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# Thermodynamic Basic Validation for the Development of Containment Thermal-Hydraulic Analysis Module in Case of Severe Accident

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## 1. Introduction

The regulation of severe accidents in nuclear power plants in Korea is entirely reliant on foreign codes. The domestic nuclear power plant industry is proposing new types of reactors, such as small modular reactor. Therefore, it is essential to develop technologies that can regulate severe accidents accordingly. However, since the U.S. no longer discloses the source code of severe accident analysis codes such as MELCOR, it is crucial to develop domestic severe accident analysis codes. To this end, Seoul National University, the Korea Institute of Nuclear Safety, and FNC Technology Co., Ltd. are collaborating to develop SAFARI code, which is a code for analyzing ex-vessel severe accidents. As part of the SAFARI development, a containment thermal-hydraulic analysis module is being developed in this study.

In contrast to the thermal-hydraulic system analysis code, the severe accident analysis code [1, 2] does not solve the pressure matrix. Instead, it relies on the state equation to calculate the pressure of all nodes. This method is also applied to the containment thermal-hydraulic analysis module. Therefore, it is imperative to validate whether the code accurately calculates the thermodynamic state. In this study, we aim to validate the thermodynamic state prediction ability of the containment thermal-hydraulic analysis module by analyzing a basic thermodynamic conceptual problem that has an analytical solution. Additionally, we will compare the calculation results with MELCOR, which code using a numerical solution that is similar to this module.

## 2. Discretized Governing Equation

The mass, energy, and momentum governing equations for the containment thermal-hydraulic analysis module can be expressed as discretized equations, as shown in equations (1) to (3). The primary unknown variables of these equations are the mass ($M^n$), internal energy ($E_l^n$, $E_g^n$), and velocity($v_{j,l}^n, v_{j,g}^n$). The solution procedure for the governing equations is as follows:

- Derive the pressure equations by converting the pressure of all nodes into a function of the old pressure, derivative term ($\frac{dP}{dM}, \frac{dP}{dE}$) and velocity.
- Substitute the pressure equations into equation (3) to obtain the velocity equations.
- Setup velocity matrix using velocity equations.
- Solve the velocity matrix to determine the velocities and then calculate the remaining variables (mass, energy, pressure, temperature, etc.).
- Compare the pressure calculated using the state equation with the pressure calculated using the pressure equation.
- Repeat the above procedure until the two pressures match.

Figure 1 shows a summary of the above process.

$$\frac{M_{i,m}^n - M_{i,m}^o}{\Delta t} = \sum_j \sigma_j \ \alpha_{j,\phi}^n \rho_{j,m}^d v_{j,\phi}^n A + \Delta M_{i,m} \tag{1}$$

$$\frac{E_{i,\phi}^n - E_{i,\phi}^o}{\Delta t} = \sum_j \sigma_j \ \alpha_{j,\phi}^n \sum_m (\rho_{j,m}^d h_{j,m}^d)\, v_{j,\phi}^n A + \Delta H_{i,m} \tag{2}$$

$$\frac{v_{j,\phi}^n - v_{j,\phi}^o}{\Delta t} = \frac{P_i^{\tilde{n}} - P_k^{\tilde{n}} + (\rho g \Delta z)_{j,\phi}^n + v_{j,\phi}^o}{\rho_{j,\phi} L} - \frac{K\left(\left|v_{j,\phi}^{n-1} + v_{j,\phi}^{n-2}\right| v_{j,\phi}^n - \left|v_{j,\phi}^{n-2}\right| v_{j,\phi}^{n-1}\right)}{2L} - \frac{\alpha_{j,-\phi} f_{Drag} L_{Drag}}{\rho_{j,\phi} L} (v_{j,\phi}^n - v_{j,-\phi}^n) \tag{3}$$

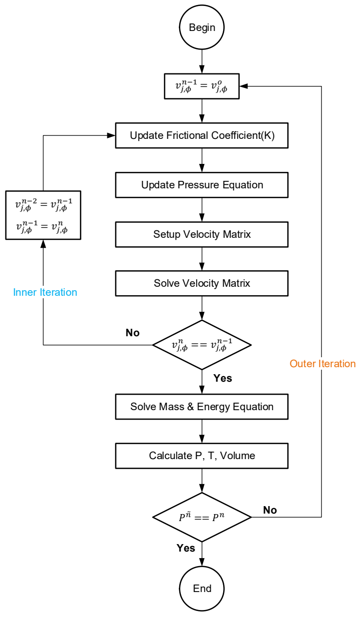

Fig. 1. Containment thermal-hydraulic solver numerical algorithm.

## 3. Calculation Results

Figures 2 to 6 depict a thermodynamic conceptual problem [3] that was selected for this study. Case 1 and 2 represent problems in which pressure and temperature change according to energy changes in a closed system (Fig. 2, 3). These problems were chosen to evaluate the thermodynamic state prediction ability of the containment module with respect to energy changes. Case 3 and 4 represent conceptual problems that pressure and temperature changes when fluid is injected into a constant volume (Fig. 4, 5). These problems were selected to evaluate the thermodynamic state prediction ability of the code with respect to mass and energy changes in static process. Finally, Case 5 was selected to evaluate the prediction ability of thermodynamic state when two gases were mixed (Fig. 6).

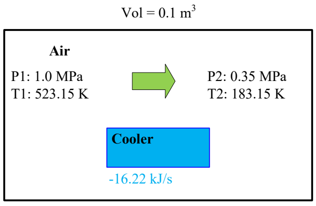

Fig. 2. Case 1: cooling of air in a constant volume process.

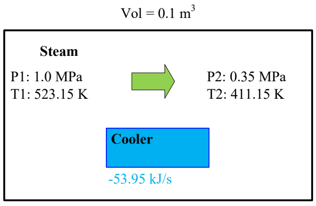

Fig. 3. Case 2: cooling of steam in a constant volume process.

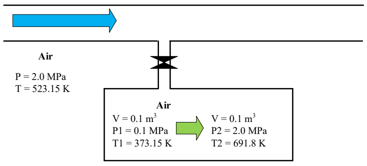

Fig. 4. Case 3: mixing of air in a constant volume process.

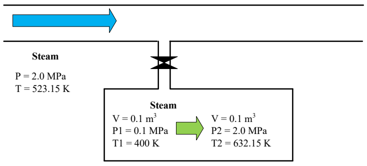

Fig. 5. Case 4: mixing of steam in a constant volume process.

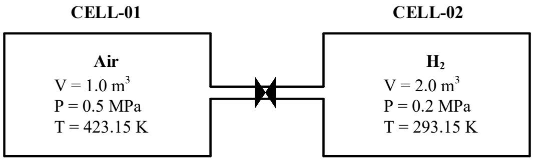

Fig. 6. Case 5: two gases mixing.

Table I: Calculation Results

| Case No. | | Analytic | MELCOR | SAFARI |
|---|---|---|---|---|
| 1 | P [MPa] | 0.35 | - | 0.35 |
| | T [K] | 183 | - | 182.4 |
| 2 | P [MPa] | 0.35 | 0.35 | 0.35 |
| | T [K] | 412.03 | 412.07 | 412.06 |
| 3 | P [MPa] | 2.0 | 2.0 | 2.0 |
| | T [K] | 691.8 | 686.03 | 687.03 |
| 4 | P [MPa] | 2.0 | 2.0 | 2.0 |
| | T [K] | 632.15 | 632.09 | 631.05 |
| 5 | P [MPa] | 0.3 | 0.3 | 0.3 |
| | T [K] | 354.15 | 363.85/<br>348.81 | 356.60/<br>352.89 |

Table I summarizes the analytical solution and code calculation results for the selected thermodynamic conceptual problem. The results of each case are as follows:

- Case 1: The SAFARI code calculate pressure and temperature the same as the analytical solution. On the other hand, MELCOR failed to calculate because it does not allow the atmosphere to cool below its freezing point.
- Case 2: The calculation results of both codes were consistent with the analytical solution.
- Case 3: Both codes calculated the pressure the same as the analytical solution, while the temperature was 4 to 5 K lower. This difference seems to be caused by assuming the specific heat capacity at constant pressure as a constant when calculating the analytical solution.
- Case 4: MELCOR showed consistent results with the analytical solution. SAFARI also calculated the pressure the same as the analytical solution; however, the temperature was 1 K lower.
- Case 5: Both codes calculated the pressure the same as the analytical solution; however, the temperature was calculated differently from the analytical solution.

Figure 7 illustrates the temperature calculation results of both codes for Case 5. In the case of SAFARI code, it can be observed that the temperature difference between the two volumes is smaller since the mass and energy transfer through the flow path is maintained longer than MELCOR. This difference is due to MELCOR calculates the pressure loss in the flow path, although the input models of both codes are modeled to ignore the pressure loss in the flow path. To confirm this, the SAFARI input modeling was modified to occur pressure loss in the flow path. Figure 8 shows the calculation results of both codes with considering pressure loss in flow path. The temperature behavior of the two codes was similar, but they still exhibited a temperature difference of 1 to 2 K with each other.

There results confirm that the containment thermal-hydraulic analysis module appropriately predicts thermodynamic state changes according to energy changes. Even when mass changes were present, the thermodynamic state changes were predicted similarly to the analytical solution, but with a slight difference remaining.

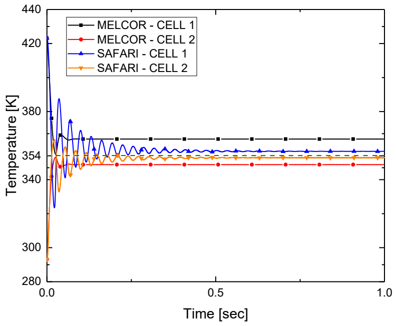

Fig. 7. Case 5: temperature results without pressure loss

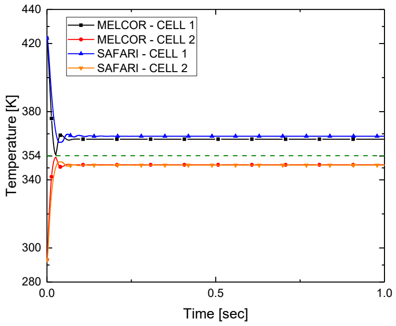

Fig. 8. Case 5: temperature results with pressure loss

## 4. Conclusions

In contrast to the thermal-hydraulic system analysis code, the severe accident analysis code does not solve the pressure matrix. Instead, it relies on the state equation to calculate the pressure of all nodes. Therefore it is crucial to confirm that the code predicts thermodynamic state properly. In this study, as part of the severe accident analysis code (SAFARI) development, the thermodynamic state prediction performance of the containment thermal-hydraulic analysis module was evaluated. The evaluation demonstrated that this module accurately predicted the thermodynamic state changes according to energy changes. Even when mass changes were present, the thermodynamic state changes, with only a slight difference remaining. In the future, we plan to improve the containment thermal-hydraulic analysis module to more accurately predict thermodynamic state changes resulting from mass changes.

## ACKNOWLEDGEMENT

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