Development and Validation of Pressure Tube Deformation and Subcooled Boiling Models of the MARS Code for Safety Analyses of the Wolsong NPP's

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1. Introduction

The MARS code is being considered by KINS(Korea Institute of Nuclear Safety) as a thermal-hydraulic regulatory auditing tool for nuclear power plants in South Korea. Because Korea currently has four operating units of the CANDU(Canadian Deuterium Uranium)-type reactor in Wolsong, analytic models such as the Wolsong pump model, the off-take model for arbitrary-angled branch pipes, the radiation heat transfer input model, and the subcooled boiling model have been implemented into the MARS code to extend its applicability into CANDU reactors as well as PWR's.[1] This part of the research series presents verification and validation of the pressure tube deformation model and the Podowski subcooled boiling model.

2. Model Development and Validation

2.1 Pressure Tube Deformation Model

Under some postulated accident conditions in a CANDU reactor, a pressure tube would balloon or sag to contact its surrounding Calandria tube due to temperature increase. For simulating this phenomenon, the pressure tube deformation model expressed by local creep strain rate has been implemented in MARS code. Assuming that the circular shape of a pressure tube would be maintained during deformation, a radial creep strain rate can be expressed as follows from the GRAD program developed by Shewfelt & Godin [2].

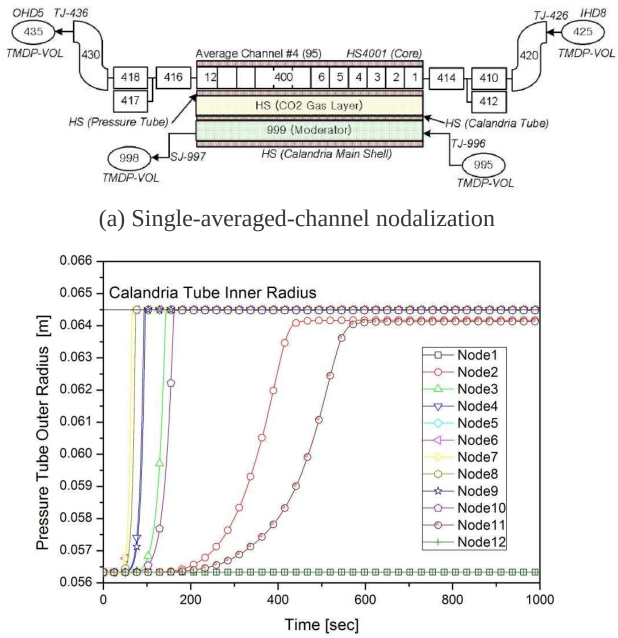
$$\dot{\varepsilon} = 10.4\sigma^{3.4}e^{-19600/T} + \frac{3.5\times10^{4}\sigma^{1.4}e^{-19600/T}}{1+274\int e^{-19600/T}\left(T-1105\right)^{3.72}dt}\ ,$$

for T > 1123 °K (1)

$$\dot{\varepsilon} = 1.3\times10^{-5}\sigma^{9}e^{-36600/T} + \frac{5.7\times10^{7}\sigma^{1.8}e^{-29200/T}}{\left[1+2\times10^{10}\int e^{-29200/T}dt\right]^{0.42}}\ ,$$

for 773 °K < T < 1123 °K (2)

Here, $\sigma = P\cdot r/w$ is the transverse stress in MPa, *P* is the pressure in MPa, *r* is the radius in meter, and *w* is the pressure tube thickness in meter. The integration over time starts from when the pressure tube temperature reaches 973 °K. Eq. (1) & (2) associated with updating procedure of related variables such as pressure tube thickness, length, radius, pressure and temperature were implemented in the heat structure solver module of the MARS code.



(a) Single-averaged-channel nodalization

(b) Geometric variation of a pressure tube

Fig. 1. Validation of the CANDU pressure tube deformation model

For a verification and validation, the simulation results by CATHENA and MARS for the LBLOCA transients of Wolsong Units 2/3/4 were compared. A RIH (Reactor Inlet Header) 35% break with a loss of ECCS (Emergency Core Cooling System) was analyzed in the single channel of a critical pass with boundary conditions at inlet/outlet headers, as shown in Fig. 1(a). In this nodalization, the pressure tube, CO_2 gas in the gap, and the Calandria tube were modeled as one heat structure.

Figure 1(b) shows time-dependent variation of the pressure tube radius at each bundle location. The pressure tube at central bundle locations (node 5 ~ 8) deform earlier and quickly due to its high temperature. The pressure tube at both ends (node 1 & 12), where the temperatures are low, seems not to deform at all. The deformation behaviors of a pressure tube predicted by the MARS calculation are well agreed with the Relap/CANDU[3] results.

2.2 Subcooled Boiling Model

The coolant flows inside CANDU fuel channels under normal operating conditions are actually two-phase. Because the CANDU-6 reactor physics is correlated to the coolant density changes due to its inherent nature, an accurate prediction of coolant steam qualities is greatly needed for the safety analysis codes. 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. In this study, the mechanistic subcooled boiling model proposed by Podowski[4] has been implemented into the MARS code and verified.

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, $q''_{1\phi} = \frac{A_{eff}}{A_{HT}} h_{1\phi}(T_w - T_l) \simeq h_{1\phi}(T_w - T_l)$,

$q''_Q = h_Q A_{bub}(T_w - T_l)$, and $q''_e = nf\left(\frac{\pi}{6} d_{bw}{}^3\right)\rho_g h_{fg}$.

The vapor departure diameter d_{bw} for evaluating the evaporation heat flux is modeled with a empirical correlation proposed by Unal[5] in 1976.

$$d_{bw} = \frac{2.42\times10^{-5} P^{0.709} a}{\sqrt{b\Phi}} = \text{maximum bubble diameter} \quad (2)$$

Where, $a = \frac{(q - h\Delta T_{sub})^{1/3} k_l \gamma}{2C_1^{1/3}\rho_v \lambda (\pi\alpha_1)^{1/2}}$, $b = \frac{\Delta T_{sub}}{2(1-\rho_v/\rho_l)} \approx 0.5\Delta T_{sub}$,

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

A normal operating condition of the Wolsong Unit 2/3/4 was analyzed for verification of the implemented subcooled boiling model. In this analytic model including the whole primary heat transfer loop, 95 fuel channels are represented by an averaged-channel so that all 380 channels are modeled as four averaged-channels. Table 1 summarizes static qualities at the outlet headers and mass flow rates of each averaged-channel by using Podowski's and Lahey's[6] subcooled boiling models. The Podowski's model predicts the static qualities at outlet headers ~4% higher, so that the mass flow rates are slightly changed accordingly. Figure 2 shows a comparison of void fractions at bundle locations for an averaged-channel. Exit (at 12th bundle) void fractions predicted by both models are about the same, while the Lahey model gives slightly higher void fractions at 9th ~11th bundles.

Table 1. Outlet header qualities and channel mass flow rates

		Lahey Model	Podowski Model
Static Quality	Outlet Header #1	4.9314E-02	5.1909E-02
	Outlet Header #2	4.9155E-02	5.1213E-02
	Outlet Header #3	4.7242E-02	4.9775E-02
	Outlet Header #4	4.7884E-02	5.0168E-02
Mass Flow Rate [kg/s]	Avg. Ch. #1	1901.2	1906.6
	Avg. Ch. #2	1894.0	1904.6
	Avg. Ch. #3	1894.5	1906.6
	Avg. Ch. #4	1840.6	1837.0

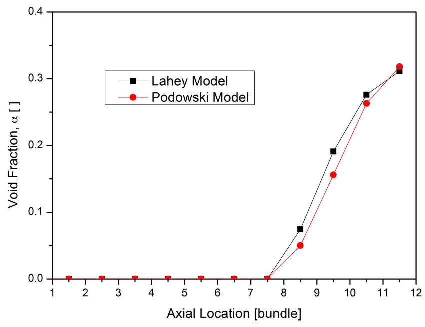


Fig. 2. Averaged-channel void fractions along stream-wise bundle locations.

3. Conclusions

The pressure tube deformation model and the Podowski subcooled boiling model has been transplanted into the MARS code to extend its applicability into CANDU reactors as well as PWR's. By a comparison of the simulation results by Relap/CANDU and MARS for the LBLOCA transients of a CANDU single channel, the pressure tube deformation model was proven to be successfully implemented in MARS code. Safety analyses of Wolsong 2/3/4 nuclear power plants were performed by using the developed Podowski's and the existing Lahey's subcooled boiling models. Comparison of the results shows that both models reasonably predict the void fraction and qualities in the channels, and that the discrepancy between the two models is not significant for the current coarse input model.

ACKNOWLEDGMENTS

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