Unsteady Two-Dimensional Multiphysical Simulation on the Sudden Contact of Pressure Tube and Calandria Tube in the Moderator Model for PHWR

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1. Introduction

Inside the Calandria tubes in the moderator system of PHWR, 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 sudden 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 computational domain for 2-D simulation are given in Fig. 1(a).

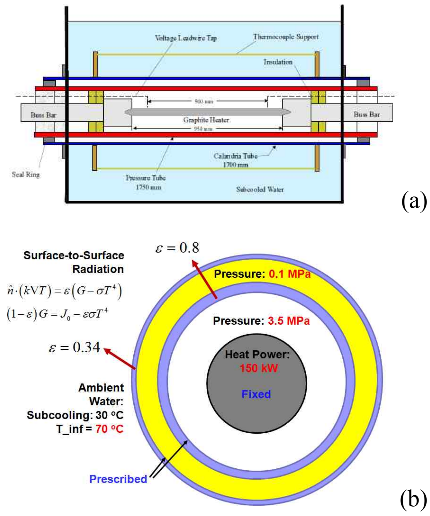


Fig. 1. Design of experiment and domain of simulation: (a) IAEA ICSP Test, (b) schematic drawing of a simplified computational domain.

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:

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

$$\tilde{\sigma}-\tilde{\sigma}_0=\tilde{C}:\left[\tilde{\varepsilon}-\tilde{\varepsilon}_0-\tilde{\alpha}\left(T-T_{ref}\right)\right] \tag{2}$$

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

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

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, but, 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: see Fig. 1(b).

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 ^oC as a Dirichlet boundary condition reflecting the subcooling effect under the ambient atmospheric condition. Inside the PT and CT, the inner radii are prescribed to avoid numerical instability of asymmetric translation, considering thermal expansion under local temperature. The initial condition is set to 20 ^oC uniform.

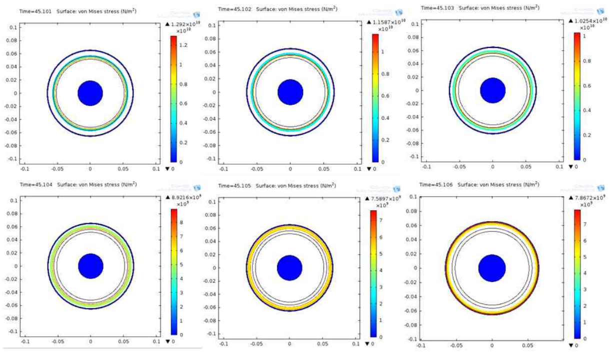


Fig. 2. von Mises stress: $\Delta t = 0.001s$.

2.3 Material Property and CreepingModel

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. [2-3].

The plastic creeping model, used in CATHENA code [4], is

$$\dot{\varepsilon} = \frac{d\varepsilon}{dt} = \begin{cases} \left(1.3\times10^{-5}\right)\sigma^{9} e^{-36600/T} + \dfrac{\left(5.7\times10^{7}\right)\sigma^{1.8} e^{-29200/T}}{\left[1+\left(2\times10^{10}\right)\int_{t_1}^{t} e^{-29200/T} dt\right]^{0.42}}, & 973K \le T \le 1123K \\ (10.4)\sigma^{3.4} e^{-19600/T} + \dfrac{\left(3.5\times10^{4}\right)\sigma^{1.4} e^{-19600/T}}{1+(274)\int_{t_2}^{t} e^{-19600/T}(T-1105)^{3.72} dt}, & 1123K \le T \le 1473K \end{cases} \tag{6}$$

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.

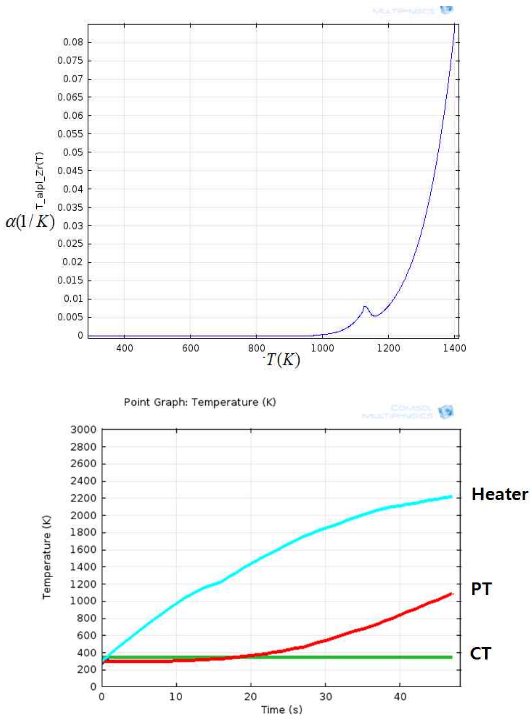
2.4 Simulation Result

The COMSOL Multiphysics solver integrates Eqs. (1-4) with FEM(finite element method) schemes, and the unsteady solution is obtained by time marching. The most interesting time domain is after 45.1 s where a sudden plastic inflation is found: see Fig. 2.

Fig. 3(a) is the thermal expansion coefficient(α) for a given local temperature, and Fig. 3(b) is the time history of temperature. α is increased from the order of 10^{-6} to 10^{-2} /K in the range of plastic deformation, so the sudden inflation is explained from Fig. 3(a). The assumption of constant time rate is valid when the surface temperature in PT is almost constant slope in Fig. 3(b).

3. Conclusions

A benchmark experiment model based on the Calandria moderator system of the CANDU reactor has been reduced to an ideal concentric 2-D computational model. A plastic deformation model is introduced, based on the creeping model in CATHENA code. The result
shows a sudden inflation and contact of PT and CT in a very short time of miliseconds.



(a)

(b)

Fig. 3. Thermal expansion ratio for a given temperature of plastic range of material, (a), and time history of temperature, (b).

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