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Preliminary Study of CANDU-6 Moderator System with the CUPID Code

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1. Introduction

Fuel channel integrity of the CANDU-6 reactor during a loss of coolant accidents (LOCA) depends on the capability of the moderator to act as the ultimate heat sink. During a LOCA, the pressure tube could strain to contact its surrounding Calandria tube, which leads to sustained C/T dry out. So, it is important to estimate a local sub-cooling of the moderator inside the Calandria vessel. However, it is possible to measure the local temperature only in the inlet/outlet region. Accordingly, to estimate the local temperature quantitatively, numerous experimental and numerical researches have been investigated [1].

In this study, the internal flow of the moderator was predicted by using CUPID code, which has been developed for two-phase flow analysis. CUPID adopts three-dimensional, transient, two-phase and three-field model, and includes various physical models and correlations of the interfacial mass, momentum and energy transfer for the closure relations of the two-fluid model [2].

2. Mathematical Model of the CUPID Code

2.1 Governing Equations

In the two-fluid model, the mass, energy, and momentum equations for each field are established separately and then, they are linked by the interfacial mass, energy, and momentum transfer models The continuity, momentum, energy and conduction equations for the k-phase are given by

$$\frac{\partial}{\partial t}(\alpha_k\rho_k) + \nabla\alpha_k\rho_k\vec{u}_k = \Gamma_k \tag{1}$$

$$\frac{\partial}{\partial t}\alpha_k\rho_k\vec{u}_k + \nabla\cdot(\alpha_k\cdot\rho_k\vec{u}_k\vec{u}_k)$$
$$= -\alpha_k\nabla P + \alpha_k u_k\nabla\vec{u}_k + \alpha_k\rho_k\vec{g} + S_k + \vec{M}_{wk} \tag{2}$$

$$\frac{\partial(\alpha_k\rho_k e_k)}{\partial t} + \nabla\cdot(\alpha_k\rho_k e_k\vec{u}_k)$$
$$= -\mathrm{P}\frac{\partial\alpha_k}{\partial t} - P\nabla\cdot(\alpha_k\vec{u}_k) + \alpha_k k_k\nabla T_k + E_k + q''_{\substack{fluid\\solid}} + q''_{\substack{fluid\\prous}} \tag{3}$$

The independent state variables, α_k, ρ_k, u_k, Γ_k, e_k are the k-phase volume fraction, density, velocity, an interface mass transfer rate, energy transfer rate, respectively. S_k represents the interfacial momentum transfer due to a mass exchange, a drag force, a virtual mass, and non-drag forces. E_k includes phase change, interfacial heat transfer and volumetric heat source. M_{wk} is wall friction term with form loss. To simulate the two-phase flow in the fuel assembly region, a porous media approach was adopted.

2.2 Frictional pressure drop model

The geometry shown in Fig 1 is the STERN 2D slice experimental apparatus. Calandria tubes of this apparatus are arranged in square lattice. The pitch-to-diameter ratio is 2.183. For the transverse flow across the tube bank, Hadaller et al. [3] investigated the pressure drop of the fluid flows crossing the staggered and in-line tube banks, in which the tube Reynolds number range is 2,000 to 9,000 and the pitch to diameter ratio is 2.16. The obtained empirical correlation for the pressure loss coefficient (PLC) is expressed below, regardless of the tube array configuration (staggered or in-line);

$$\mathrm{PLC} = \frac{\Delta P}{N_f\cdot\rho\cdot{V_{fs}^2}/{2}} = 4.54\cdot Re^{-0.172} \tag{4}$$

and $V_{fs} = \varepsilon V = \varepsilon\sqrt{\sum u}$.
Rearranging Eq. (4) with substitutions for N_f and V_{fs} yields

$$\left.\frac{\Delta P}{\Delta L}\right)_{crossflow} = \frac{PLC}{p\cos\theta}\cdot\rho\frac{(\varepsilon V)^2}{2} \tag{5}$$

Eq. (5) is implemented into the CUPID code as linear form as follows;

$$M_i = -\frac{\Delta P}{\Delta L} = -\left(\frac{4.54\cdot Re_{tube}^{-0.172}}{pitch}\right)\cdot\frac{\rho(\varepsilon V)}{2}\cdot u_i \tag{6}$$

where i is the flow direction.

3. Verification of the pressure drop model

The predicted pressure drop in the rectangular channel containing porous media blockage is compared with experimental data. The rectangular channel of the experimental test section has a cross section of 0.2856m×0.2m, with a length of 2m. For verification, a pressure difference between PT1 to PT3 shown in Fig. 1 is compared. The results according to different inlet velocities are shown in Table I. The pressure drop predicted by CUPID is in a good agreement with other simulation results and experimental data. It can be said that the empirical pressure drop model for the porous media is appropriately implemented in CUPID.

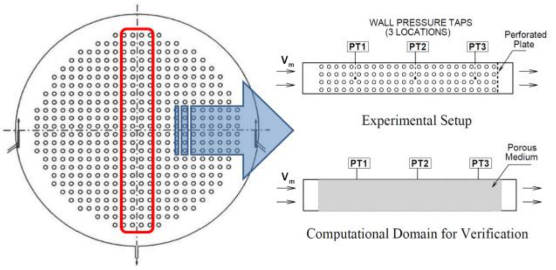

Fig. 1 Experimental setup for frictional pressure drop model

Table I : Comparison of the frictional pressure drop

V_{fs}[m/s]		0.054	0.070	0.103
Mass Flow[kg/s]		3.089	3.904	5.734
Temp.[℃]		39.5	63.6	79.8
Tube Reynolds No.		2746	5237	9392
∆P [Pa]	Measurement	28.2	41.3	78.7
	CFX-4	28.8	41.7	80.13
	CFX-10	27.8	41.6	80.1
	MODTURC	30.5	44.9	87.3
	CUPID	27.2	40.2	77.8

4. Validation of the STERN Lab Experiment

The CUPID code with empirical pressure drop model is validated against the STERN 2D experiments. The moderator test vessel in Fig. 2 is a cylinder with a diameter of 2m and a length of 0.2m. In the core region, there is a matrix of 440 inconel heating elements with a total power of 100kW. The coolant inlet nozzle is 6 mm in width (flow rate 2.4kg/s) and the outlet nozzle is 15mm in width.

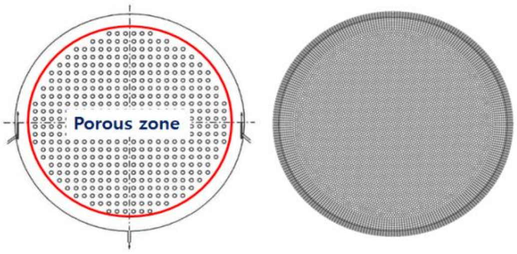

Fig. 2 Computational domain and grid system

The porosity of the porous media region is 0.832. In this calculation, a polygon mesh system is utilized, because the polygon mesh has an advantage of maintaining the orthogonality among neighboring cells. In the CUPID simulation, three different grids were used.

In the results of a nominal test prediction, a flow asymmetry is observed in one side. Fig. 3 shows the contours of the velocity vector and liquid temperature distribution. The hottest spot is located at upper center area of the core region, which slightly tilts to one side from the vertical centerline. Vertical profile of the liquid temperature at centerline(x=0) is plotted in Fig. 4. The CUPID simulation results according to the number of grid have a unique pattern; that is, the axial position of the local maximum temperature is getting lower as decreasing the number of total meshes.

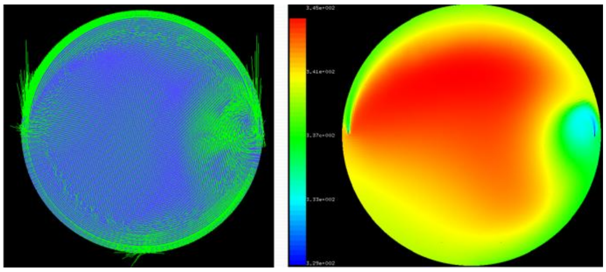

Fig. 3 Velocity and temperature distribution of nominal test

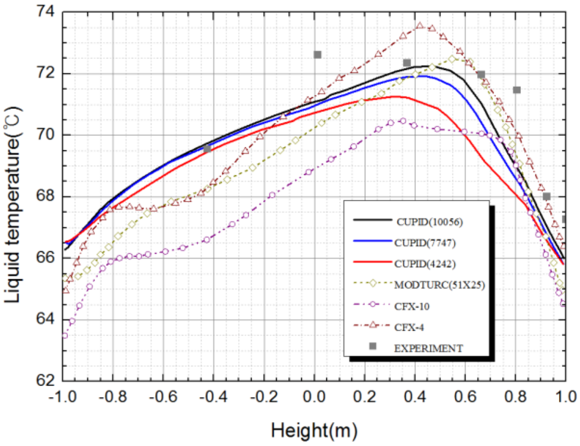

Fig. 4 Profile of the liquid temperature(x=0) in the nominal case

5. Summary and Conclusions

In this study, the empirical pressure drop model for a porous media was implemented into the CUPID code first. Then, the CUPID was validated against nominal test condition of the STERN 2D experiment. The results showed good agreement with both the experiments and the previous researchers' results.

ACKNOWLEDGMENTS

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