Developing Status of Single Channel TH Module of a 3D Core Transient Physics Code for CANDU 6 Reactor

Dongwook Kho*
KHNP Central Research Institute, 70 Yuseong-daero, 1312-beongail, Yuseong-gu, Daejeon, 34101
**Corresponding author: dongwookkho@khnp.co.kr*

1. Introduction

In May 2014, Canadian regulatory body, CNSC(Canadian Nuclear Safety Commission) issued a regulatory document, REGDOC-2.4.1[1], which was about deterministic safety analysis for newly constructed CANDU NPPs. In the document, initial events for safety analysis are classified into AOO(Anticipated Design Basis Accident), DBA(Design Basis Accident) and BDBA(Beyond Design Basis Accident) according to their frequency of occurrence. In order to take preemptive measures to cope with regulatory environment change, a project was initiated on development of 3D core transient physics code for CANDU 6 reactor. The code needs to calculate thermal-hydraulic(TH) characteristic of each fuel channel for considering TH feedback effect caused by changes of density and temperature of coolant. This paper describes developing status of a single channel TH module for the code.

2. Mathematical and Numerical Models

The single channel TH module uses a TH model and numerical method of TRANSG-01[2], a transient TH code for two phase flow analysis of steam generator, which was developed by EPRI(Electric Power Research Institute) in 1980s. However, CANDU 6 reactor has horizontal fuel channels, so the mathematical model of the TRANSG-01 code should be modified to exclude gravity term.

2.1 Two-phase slip flow model

Governing equations of the single channel TH module was from those of the TRANSG-01 code except a gravity term in momentum equation. The governing equations are as follows:

$$\frac{\partial \rho}{\partial t} = -\frac{\partial G}{\partial z} \quad (1)$$

$$\frac{\partial G}{\partial t} = -\frac{\partial P}{\partial z} - \frac{\partial}{\partial z}\left(\frac{G^2}{\rho_m}\right) - \frac{G|G|}{\rho_f}\frac{2f_l}{D_h}\Phi_{TP}^2 \quad (2)$$

$$\frac{\partial(\rho h)}{\partial t} = -\frac{\partial(Gh)}{\partial z} + q_w\frac{M_w}{A} + \frac{\partial P}{\partial t} \quad (3)$$

where ρ is fliud density, G is mass flux, P is pressure, ρ_m is momentum density, ρ_f is liquid density in saturated two-phase flow, f_l is liquid friction factor, D_h is hydraulic diameter, Φ_{TP} is two-phase flow frictional multiplier, h is specific enthalpy, A is flow cross sectional area, M_w is wetted perimeter of a fuel channel and q_w is heat flux into fluid from wall.

In the two-phase slip flow model, mixture density, mixture mass flux, volumetric energy term, enthalpy flow term and momentum density are defined like below:

$$\rho = \alpha\rho_g + (1-\alpha)\rho_f \quad (4)$$

$$G = \alpha\rho_g v_g + (1-\alpha)\rho_f v_f \quad (5)$$

$$(\rho h) = \alpha\rho_g h_g + (1-\alpha)\rho_f h_f \quad (6)$$

$$(Gh) = \alpha\rho_g v_g h_g + (1-\alpha)\rho_f v_f h_f \quad (7)$$

$$\frac{1}{\rho_m} = \{1 + x(\gamma-1)\}\left(\frac{1-x}{\rho_f} + \frac{x}{\gamma\rho_g}\right) \quad (8)$$

Moreover, a relation between void fraction and quality from the Thom two-phase slip model[3] is used like below:

$$\alpha = \frac{\gamma x}{1+x(\gamma-1)} \quad (9)$$

where γ, which is a dimensionless parameter defined like below, is obtained from an experimental data[3].

$$\gamma = \frac{v_f}{v_g}\frac{\rho_f}{\rho_g} \quad (10)$$

2.2 Numerical Model and Method

In order to discretize the governing equations, a fixed Eulerian mesh model was used as shown in the Fig. 1. In each center of the mesh of location z_i, there are point i(=1,2, … ,I) and there density, pressure and enthalpy are defined. Meanwhile, mass flux and enthalpy are defined at boundaries between cells, that is, staggered mesh was used. Each cell has a length of $\Delta z_i = z_{i+1/2} - z_{i-1/2}$ and a length between mesh i and i-1 is defined as $\Delta z_{i-1/2} = z_i - z_{i-1}$.

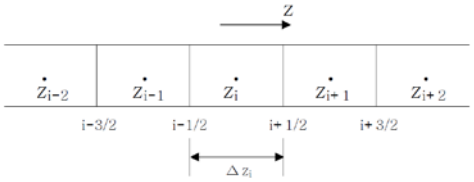

Fig. 1. Discrete spatial mesh model for fuel channel flow

Mass and energy conservation equations were discretized at cell centers, and momentum equation was discretized at junctions (that is, boundaries). Enthalpies were defined at cell centers and also at junctions. So, it was needed an enthalpy relation between cell center and junction as follows:

$$h_i = (0.5-\xi)h_{i+1/2} + (0.5+\xi)h_{i-1/2}$$

where $-0.5 < \xi < 0.5$.

The discretized governing equations are as follows:

$$\frac{\rho_i^{n+1}-\rho_i^n}{\Delta t^n} = \vartheta \frac{G_{i-1/2}^{n+1}-G_{i+1/2}^{n+1}}{\Delta z_i} + (1-\vartheta)\frac{G_{i-1/2}^{n}-G_{i+1/2}^{n}}{\Delta z_i} \quad (11)$$

$$\frac{G_{i-1/2}^{n+1}-G_{i-1/2}^{n}}{\Delta t^n} = \phi \frac{P_{i-1}^{n+1}-P_i^{n+1}}{z_{i-1/2}} + (1-\phi)\frac{P_{i-1}^{n}-P_i^{n}}{z_{i-1/2}} + \frac{G_{i-1/2}^n}{\Delta z_{i-1/2}}\left(\frac{G_{i-3/2}^n}{\rho_{m,i-1}^n} - \frac{G_{i+1/2}^n}{\rho_{m,i}^n}\right) - G_{i-1/2}^n\left|G_{i-1/2}^n\right|\left(\frac{f_{l,i}^n}{\rho_{f,i}^n D_{h,i}} + \frac{f_{l,i-1}^n}{\rho_{f,i-1}^n D_{h,i-1}}\right)\Phi_{TP}^2 \quad (12)$$

$$\frac{(\rho h)_i^{n+1}-(\rho h)_i^n}{\Delta t^n} = \vartheta \frac{G_{i-1/2}^{n+1}h_{i-1/2}^{n+1}-G_{i+1/2}^{n+1}h_{i+1/2}^{n+1}}{\Delta z_i} + (1-\vartheta)\frac{G_{i-1/2}^{n}h_{i-1/2}^{n}-G_{i+1/2}^{n}h_{i+1/2}^{n}}{\Delta z_i} + \frac{4}{D_h}q_i^n + \frac{P_i^{n+1}-P_i^n}{\Delta t^n} \quad (13)$$

In addition to the above equations, an arbitrary equation of state, $\rho = \rho(h, P)$ is used as a form discretized after first-order Taylor series approximation.

$$\rho_i^{n+1} = \rho_i^n + \left(\frac{\partial \rho}{\partial P}\right)_i^n (P_i^{n+1} - P_i^n) + \left(\frac{\partial \rho}{\partial h}\right)_i^n (h_i^{n+1} - h_i^n) \quad (14)$$

In order to solve the above equations, the EICE numerical solution method was used[2]. Thermodynamic heavy water properties was from the reference[4].

3. Calculation Results at Steady State

In order to validate steady sate calculation results, a CATEHNA[5] single channel model was used. The CATHENA single channel model was an O6 channel with maximum limits of bundle and channel powers that was used in safety analysis for CANDU 6 NPPs. CATHENA code uses two-fluid model and can simulate subcooled boiling phenomenon.

Fig. 2 and 3 show pressure and equilibrium quality of coolant at each node in fuel channel. The pressure calculated by TH module was decreased linearly in Fig. 2, so it was a single phase pressure drop. Here it could be known that two-phase multiplier was not applied in pressure calculation. Moreover, equilibrium quality at downstream end calculated by TH module was still negative value while equilibrium quality calculated by CATHENA was positive from 16th node to the end. That is, there was no boiling in the channel of the TH module. Also, since the TH module can't simulate subcooled boiling dislike CATHENA code, boiling in fuel channel could be calculated to be delayed more downstream. Therefore, it should be checked why boiling in the channel was delayed and only liquid phase flows in the channel.

In order to find out the reason, first, a subroutine of the TH module which calculates enthalpy have to be reviewed if there is some errors. Second, it should be checked the necessity of a void model under subcooled condition because the slip flow model only considers homogeneous bulk boiling.

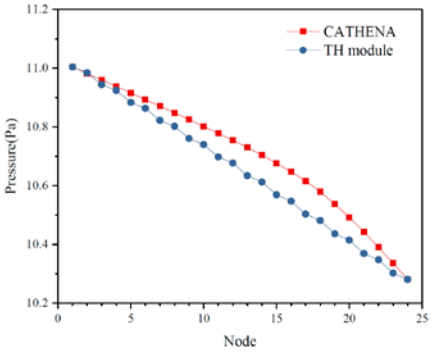

Fig. 2. Coolant pressure at each node

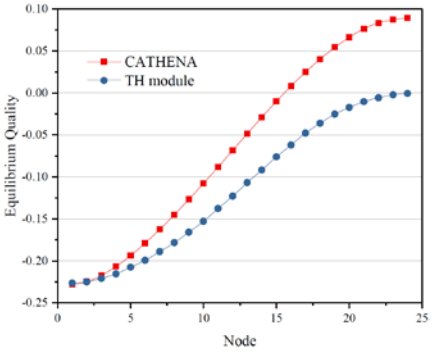

Fig. 3. Equilibrium quality at each node

4. Summary and Future Work

The TH module is being developed to provide TH feedback effect to the 3D transient physics code. For simulating heavy water two-phase flow in a fuel channel of CANDU 6 reactor, slip flow model was used with the Thom two-phase slip model. As in the TRANSG-01 code, the EICE method for numerical solution was used.

In a process of verification, it was found that there were some errors in calculation of enthalpy. It will be reviewed and fixed in the near future. Additionally, a subcooled void model should be considered if boiling is still delayed in the fuel channel after fixing the errors in enthalpy calculation.

REFERENCES

[1] REGDOC-2.4.1, "Safety Analysis: Deterministic Safety Analysis," CNSC, May 2014.
[2] J. C. Lee, A. Z. Akcasu, J. J. Duderstadt, M. W. Crump and R. Fortino, "TRANSG-01: A Computer Code for Transient Analysis of Nuclear Steam Generators, Volume 1: Theory and Mathematical Formulation," NP-3394-CCM, EPRI, Jan. 1984.
[3] J. R. S. Thom, "Prediction of Pressure Drop during Forced Circulation Boiling of Water," Int. J. Heat Mass Transfer, Vol. 7, 1964, pp. 709-724.
[4] Ahmet Duramayaz, "Approximate Functions for the Fast Computation of the Thermodynamic properties of Heavy Water," Nuclear Engineering and Design, Vol. 178, 1997, pp. 309-329.

[5] Beuthe Thomas and Hanna Bruce N., "Software Theory Manual: CATHENA MOD-3.5D THEORY MANUAL," 153-112020-STM-001 Rev.2, AECL, Nov. 2013.