MELCOR and ASTEC Double-Blind Benchmark Calculations for the TH-37 Recommissioning Test

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1. Introduction

The THAI experimental facility has been utilized in several OECD/NEA international joint research projects to investigate various nuclear containment phenomena, including thermal-hydraulic behavior, hydrogen behavior, and fission-product behavior. KINS has participated in OECD/NEA international joint research projects, including the Analysis Working Groups (AWGs) of THAI-1 and THAI-3. KINS is also participating in the ongoing THEMIS-2 project.

Following the relocation of the THAI experimental facility by its operating organization, Becker Technologies (BT), the TH-37 experiment was designed as a recommissioning test of the THAI+ facility. The TH-37 experiment involves several relevant phenomena, including natural circulation driven by prescribed heating and cooling boundary conditions and aerosol behavior.

A double-blind, blind and open simulation benchmark exercise for the TH-37 experiment was proposed. During the double-blind phase, the experimental results are withheld from the participants, and only limited information regarding the planned experimental procedure and expected test conditions is provided for the pre-test analysis. For participation in this exercise, KINS developed a MELCOR input model based on several assumptions due to the limited information available during the double-blind phase. In addition, an ASTEC input model was developed based on the MELCOR model. The MELCOR and ASTEC input models will be further refined through inter-code comparison of the calculation results and subsequently used to participate in the blind and open simulation phases of the TH-37 benchmark exercise. The THAI input models developed in this study and the experience gained from the analyses are expected to provide a technical basis for KINS participation in the THEMIS-2 AWG.

2. MELCOR and ASTEC Input Modeling

The experimental configuration of TH-37 is identical to that used in the TH-27 experiment, which was previously conducted to investigate natural circulation phenomena. However, because the objectives of the two experiments are different, the test conditions, including the injection locations of steam and helium, boundary conditions, and experimental procedures, differ between TH-27 and TH-37. For the TH-27 experiment, a collaborative benchmark study involving both blind and open simulation phases was previously conducted using various computational tools, including ASTEC, MELCOR, and computational fluid dynamics (CFD) codes[2, 3]. The lessons learned from the previous benchmark indicated that heat loss to the environment should be appropriately modeled to accurately predict the pressure behavior in the facility. In addition, sufficiently detailed nodalization was recommended to adequately account for phenomena such as upward-directed jets and atmospheric stratification. These findings and recommendations were taken into account in the development of the MELCOR and ASTEC input models. Figure 1 shows the MELCOR and ASTEC nodalization schemes for the THAI+ facility.

2.1 Test Procedure

The experiment is conducted over a total duration of 72 h. From the start of the test to 10 h, steam is injected to maintain the system pressure at approximately 2 bar. Subsequently, additional steam is injected to increase and maintain the pressure at approximately 2.5 bar. At 14 h, the cooling oil jacket of the TTV is activated and remains in operation until 24 h. The heating oil jacket of the PAD is activated at 17 h and turned off at 19 h. At 19.25 h, SnO_2 and CsI aerosols are injected into the facility. At approximately 21 h, helium is injected for about 2,000 s while the helium gas sampling line is in operation. From 24 h onward, the facility undergoes passive cooldown until the end of the experiment.

2.2 MELCOR Modeling

During the double-blind phase, the experimental data are not disclosed to the participants, and only the planned experimental procedure and a limited set of boundary-condition information are provided. The available information includes the ambient temperature, steam injection flow rate (g/s) until the target test pressure is reached, heating power supplied to the PAD through the oil jacket (W), cooling power removed from the TTV through the oil jacket (W), expected

aerosol density in the experimental facility (g/m³), helium injection rate (g/s), and gas sampling rate (l/h). Based on this information, a MELCOR input model was developed for the TH-37 experiment.

The overall MELCOR model consists of 173 control volumes: 111 for the TTV, 57 for the PAD, three for the upper connecting pipe, one for the lower connecting pipe, and one representing the environment. For the TTV, the nodalization was developed considering the sump, inner cylinder, trays, and vessel. The vessel was subdivided into a central cylindrical region with 8 radial subdivisions and up to 15 axial levels. The radial control volume subdivisions were designed considering the 4 trays. For the PAD, the sump and oil jacket were taken into account, and the vessel was nodalized using a central cylindrical region, 4 radial subdivisions, and up to 14 axial levels. The TTV and PAD are connected through upper and lower connecting pipes. Considering that the primary objective of the experiment was judged to be the investigation of steam-driven natural circulation rather than atmospheric stratification, additional control volume subdivision specifically intended to represent jet behavior during steam, helium, and aerosol injections was not adopted.

The actual wall structure of the oil-jacketed regions consists of stainless steel, oil, an outer cover, mineral-wool insulation, and aluminum foil, whereas the remaining regions consist of stainless steel, mineral-wool insulation, and aluminum foil. However, in the MELCOR model, the oil jacket and insulation layers were not explicitly modeled in order to implement the prescribed heat-flux boundary condition directly at the stainless-steel vessel wall.

For the MELCOR boundary conditions, the thermal-resistance formulation was implemented using Control Functions (CF) package so that heat fluxes associated with heating and cooling could be imposed as boundary conditions at the stainless-steel vessel wall. The wall temperature used in the thermal-resistance calculation was obtained from the heat-structure temperature calculated by MELCOR. To account for heat loss to the ambient environment, an external heat transfer coefficient of 5 W/m²·K was assumed. The free-convection heat transfer coefficient for gases generally ranges from approximately 2 to 25 W/m²·K [4]. Accordingly, a heat transfer coefficient of 5 W/m²·K was applied to the external boundary conditions for regions other than the oil-jacketed sections.

Steam injection was modeled using the CF so that the steam flow rate could be adjusted when the specified system pressure was reached. For the aerosol analysis, CsI and SnO2 were modeled using the DCH and RN packages. The aerosol injection rates were determined based on assumed target concentrations and injection durations. Helium sampling was modeled using the CF as a gas discharge from the facility to the environment.

2.3 ASTEC Modeling

The ASTEC input model was developed by applying, as far as practicable, the same model configuration and boundary conditions as those used in the MELCOR input model. However, the helium sampling line was not modeled in ASTEC because its effect on the pressure behavior within the experimental facility was expected to be insignificant.

In ASTEC, the CPA module was used to simulate the thermal-hydraulic behavior of the experimental facility. The control volumes were represented using ZONE structures, the flow paths between the control volumes using CONN structures, and the thermal boundary conditions using WALL structures. The SOPHAEROS module was employed to simulate aerosol behavior. The logic for steam injection and heat-flux boundary conditions was implemented using EVENT and CONNECTI structures.

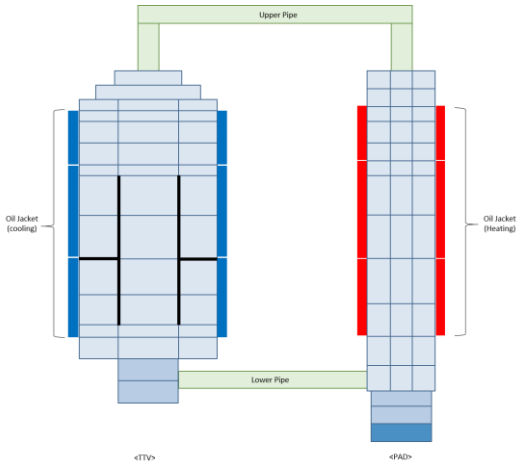


Fig. 1. MELCOR and ASTEC nodalization for THAI+ facility

3. MELCOR and ASTEC Calculation Results

Figure 2 shows the pressure behavior inside the experimental facility. The green dotted line represents the expected pressure trend during the experiment and does not correspond to actual experimental data. The expected pressure was provided in the double-blind specification report. The pressure behavior predicted by MELCOR was generally consistent with the expected pressure trend. In the ASTEC calculation, the pressure was successfully maintained at approximately 2.0 and 2.5 bar during the steam injection periods; however, the predicted peak pressure was higher than the expected value. During the passive cooldown period, both MELCOR and ASTEC predicted a gradual decrease in pressure as the facility cooled down. However, the pressure predicted by ASTEC remained consistently higher than that predicted by MELCOR.

Figure 3 shows the steam injection rate. The steam injection rates required to maintain the prescribed pressure in the experimental facility are generally consistent between the MELCOR and ASTEC calculations. At approximately 50,400 s (14 h), the TTV cooling oil jacket is activated. In the MELCOR calculation, additional steam is injected to compensate for the pressure decrease caused by the operation of the cooling jacket, whereas the steam injection rate in ASTEC remains relatively low. The PAD heating oil jacket is operated for 2 h from 61,200 s (17 h), after which steam is injected at a rate of 15 g/s. During this period, the ASTEC calculation shows a significant increase in pressure. These results suggest that the cooling effect of the TTV oil jacket may not be properly represented in the ASTEC calculation. Therefore, the operating logic implemented in the ASTEC input model needs to be further examined.

Figure 4 shows the wall temperatures of the TTV and PAD. Steam is initially injected into the TTV, and the injection location is switched to the PAD at approximately 36,000 s (10 h). Accordingly, the ASTEC calculation predicts a slight increase in the PAD wall temperature after the steam injection is switched to the PAD. In contrast, the TTV and PAD wall temperatures predicted by MELCOR remain similar throughout this period.

Figure 5 shows the steam concentrations in the TTV and PAD. When the steam injection location is switched from the TTV to the PAD at 36,000 s (10 h), both MELCOR and ASTEC predict a higher steam concentration in the PAD. The steam distribution is subsequently affected by the operation of the TTV cooling and PAD heating systems. During the passive cooldown period after 24 h, the steam concentrations gradually decrease. In the MELCOR calculation, the difference in steam concentration between the TTV and PAD decreases relatively rapidly, and the concentrations gradually approach an equilibrium state. In contrast, the ASTEC calculation shows a persistent difference between the steam concentrations in the two vessels. At approximately 172,800 s (48 h), the steam concentration in the PAD decreases abruptly, resulting in a reversal of the concentration difference between the TTV and PAD. Since no specific experimental operation is scheduled during this period, the cause of this behavior needs to be further investigated to determine whether it originates from numerical behavior of the calculation or from the ASTEC input model.

Figure 6 shows the helium concentrations in the TTV and PAD. Both MELCOR and ASTEC predict a rapid increase in the helium concentration at the onset of helium injection, followed by a gradual approach toward an equilibrium distribution due to atmospheric circulation between the TTV and PAD. In the MELCOR calculation, the helium concentration in the PAD initially decreases and then increases rapidly, whereas ASTEC predicts a relatively slower increase. In particular, during the passive cooldown period after 24 h, the ASTEC results suggest that atmospheric circulation between the TTV and PAD may not be adequately represented.

Figure 7 shows the aerosol densities in the TTV and PAD. In both the MELCOR and ASTEC calculations, the aerosol density increases rapidly at the onset of aerosol injection. Subsequently, MELCOR predicts that the aerosol densities in the TTV and PAD rapidly approach equilibrium. In contrast, the ASTEC calculation shows a noticeable difference in aerosol density between the two vessels until approximately 172,800 s (48 h).

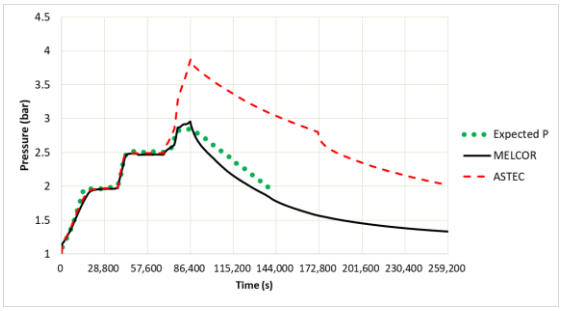


Fig. 2. Comparison of TTV pressure predicted by MELCOR and ASTEC with the expected pressure profile (not experimental data)

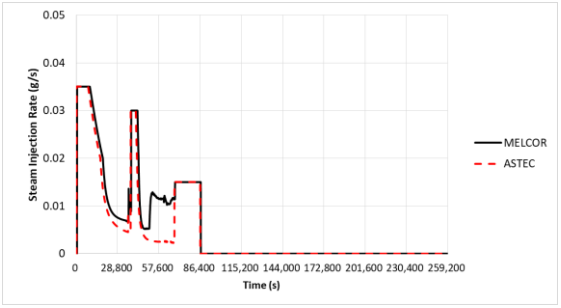


Fig. 3. Comparison of steam injection rates calculated by MELCOR and ASTEC

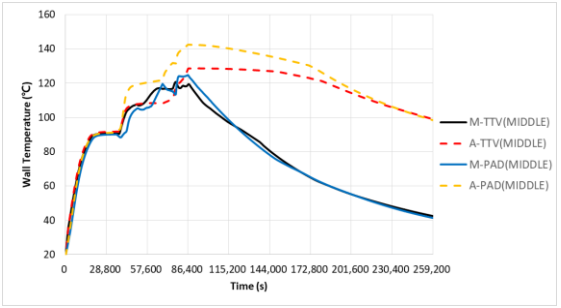


Fig. 4. Comparison of TTV and PAD wall temperatures calculated by MELCOR and ASTEC

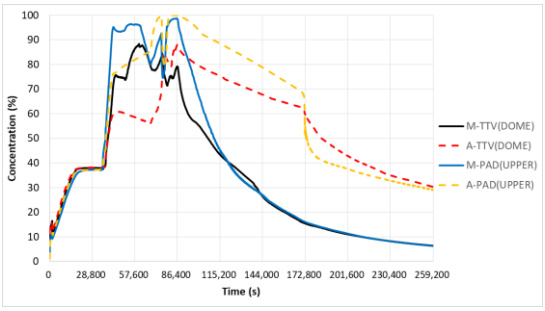


Fig. 5. Comparison of TTV and PAD steam concentrations calculated by MELCOR and ASTEC

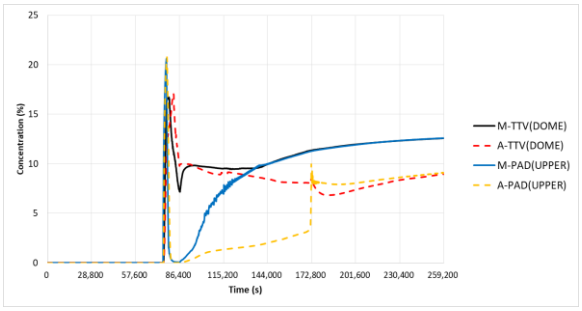


Fig. 6. Comparison of TTV and PAD helium concentrations calculated by MELCOR and ASTEC

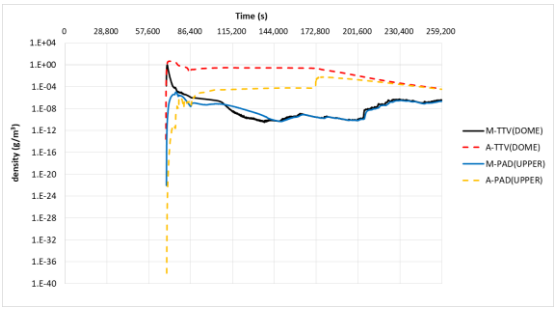


Fig. 7. Comparison of TTV and PAD aerosol densities calculated by MELCOR and ASTEC

4. Conclusions

MELCOR and ASTEC input models for the TH-37 recommissioning test were developed, and double-blind simulations were performed using both codes. During the subsequent blind simulation phase, the models will be revised to incorporate the actual test conditions, and any identified input errors will be corrected. Differences between the MELCOR and ASTEC results were observed in the predicted peak pressure and pressure evolution during the passive cooldown period. To better understand these differences, the thermal boundary condition modeling should be further examined, particularly the effect of representing the oil-jacket heating and cooling as prescribed power sources rather than as heat-flux boundary conditions. Once the experimental data become available during the open simulation phase, the input models should be further refined through detailed comparison with the measurements. In addition, the heat-transfer models implemented in MELCOR and ASTEC should be compared to assess their influence on the calculated results. These lessons will be incorporated into the input models as the benchmark progresses toward the blind and open simulation phases, supporting KINS's THEMIS-2 activities.

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