MELCOR Analysis of TOSQAN ISP-47 Experiment

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1. Introduction

The condensation heat transfer model is very important for the analysis of accidents in nuclear power plants because it is closely related to the prediction of pressure behavior in the containment building of nuclear power plants. In this study, a TOSQAN ISP-47 experimental analysis is adopted to simulate condensation in the containment building using MELCOR, a lumped parameter (LP) code.

The present work suggests two insights for modelling the MELCOR code to predict the results of the TOSQAN ISP-47: 1) recommendation of the double channel-channel model in region of the condensation wall and 2) the effectiveness of the default convective heat transfer coefficient.

2. Methods and Results

The main objective of ISP-47 [1,2] is to evaluate the capabilities of lumped parameter (LP) and computational fluid dynamics (CFD) codes in the field of containment thermal-hydraulics. This International Standard Problem (ISP) was based on the application of different complementary experimental facilities and an approach to interpretation by increasing the difficulty of modeling gradually, as recommended by the state-of-the-art report (SOAR) on "Containment Thermal-hydraulics and Hydrogen Distribution". Three experimental facilities, TOSQAN, MISTRA, and ThAI, provided experimental data suitable for benchmarking CFD and LP codes under steady-state and transient conditions (control of initial and boundary conditions, accuracy of measurement techniques). These mainly include pressure transient and gas temperature fields, as in previous verification data. The detailed gas velocity and gas concentration (air, vapor, and helium) distribution fields involved are the first to be obtained in this ISP program.

2.1 TOSQAN ISP-47 experiment

The TOSQAN experimental program [3] was performed to simulate the thermal-hydraulic phenomenon that can typically occur in reactor containment buildings. The heat and mass exchange between spray droplets and gases as thermal-hydraulic conditions representing these hypothetical severe accidents has been studied with a focus on wall condensation [4].

The TOSQAN facility (Fig. 1) consists of a large container that can simulate the PWR containment building space, so it simulates various thermal-hydraulic fluid conditions in this space. In particular, non-invasive optical measurement equipment is installed here and the measurement results are used to verify the 3-dimensional CFD code as well as the one-dimensional safety analysis code.

In the TOSQAN ISP-47 experiment, steam or non-condensable gas is injected through a vertical pipe located at the central axis of the container with a sealed cylindrical container (7 m^3 of volume, inner diameter of 1.5m, total height of 4.8 m, condensation height of 2 m). This container has a wall that is automatically controlled to allow steam condensation to occur in one part of the wall (condensing wall) and overheat the other part (non-condensing wall). In this study, the entire transient of the ISP-47 experiment was simulated by code calculation for about 18,000 seconds.

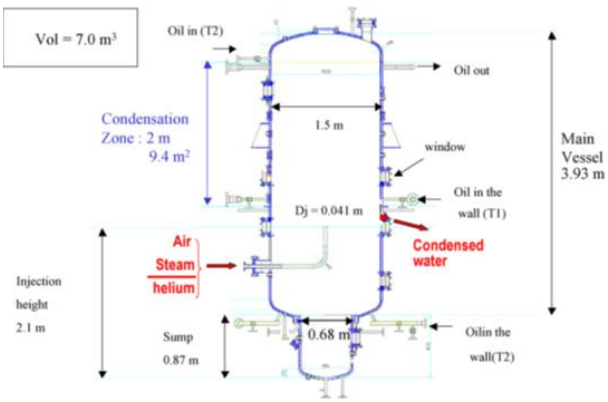


Fig. 1. Configuration of the TOSQAN test facility.

Code analysis for the entire transient of the TOSQAN ISP-47 experiment was performed in a calculation time of about 18,000 seconds. The initial conditions for the hydrothermal variables required to start the simulation of the transient were evaluated in advance through preliminary calculations with no mass flow at the inlet and only air inside the container.

The TOSQAN ISP-47 experiment consists of a series of different steady states obtained by changing the injection conditions in the test vessel [5]. The main stages of interest in measuring (hence for numerical calculation) are four steady states. Three steady states of the air-steam mixture (step A) and one steady state of the air-steam-helium mixture (step B) at two different pressure levels. Each steady state is naturally reached by maintaining a constant steam injection flow rate. A series of experimental steps (Fig. 2) are as follows.

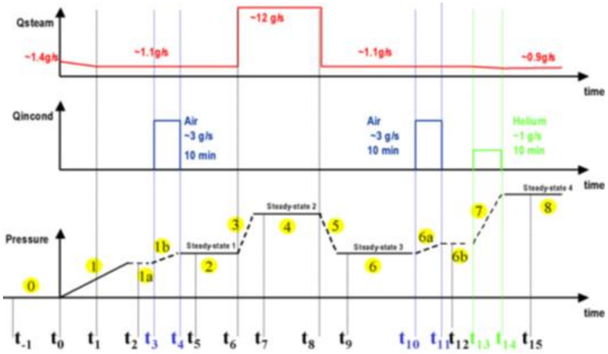


Fig. 2. Experimental procedures in the TOSQAN ISP-47.

2.2 MELCOR modeling of the TOSQAN ISP-47

In this study, TOSQAN ISP-47 experimental analysis using MELCOR 1.8.6 [6] was performed.

The nodalization for MELCOR code analysis is constructed based on the geometric information of the TOSQAN experimental vessel shown in Fig. 3. The basic principle maintains the entire volume, and according to the conditions for subdividing the entire volume according to the characteristics of the one-dimensional lumped parameter code, the thermal-hydraulic diameter, heat transfer area, and volume are calculated for each area and reflected in the CVH (Control Volume Hydraulic) model of the MELCOR code. In Fig. 3, three wall temperature setting areas are divided and the geometric information to be input into the CVH of the MELCOR code is organized and schematized.

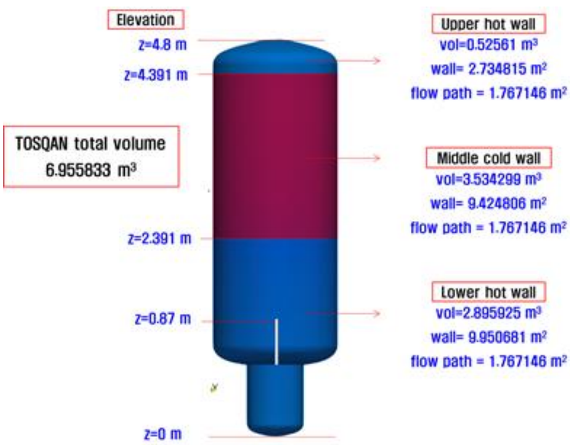
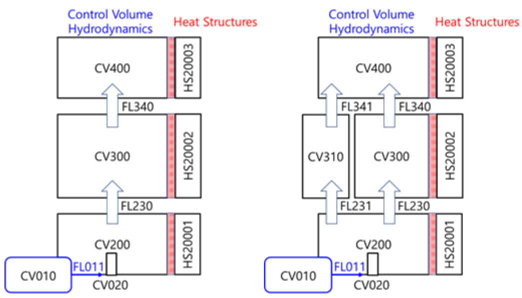


Fig. 3. Geometric information of TOSQAN test vessel used in the CVH of MELCOR input.

In addition, in order to simulate downward flow near the condensation wall and upward flow at the central axis of the container by natural circulation in the middle area of the container, a nodal sensitivity analysis was performed in consideration of the case of nodalizing this part as a two-channel model divided into two. These two nodalization models are compared and shown together in Fig. 4. In the single-channel model in Fig. 4(a), the container part containing the condensation wall is one volume (CV300), but in the dual-channel model in Fig. 4(b), it was divided into two volumes (CV300 and CV310, respectively). The volume ratio of CV300: CV310 was tested from 1:1, and we finally changed this ratio up to 1:3.42, where the main calculation results were shown to be similar.



(a) Single channel model (b) Double channel model

Fig. 4. MELCOR nodalization of the TOSQAN ISP-47.

CV200 is input in the lower hot wall area, and the injection pipe of gas (steam, helium, air, etc.) is modeled as CV020. State values such as the temperature of incoming gases are defined as boundary values over time at CV010. In addition, flow boundary values given from the experiment are input into the flow path of FL011 connecting CV010 and CV020. The inflow of gases over time used in the MELCOR input is shown in Fig. 5.

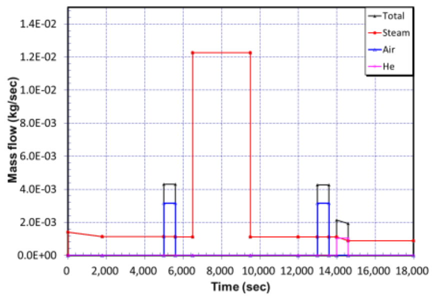


Fig. 5. Inflow of gas boundary conditions used for MELCOR simulation.

2.3 Code simulation results

Figure 6 compares the prediction results of the pressure change of the code according to the single and double channel model (Fig. 4). In the ISP-47 experiment, energy loss of the gas in the adjacent volume occurs in the condensation wall region, so when simulating it with a computerized code, the prediction of pressure change also varies depending on the difference in the heat transfer rate calculation. For single-channel and double-channel models, the pressure rises almost the same until the first pressurization stage of step 1 (~4,000 seconds). In this stage, the effect of condensation is insignificant because high-temperature dry air is present in the container. However, after that, since the heat transfer at the wall is different due to the prediction difference in the internal circulation, the prediction of the pressure change in the internal container of the single and double-channel models begins to differ. In particular, after the decompression step of step 5 (Fig. 2), the single-channel model predicts larger than the experimental results.

In the dual-channel model, the effect of the analysis result according to the volume ratio of CV300: CV310 was also analyzed, which was similar to the result shown in Fig. 6 from the first 1:1 volume ratio to the 1:3.42.

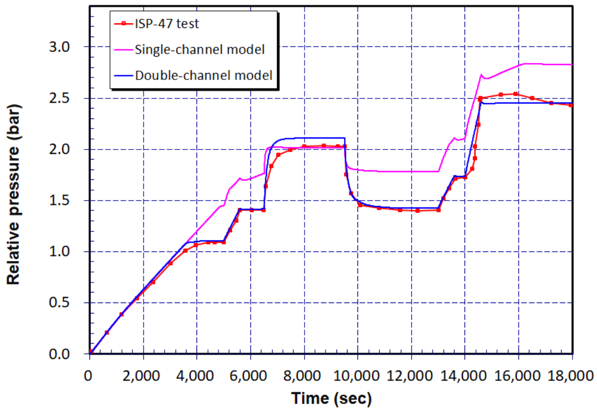


Fig. 6. Comparison of pressure predictions according to the effect of nodalization in condensation wall area.

The natural convective heat transfer on a cylindrical surface used in the MELCOR code is divided into laminar flow and turbulent flow correlation equations according to the number of Ra. In this study, the difference in the predicted value of the pressure trend according to the turbulence correlation was confirmed.

In order to evaluate the effect of the convective heat transfer correlation in the turbulent region, the sensitivity analysis was performed using different values instead of the constant '0.1' value multiplied by the number of Ra. As shown in Fig. 7, the predicted values of pressure change were compared when the values of 0.05, 0.1 (default), 0.15, and 0.2 were used, respectively. As the constant values changed here increase, the heat transfer coefficient value increases, and the pressure prediction value changes significantly, especially in the second steady-state step, which is the fourth step of the experiment. In this stage, as the constant value multiplied by the heat transfer coefficient increases, the pressure prediction value decreases, which is believed to be due to the increase in heat loss at the condensation wall.

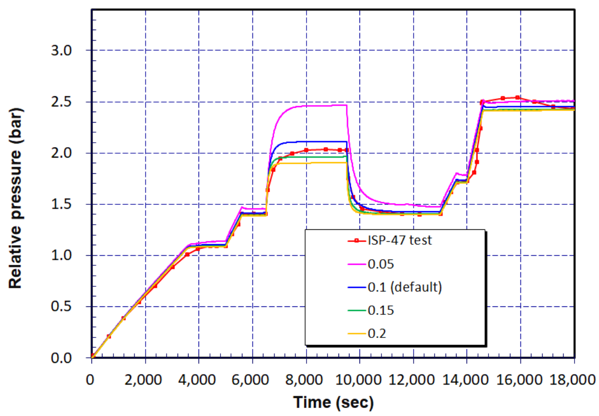


Fig. 7. A comparison of pressure change with the effect of convection heat transfer coefficient in turbulent regions.

The natural convective heat transfer correlation [6] used in the MELCOR code is as follows:

$$Nu_{laminar} = 0.59\,Ra^{1/4} = 0.59\,(Gr\,Pr)^{1/4} \quad Ra < 10^9 \quad (1)$$

$$Nu_{turbulent} = 0.10\,(Gr\,Pr)^{1/3} \qquad Ra > 10^9 \quad (2)$$

where, Ra = Rayleigh number, Gr = Grashof number, Pr = Prandtl number.

The energy of the gas in the adjacent volume (CV300) of the condensation wall is lost by the condensation heat transfer. In Fig. 8, when the convective heat transfer coefficients of Eq. (2) were used at 0.05, 0.1 (default), 0.15, and 0.2, respectively, the gas temperature values in the CV300 volume were compared.

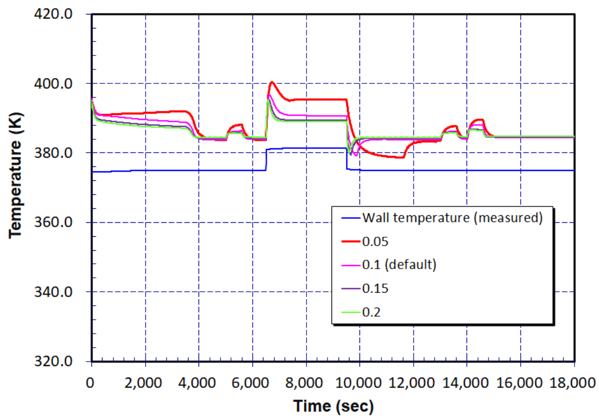


Fig. 8. A comparison of gas temperature change with the effect of convection heat transfer coefficient in turbulent regions.

As the constant value multiplied by the heat transfer coefficient increases in this stage, the gas temperature prediction value of the adjacent volume decreases, which is also believed to be due to the increase in heat loss at the condensation wall

As mentioned earlier, the values of the thermal structure wall temperature (solid blue line in Fig. 8) were given as experimental measurements, and the adjacent gas temperature values were calculated higher than this, confirming heat loss to the outer wall due to condensation heat transfer.

3. Conclusions

The TOSQAN ISP-47 experimental is simulated with MELCOR code and the calculation results are compared with the experimental results. As a result, the total pressure in the TOSQAN vessel predicted by the MELCOR code is relatively well consistent with the experiment result for the case of low steam injection rates (experimental state 1, 3, 4). When the steam injection rate (stage 2) is high, the MELCOR results are shown to be sensitive to changes in some input parameters.

In the basic input model, the nodalization of the vessel consists of three volumes by dividing it into three sections: upper, middle, and lower regions of the vessel. However, in order to simulate the internal circulation flow in the condensation wall of the middle part, this part is divided into two volumes to distinguish the condensation wall area from the central area away from it. The pressure change calculated by the code by changing the node in this way is shown to be in good agreement with the experimental results.

For additional sensitivity analysis, the calculation results are compared by changing the heat transfer coefficient value for the turbulence flow regime. In the second steady-state stage, which is the fourth stage of the experiment, the pressure prediction is significantly affected by the change of heat transfer coefficient value. As the constant coefficient multiplied by the heat transfer coefficient increases, the predicted value of pressure decreases, which is considered to be due to an increase in heat loss in the condensation wall.

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