Preliminary Validation of Thermal-Hydraulic Module for Ex-vessel Severe Accident Analysis Through Containment Experiments

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, Preliminary Validation

1. Introduction

South Korea's regulations for severe accident regulation primarily utilize computational codes, such as MELCOR [1], which were developed with support from the U.S. Nuclear Regulatory Commission (NRC). However, the NRC's decision to restrict access to their source codes has posed challenges in adapting these tools to meet Korea's specific regulatory needs for severe accidents. As a result, there is a pressing need to develop an independent analysis code tailored for severe accident regulation. To address this, a dedicated module for simulating the thermal-hydraulic behavior in the ex-vessel environment is currently under development, provisionally named SAVANNAH.

The SAVANNAH module[2] employs a lumped-parameter approach, dividing the control volume into two distinct regions: the water pool and the atmospheric phase. Its numerical scheme is designed to align closely with methodologies used in MELCOR. The model assumes that the water pool consists exclusively of liquid water and its vapor, while the atmosphere is composed of water vapor and non-condensable gases. To validate the performance of SAVANNAH in this study, a series of containment experiments were chosen, and the results generated by SAVANNAH were compared against those produced by MELCOR.

2. Constitute Models

In the event of a severe accident at a large nuclear power plant, the thermal-hydraulic behavior of the containment building is greatly influenced by steam/water released from the system, various radioactive materials, and various engineering safety features. Containment experiments observe changes in the thermal-hydraulic behavior of the containment due to these factors. To properly predict the experiments, the code must be equipped with models that can analyze heat and mass transfer from heat sinks such as walls. The convective heat transfer model and condensation heat transfer model used in MELCOR and SAVANNAH are as follows:

2.1 Convective Heat Transfer Model

MELCOR distinguishes convection regimes using the relationship between the Reynolds number (Re) and the Grashof number (Gr), as shown in the discriminant of Eq. (1).

$$\begin{aligned} &\mathrm{Re}^2 < 1.0\ \mathrm{Gr} : \text{Natural Convection} \\ &\mathrm{Re}^2 > 10.0\ \mathrm{Gr}: \text{Forced Convection} \\ &1.0\mathrm{Gr} \le \mathrm{Re}^2 \le 10.0\ \mathrm{Gr}: \text{Mixed Convection} \end{aligned} \quad (1)$$

In each convection regime, the heat transfer coefficient is calculated as follows, with the coefficients and exponents in the equations applied according to the shape of the heat structure.

Natural convection:
$$\mathrm{Nu_{nat}} = \mathrm{C}(\mathrm{Gr}\cdot\mathrm{Pr})^{\mathrm{m}} + \mathrm{D} \quad (2)$$

Forced convection:
$$\mathrm{Nu_{for}} = \mathrm{C}\cdot\mathrm{Re}^{\mathrm{m}}\mathrm{Pr}^{\mathrm{n}} + \mathrm{D} \quad (3)$$

Mixed convection:
$$\mathrm{Nu_{mix}} = \left[\left(\frac{\mathrm{Re}^2}{\mathrm{Gr}} - 1\right)/9\right][\mathrm{Nu_{for}} - \mathrm{Nu_{nat}}] + \mathrm{Nu_{nat}} \quad (4)$$

SAVANNAH also uses natural convection and forced convection heat transfer models in the form of Eq. (2) and Eq. (3). However, SAVANNAH does not consider the mixed convection regime and instead uses the maximum value between the natural convection heat transfer coefficient and the forced convection heat transfer coefficient as the convective heat transfer coefficient.

2.2 Condensation Heat Transfer Model

Both MELCOR and SAVANNAH use a condensation heat transfer model based on HMTA (Heat and Mass Transfer Analogy), and the phase change rate due to condensation at the wall is calculated as in Eq. (5).

$$\dot{m}_{cond} = h_D \rho_v \ln(\Delta P_{srf}/\Delta P_{atm}) \quad (5)$$

Where,
$\mathrm{h_D}$: mass transfer coefficient [m/s],
ρ_v: vapor density at $\mathrm{T_{sat}(P_{Tot})}$ [kg/m^3],
$\Delta \mathrm{P_{srf}}$: $\mathrm{P_{tot} - P_{srf}}$ [Pa],
$\Delta \mathrm{P_{atm}}$: $\mathrm{P_{tot} - P_{stm}}$ [Pa],
$\mathrm{P_{srf}}$: $\mathrm{P_{sat}}$ of steam at surface temperature [Pa],
$\mathrm{P_{stm}}$: bulk steam partial pressure [Pa].

3. Validation

The thermal-hydraulic prediction performance of MELCOR has been validated through various conceptual problems and containment experiments, with the HDR V44 experiment and Battelle-Frankfurt experiment used for validation [3]. Reference [3] provides the MELCOR 1.6 input models for some of these experiments.

In this study, the HDR V44 experiment and Battelle-Frankfurt test 2, for which input models are publicly available, were selected for validation.

3.1 HDR V44 Experiment

The HDR V44 experiment observes changes in pressure and temperature in the containment due to steam-water injection during 50 seconds. As shown in Figure 1, the containment, with a diameter of 20 m, height of 60 m, and volume of 11,300 m³, is divided into 62 compartments. However, MELCOR modeled the experimental setup in a simplified manner using 5 compartments and 9 flow paths, as shown in Figure 2, with 41 heat structures employed.

Figures 3 to 6 compare the calculated pressure and temperature of the Upper Rooms (Cell #5) with experimental data. Both MELCOR and SAVANNAH predict peak pressure higher than the experimental values, but the final pressure closely matches the experiment. For temperature, the results of both codes are similar up to 300 seconds, but differences arise thereafter. Before 300 seconds, the atmosphere undergoes condensation due to condensation heat transfer, and afterward, the containment is cooled by convective heat transfer. This indicates that SAVANNAH predicts a lower convective heat transfer coefficient compared to MELCOR.

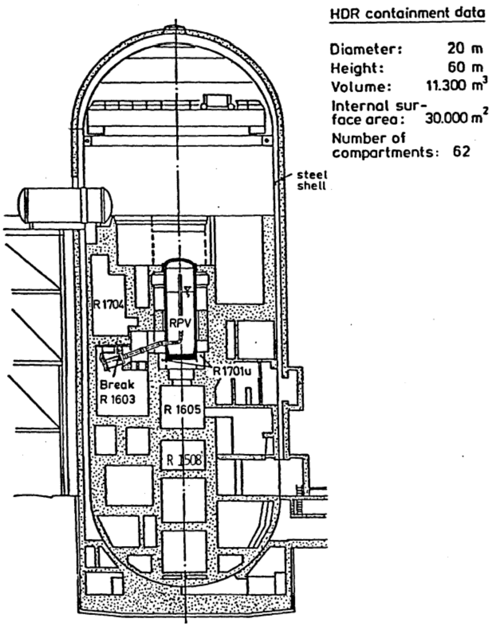

Fig. 1. Schematic of HDR Containment [3]

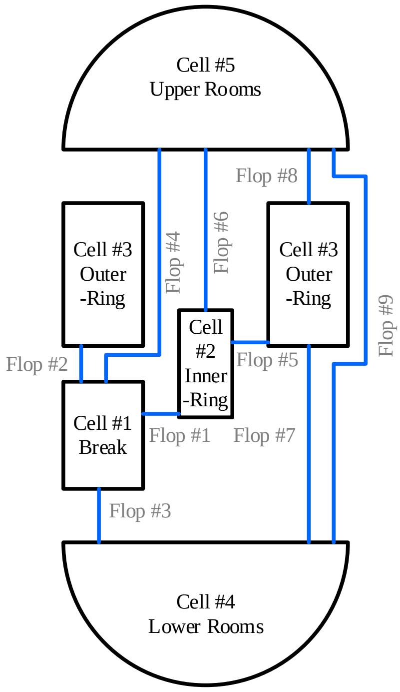

Fig. 2. HDR Nodalization

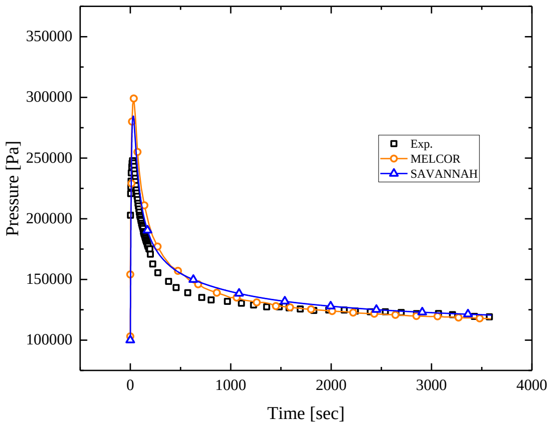

Fig. 3. Containment Dome Pressure (Long Term)

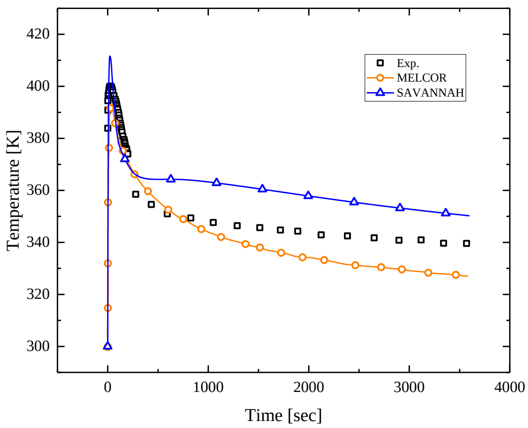

Fig. 4. Containment Dome Temperature (Long Term)

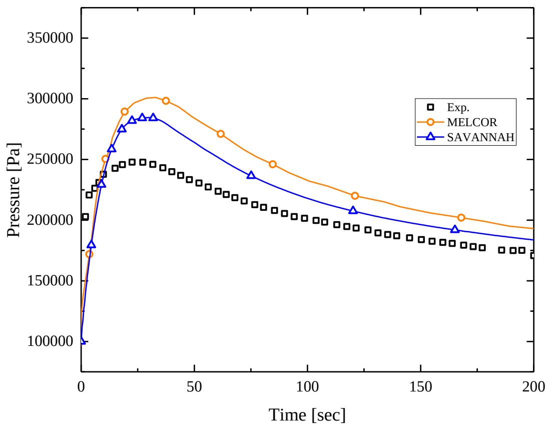

Fig. 5. Containment Dome Pressure (Short Term)

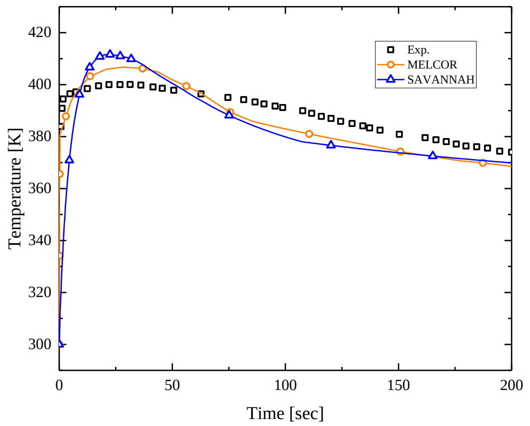

Fig. 6. Containment Dome Temperature (Short Term)

3.2 Battelle-Frankfurt Experiment – Test 2

The Battelle-Frankfurt experiment observes changes in gas concentration within compartments due to the injection of hydrogen and nitrogen gases. The experiment includes Test 2 and Test 10, where all compartments have the same initial temperature, and Test 20 and Test 30, where the initial temperature of the upper compartments is set 20–30 K higher than the lower ones. This study validates Test 2, which involves injecting a hydrogen-nitrogen gas mixture for 13,610 seconds. The initial conditions are as follows:

Compartments: 1 atm, 290.15 K, relative humidity 95%
Heatstructure: Wall temperature 290.15 K

To model this experiment, MELCOR uses 16 compartments and 21 flow paths, as shown in Figure 10, and includes 16 heat sinks, though not depicted in the figure. Hydrogen and nitrogen are injected into compartment 15 via boundary conditions.

Figure 8 compares the hydrogen mole fraction in the upper (Cell #1) and lower (Cell #15) compartments with experimental data. Both MELCOR and SAVANNAH predict the hydrogen mole fraction very closely to the experimental values, with minimal differences between the two codes. This is attributed to the negligible heat transfer through the heatstructures in Test 2 and the even distribution of the injected hydrogen-nitrogen gas mixture across all compartments over the 13,610-second duration.

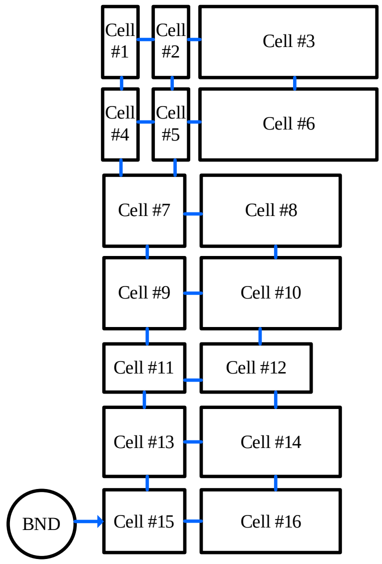

Fig. 7. Battelle-Frankfurt Nodalization

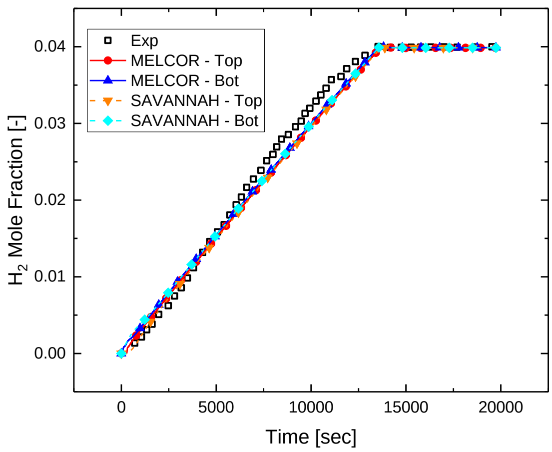

Fig. 8. Hydrogen Mole Fraction

4. Conclusion

This study validated the thermal-hydraulic performance of the SAVANNAH module using the HDR V44 and Battelle-Frankfurt Test 2 experiments. SAVANNAH accurately predicted gas concentration behavior in the Battelle-Frankfurt experiment, where heat structure effects are minimal, closely aligning with both experimental data and MELCOR results. However, in the HDR V44 experiment, where heat structures significantly influence outcomes, SAVANNAH's predictions were similar to MELCOR's up to the point where condensation heat transfer dominates (around 300 seconds), but significant differences emerged thereafter. This imply that SAVANNAH’s convective heat transfer model predicts a lower heat transfer coefficient compared to both MELCOR and experiment.

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, J. H. Lee, and Y. J. Choo, Conceptual Problem-Based Verification of the Containment Thermal-Hydraulics Analysis Module for Severe Accident Analysis, Transactions of the Korean Nuclear Society Spring Meeting, Jeju, Korea, May 22-23, 2025

[3] Leigh, Christi D. MELCOR validation and verification: 1986 papers. No. NUREG/CR-4830; SAND-86-2689. Sandia National Lab.(SNL-NM), Albuquerque, NM (United States); Nuclear Regulatory Commission, Washington, DC (USA). Div. of Reactor Systems Safety, 1987.