Development of Pressure Tube Deformation Model in RELAP-CANDU Code

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I. Introduction

In CANDU reactors, for the Loss of Coolant Accident (LOCA) with the failure of Emergency Core Cooling System (LOECCS), the inventory of primary coolant decreases until the primary system is filled with steam. And the fuel and pressure tube are heated by the decay heat and begin to be ballooned in the radial direction. The heat transferred to moderator increases rapidly due to the direct contact between pressure tube and calandria tube. The integrity of pressure tube depends on the heat transfer condition between the calandria tube and moderator.

To properly analyze these phenomena, the Pressure Tube Deformation (PTD) model was developed to improve the capability of RELAP/CANDU code in the safety analysis of CANDU reactor.

II. Methods and Results

1. Pressure Tube Deformation Model

The PTD model developed by Shewfelt and Godin [1] has been modified and incorporated to RELAP/CANDU code. In RELAP/CANDU code, it is difficult to divide the pressure tube into several sectors. So the pressure tube is regarded to be one sector and ballooned uniformly in the radial direction maintaining constant volume. The local transverse creep (strain) rate is given by:

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

$$\dot{\varepsilon}_2 = 1.3\cdot 10^{-5}\sigma^{9}e^{-36600/T} + \frac{5.7\cdot 10^7 \sigma^{1.8} e^{-29200/T}}{[1+2\cdot 10^{10}\int e^{-29200/T}\,dt]^{0.42}} \tag{2}$$

where $\sigma = \mathrm{P}\cdot\mathrm{r}/w$ is the transverse stress in MPa (P is the pressure and r/w is the radius divided by the pressure tube thickness).
The Eq. (1) is applied to the condition of T>1123K, and the Eq. (2) is applied to the condition of 73K<T<1123K.

2. Radiation Heat Transfer Models

Fuel Rods-Pressure Tube

The 37 fuel rods are divided into 4 groups according to the rod power and geometrical position as shown in Figure 1. It is very difficult to precisely simulate the radiation heat transfer among fuel rods and pressure tube. So it is assumed that the radiation heat transfer exists only in the adjacent heat structures.

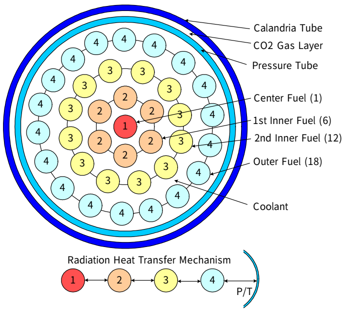

Figure 1. Fuel Rod Model and Radiation Heat Transfer Mechanism

Pressure Tube-Calandria Tube

In RELAP/CANDU, the pressure tube, CO2 gas layer, and the calandria tube are considered to be one heat structure. So the convection heat transfer by the CO2 gas is simulated by the thermal conduction. But the radiation heat transfer can not be simulated in the previous heat structure of RELAP/CANDU. So, the radiative gap conductance model [2] was applied to RELAP/CANDU to simulate the radiation heat transfer between pressure tube and calandria tube. The radiation heat transfer between pressure tube and calandria tube is defined by the Eq. (3)

$$q_{rad} = \frac{\sigma A_{PT}(T_{PT}^4 - T_{CT}^4)}{\{\frac{1}{\varepsilon_{PT}} + \frac{R_{PT}}{R_{CT}}[\frac{1}{\varepsilon_{CT}} - 1]\}} = h_{rad}A_{PT}(T_{PT} - T_{CT}) \tag{3}$$

where, ε is the emissivity and σ is the Stefan-Boltzmann constant. The radiative gap conductivity is applied to simulate the radiation heat transfer by conduction heat transfer as shown in Eq. (4) and (5).

$$q_{rad} = h_{rad}A_{PT}\Delta T = -k_{rad}A_{PT}\frac{\partial T}{\partial x} = k_{rad}A_{PT}\frac{\Delta T}{\Delta x} \tag{4}$$

$$k_{rad} = h_{rad}\Delta x = \frac{\sigma\Delta x(T_{PT}+T_{CT})(T_{PT}^2 - T_{CT}^2)}{\{\frac{1}{\varepsilon_{PT}} + \frac{R_{PT}}{R_{CT}}[\frac{1}{\varepsilon_{CT}} - 1]\}} \tag{5}$$

Finally, the total conductivity is the sum of thermal conductivity and radiative gap conductivity.

$$k_{tot} = k_{th} + k_{rad} \tag{6}$$

III. Simulation of RIH35% Break with LOECC

To verify the developed PTD model, the simulation of RIH35% break with loss of ECC injection in Wolsong

Unit 2 was performed through single channel nodalization model. The two nodalization models for the pressure tube, CO2 gas layer, and calandria tube were proposed. In one case with PTD model (case-i), the pressure tube, CO2 gas layer, and calandria tube are regarded as one heat structure. And in the other case without PTD model (case-ii), the pressure tube and calandria tube are regarded as independent heat structure having outer and inner surface boundary respectively with hydrodynamic volume of CO2 gas. The moderator system adjoined to the outer surface of calandria tube has been modeled to serve as heat sink.

The primary system is filled with the saturated steam of 2.4MPa pressure at initial state. And there is no flow at inlet and outlet header. Steam-zircalloy reaction was considered to produce additional heat and hydrogen. Option 81 using Baker-Just metal-water reaction equation was used to represent the characteristics of CANDU reactors.

Figure 2 shows temperature transient of fuel cladding, pressure tube and calandria tube with and without PTD model. Both cases, the center fuel rod has minimum temperature and the outer fuel rod has maximum temperature at early state. It is because that the fuel rod power in the outer region is larger than that in the center region. But after 150 sec, the temperature in the center region becomes larger than that in the outer region due to radiation heat transfer.

In case-i, pressure tube contacts with calandria tube about at 70 sec due to ballooning of pressure tube. Then the temperature of pressure tube decreases rapidly and that of calandria tube increases rapidly. The maximum temperature of pressure tube is 1025K. But in case-ii, there is no deformation of pressure tube and the temperature of pressure tube becomes up to 1800K. While the temperatures of center fuel rod and outer fuel rod in case-i increases up to 2450K and 1570K respectively, those in case-ii increases up to 2910K and 2350K.

The differences of temperature of center fuel, 1st inner fuel, and 2nd inner fuel between case-i and case-ii are relatively smaller than those of outer fuel and pressure tube.

Figure 3 shows axial temperature profiles of fuel cladding, pressure tube and calandria tube as time goes by. In case-i, the temperature profile of pressure tube becomes concave due to pressure tube contact with calandria tube. But in case-ii, the temperature profile of pressure tube always maintains convex shape.

In summary, the temperatures of fuel rod and pressure tube with PTD model are lower than those without PTD model.

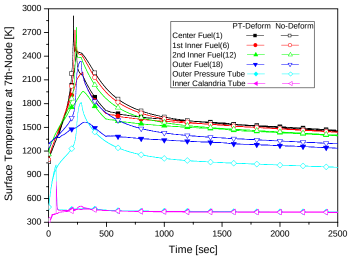

Figure 2. Temperature transient of fuel cladding, pressure tube and calandria tube at node 7 with and without PTD model

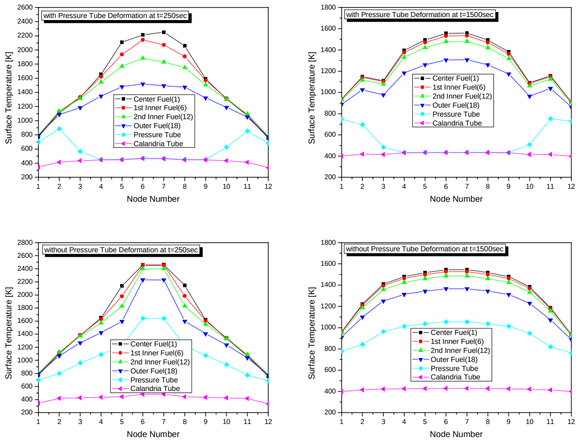

Figure 3. Fuel cladding, pressure tube, and calandria tube temperature along the fuel channel with and without PTD model

IV. CONCLUSION

The PTD model was developed to improve the capability of RELAP/CANDU code in the safety analysis of CANDU reactors. The simulation of RIH35% break with loss of ECC injection was performed to verify the developed PTD model. It can be concluded that the developed PTD model shows reasonable results through the sensitivity study with and without PTD model.

REFERENCES

[1] R.S.W. Shewfelt and D.P. Godin, “Ballooning of thin-walled tubes with circumferential temperature variations”, 18, 21-33, Res Mechanica, AECL-8317, 1986

[2] RELAP5/MOD3 Code Manual, NUREG/CR-5535 (Vol. 1), USNRC, 2003