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Development of RELAP/CANDU Thermal/Mechanical Model for Fuel Channel Analysis

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1. Introduction

In CANDU reactors following a large LOCA, blowdown may be followed by a prolonged stagnation period. Pressure tube(PT) ballooning(high internal pressure) or sagging(low internal pressure) takes place sometime during the blowdown/stagnation period. The modeling capability for circumferential conduction and deformation is important in CANDU's horizontal geometry and related stratification effects.

RELAP/CANDU can calculate radial heat conduction only. Therefore, to evaluate PT integrity due to local strain, the capability to calculate heat conduction and deformation in both radial and azimuthal (circumferential) coordinates is required. A finite element, variational technique was used to develop a realistic fuel channel module for fuel channel analysis. The implementation of the model into RELAP/CANDU and its verification was performed to develop best-estimate core heat transfer code.

2. Development of Thermal/Mechanical Model

2.1 2D Heat Conduction Equation

The equation solved is heat conduction in the radial and the circumferential direction:

$$\frac{\partial}{\partial r}(kr\frac{\partial T}{\partial r}) = -r[q''' + \frac{k}{r^2}\frac{\partial^2 T}{\partial\theta^2} - \rho Cp\frac{\partial T}{\partial t}] \quad (1)$$

Where q''' is heat generation per unit volume, T is temperature, ρ is density, C_p is specific heat, and k is thermal conductivity.

This heat conduction equation is solved by a finite element, variational technique in the radial direction with a finite-difference method for the circumferential conduction term.

Discretization for Radial Heat Conduction

The variational approach to the solution of the radial heat conduction equation is used to seek a stationary value to the functional, F. At the stationary point, δF is equal to zero for an arbitrary δT. The matrix equation generated is:

$$A_1(\frac{d\bar{c}}{dt}) + A_2\bar{c} = B \quad (2)$$

where c is a vector notation for undetermined coefficients for the trial function, ψ.

This equation is solved by an implicit finite difference scheme. Consequently, we can generate A_1, A_2 and B to enter into the global matrix Eq. (2) and form a tri-diagonal equation. This matrix equation can be solved easily with a modified Gaussian elimination-back substitution to seek a stationary algorithm.

Discretization for Radial /Azimuthal Heat Conduction

Now we consider the case when heat is conducted in both radial and circumferential directions. In the present case, the q''' in the right hand side of Eq. (1) is replaced by:

$$B = \int_{r_i}^{r_{i+1}} r\beta(r)(q''' + \frac{k}{r}\frac{\partial^2 T}{\partial\theta^2})\ dr \quad (3)$$

We further use the finite-element expression for approximation of T. Then Eq. (3) becomes:

$$B = \int_{r_i}^{r_{i+1}} r\beta(r)q'''\ dr + \int_{r_i}^{r_{i+1}} \beta(r)\,\beta^T(r)\frac{k}{r\triangle\theta^2}\ dr\ (\underline{\psi_L} - 2\underline{\psi} + \underline{\psi_R}) \quad (4)$$

where β is independent coordinate functions.

The principles described in the previous section can be also applied with slight modifications. Therefore, we solve for c in Eq. (1) and obtain the temperature distribution.

2.2 Pressure Tube Deformation Model

To predict non-uniform PT deformation, the computer program GRAD, developed by Shewfelt and Godin, was modified and incorporated into the fuel channel module. The model assumes that the tube remains circular and that only membrane stresses need be considered. The local transverse creep(strain) rate is given by:

For $T_{pt} > 850℃$,

$$\dot{\varepsilon}_1 = 10.4\sigma^{3.4}e^{-19600/T} + \frac{3.5 \cdot 10^4\sigma^{1.4}e^{-19600/T}}{1 + 274\int e^{-19600/T}(T - 1105)^{3.72}dt} \quad (5)$$

For $T_{pt} < 850℃$,

$$\dot{\varepsilon}_1 = 1.3 \cdot 10^{-5}\sigma^9 e^{-36600/T} + \frac{5.7 \cdot 10^7\sigma^{1.8}e^{-29200/T}}{[1 + 2.10^{10}\int e^{-29200/T}dt]^{0.42}} \quad (6)$$

where σ = P·r/w is the transverse stress in MPa(P is the pressure and r/w is the radius divided by the PT thickness).

The characteristic creep rate equation is numerically integrated for each circumferential sector on the PT. At the end of each time step, the geometry is updated by calculating new sector lengths and local wall thickness, using the increments in creep strain determined for each sector.

2.3 CANDU Fuel Channel Module

Rather than extend development of the current RELAP/CANDU HEAT STRUCTURE capability to a second dimension, 2D standalone fuel channel module was developed. In the fuel channel module, the following modifications are included for the integration of thermal-mechanical model into RELAP/CANDU (Figure 1):

- Input extension for 2D sector information
- Initialization extension for 2D sector
- Material properties and heat transfer coefficients for 2D sector
- Void fraction for horizontal stratified flow(wet/dry fraction) and energy partitioning
- Multi-D plot using TECPLOT format

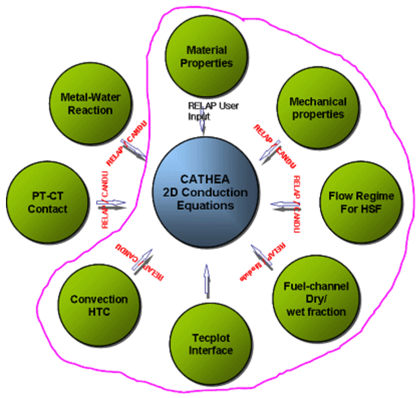
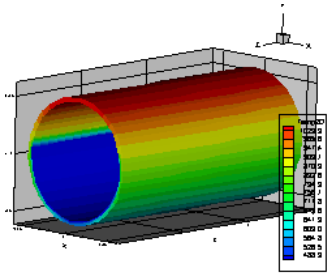


Figure 1. CANDU Fuel Channel Module Integrated into RELAP/CANDU.

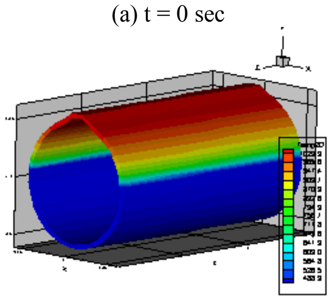
3. Verification and Assessment of Improved Fuel Channel Model

To check the overall applicability of new version of RELAP/CANDU, a code-to-code comparison study between CATHENA and RELAP/CANDU was done. Following a large LOCA, a period of very low flow and stagnation exists with the potential for PT deformation. The fuel channel model was used to analyze circumferential variations in the PT temperature and deformation under thermohyraulically asymmetrical coolant conditions. To simulate the PT behavior, circumferential sectors on the PT were used. The inner surface boundary condition applicable to each azimuthal sector depends on the liquid level in PT. For each sector, the code calculates whether the sector is in contact with steam, liquid or two-phase fluid, and applies the appropriate convective heat transfer.

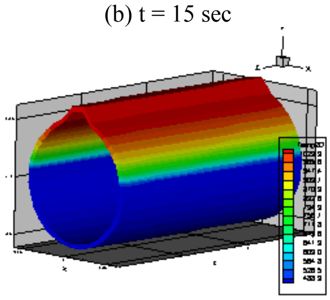
Figure 2 shows the temperature transients predicted by RELAP/CANDU. PT deformation is also calculated for each sector. Thermal gradients, across the circumference of the PT, was induced by thermohydraulic effects, such as stratified coolant in the channel. Because the non-uniform heatup in the circumferential direction was assumed, the PT is predicted to strain locally at hotspot. RELAP/CANDU tracks PT temperature and thinning successfully in each circumferential sector in comparison to CATHENA results.



(a) t = 0 sec



(b) t = 15 sec



(c) t = 30 sec

Figure 2. PT Temperature and Strain Behavior for Horizontal Stratified Flows(Non-uniform Heat Transfer Coefficients).

4. Conclusion

The CANDU fuel channel module was developed to improve the capability of RELAP/CANDU code. Model for 2D heat conduction and non-uniform PT deformation was included in the fuel channel model. A series of simulations for horizontal stratified flow was performed to verify the model. It can be concluded that the modified model shows reasonable results through the comparison to CATHENA results.

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