Conceptual Problem-Based Verification of the Containment Thermal-Hydraulics Analysis Module for Severe Accident Analysis

Kum Ho Han, Jehee Lee, Yeon-Jun Choo*
FNC Tech., Heungdeok IT Valley, Heungdeok 1-ro, Giheung-gu, Yongin-si, Gyeonggi-do, 446-908, Korea
**Corresponding author: yjchoo@fnctech.com*

***Keywords :** Containment, Thermal-hydraulics, Verification

1. Introduction

Korea's severe accident regulation relies on codes developed under the sponsorship of the U.S. Nuclear Regulatory Commission (NRC), such as MELCOR [1]. The NRC stopped sharing their source codes. This makes it inconvenient to adjust the current approach to severe accident regulations for Korea. Consequently, the development of an analysis code for severe accident regulations is required. As part of this initiative, a module designed to predict the thermal-hydraulic behavior of ex-vessel is under development. This module has been tentatively named SAVANNAH.

SAVANNAH is a lumped-parameter-based code that partitions the containment into two phases: the water pool and the atmosphere. And it adopts the numerical scheme similar to those of MELCOR. The code assumes that the water pool contains only liquid water and water vapor, whereas the atmosphere comprises solely water vapor and non-condensable gases. To verification SAVANNAH in this study, several conceptual problems were selected, and the calculation results obtained from SAVANNAH were compared with those of MELCOR.

2. Discretized Governing Equations

Fig. 1 illustrates an example of the connectivity between compartments and flow paths in SAVANNAH. A single compartment can be linked to multiple flow paths, with their positions flexibly specified within the compartment. This chapter presents the discretized governing equations of SAVANNAH.

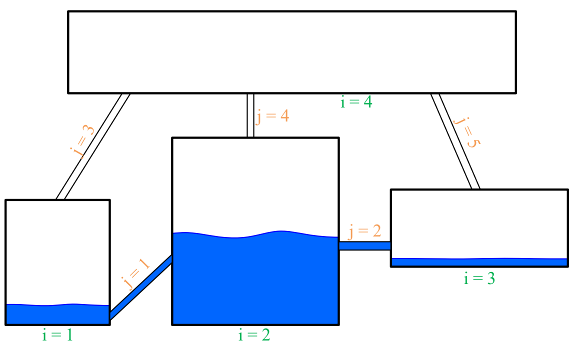

Fig. 1. Example connections between compartments and flow paths

2.1 Discretized Mass Equation

$$M_{i,m}^{n} - M_{i,m}^{n} = \sum_j \sigma_{ij} \alpha_{j,\phi}^{n} \rho_{j,m}^{d} v_{j,\phi}^{n} A_j \Delta t + \delta M_{i,m} \quad (1)$$

Eq. (1) expresses the discretized mass conservation equations for each material within compartment i. Here, the subscript i denotes the compartment index, m represents the material index (where 1 corresponds to pool water, 2 to water vapor in the atmosphere, and 3 onward to non-condensable gases), Φ indicates the phase (either pool or atmosphere), and j signifies the flow path index. The superscript d denotes the upstream (donor) compartment value, n represents the current time step, and o indicates the previous time step. The variable $M_{i,m}$ denotes the mass of material m in compartment i, $\delta M_{i,m}$ represents the external mass source, and σ_{ij} describes the connectivity between compartment i and flow path j. The value of σ_{ij} depends on this connectivity: it is – 1 if compartment i is linked to the 'from' direction of flow path j, 1 if linked to the 'to' direction, and 0 if no connection exists. The primary unknowns in this discretized mass conservation equation are the mass of each material ($M_{i,m}^{n}$) and the velocity of each phase in the flow path ($v_{j,\phi}^{n}$).

2.2 Discretized Energy Equation

$$E_{i,\phi}^{n} - E_{i,\phi}^{n} = \sum_j \sigma_{ij} \alpha_{j,\phi}^{n} (\rho_{j,m}^{d} h_{j,m}^{d}) v_{j,\phi}^{n} A_j \Delta t + \delta E_{i,\phi} (2)$$

Eq. (2) expresses the discretized energy conservation equations for each phase within compartment i. Here, $E_{i,\phi}$ represents the total internal energy of phase Φ in compartment i, and $\delta E_{i,\phi}$ denotes the external energy source. The primary unknowns in this discretized energy conservation equation are the internal energy of each phase ($E_{i,\phi}^{n}$), and the velocity of each phase in the flow path ($v_{j,\phi}^{n}$).

2.3 Discretized Momentum Equation

$$v_{j,\phi}^{n} = v_{j,\phi}^{o} + \frac{\Delta t}{\rho_{j,\phi} L_j} \Big[P_i^{\tilde{n}} + \Delta P_{pp} - P_k^{\tilde{n}} + (\rho g \Delta z)_{j,\phi}^{\tilde{n}} - \left(f \frac{L_j}{D} + \sum K\right) \frac{\rho_{j,\phi}}{2} \left(\left| v_{j,\phi}^{n-1} + v_{j,\phi}^{n-2} \right| v_{j,\phi}^{n} - \left| v_{j,\phi}^{n-2} \right| v_{j,\phi}^{n-1} \right) \Big] \quad (3)$$

Eq. (3) describes the discretized momentum conservation equation for each phase in flow path j, indicating that the momentum of flow path j is influenced by the pressure of the adjacent volumes i and k($P_i^{\tilde{n}}$, $P_k^{\tilde{n}}$). In this equation, ΔP_{pp} represents the pressure change due to the pump, f is the friction coefficient, and K is the minor loss coefficient.

The momentum change in the flow path is governed by the pressure (including local head) of adjacent compartments, whereas the pressure and water level in each compartment are influenced by the velocity along the flow path. Consequently, the momentum of the flow path is closely coupled with the mass and energy of the compartments. Among the variables in Eq. (3), those denoted with superscript $\tilde{n}$ vary due to the convection term. For instance, $P_i^{\tilde{n}}$ represents the pressure updated by incorporating the pressure change due to the mass and energy transfer through flow path, based on the previous pressure value.

2.4 Numerical Scheme

As depicted in Fig. 2, SAVANNAH employs two iteration steps: an inner iteration to calculate the velocity and an outer iteration to determine the thermal-hydraulic state corresponding to the mass and internal energy of the cell.

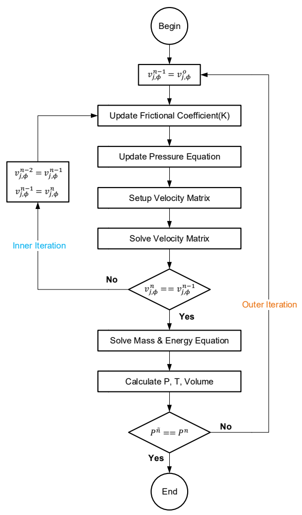

Fig. 2. Numerical scheme of SAVANNAH [2]

3. Verification

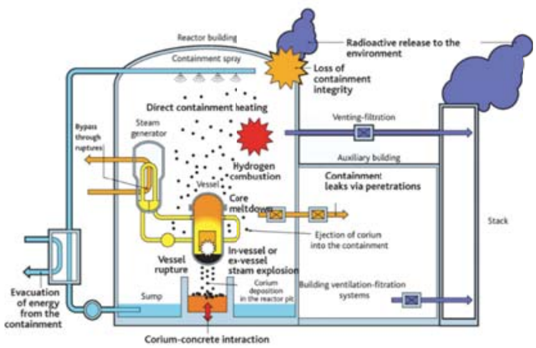

Fig. 3. Major phenomena during a severe accident [3]

Fig. 3 illustrates the key phenomena that occur during a severe accident. These phenomena impact the thermal-hydraulic behavior of the containment. As the reactor vessel ruptures, a portion of the molten fuel is released to the containment. Most of the released molten fuel falls into the containment cavity, while some remains suspended in the atmosphere of the containment in the form of aerosols. These materials carry decay heat, which transfer heats and generates various gases as they interact with the concrete within containment structure. Additionally, engineering safety features such as containment spray, passive autocatalytic recombiner (PAR), and heat exchangers also influence the thermal-hydraulic behavior of the containment.

3.1 Conceptual Problem Selection

For SAVANNAH to analyze the thermal-hydraulic behavior of the containment during a severe accident, it must accurately predict the thermal-hydraulic behavior in response to changes in mass and energy, or gas composition. To verify this, the following conceptual problems have been selected:

- Cooling process in a closed system
- Mixing of two gases
- Natural circulation based on density differences
- Gas injection and advection

Fig. 4 depicts a conceptual problem within a closed system, where superheated steam at a pressure of 1.0 MPa and a temperature of 523.15 K is cooled at a rate of 53.95 kW. This problem enables the verification of SAVANNAH's ability to accurately predict thermodynamic states based on energy variations. Fig. 5 illustrates a conceptual problem involving the interconnection of two volumes containing air and H_2, respectively, to evaluate the gas mixing process. This tests SAVANNAH's capability to correctly predict temperature and pressure in accordance with the convection term. Fig. 6 presents a natural circulation problem driven by a heat sink and source. Finally, Fig. 7 depicts a scenario in which air is injected into a steam-filled volume during 300 seconds.

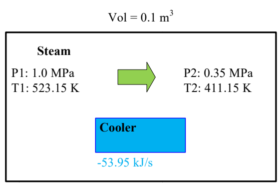

Fig. 4. Case 1: cooling process in a closed system

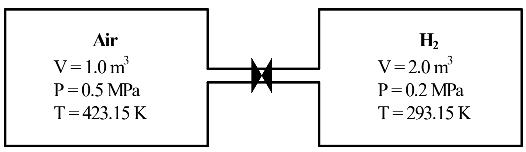

Fig. 5. Case 2: mixing of two gases

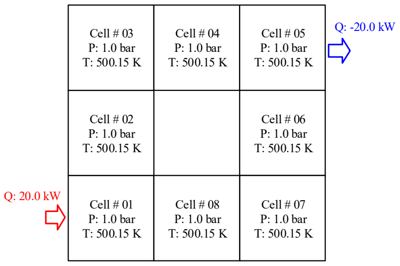

Fig. 6. Case 3: natural circulation based on density differences

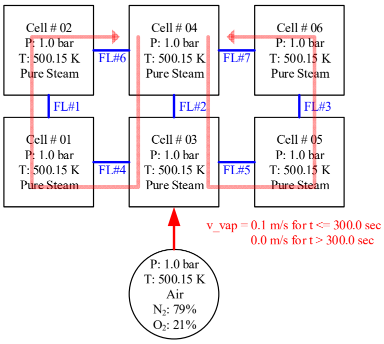

Fig. 7. Case 4: gas injection and advection

3.2 Conceptual Problem Calculation

Figs. 8 and 9 present the calculation results for conceptual problem Case 1, obtained using MELCOR and SAVANNAH. These results confirm that SAVANNAH predicts thermodynamic states according to energy change with equivalence to MELCOR. Figs. 10 and 11 compare the analysis results of both codes for conceptual problem Case 2, demonstrating that they predict pressure and temperature equivalently based on variations in mass and energy.

Figs. 12 and 13 display the analysis results for Case 3. These graphs illustrate that the temperature of Cell #1, initially increases, and then decreases as the natural circulation flow rate rises, ultimately stabilizing at a steady state. Finally, Figs. 4 to 18 depict the analysis results for Case 4. Figs. 4 to 16 show the mass flow rates of FL#2, #4, and #5, respectively. These figures reveal that fluid descends at the center of the compartments (Cells #3 and #4) and ascends at both ends. In the analysis of both codes, a downward flow occurs at the center of the compartment, resulting from the omission of momentum flux. Consequently, the fluid flow is governed by the pressure difference. Figs. 17 and 18 present the N_2 and H_2O mass changes in Cell #6, respectively. During the initial 300 seconds of air injection, SAVANNAH predicts the steam mass with slight deviations from MELCOR; however, beyond this period, the predictions of both codes converge closely.

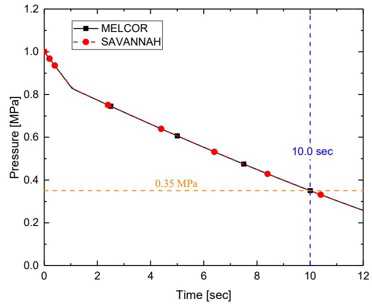

Fig. 8. Case 1: pressure

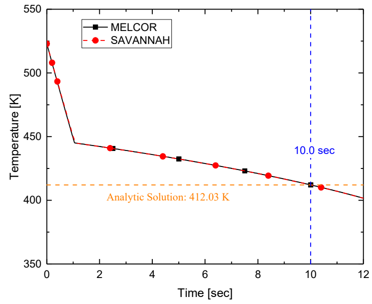

Fig. 9. Case 1: temperature

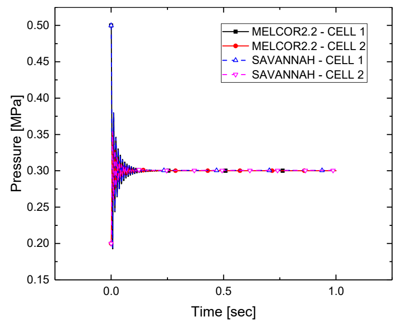

Fig. 10. Case 2: pressure

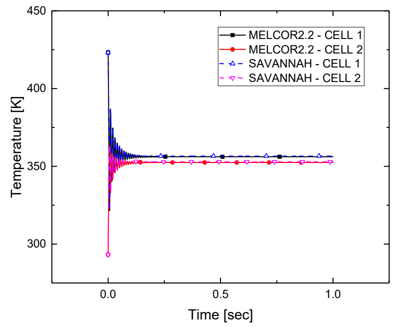

Fig. 11. Case 2: temperature

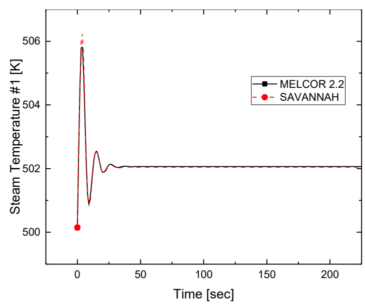

Fig. 12. Case 3: temperature of cell #1

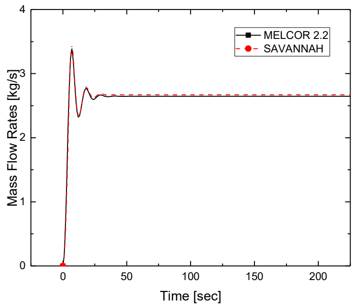

Fig. 13. Case 3: mass flow rates between cell #1 and cell #2

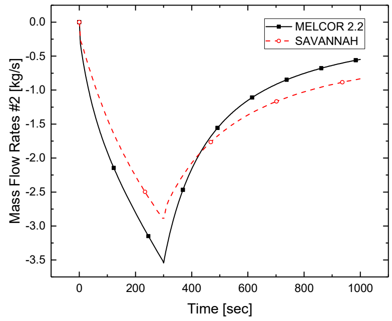

Fig. 14. Case 4: mass flow rates of FL#2

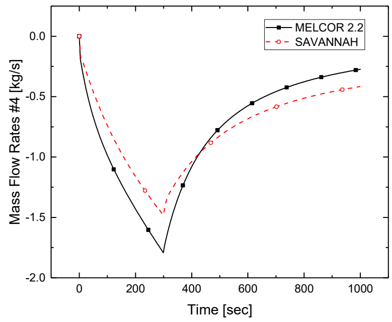

Fig. 15. Case 4: mass flow rates of FL#4

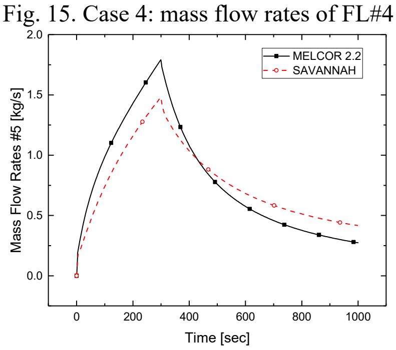

Fig. 16. Case 4: mass flow rates of FL#5

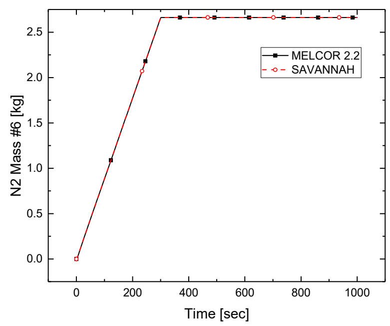

Fig. 17. Case 4: N2 mass of cell #6

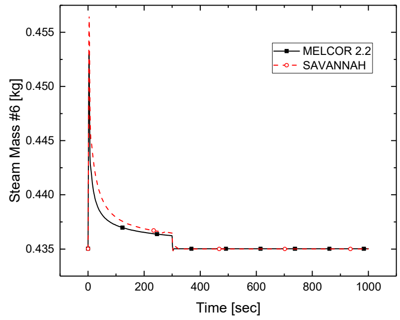

Fig. 18. Case 4: steam mass of cell #6

4. Conclusion

Korea's reliance on NRC-sponsored codes like MELCOR for severe accident regulations has been challenged by the NRC's decision to withhold source codes. SAVANNAH, a lumped-parameter-based code currently under development, addresses this by predicting ex-vessel thermal-hydraulic behavior with numerical methods akin to MELCOR. Verification through conceptual problems (Figures 4–18) confirms that SAVANNAH predicts conceptual problem similar with MELCOR. For Case 4, SAVANNAH predicts flow behavior similarly to MELCOR, though slight differences in values are observed. This discrepancy is attributed to variations in the procedures for determining flow path velocities when complex flow path connections are involved.

ACKNOWLEDGEMENT

This work was supported by the Nuclear Safety Research Program through the Korea Foundation Of Nuclear Safety(KoFONS) using the financial resource granted by the Nuclear Safety and Security Commission(NSSC) of the Republic of Korea. (No. 2106032)

REFERENCES

[1] L.L. Humphries, B.A. Beeny, F. Gelbard, D.L. Louie, and J. Phillips, MELCOR Computer Code Manuals Vol. 2: Reference Manual, Sandia National Laboratories, SAND2017-0876, 2017.

[2] K. H. Han, B. D. Chung, and Y. J. Choo, Thermodynamic Basic Validation for the Development of Containment Thermal-Hydraulic Analysis Module in Case of Severe Accident, Transactions of the Korean Nuclear Society Autumn Meeting, Gyeongju, Korea, Oct. 26-27, 2023

[3] J. P. Van Dorsselaere, T. Albiol, & J. C. Micaelli, Research on severe accidents in nuclear power plants, Nucl. Power-Oper. Saf. Environ., InTech, 155e182., 2011