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Unsteady Two-Dimensional Multiphysical Simulation on the Radiating Calandria Tube Under the Subcooling Boundary Condition

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1. Introduction

Inside the Calandria tubes in the moderator system of a heavy water reactor, there are pressure tubes undergoing high pressure and temperature. If the cooling water dries out due to the local film boiling at the outer tube boundary, the excessive heat flux can deform the pressure tube to even contact with outer Calandria tube.

To limit the subcooling for the avoidance of dryout condition in a CANDU reactor, a suitable experiment should be proposed such as Ref. [1]. In this study, we simulated this experiment in 2-D with COMSOL Multi-physics.

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.

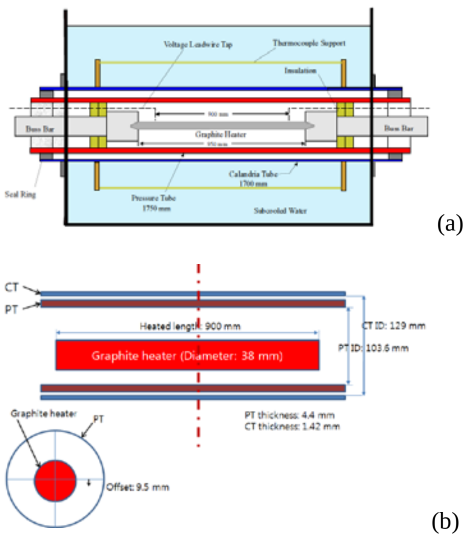

Fig. 1. Design of experiment and domain of simulation: (a) IAEA ICSP Test, (b) schematic drawing of a simplified model in three dimension.

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:

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

$$\rho C_p \left(\frac{\partial T}{\partial t} + \vec{u} \cdot \nabla T \right) = \nabla \cdot \left(k \nabla T \right) + Q \tag{2}$$

The computational domain is simplified to the two dimension, which lies in the cross section, or the central dashed-dot line in Fig. 1(b). In the graphite heater, the volumetric heat source, Q in Eq. (2) 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

$$\begin{aligned} \hat{n} \cdot \left(k \nabla T \right) &= \varepsilon \left(G - \sigma T^4 \right) \\ \left(1 - \varepsilon \right) G &= J_0 - \varepsilon \sigma T^4 \end{aligned} \tag{3}$$

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.

Outside the CT, the temperature is set to $70\,^{o}C$ as a Dirichlet boundary condition reflecting the subcooling effect under the ambient atmospheric condition.

The initial condition is set to $20\,^{o}C$ uniform on the whole computational domain.

2.3 Material Property

Both PT and CT are regarded to be made of Zircaloy 2. However, material properties are not constants but functions of temperature, which are listed in Ref. [2-4].

2.4 Multiphysics Simulation

The COMSOL Multiphysics solver integrates Eqs. (1-2) with FEM(finite element method) schemes, and the approximate solution is obtained by time marching. If it is a simple heat transfer problem, it has a converged steady solution. Instead, the solution oscillates to be unstable: see Fig. 2.

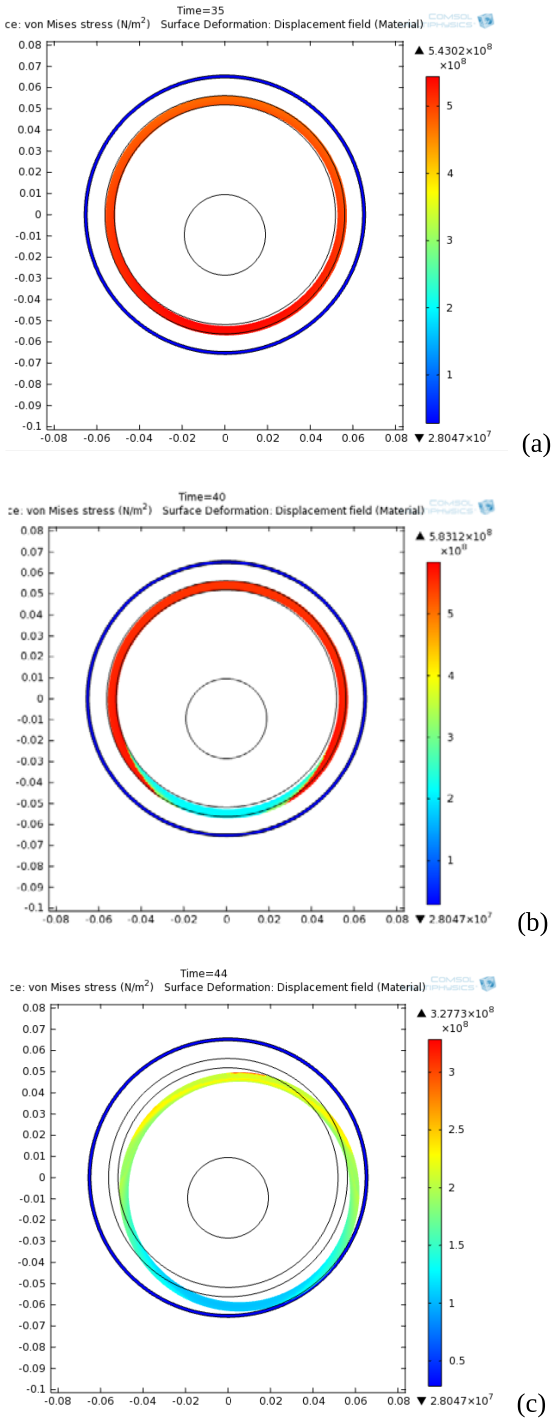

Fig. 2. von Mises stress of movable PT and fixed CT: (a) 35 s, (b) 40 s, (c) 44 s.

As shown in Fig. 2(a), the lower part of PT is more heated since the graphite heater is 9.5 mm eccentrically located from the center. High temperature affects on PT to extend thermally, which relax the tensile stress: see Fig. 2(b). The non-uniform deformation results in the instability of computation, and the extended PT starts to move until contact to the inner surface of CT in Fig. 2(c).

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. The multiphysics analysis results in the conclusion that there is no steady solution in this problem. However, the real physics is three-dimensional, so relative bending and torsion of the pressure tube should be investigated in precise.

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