ARP1400 DVI break analysis using the MARS 3.1 multi-D component

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1. Introduction

The current version of MARS 3.1 has a multi-D component intended to simulate an asymmetric multi-dimensional fluid behavior in a reactor core, downcomer or in a steam generator, in a more realistic manner. The feature is implemented in the 1-D module of the code. As opposed to the cross flow junction modeling, the multi-D component allows for a lateral momentum transfer as well as a sheer stress. Thus, a full three-Dimensional analysis capability is available as in the case of RELAP5-3D[1] or CATHARE [2].

In this study the multi-D component is applied to the hypothetical accident of a DVI (Direct Vessel Injection) break in the APR1400 plant, and the results are analyzed.

2. Theory

2.1 Multi-D two-phase flow model

The multi-D tow-phase model, in the MARS code, is implemented by adding a three-dimensional terms to the original one-dimensional equations. The mass and energy equations of the original equation set already consider the multi-dimensional conservatism. The momentum equations have been extended to account for the multi-dimensional aspects [3]. The relevant momentum equation is:

$$\gamma_v \frac{\partial}{\partial t}\alpha_k \rho_k \underline{v}_k + \nabla\cdot(\gamma_a \alpha_k \rho_k \underline{v}_k \underline{v}_k) + \gamma_v \cdot \alpha_k P = \gamma_v \alpha_k \rho_k g + \nabla\cdot(\gamma_a \alpha_k \underline{\underline{\tau}}') - \gamma_v F_i - \gamma_v F_w \quad (1)$$

The equation (1) is adapted to the MARS code, in the case for a gas phase, as:

$$\begin{aligned}
&\alpha_g \rho_g \frac{\partial u_g}{\partial t} \\
&+ \frac{1}{\gamma_v}\left(\frac{1}{2}\alpha_g \rho_g \gamma_{a,x} \frac{\partial u_g^{\,2}}{\partial x} + \alpha_g \rho_g \gamma_{a,y} v_g \frac{\partial u_g}{\partial y} + \alpha_g \rho_g \gamma_{a,z} w_g \frac{\partial u_g}{\partial z}\right) \\
&= \alpha_g \frac{\partial P}{\partial x} + \alpha_g \rho_g B_x - \alpha_g \rho_g (FWG) u_g + \Gamma_g (u_{gI} - u_g) \\
&- \alpha_g \rho_g (FIG)(u_g - u_f) - C\alpha_g \alpha_f \rho_m \left[\frac{\partial (u_g - u_f)}{\partial t} + u_f \frac{\partial u_g}{\partial x} - u_g \frac{\partial u_f}{\partial x}\right] \\
&+ \frac{\alpha_k (\mu_g + \mu_{g,\tau})}{\gamma_v}\left[\gamma_{a,y}\frac{\partial^2 u}{\partial y^2} + \gamma_{a,z}\frac{\partial^2 u}{\partial z^2}\right] \quad (2)
\end{aligned}$$

2.2 two-phase turbulent models

The most agreed upon standard model for a turbulent flow is the $k-\varepsilon$ model. In the standard $k-\varepsilon$ model, two-transport equation models with respect to the turbulent energy (k) and a dissipation (ε) are used to determine the turbulent term. The model considers the initiation of a turbulence, disappearance, convection, and a diffusion. The $k-\varepsilon$ model in the two-phase flow is employed in the MARS code with the user input of a mixture length. The guide line was found based on the sensitivity test:

$$\frac{\Delta x}{5} \le l_m \le \Delta x \quad (3)$$

3. DVI break test

The DVI (Direct Vessel Injection) is a standard safety injection system in APR1400. The diameter of the inject line is 0.284m. A total of 4 injection lines are provided in a form of two-trains. The results of a steady state calculation for APR-1400 are as shown in Table 1.

Table 1. Steady Calculation for APR-1400

	Plant Parameter	Design	Calcuation
Core	Thermal power [MWt]	3,983	3,983
Primary Loop	Total coolant flow [kg/s]	20991.7	21000.0
	Hot leg temp [K]	597.04	599.70
	Cold leg temp [K]	563.71	567.16
	Average Temp [K]	580.37	583.43
Main steam System	Feed water per S/G [kg/s]	1130.81	1130.45
	Steam rate per S/G [kg/s]	1130.81	1130.43
	S/G head pressure [bar]	68.95	68.94
	S/G narrow range [%]	60.00	59.84
Pressurizer	Pressurizer pressure [bar]	155.1	156.5
	Pressurizer level [%]	50.00	49.79

For the nodding of the APR1400 system, the 1-D nodding has been modified to accommodate the multi-D component. The multi-D component is applied to the downcomer, core, and steam generator. The downcomer is divided into six regions azimuthally, whereas a single node is assigned in the radial direction. The reactor core has the same number of θ-directional nodes. In the radial and axial directions, however, 3 and 27 nodes are assigned, respectively.

For the DVI break calculation, the conditions listed in Table 2 are assumed. The DVI injection, especially, is limited to one channel only based on a single failure assumption of a one-train unavailability.

Table 2. System parameter conditions for DVI breaks

System Parameters	Conditions
Charging/Letdown	OFF
PZR Heater	OFF
Thermal Power (MW)	3983 (nominal)
Decay Heat	ANS73 (1.2)
# of SIT (available)	3
SIT pressure & inventory	Nominal
# of HPSI (available)	1
HPSI flow	Minimum
Reactor trip & HPSI injection setpoint (PZR pressure)	Minimum 40 sec for HPSI pump On
SG downcomer flow after Rx trip	ON
Brea area (ft2)	0.1, 0.4

4. Calculation Results

The hypothetical DVI break accident is simulated for 500 seconds. Figure 1 shows the primary side pressures and break flow rates, for 0.1 ft^2 and 0.4 ft^2 breaks, respectively. The levels for the core and downcomer are shown in Figures 2 and 3, respectively. The levels for all 6 angular regions are depicted.

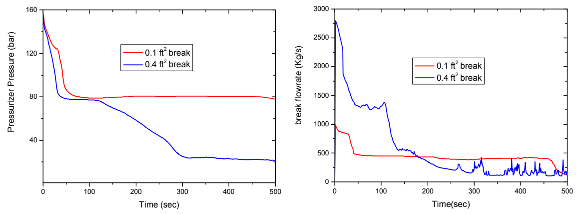

Figure 1. Primary side pressures and break flow rates

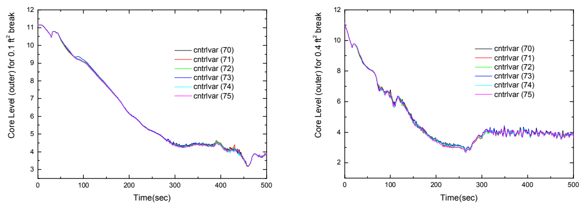

Figure 2. Core levels for 0.1 ft^2 and 0.4 ft^2

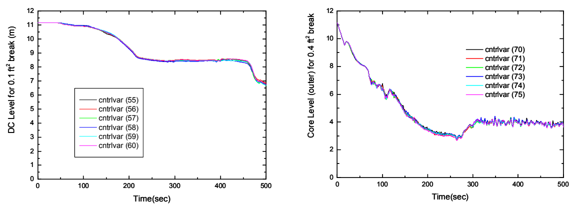

Figure 3. Downcomer levels for 0.1 ft^2 and 0.4 ft^2

As seem from these figures, an asymmetric behavior in the downcomer of the core is not obvious, even with the multi-D calculations. The same observation would also be true for void fraction distribution in the core, as shown in Figure 4. The contour plane in the figure is chosen to be in line with the broken DVI line. The intact dvi line is located at the opposite side of the broken line. The void distributions from 100 sec to 500 sec with an interval of 100sec are depicted.

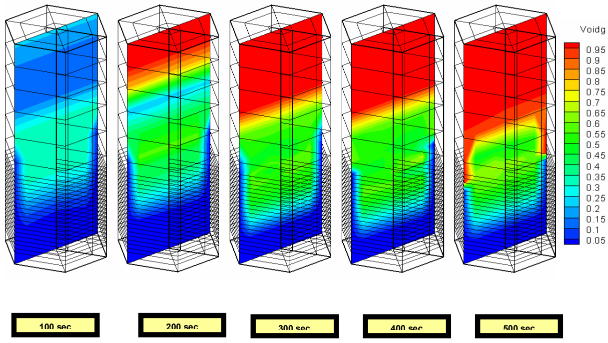

Figure 4. Void fractions in the Core region

It is, however, noted that the multi-dimensional effect might have been smeared out due to the rather coarse meshes assigned in the θ-direction. A finer mesh calculation would be necessary for a more detailed analysis. Due to the absence of a hot channel modeling, the PCT analysis is not performed in this study. A further work would be required in this regards as well.

5. Summary

In this study, a multi-D component feature of the MARS 3.1 has been applied to the hypothetical DVI break accident. Accidents with two break sizes of 0.1 ft^2 and 0.4 ft^2 were simulated with a single failure assumption of one DVI train. Only one DVI injection, therefore, is allowed to perform as a HPSI system. The calculations were successfully completed, demonstrating a sound stability of the implemented multi-D feature. In the specific event of a DVI break accident, however, an asymmetric behavior in the core or in the downcomer region was not found to be significant with the six θ-direction nodes calculations.

REFERENCES

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[3] 정법동 등, “Development and assessment of multi-dimensional flow models in the thermal-hydraulic system analysis code MARS,” KAERI/TR-3011/2005

[4] 한국수력원자력주식회사, “신고리 3,4 호기 예비안전성 분석보고서”