Development of a CANDU Moderator Analysis Model; Based on Coupled Solver

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1. Introduction

A CFD model for predicting the CANDU-6 moderator temperature has been developed for several years in KAERI, which is based on CFX-4.[1] This analytic model(CFX4-CAMO) has some strength in the modeling of hydraulic resistance in the core region and in the treatment of heat source term in the energy equations. But the convergence difficulties and slow computing speed reveal to be the limitations of this model, because the CFX-4 code adapts a segregated solver to solve the governing equations with strong coupled-effect.

Compared to CFX-4 using segregated solver, CFX-10 adapts high efficient and robust coupled-solver. Before December 2005 when CFX-10 was distributed, the previous version of CFX-10(CFX-5.* series) also adapted coupled solver but didn't have any capability to apply porous media approaches correctly. In this study, the developed moderator analysis model based on CFX-4 (CFX4-CAMO) is transformed into a new moderator analysis model based on CFX-10. The new model is examined and the results are compared to the former.

2. Hydraulic Resistance Model in the Porous Region

The newly developed model as well as CFX4-CAMO uses Porous Media Approaches for the core region containing 380 Calandria tubes. A 3-D hydraulic resistance model was developed and implemented from empirical correlations. In this section the hydraulic resistance model is verified and validated against the experimental data.

2.1 Verification of Hydraulic Resistance Model

Predicted pressure drops of the fluid flow in a rectangular channel containing porous media blockage are compared with experimental data, for the verification of Porous Domain implementation in CFX-10. The rectangular channel of the experimental test section has a cross section of 0.2856 m (Width) x 0.2 m (Height), and is 2 m-long. The pressure loss correlation experimentally obtained by Hadaller et al.[2] is expressed as,

$$\frac{\Delta P}{\Delta L} = \frac{4.54\,\gamma^2}{pitch} \mathrm{Re}_{tube}^{-0.172} \frac{\rho U}{2} u_i \qquad (1)$$

Where γ is porosity, and *pitch* is the shortest distance between tubes. Re_{tube} is a tube Reynolds number, which is defined by $V_m D / \nu$. D is a tube diameter. The tube diameter is 0.03302 meter, and the pitch is 0.0714 meter.

Thus, porosity of the assumed porous media is 0.832. Table 1 shows boundary conditions and fluid properties for three test cases and the comparison with previous simulation results and the experimental data. In the CFX-10 simulation, the momentum loss can be expressed

$$S_{M,i} = -\frac{\Delta P}{\Delta L} = -K_{loss} \frac{\rho U^S}{2} u_i^S \ , \qquad (2)$$

with $U^S(=\gamma U)$ is a superficial velocity and $u^S(=\gamma u)$ is a superficial velocity component. Here, the loss coefficient becomes $K_{loss} = \frac{4.54}{pitch} \mathrm{Re}_{tube}^{-0.172}$.

Table 1. Comparison of Simulation Results of the STERN Lab. Experiments

		STERN T.P. 326	STERN T.P. 299	STERN T.P. 306
Mass Flow [kg/s]		3.089	3.904	5.734
Temp. [^oC]		39.5	63.6	79.8
Density [kg/m^3]		992.4	990.98	977.8
Dyn.Viscosity [kg/m/s]		6.77E-4	4.48E-4	3.56E-4
V_m [m/s]		0.054	0.070	0.103
Loss Coeff. K_{loss} [/m]		16.425	14.64	13.198
Tube Reynolds No.		2746	5237	9392
*ΔP [Pa]	Measurement	28.2	41.3	78.7
	CFX-4	28.8	41.7	80.13
	**MODTURC	30.5	44.9	87.3
	CFX-10	27.8	41.6	80.1

* ΔP is the pressure differences between the Pressure Tap 1 (0.5002 m from inlet) and the Pressure Tap 3 (1.6526 m from inlet).
** This simulation results by MODTURC code are obtained from ref. [2].

2.2 Validation of Hydraulic Resistance Model

Validation is a procedure to test the extent to which the model accurately represents reality. The small scale CANDU moderator experiments of the Stern Laboratories Inc.(SLI) by Huget et al.[3] are used for validation. The vessel does not have scaled geometry from actual CANDU reactors and is rather close to a thin axial slice of a CANDU-6 Calandria vessel. The working fluid is light water (H_2O). In the core region, there is a matrix of 440 heating pipes, which have the same pitch-to-diameter ratio as the CANDU-6 NPPs. The experimental data used for validation in this study are classified as the nominal-conditions test with a flow rate of 2.4 kg/s and a heat load of 100 kW. The inlet temperature is maintained at 55^{o}C for the nominal-conditions test.

Equation (1) is used for the hydraulic resistance in the porous core region. The temperature differences between the current results and the measurements are more than ± 2°C in the core region, and the trend is quite reasonable.

3. Steady-State CANDU Moderator Circulation

For the moderator analysis of Wolsong NPP Units 2/3/4, the spatial heat distribution of the core region is calculated based on the actual core power map. The 3-D hydraulic resistance is accounted for in the same way of Yoon et al.[4] The numbers of nodes are 18,445 for the core region and 30,552 for the reflector region, while the total number of nodes in CFX4-CAMO was 35,776.

The steady state computation using CFX-10 was performed in a Pentium IV CPU. The energy imbalances were checked for the convergence. The total CPU time for convergence was 15 hour 3 min 31 sec, which is much shorter than that of CFX4-CAMO.

Under normal operating conditions, the calculated maximum temperature of the moderator is 81.1 °C at the upper center region of the core, which corresponds to the minimum subcooling of 26.5 °C. Figure 1 shows the temperature distributions and velocity vector fields in some selected planes. Compared to the results of CFX4-CAMO, flow patterns are well matched to each other. The jet reversal occurs at an angle of about 50° over the horizontal centerline and the hottest spot is located at the upper center area of the core region, which slightly tilts to one side from the vertical centerline.

Other remarkable result shows that this simulation gave two stable circulations. In the alternative moderator circulation, a hot spot appears on the same side of the outlets and the jet reversal appears on the opposite to the outlet, which are switched from in Fig. 1. Quasi-steady moderator circulation and its oscillation were already reported in Collins [5]. In this study, it is ensured that alternative steady circulation conditions could be produced depending on different initial condition.

4. Conclusion

The transformation of CFX4-CAMO into a CFD model based on CFX-10 has been accomplished successfully. Because CFX-10 adapts coupled solver to solve the governing equations, the computing cost is reduced largely and the results seem quite reasonable.

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REFERENCES

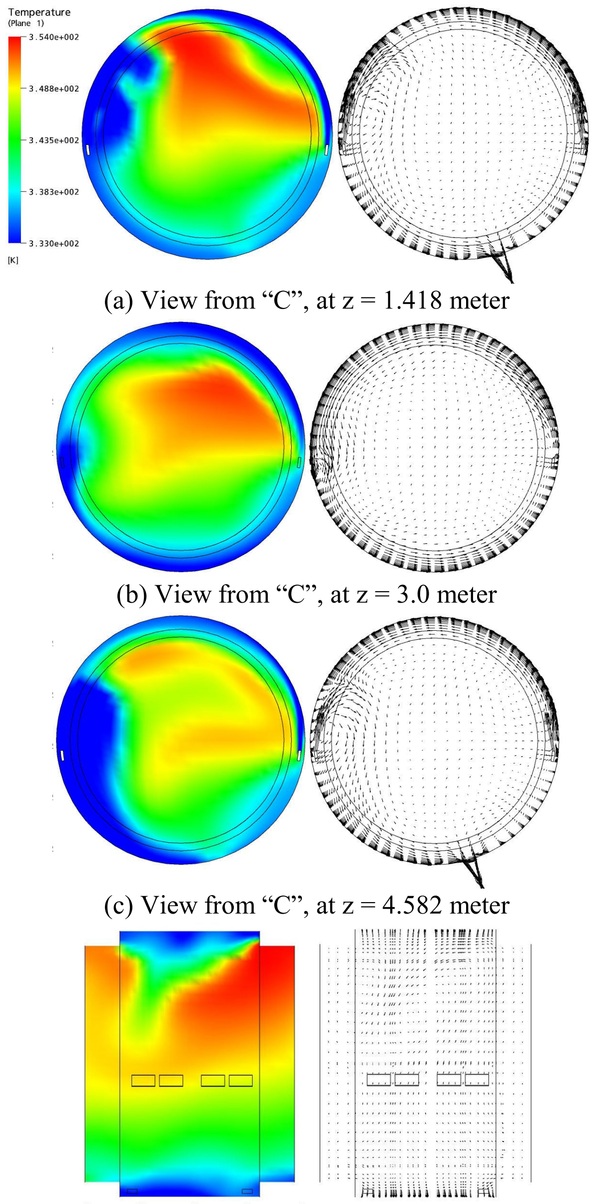
[1] C. Yoon, B.W. Rhee, and B.-J. Min, "Development and Validation of the 3-D Computational Fluid Dynamics Model for CANDU-6 Moderator Temperature Predictions," Nuclear Technology, Vol. 148, No. 3, pp 259-267 (2005)

[2] G.I. Hadaller, R.A. Fortman, J. Szymanski, W.I. Midvidy, and D.J. Train, "Frictional Pressure Drop for Staggered and In-line Tube Banks with Large Pitch to Diameter Ratio," 17th Annual Canadian Nuclear Society Conference, Fredericton, New Brunswick, Canada, June 9-12 (1996)

[3] R.G. HUGET, J.K. SZYMANSKI, and W.I. MIDVIDY, "Experimental and Numerical Modelling of Combined Forced and Free Convection in a Complex Geometry with Internal Heat Generation", Proceedings of 9th International Heat Transfer Conference, **3**, 327 (1990)

[4] C. Yoon, B.W. Rhee, H.T. Kim, J.H. Park, and B.-J. Min, "Moderator Analysis of Wolsong Units 2/3/4 for the 35% Reactor Inlet Header Break with a Loss of Emergency Core Cooling Injection," J. of Nuclear Science and Technology, Vol. 43, No. 5 (2006)

[5] W.M. Collins, "PHOENICS2 Model Report for Wolsong 2/3/4 Moderator Circulation Analysis Report, 86-03500-AR-053 (1995)



(a) View from "C", at z = 1.418 meter

(b) View from "C", at z = 3.0 meter

(c) View from "C", at z = 4.582 meter

(d) View from "B", at x = 0.3 meter

Figure 1. Steady-State Velocity Fields and Temperature Distributions of the CANDU-6 Moderator