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A Component-Scale Thermal-Hydraulic Analysis of the Flow in a CANDU Moderator Tank

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1. Introduction

When the core cooling system fails to remove the decay heat from the fuel channels during a loss of coolant accident (LOCA) in a CANDU reactor, the pressure tube(PT) could strain to contact its surrounding the Calandria tube (CT), which leads to sustained the CTs dry out, finally resulting in damages to nuclear fuel. This situation can occur when the degree of the subcooling of the moderator inside the Calandria vessel is insufficient. In this regard, to estimate the local subcooling of the moderator inside the Calandria vessel is very important. However, the local temperature is measured at the inlet and the outlet of the vessel only. Therefore, we need to accurately predict the local temperature inside the Calandria vessel[1-2].

In this study the component-scale thermal-hydraulic analysis of a real CANDU moderator tank is performed by using the CUPID code, which is based on the lessons from the previous results[3-4]. The porous media approach is used for an efficient simulation at a component scale. The inlet nozzles are also modeled using a simplified mesh. The validity of the results is checked and effects of the inlet nozzle modeling on the results are discussed.

2. Mathematical model of the CUPID code

The CUPID code has been developed for a high-resolution component-scale thermal-hydraulic analysis of two-phase flows in nuclear reactor components. The code adopts a two-fluid, three-field model to analyze two-phase flows. The three fields represent continuous liquid, droplets, and vapor, respectively. The governing equations of the CUPID code have been established to be applicable to both open media and porous media

A special pressure drop model for a porous media zone is needed to accurately simulate the flow behavior there. In the tube bundle region, the frictional pressure drop for the cross flow is represented as follows [5];

$$PLC = \frac{\Delta P}{N_f \cdot \rho \cdot v_{fs}^2/2} = 4.54 \cdot Re^{-0.172}, \qquad (1)$$

where $v_{fs} = \varepsilon v = \varepsilon\sqrt{\sum u}$, and PLC, P, N_f, v_{fs} are the pressure loss coefficient, pressure, number of tubes in the direction of flow, and free stream velocity, respectively. For an axial flow, the hydraulic resistance could be expressed by the conventional correlations for the pressure drop in a cylindrical pipe;

$$\left.\frac{\Delta P}{\Delta L}\right)_z = \frac{\Delta P}{\Delta z} = \frac{f\rho u_z^{\ 2}}{2D_e}, \qquad (2)$$

where $f = 0.316Re^{-0.25}$. This model was implemented in the CUPID code [5].

3. Modeling of the Calandria tank of a CANDU reactor

3.1 Description of the Calandria vessel

Fig. 1 shows the schematic of the Calandria tank of the CANDU reactor. The Calandria vessel of the CANDU reactor is a cylindrical tank with an axial length of 6 m and a diameter of 7.6 m as shown in Fig. 1[6]. Inside the Calandria shell, there is a coaxial cylindrical tank with a diameter of 6.8 m in the core region. As shown in Fig. 2, to cool the moderator tank, the four inlet nozzles with an inclination of 14 degrees towards the center of the vessel, pointing to the top, are located symmetrically at the middle of left and right sidewall. At the bottom of right side in the Calandria vessel, two outlets are installed.

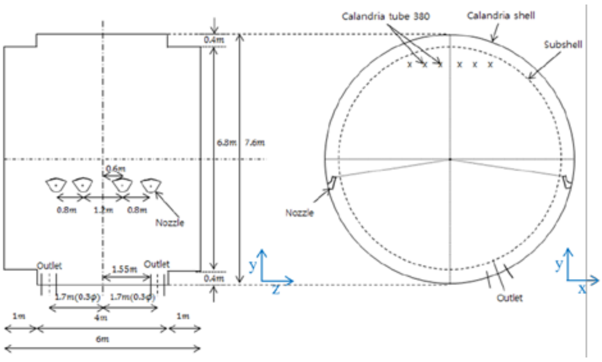

Fig. 1. CANDU moderator system.

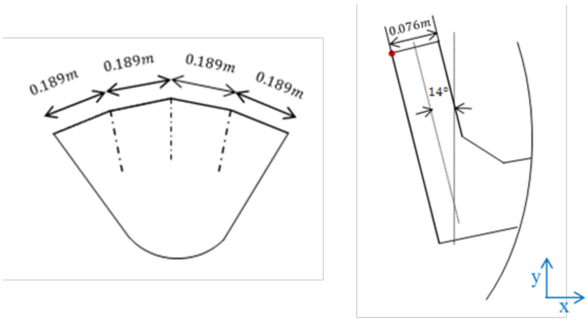

Fig. 2. The inlet nozzle.

Since the core region in the Calandria tank has a matrix of 380 Calandria tubes, it is not efficient to realistically simulate all subchannel regions in between the tubes. Therefore, a porous media approach is adopted for the region. And an open media approach is used for the outer region of the bundle[3].

Fig. 3 shows the three-dimensional grid for the Calandira tank; two-dimensional 1200 polyhedral grids are used for the core region, where a porous media approach is applied, and they are extruded along the axial direction. And the outer fluid region, regarded as an open media region, is made up of 1500 bent structured grids. The radial length and the circumferential length of a grid in the fluid region are 0.04m and 0.139m, respectively. These are also extruded axially. The axial length of a grid is between 0.075m and 0.120m. The total number of the meshes is nearly 160,000 in the calculations.

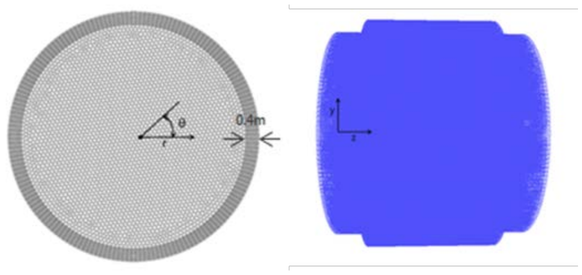

Fig. 3. Three dimensional mesh of the moderator tank.

3.2 Local power distribution in the Calandria tank

To simulate a steady-state flow in a moderator tank, the power distribution of a real CANDU reactor is used. For the 2,064 MW_{th} nuclear reactor, the total heat load in the moderator is about 103MW. Figure 4 shows a typical average power distribution in the radial direction from the center of the core[6]. The maximum power appears to be located at approximately 1.5m away from the center of the core in the radial direction. Figure 5 shows the normalized power distribution in the axial direction. The axial power distribution is trigonometric. However, the shape of a step function is used for simplicity.

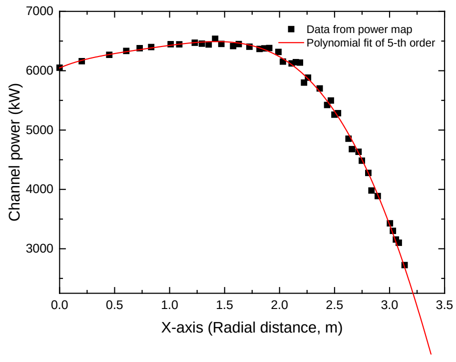

Fig. 4. Power distribution in the radial direction.

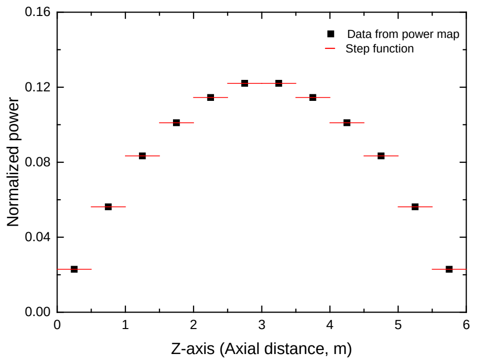

Fig. 5. Normalized power distribution in the axial direction.

4. Results of simulations in the Calandria tank of a CANDU Reactor

The total inlet mass flow is 1019kg/s (v_{in}= 2.043m/s) at the inlet nozzles, and the inlet temperature is 320K. Because the CUPID code can treat light water only, the heavy-water moderator in the tank is regarded as light water. Since the density of light water is lower than that of heavy water, the inlet nozzle velocity should be increased to preserve the mass flow rate at the inlet nozzles, resulting in an average velocity of 2.123m/s. Table 1 shows boundary conditions at nominal operating condition of a CANDU reactor, which is based on heavy water properties.

For the boundary conditions at the inlet nozzles, the following three conditions were taken into account:

(i) Uniform velocity condition (Case 1): This preserves the mass flow only at the inlet.

(ii) Non-uniform velocity condition (Case 2): The area-averaged velocities at 8 meshes of the inlet diffusers are obtained using the velocity profile obtained by Yoon et al.[4], which is shown in Figure 6, and these are imposed on each cells. In this case, total mass flow rate is preserved and local velocity profiles are roughly considered. However, the momentum flow is not accurate, which has a strong effect on the flow regime in the moderator tank.

(iii) Momentum-weighted non-uniform velocity condition (Case 3): A momentum-weighting factor at each cell is defined first as:

$$\gamma = \int v \cdot v dA / \bar{v}^2 A , \qquad (3)$$

where the average velocity at each cell is obtained by

$$\bar{v} = \int v dA / \int dA . \qquad (4)$$

Then, the momentum-weighted area-averaged velocity, $\bar{v}'(=\gamma\bar{v})$, is applied at each cell and the flow area of each cell is corrected as $A'(=A/\gamma)$. This results in the preservation of both the mass and momentum flow at the inlet nozzle.

At the outlet nozzles of the tank, a constant pressure boundary condition is given.

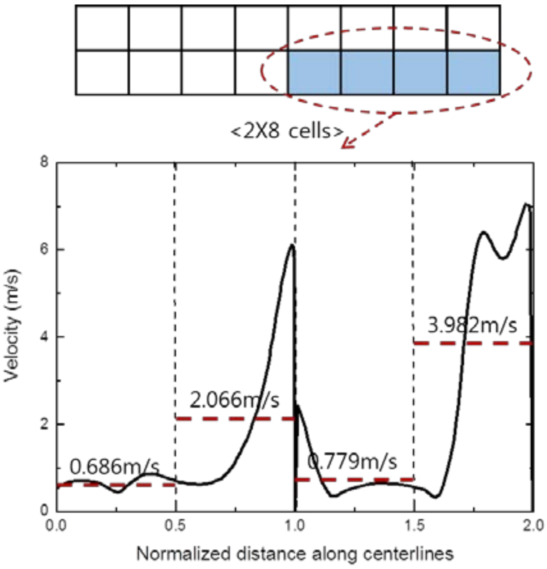

Fig. 6. Case 2: velocity profiles at the inlet diffusers.

Table I: Boundary conditions at nominal operating conditions of a CANDU reactor (based on heavy water properties)

Parameter	*Value*
ρ [kg/m^3]	1085
C_p [J/kg·K]	4207
$\dot{m}$ [kg/s]	1019
v_{in} [m/s]	2.043
q [MW]	103
T_{in} [K]	320
T_{out} [K]	344

4.1 Results of Case 1

The simulation results with Case 1 conditions shows a buoyant-dominant flow pattern; a thermal stratification is predicted, which is caused by lacking the momentum at the inlet nozzles as shown in Fig. 6. This leads to a boiling from the top of the moderator tank as shown in Fig. 7. Actually, a thermal stratification does not occur in the CANDU power plant. If a thermal stratification occurs in the tank, the plant cannot be normally operated. Thus, it is clear that these results are not realistic.

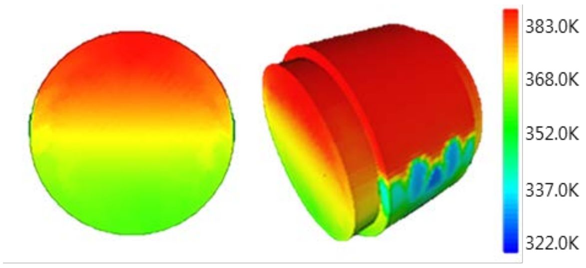

Fig. 6. Case 1: temperature distribution of the moderator in the transient state at t=2300s.

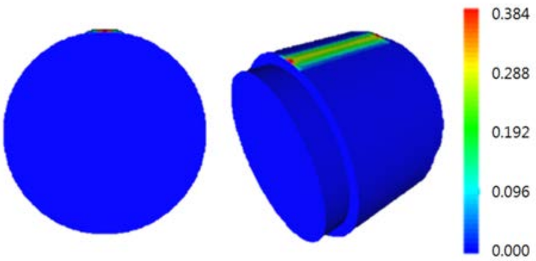

Fig. 7. Case 1: void fraction distribution of the moderator in the transient state at t=2300s.

4.2 Results of Case 2

This calculation with Case 2 conditions reached a steady-state at about 1500 s. Fig. 8 shows the snapshots of temperature distribution and velocity vector in the Calandria tank at an axial cross-section. In the beginning of the calculation, the moderator flow reaches the top of the moderator tank from the slanting inlet nozzles. At about 400s, the flow pattern becomes asymmetrically leant to the left side and, finally, a mixed flow regime [3] is established, which was shown at the nominal operating conditions of the STERN experiments. The local maximum temperature is 361.0K in the upper right region. This is similar to that of Yoon et al.[1] using CFX-4.4; the calculated maximum temperature was 355.9K under nominal operating conditions at the upper center region of the core. The temperature difference between the CUPID code and CFX 4.4 code is 5.1K in the full-power steady state condition. One of the reasons for the maximum temperature difference is that Yoon et al. used heavy water as the moderator. The temperature distributions of the two calculations show very similar trend.

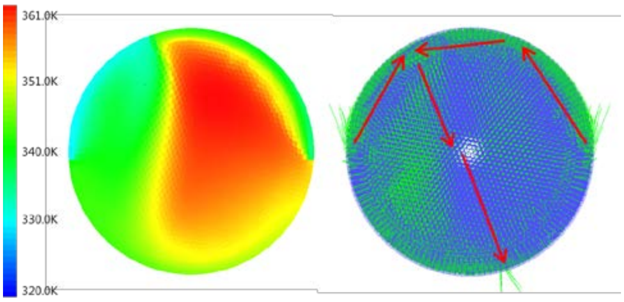

Fig. 8. Case 2: temperature distribution and velocity vector of the moderator in a steady-state (z=3.0m).

4.3 Results of Case 3

The Case 3 aims at the implementation of a more realistic boundary condition at the inlet nozzles. As mentioned previously, both the mass flow rate and the momentum flow rate at the boundary are preserved in the Case 3. Figure 9 shows the steady-state temperature distribution and velocity vector at an axial cross-section of the Case 3. The flow pattern of the Case 3 is very similar to that of the Case 2. The flow field in the moderator tank is formed asymmetrically. After 1500s, the flow reached a steady-state, resulting in a mixed flow regime with the local maximum temperature is 355.0K.

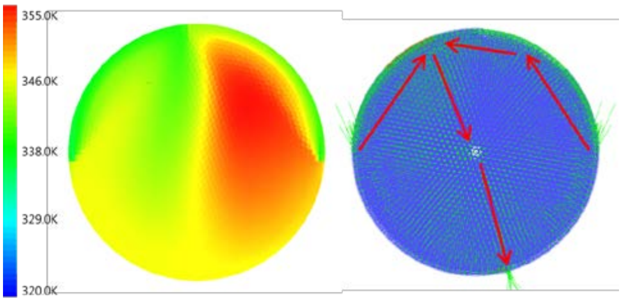

Fig. 9. Case 3: temperature distribution and velocity vector of the moderator in a steady-state (z=3.0m).

Unfortunately the real temperature distribution in the tank is not known at all. The local maximum temperature of the Case 3 is closer to that of the CFX calculation[1] and the flow pattern is very similar to the experimental observation in the STERN facility and that of other computational analyses[1,6,7]. The temperature distribution is reasonable and similar to that of the CFX calculation.

Thus, it can be said that the applicability of the CUPID code to the moderator flow analysis was confirmed. This allows a cost-effective calculation using the porous media approach. In this work, it was shown that the inlet nozzle modeling is one of the most important factors.

5. Conclusions

In this study, a component-scale thermal-hydraulic analyses for the Calandria tank of a CANDU reactor moderator tank are performed using the CUPID code. A porous media model is applied to the tank and simplified models are adopted to implement the boundary conditions at the inlet nozzles. To examine the effects of the inlet nozzle modeling, three inlet nozzle models are proposed.

The Case 1 using a uniform velocity at the nozzles presented a thermal stratification in the upper region of the Calandria tank, which is caused by the lack of the flow momentum injected into the inlet nozzles. The results are not realistic. The Case 2 using a more realistic velocity distribution instead of the uniform velocity, predicted an asymmetric mixed flow regime, maintaining with a balance between the momentum and buoyancy force, which was experimentally shown the STERN test facility in the nominal operating conditions. For a further improvement, the Case 3 was attempted, which aims at the preservation of both the mass and momentum flow at the inlet nozzles. The results of the Case 3 seem the best among the three cases. The local maximum temperature was very close to that of other calculations and the flow pattern was also very similar to the experimental and computational results.

From the results of calculations, it was shown that the CUPID code can be applied for the CANDU moderator flow analysis. The porous media approach allowed a cost-effective calculation. It was also shown that the inlet nozzle modeling is one of the most important factors for a realistic simulation of the CANDU moderator tank thermal-hydraulics.

Acknowledgement

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