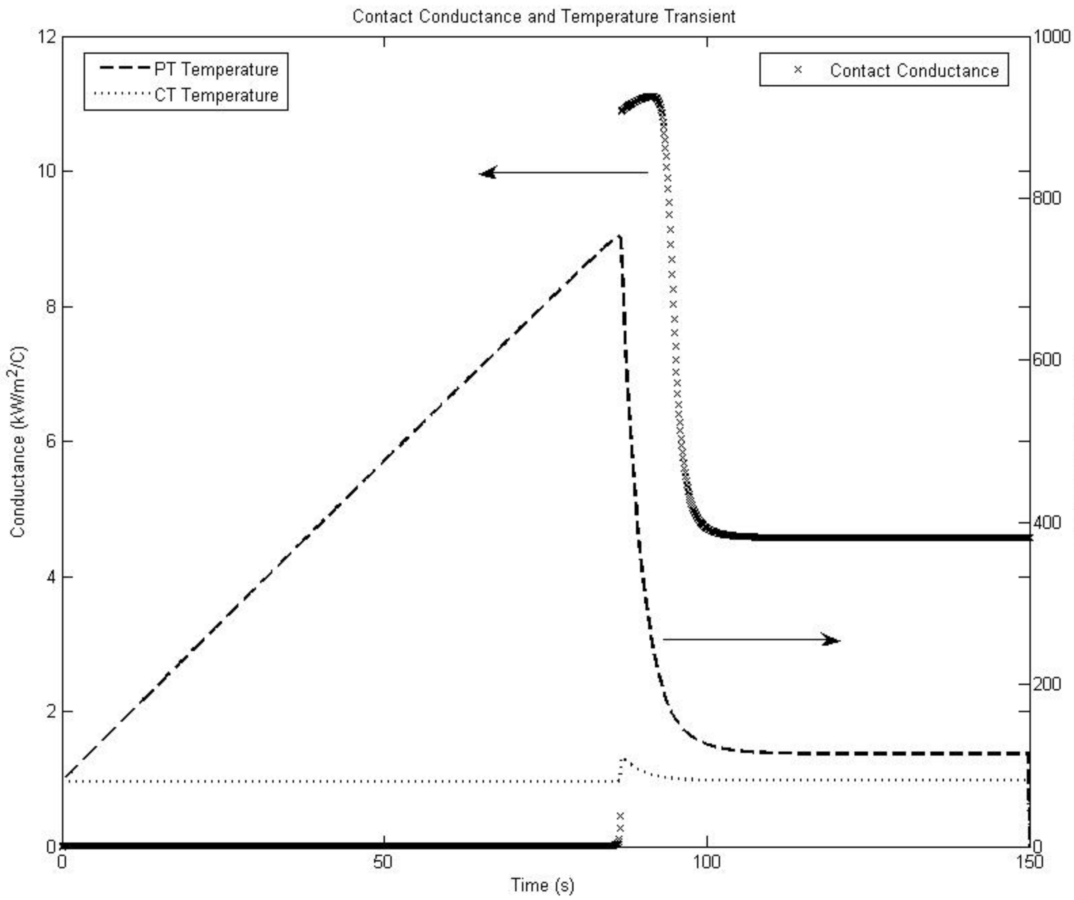

Figure 4 Temperature and contact conductance assuming high convection coefficient between CT and moderator

When CT-moderator heat transfer is limited by a small heat transfer coefficient, as would be the case in calandria tube dryout, CT temperature at contact rises to a higher level. Figure 5 shows the results in which the convective heat transfer coefficient was fixed at 1 kW/m^2/°C. Incident heat load on the pressure tube remains at 25 kW/m. The peak and steady state values of contact conductance remain the same as the no film boiling case in figure 4, but the time to reach steady state in the post-contact phase is considerably longer. Since the CT experiences higher temperatures, it undergoes a small amount of creep at initial contact. The calandria tube creep results in an initial rapid drop in contact pressure and therefore a decrease in conductance followed by a slight recovery as the pressure tube expands further.

In order to obtain these results from the created mathematical model, estimates were needed for certain parameters in the code. The values used for the results shown are summarized in table A1.

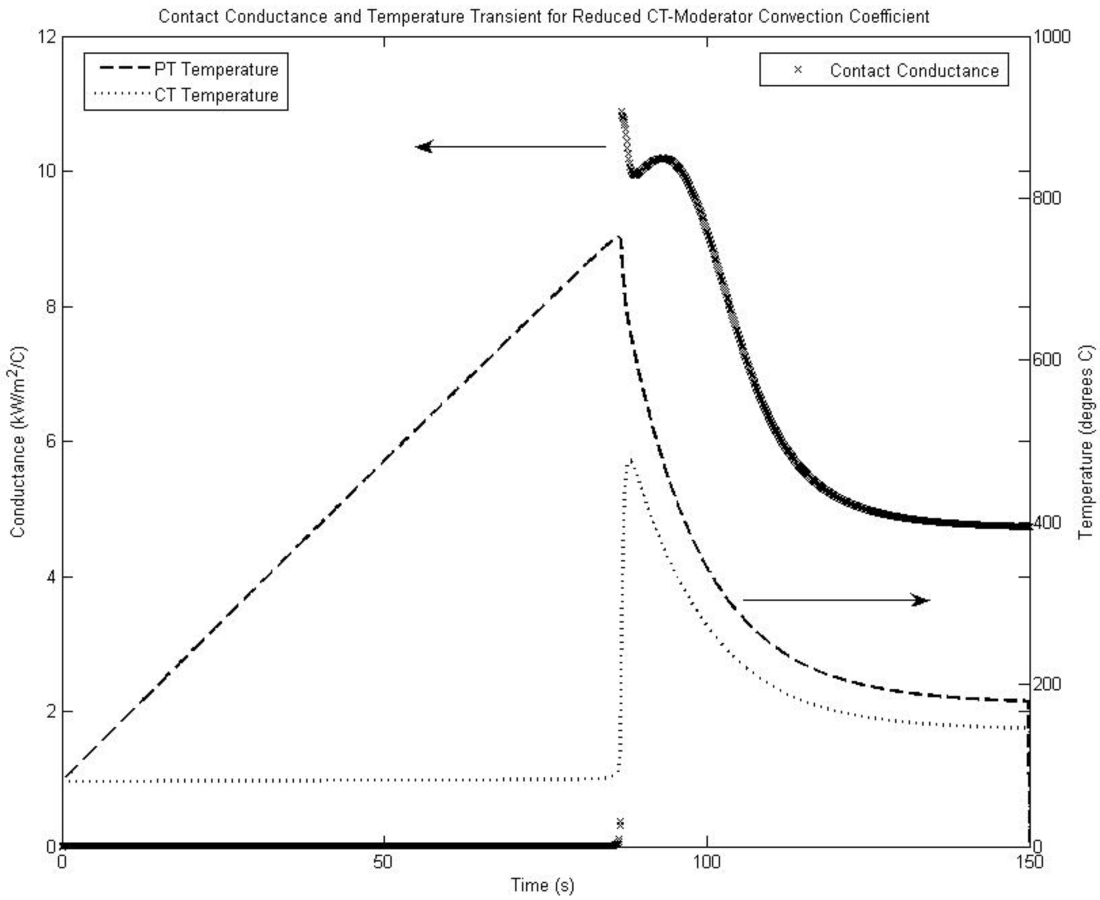

Figure 5 Temperature and contact conductance assuming low convection coefficient between CT and moderator

Contact conductance data was extracted from one graphite heater experiment [9] by using the known temperature transients of pressure tube and calandria tube for the test. Conditions of this test included a high subcooling and high PT heatup rate (high PT incident heat flux). The results can be seen in figure 6. Boundary conditions included PT heatup rate and a calculated heat transfer coefficient between the outside of the CT and the moderator.

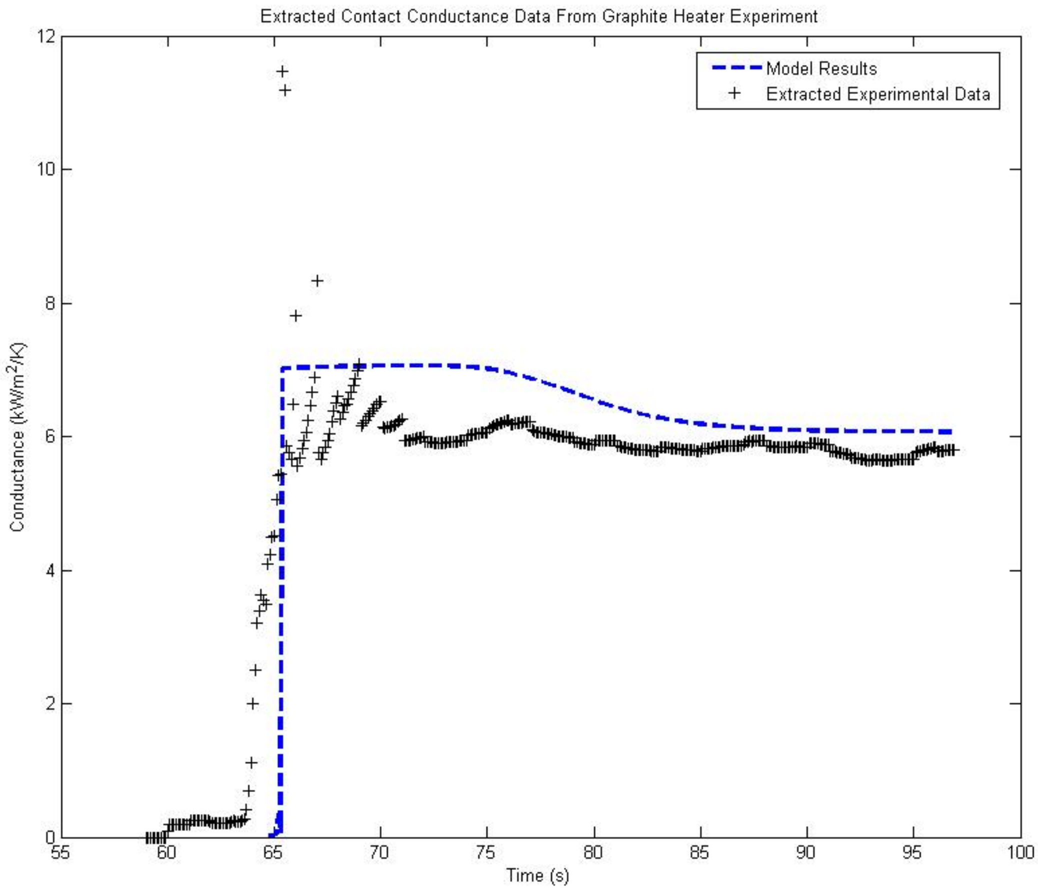

Figure 6 Extracted contact conductance data from experiment SUBC3 compared against results from mechanistic model

Figures 7 and 8 are plots of the transient stress and strain in the two tubes, respectively. In the stress plot, PT stress is constant during the majority of the heatup phase. This is because the internal pressure of the PT remains constant. As the PT heats up it starts to creep. A positive creep in the azimuthal direction results in negative radial creep strain and thinning of the tube wall which explains the increase in PT strain just prior to PT-CT contact (Equation 9). Calandria tube stress is zero until PT-CT contact is made. Immediately after contact CT stress jumps to a high value because of high initial contact pressure. CT stress then decreases with contact pressure. A mirroring effect can be seen in PT stress after initial contact as the contact pressure between PT and CT serves to decrease stress in the pressure tube.

The creep strain of the PT increases fairly rapidly once a certain threshold temperature is reached as can be seen in figure 8. This results in rapid ballooning of the pressure tube into contact with the calandria tube. Shortly after contact, CT temperature increases. High temperature and stress in the calandria tube leads to a small amount of CT creep. Note that figures 7 and 8 represent the case where CT-moderator heat transfer is limited. For high CT-moderator heat transfer, CT creep is negligible.

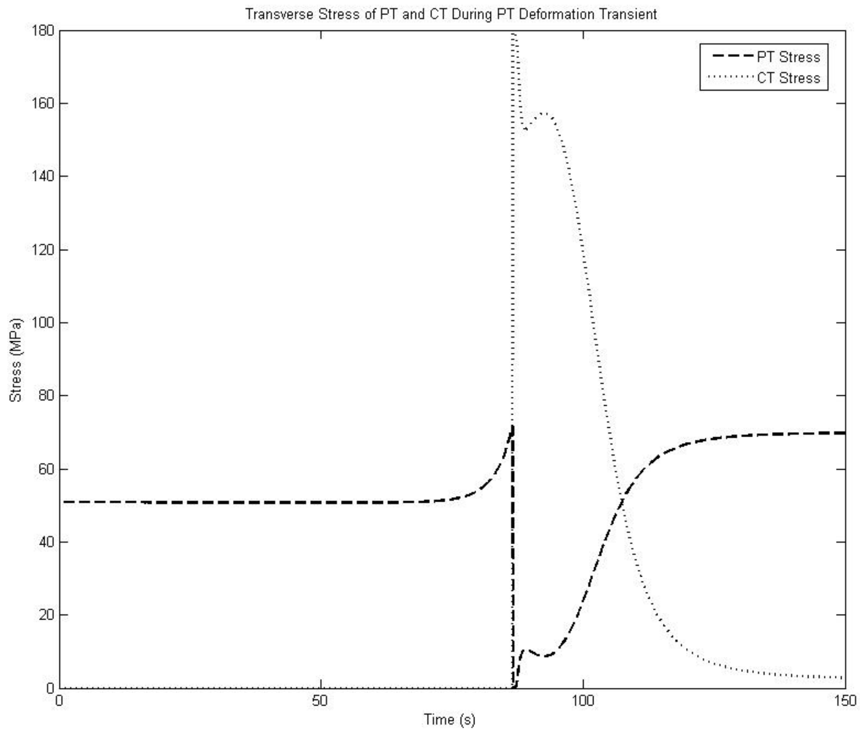

Figure 7 Calculated stress transient for CT and PT

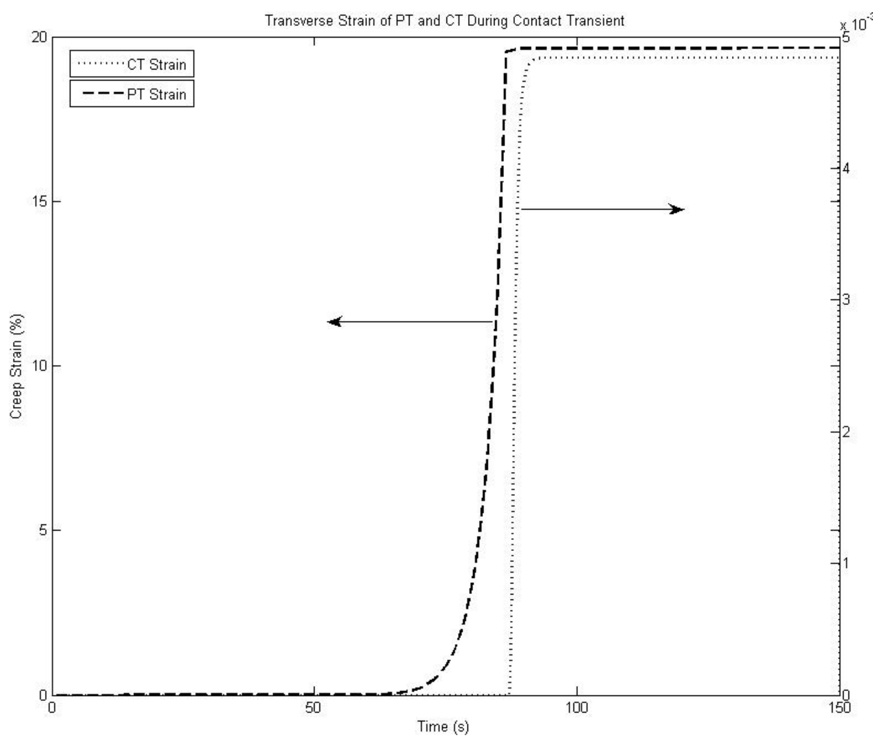

Figure 8 Calculated creep strain transient for PT and CT

4. Conclusion

A contact conductance model has been developed which simulates the event of a pressure tube heating up and ballooning into contact with the calandria tube in a CANDU reactor. The mechanistic model was developed using proven equations and correlations to describe the postulated event. Results demonstrate transient contact conductance values that are consistent with data determined experimentally. During such a transient, high values of PT-CT contact conductance are not sustained for extended periods of time. Future work will include further validation and analysis of the developed mechanistic model using experimental data.

5. References

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[6] Yovanovich, M. M., "New Contact and Gap Conductance Correlations for Conforming Rough Surfaces", AIAA paper No. 81-1164, AIAA 16th Thermophysics Conference, Palo Alto, California, June 23-25.

[7] Incropera, F. P. and DeWitt, D. P., "Introduction to Heat Transfer", John Wiley & Sons, New York, 1985.

[8] Fan H.Z., Shams M., Sanderson D.B., "Methodology to Assess the Transient Contact Heat Transfer Coefficient between Pressure Tube and Calandria Tube Using Contact Boiling Test Data", the 22nd Nuclear Simulation Symposium, Ottawa, November 2002.

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6. Nomenclature

h_c, h_g	Heat transfer coefficient of solid contact region and gap region, kW/m^2K
k_s, k_g	Thermal conductivity of solid zircaloy and carbon dioxide annulus gas
m	Surface asperity slope, rad
σ	Surface roughness, m
P	Contact pressure between CT and PT
H	Hardness of zircaloy
Y	Mean plane separation
α_a	Accomodation parameter for gas gap
β	Fluid parameter in gas gap
Λ	Molecular mean free path for gas in gap
$\dot{\varepsilon}_{pt}, \dot{\varepsilon}_{ct}$	Creep strain rate of pressure tube and calandria tube
$\dot{\varepsilon}_{d}, \dot{\varepsilon}_{gb}$	Disloacation and Grain boundary creep strain rates for calandria tube
σ_{pt}, σ_{ct}	Pressure tube and calandria tube hoop stress
r_{pt}, r_{ct}	Radius of pressure tube and calandria tube, respectively
τ_{pt}, τ_{ct}	Thickness of pressure tube and calandria tube, respectively
δ	PT-CT separation distance prior to contact
m'_{pt}, m'_{c}	Mass per unit length of pressure tube and calandria tube, kg/m
c_{ppt}, c_{pc}	Specific heat of pressure tube and calandria tube
q'_{pt}	Linear incident heat flux on pressure tube
h'_{eff}	Effective heat transfer coefficient between PT and CT centres
h'_{conv}	Convective heat transfer coefficient between calandria tube and moderator

7. Appendix

Parameter	Units	Value
Microhardness	MPa	1000
Mean surface Asperity slope	Rad	0.3
Mean combined surface roughness	m	6*10^-6
PT thermal conductivity	W/m*K	18
CT thermal conductivity	W/m*K	13.7

Table A1 Values used in code