Development of Off-take Model, Subcooled Boiling Model, and Radiation Heat Transfer Input Model into the MARS Code for a Regulatory Auditing of CANDU Reactors

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1. Introduction

Korea currently has four operating units of the CANDU-6 type reactor in Wolsong. However, the safety assessment system for CANDU reactors has not been fully established due to a lack of self-reliance technology. Although the CATHENA code had been introduced from AECL, it is undesirable to use a vendor's code for a regulatory auditing analysis. In Korea, the MARS code has been developed for decades and is being considered by KINS as a thermal hydraulic regulatory auditing tool for nuclear power plants. Before this decision, KINS (Korea Institute of Nuclear Safety) had developed the RELAP5/MOD3/CANDU code for CANDU safety analyses by modifying the model of the existing PWR auditing tool, RELAP5/MOD3. The main purpose of this study is to transplant the CANDU models of the RELAP5/MOD3/CANDU code to the MARS code including a quality assurance of the developed models.

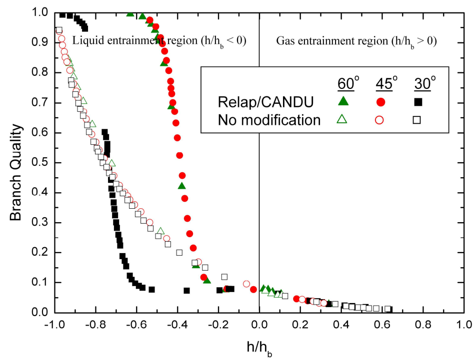
2. Model Development

This part of the research series presents the implementation and verification of the off-take model for arbitrary-angled branch pipes, subcooled boiling model, and radiation heat transfer input model.

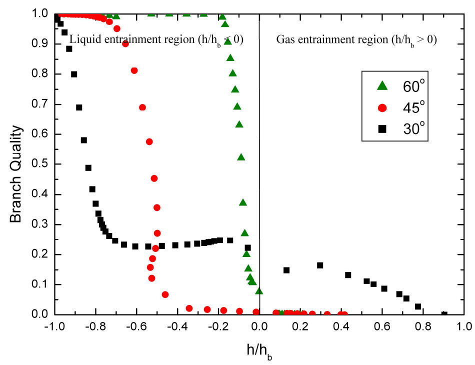
2.1 Off-take Model for Arbitrary-Angled Branch Pipes

The phenomena of a two-phase flow discharging from a stratified region through arbitrary-angled branch pipes are found in the flow through small breaks in horizontal cooling channels of a CANDU reactor during postulated loss-of-coolant accidents (LOCA), the flow distribution at the header-feeder systems during accidents and two-phase distribution in the headers, where a certain incoming stream fed into a large header is divided among a number of discharging streams. Therefore, knowledge of the flow phenomena including the mass flow rate and quality of all the discharging streams is essential for the design and safety analysis of such systems. The off-take models for arbitrary-angled branch pipes were incorporated into HSEM (Horizontal Stratification Entrainment Model) inside the MARS code.

To verify the improved MARS code, a conceptual problem was generated. A header pipe was modeled as a horizontal circular pipe constructed with three nodes and single or multiple branch pipes are connected onto the center node. Figure 1 shows the quality of a branch pipe as a function of header water level. In this validation test, vortex flow entrainment occurs only when $h/h_b < 0$. The improved off-take model in RELAP5/MOD3/CANDU shows different results from the previous RELAP5/MOD3 code, and the current MARS code gives similar results to the improved RELAP5/MOD3/CANDU code.



(a) RELAP5/MOD3/CANDU & RELAP5/MOD3



(b) Improved MARS

Fig. 1. Quality as a Function of Header Water Level in a Positive-Angled Branch Pipe.

2.2 Subcooled Boiling Model

The coolant flow inside a CANDU fuel channel is actually two-phase, in which various flow regimes exist and the flow becomes unstable. Considering the phenomena of subcooled boiling, the boundary between single-phase and two-phase flows would be moved from a saturation point into the realistic point where subcooled void fraction increases rapidly. Therefore, in this study the subcooled boiling model proposed by Podowski[3] has been modified and implemented into the MARS code.

Podowski's subcooled boiling model explains local heat transfer rate with three mechanisms such as advection, quenching, and evaporation.

$$q''_w = q''_{1\phi} + q''_Q + q''_e \quad (1)$$

Here, $q''_e = nf\left(\frac{\pi}{6} d_{bw}{}^3\right)\rho_g h_{fg} = evaporation\ heat\ \ flux$

The vapor departure diameter d_{bw} for evaluating the evaporation heat flux is modeled with a empirical correlation proposed by Unal[4] in 1976.

$$d_{bw} = \frac{2.42\times 10^{-5} P^{0.709} a}{\sqrt{b\Phi}} = \max imum\ bubble\ diameter \quad (2)$$

Where, $a = \frac{\left(q - h\Delta T_{sub}\right)^{1/3} k_l \gamma}{2C_1^{1/3}\rho_v \lambda\left(\pi\alpha_1\right)^{1/2}}$,

$b = \frac{\Delta T_{sub}}{2\left(1-\rho_v/\rho_l\right)} \approx 0.5\Delta T_{sub}$, and

$\Phi = \left(\frac{v}{v_0}\right)^{0.47} \quad for\ v > v_0 = 0.61 m/s$.

The subcooled boiling correlation was implemented in a subroutine 'SubcooledBoiling' in the module 'WallHeattransfer.f90' of the MARS code, and a new option of 'chnhno=61' was added in the module 'ReadNewProblem.f90' to use the Podowski's correlation instead of the Lahey's subcooled boiling model. The improved subcooled boiling model will be validated and verified against experimental data and CFD analysis results for the future study.

2.3 Radiation Heat Transfer Input Model

In the existing radiation heat transfer model in RELAP5/MOD3/CANDU, 37 fuel rods of a fuel bundle is simplified as 4 fuel annuli and modeled as four fuel rods representing each annulus. To improve this simplified radiation heat transfer model for fuel bundles, the geometry between the 37 rods of fuel bundles, the surrounding pressure tube and the calandria tube is maintained and the view factors between a rod and rods, a rod and the pressure tube, the pressure tube and the calandria tube are calculated. The improved radiation heat transfer model is applied in writing an input file.

In the improve radiation heat transfer model the view factors are calculated by MATRIX code, that had benn developed by AECL to be used in the CATHENA code. The generated view factors are verified by using the self-consistency test equation in the MARS code as the below.

$$\sum_{i=1}^{n} F_{ij} = 1 \qquad A_i\ :\ \text{area of surface i}$$

$$A_i F_{ij} = A_j F_{ji} \qquad F_{ij}\ :\ \text{view factor from surface i to surface j}$$

To validate the improved radiation heat transfer model, a simulation on the transient stratified two-phase flow in a CANDU channel was performed as like the RELAP5/MOD3/CANDU validation. Initially the channel was filled with saturated water at 10.69 MPa, and then two-phase fluid with a quality of $1.556\text{x}10^{-7}$ and a mass flow rate of 74.7 kg/sec.m^2 was injected through the inlet. The heat generation from fuel rods was 500kW and the power distribution follows a shape of chopped cosine. As transient time went by more steam was generated and water level was lowered, so that the heat transfer style of each rod becomes single-phase liquid mode, two-phase stratified heat transfer mode, and then single-phase gas mode, sequentially. These gradual changes of the heat transfer mode were well simulated by the improved MARS code.

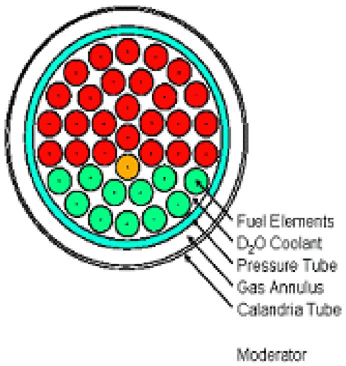


Fig. 2. Analysis Results of the Radiation Heat Transfer in a Typical CANDU Fuel Channel under Stratified Two-Phase Flow Conditions.

3. Conclusions

Among the CANDU models and correlations in RELAP5/MOD3/CANDU, the off-take model for arbitrary-angled branch pipes was implemented and successfully validated against a conceptual test problem, and Podowski's subcooled boiling model was implemented in the MARS code too. Additionally, a radiation heat transfer input model was developed and validated.

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