2-D Simulation on the Contact of Pressure Tube and Calandria Tube in the Severe Accident of PHWR System

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1. Introduction

One of the important design features of a CANDU reactor (a pressurize heavy water reactor) is the use of moderator as a heat sink during some postulated accidents such as a large break Loss of Coolant Accident (LOCA). If the pressure tube is sufficiently hot while the channel pressure is still relatively high, the pressure tube may deform in the radial direction and would fully contact with its surrounding calandria tube (PT/CT ballooning contact).

The present study is about preliminary calculation results for the ICSP (International Collaborative Standard Problem) activity works[1], where the COMSOL Multiphysics code is used to simulate plastic deformation of a pressure tube of CANDU reactor as a result of the interaction of stress and temperature. It is shown that the thermal stress model of COMSOL is compatible to simulate the multiple heat transfers (including the radiation heat transfer and heat conduction) and stress strain in the simplified two dimensional problem.

2. Methods and Results

In this section, the numerical method and some selected result is presented. The experimental setup [1] and its simplified schematic are given in Fig. 1.

2.1 Governing Equations

The thermal stress model in structural dynamics and the energy equation in heat transfer are simultaneously solved in each numerical time step:

$$-\nabla\cdot\tilde{\sigma}=\vec{F}v \tag{1}$$

$$\tilde{\sigma}-\tilde{\sigma}_0=\tilde{C}:\left[\tilde{\varepsilon}-\tilde{\varepsilon}_0-\int_{T_0}^{T}\tilde{\alpha}dT\right] \tag{2}$$

$$\frac{\partial\tilde{\varepsilon}}{\partial t}=\frac{1}{2}\left[\left(\nabla\vec{u}\right)^T+\nabla\vec{u}\right] \tag{3}$$

$$\rho C_p\left(\frac{\partial T}{\partial t}+\vec{u}\cdot\nabla T\right)=\nabla\cdot\left(k\nabla T\right)+Q \tag{4}$$

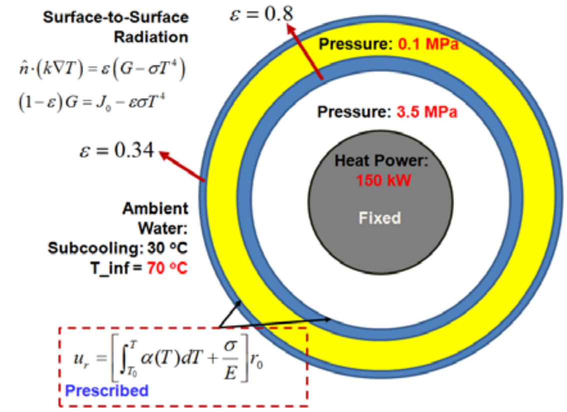


Fig. 1. Computational domain and boundary condition.

The computational domain is simplified to the two dimension like Fig. 1 where the span depth is 0.9 m. In the graphite heater, the volumetric heat source, Q in Eq. (4) is set to 150 kW [1].

2.2 Boundary Condition

At the gap of CT and PT, CO_2 gas in the nearly ambient pressure is filled, the heat conduction in this medium should be considered with surface radiation. However, in this preliminary investigation, only the radiation boundary condition is exerted since the heat conduction effect is very small in the small gap.

The radiation B/C at the Zircaloy interface is

$$\begin{aligned}\hat{n}\cdot\left(k\nabla T\right)&=\varepsilon\left(G-\sigma T^4\right)\\ \left(1-\varepsilon\right)G&=J_0-\varepsilon\sigma T^4\end{aligned} \tag{5}$$

where ε is the total hemispherical emissivity at each surface: 0.8 for PT and 0.34 for CT, respectively. Surface-to-surface radiation condition is imposed at each solid interface.

Inside the PT, the high pressure of 3.5 MPa is uniformly exerted, and the CT is fixed to the reference frame: see Fig. 1(b).

Outside the CT, the temperature is set to 70^oC as a Dirichlet boundary condition reflecting the subcooling effect under the ambient atmospheric condition.

The initial condition is set to 20^oC uniform on the whole computational domain.

2.3 Material Property and Creeping Model

The heater, or graphite core is treated with a isotropic property model[2]. Both PT and CT are regarded to be made of Zircaloy 2. However, material properties are not constants but functions of temperature.

The plastic creeping model, used in CATHENA code [2], is

$$\dot{\varepsilon} = \frac{d\varepsilon}{dt} = \begin{cases} \left(1.3\times10^{-5}\right)\sigma^{9} e^{-36600/T} + \dfrac{\left(5.7\times10^{7}\right)\sigma^{1.8} e^{-29200/T}}{\left[1+\left(2\times10^{10}\right)\int_{t_1}^{t} e^{-29200/T}dt\right]^{0.42}}, & 773K \le T \le 1123K \\ (10.4)\sigma^{3.4} e^{-19600/T} + \dfrac{\left(3.5\times10^{4}\right)\sigma^{1.4} e^{-19600/T}}{1+(274)\int_{t_2}^{t} e^{-19600/T}(T-1105)^{3.72}dt}, & 1123K \le T \le 1473K \end{cases} \quad (6)$$

For the implementation of the time integration in Eq. (6), a constant time rate of temperature is assumed, and the transformed form is integrated with a numerical method of two-point Gaussian quadrature.

2.4 Multiphysics Simulation

The COMSOL Multiphysics solver integrates Eqs. (1-4) with FEM(finite element method) schemes, and the approximate solution is obtained by time marching.

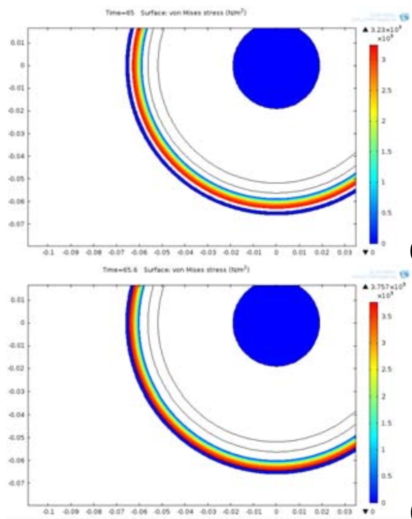
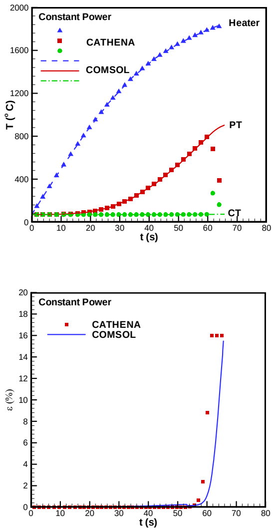

(a)
(b)

Fig. 2. von Mises stress: (a) 65s, before contact, (b) 65.6 s, after contact.

As shown in Fig. 2(a), the PT is *ballooned* to contact to CT in Fig. 2(b). The thermal expansion term in Eq. (2) is modeled as a nonlinear one, so the expansion rate is smoothened in Fig. 2(a), (b).

2.5 Comparison with CATHENA Code Result

Under the same condition as CATHANA code[2], the simulation is done, and the final result for temperature and strain in Fig. 3(a), (b), respectively.



(a)
(b)

Fig. 3. Time history of temperature and strain: (a) temperatures in fixed points, (b) strain at PT surface.

CATHENA code result is compared with that of the present simulation. The quantitative results coincide with each other, but the two-point Gaussian quadrature is somewhat low-order accurate, so the expansion rate is overestimated.

3. Conclusions

A benchmark experiment model based on the Calandria moderator system of the CANDU reactor has been reduced to a 2-D computational model. Thermal radiation and linear stress-strain with creeping model is applied in this simulation. The multiphysics analysis results in a reasonable qualitative and quantitative trend, and is compared with CATHENA code results.

The model after the contact of PT and CT should be considered in the future, and the accuracy order of the integration with numerical method of Gaussian quadrature should be modified for the improvement of numerical quality.

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