Numerical Simulation of PHEBUS FPT-3 Experiment by using COMPASS code

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Core degradation phenomena in PHEBUS FPT-3 experiment has been simulated by using COMPASS code, which has been under developing in Korea to simulate severe accident scenario. In the test section of PHEBUS FPT-3 experiment, a fuel assembly consisting of 20 fuel rods and 1 control rod with a height of 1m has been installed within a surrounding in-vessel structure having 2 layers of shroud and pressure tube. Steam has been injected from the bottom of test section with a flow rate of 0.5g/s in a temperature of 165℃. The bundle power has been increased with time step by step in order to simulate the core degradation phenomena. Since the PHEBUS FPT-3 experiment had been served as the International Standard Problem in 2011, the initial and boundary conditions for the simulation has been obtained from the ISP-46 specification. In the PHEBUS FPT-3 experiment, thermocouples have been installed at the various vertical locations on a cladding surface, fuel rods, control rod and in-vessel structures. Most of the measured temperatures have been compared with the numerical simulation results, except the failed thermocouples. The cladding temperature has shown a steep temperature increase by the Zircaloy-steam oxidation about 10,000sec. In a COMPASS code, in order to simulate steam oxidation process, the Cathcart model has been used for the low temperature region and Baker-Just model for the high temperature region. For the comparison purpose, the numerical simulation by using MELCOR 2.1 has also been performed and the results of COMPASS and MELCOR 2.1 have been compared with the experimental data. Generally, the simulation results of COMPASS and MELCOR 2.1 are shown to have a good agreement with the experimental results. The temperature evolution patterns of numerical simulations are well predicting the thermocouple data, while the shroud temperature of MELCOR 2.1 is shown to have a little higher temperature compared with the experimental data. The hydrogen mass generation rate and the total generated mass of hydrogen are also compared. The oxidation starting time are a little bit earlier for the case of MELCOR 2.1 simulation, while the total generated mass of hydrogen are shown to have a good agreement between the numerical simulation and the experimental data. The final mass distributions by the mass relocation are also compared. COMPASS results are showing a smaller mass relocation compared with the experimental data, while MELCOR 2.1 are showing a higher mass relocation due to the earlier debris bed formation. In this stage, the numerical simulation has been performed only for the degradation phase of PHEBUS FPT-3 experiment, the analysis for the aerosol phase showing a fission product behavior are remained as the future works.

I. INTRODUCTION

Recently, the necessity for the development of a domestic severe accident analysis code system has been discussed with the Korean industry even before the Fukushima accident, to support the anticipated NPP export in late 2010s. Consequently, a new project named “Development of Severe Accident Analysis Code and Methodology,” started in 2011 with a 6-year development plan. The main goal of this project is to design an integrated severe accident analysis code, named as CINEMA (Code for INtegrated severe accidEnt Management and Analysis), which would simulate the overall severe accident phenomena in NPP. Hence, CINEMA code are containing the in-vessel and ex-vessel models of severe accident phenomena and also involves the modeling of fission product behavior and of severe accident progression in the reactor spent fuel pool. Four organizations are currently involved in the project including KAERI (Korea Atomic Energy Research Institute), which are responsible to develop the in-vessel models of severe accident phenomena. Hence, KAERI has been developing the stand-alone severe accident analysis code, COMPASS (COre Meltdown Progression Accident Simulation Software), which simulate the in-vessel severe accident phenomena including the core heat up, material melting and relocation, corium behavior in lower plenum, vessel failure.

COMPASS have been developed as a stand-alone simulation tool which can be run for a variety of prescribed ex-vessel boundary conditions. At the same time, to make up the in-vessel module including the primary loop, the core degradation model in COMPASS have been coupled with the SPACE code [4], which is DBA code developed in Korea. And, it will finally build up the integrated severe accident analysis code, CINEMA, through the coupling with the severe accident ex-vessel module.

On the other hand, in the development of simulation code, the verification and validation is an important process to allow the code to have more realistic model and simulation methods. The validation of COMPASS models can also be performed based on both experiments at test facilities and numerical simulations using codes such as MELCOR. Several important international experiments have been made on severe accident research, involving integral experiments, separate-effect tests (CORA [5], COBE [6], COLOSS [7] etc on.). Amongst the integral experiments, a series of PHEBUS experiments have been of major importance, which has been initiated in 1988 by the French “Institut de Radioprotection et de Surete Nucleaire” (IRSN) and the Joint Research Centre of the European Commission [8]. The program consisted of five in-pile test (FPT0, FPT1, FPT2, FPT3 and FPT4), performed with different initial configuration and conditions. Particularly, PHEBUS FPT-3 experiment is important in the Nuclear Power Plants operating in Korea like OP1000, APR1400, since it is adopting the B_4C absorber material instead of Ag-In-Cd (SIC).

The objective of this paper is to assess the core degradation modeling in COMPASS code by simulating the PHEBUS FPT3 experiment. For the comparison purpose, the numerical simulation by using MELCOR 2.1 have also conducted for the FPT3 experiment. Consequently, COMPASS results of PHEBUS FPT3 have been compared with the experimental data and MELCOR results.

II. Numerical Simulation of PHEBUS FPT3 Experiment

II.A. Introduction of PHEBUS FPT3 Experiment

PHEBUS FPT3 experiment has been conducted with the purpose of simulation of severe accident progression. It is the overall experiment including the core degradation, material melting and relocation, fission product generation, transportation and deposition. It is consisted of four phases in main experiment period, which is fuel degradation phase, aerosol phase, washing phase, chemistry phase. Except the fuel degradation phase, which are simulating the core degradation in a reactor pressure vessel, the remaining three phases are dealing with the fission product behavior in a primary circuit. Since this study has been focused to validate the severe accident code, COMPASS for the core degradation progression, the fuel degradation phase in PHEBUS FPT3 has been simulated.

Figure 1 shows the overall schematic diagram for PHEBUS FPT3 experiment. The test section has been inserted into the real PHEBUS core and it is connected to the vertical and horizontal pipes which is modeling a hot leg in RPV and connected to the U-tube which is modeling a steam generator. And it is connected to the horizontal pipe which is modeling a cold leg in RPV and finally connected to the cylindrical tank which is modeling a containment. From the bottom of test section, hot steam of 165 °C is inserted into the test section with a low flow rate of 0.5g/s. The inside of test section is remained at a constant pressure 0.2MPa and the outside of the test section is at a constant pressure of 2.5MPa. Hot water of 165 °C was flowing outside the test section with a high flow rate of 35ton/h, which roles as the heat sink of test section.

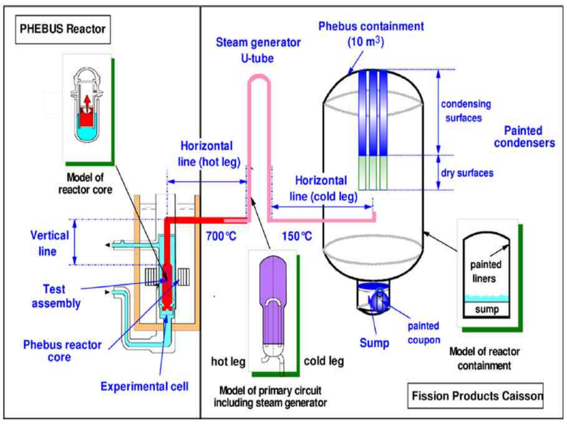


Fig.1 Schematic diagram of PHEBUS FPT3 [9]

Figure 2 shows the cross-sectional view of test section. In the test section, a fuel assembly has been installed, which consist of 18 irradiated fuel rods, 2 fresh fuel rods, 1 control rod and the surrounding shroud tube. Control rod is located at the center of fuel assembly and 20 fuel rods are surrounded by the shroud tube, consist of inner shroud, outer shroud and pressure tube. In a radial direction, these three layers of shroud tube are separated with two vapor gaps.

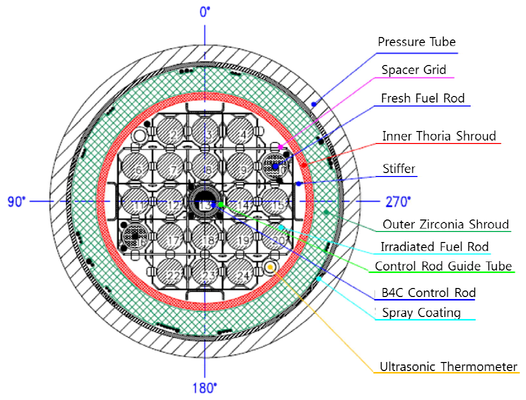


Fig. 2 Cross-sectional view of test bundle [9]

II.B. Numerical Simulation Method

In the fuel degradation phase of a PHEBUS FPT3 experiment, the core power has been increased step by step with time in order to simulate the core degradation phenomena. Figure 3 shows the bundle power history in a test section, showing the increased power pattern to the end of experiment at 17,200 sec. It is noted that COMPASS and MELCOR codes have used the power history data suggested by ISP-46 (International Standard Problem), which is a little bit lower value than the measured value in an experiment. The axial and radial power profiles are also important calculation conditions. In the experiment, the axial power profile has a cosine shape in a vertical direction and, in a radial direction, fuel rods of outer region has higher decay power fraction than that of inner region. In this study, the suggested value of ISP-46 for the axial and radial power profiles has been identically used for the COMPASS and MELCOR calculation, which is not shown in this paper. Figure 4 shows the node system used in the calculation of COMPASS. COMPASS has 27 axial nodes and 2 radial nodes to simulate the test section in the experiment. Among the 27 axial nodes, the 21 nodes correspond to the core region having a fuel assembly.

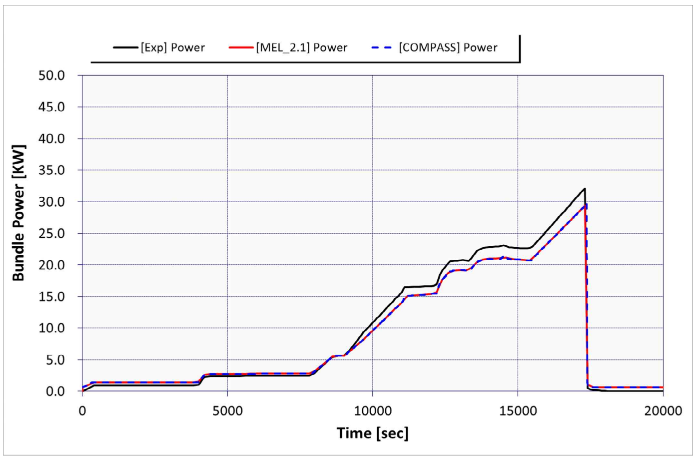


Fig.3 Bundle power history

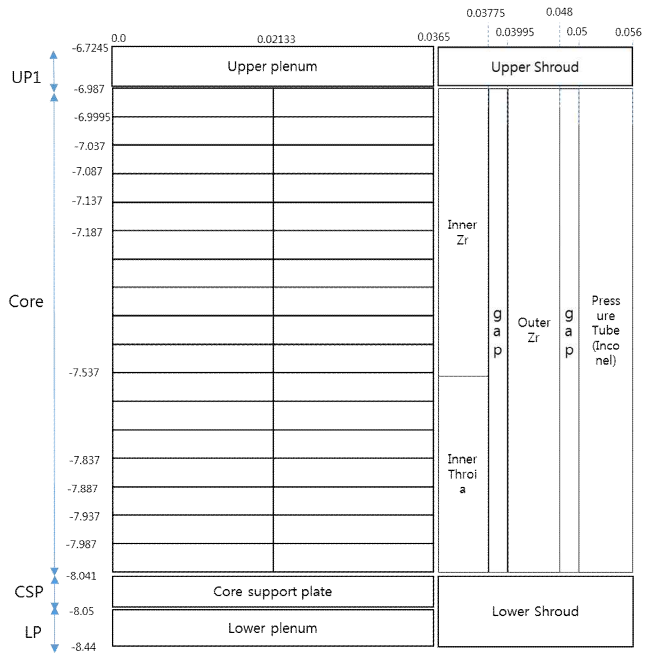
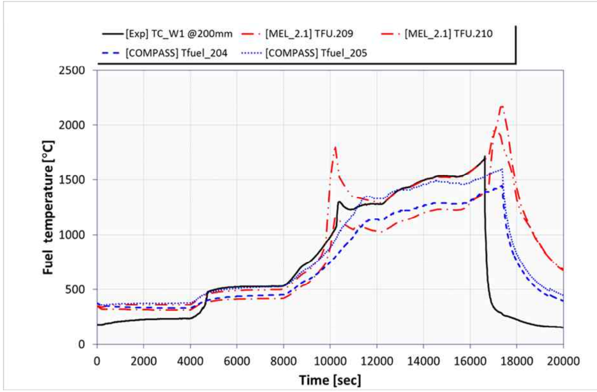


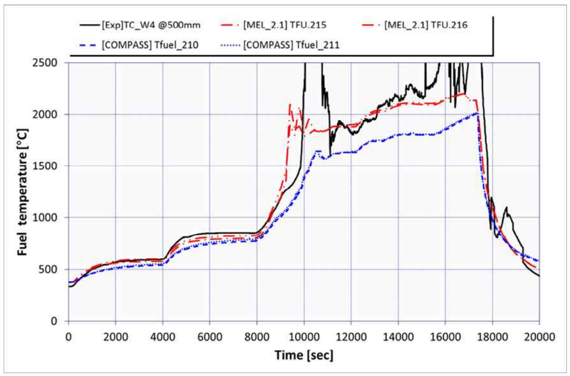
Fig.4 Node system of COMPASS

III. Computational Results and Discussion

In the fuel degradation phase in PHEBUS FPT3 experiment, it is important to analyze the fuel rod heat up, material melting and relocation, hydrogen generation by steam oxidation. Hence, lots of thermocouples are installed in the experiment to analyze the fuel degradation progression. Figure 5 shows the fuel temperature evolutions at the location of 200mm and 500mm from the bottom of fuel bundle. Black solid line denotes the experimental results and 2 red dashed lines are MELCOR results and 2 blue dotted lines are COMPASS results. It is shown from the figure that COMPASS and MELCOR codes are well predicting the overall fuel temperature evolution of the experiment. Although, for the case of 200mm location, MELCOR and COMPASS results are showing a little bit higher value than experimental data during the early time interval (~ 5,000sec), the numerical results for the case of 500mm location is well accord with the experimental data during the time interval. It is noted that, for the case of 500mm location, the thermocouple in the experiment is guessed to be failed after oxidational reaction around 10,000 because it shows an unreasonable high temperature and large temperature fluctuation. The figure also shows that the fuel temperature rapidly increase by the oxidation reaction around 10,000 for the both of experiment and numerical simulation, although COMPASS are showing a smoother temperature increase compared to the experimental data. COMPASS have used the hybrid oxidation model (Cathcart model below 1150K and Baker-Just model above 1150K) for steam-Zircaloy oxidational reaction, and the B4C oxidation model has not been installed in the code, yet.

For the case of 500mm location, the fuel temperature of numerical simulation drops having the same pattern with the experimental data around 17,000sec, although the fuel temperature in the experiment drops earlier than the numerical results for the case of 200mm location.



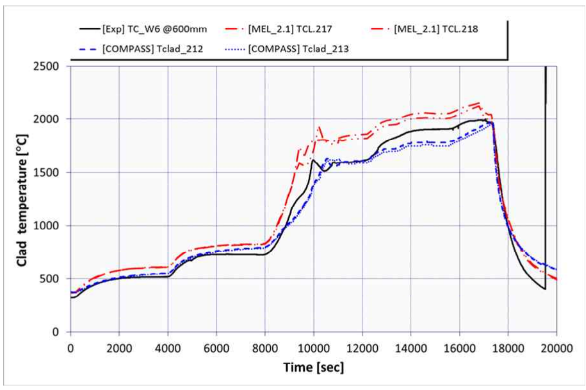


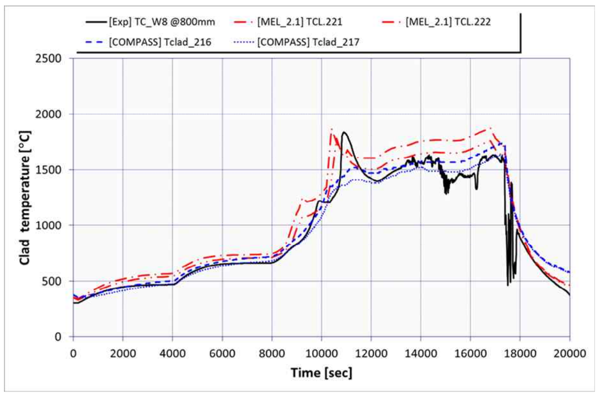
(a) At 200mm from core bottom (b) At 500mm from core bottom

Fig. 5 Fuel temperature evolution

Figure 6 shows the cladding temperature evolution at the 600mm and 800mm locations from the bottom of fuel bundle. The clad temperature is shown to increase having the similar pattern with the fuel temperature. For the case of 600mm location, MELCOR results are showing the earlier temperature increase by the oxidation reaction compared with the experiment and shows a little bit higher temperature after the oxidational reaction, while MELCOR shows a good agreement with the experimental data for the case of 800mm location. On the other hand, the figure shows that COMPASS are well predicting the cladding temperature of the experimental data for the both of 600mm and 800mm locations.

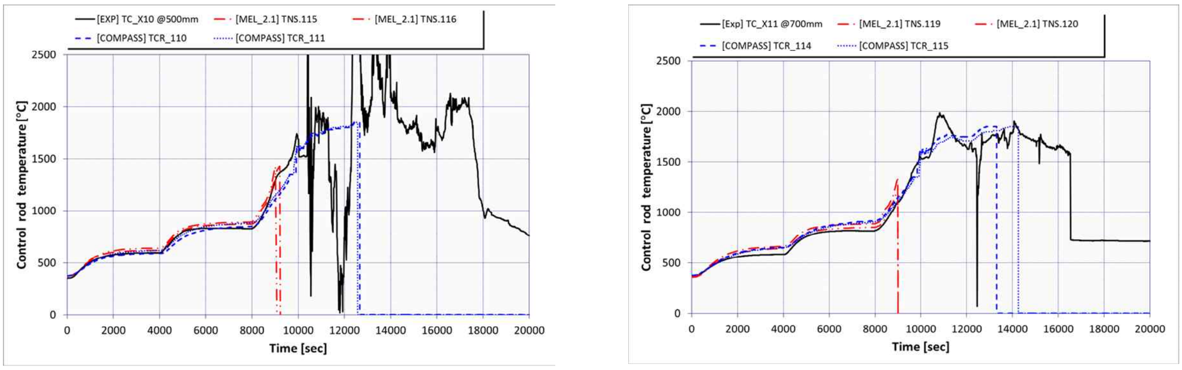
Figure 7 shows the control rod temperature evolution at the 500mm and 700mm locations from the bottom of fuel bundle. In the PHEBUS FPT3 experiment, differently with FPT0, FPT1 and FPT2, the control rod is consisted of B_4C and Inconel. Since the thermocouples are installed on the control rod guide tube, which is made of Inconel having a low melting temperature, the thermocouple is shown to experience earlier failure rather than the other thermocouples. After the oxidational reaction around 10,000sec, the thermocouples are guessed to experience a failure. It is shown from the figure that COMPASS and MELCOR codes are well predicting the control rod temperature in the experiment. For the numerical simulation of COMPASS and MELCOR, the melting temperature of material is given by the user input with the consideration of the eutectic material formation. Since, for the case of control rod guide tube, MELCOR have used 1450 °C for the eutectic material of B_4C and Inconel, while COMPASS used 1670 °C, the material melting time is shown to be different between COMPASS and MELCOR. However, before the material melting occurs, the temperature evolution pattern is very good agreement among COMPASS, MELCOR and experimental data.





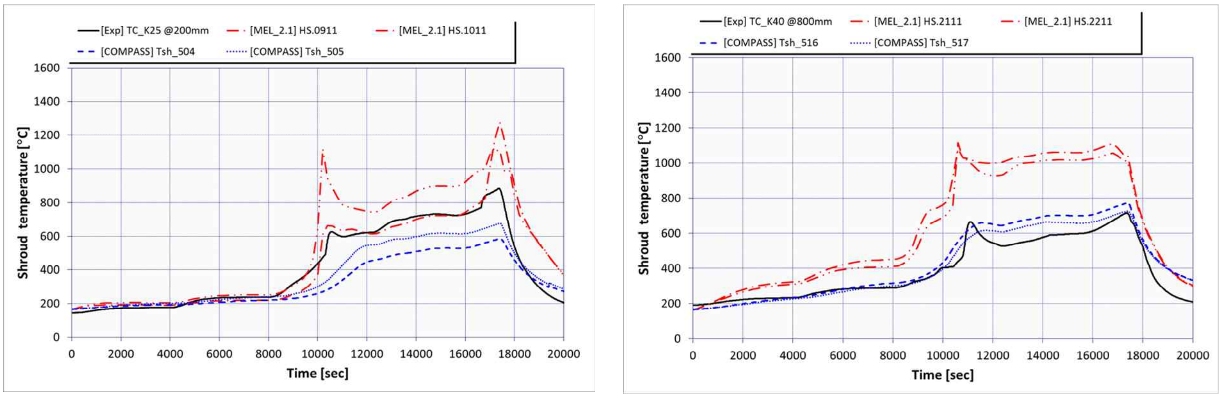
(b) At 600mm from core bottom (b) At 800mm from core bottom

Fig. 6 Clad temperature evolution



(a) At 500mm from core bottom (b) At 700mm from core bottom

Fig. 7 Control rod temperature evolution



(a) At 200mm from core bottom (b) At 800mm from core bottom

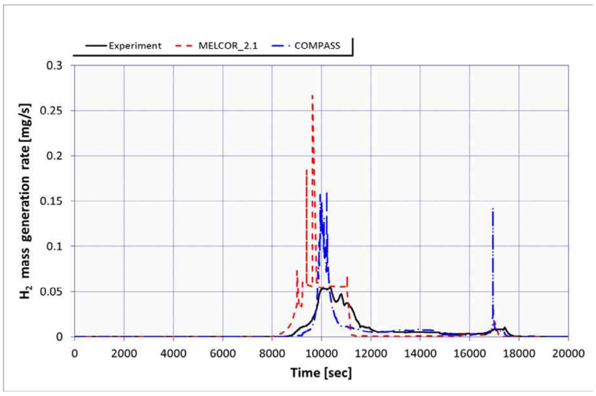
Fig. 8 Shroud temperature evolution

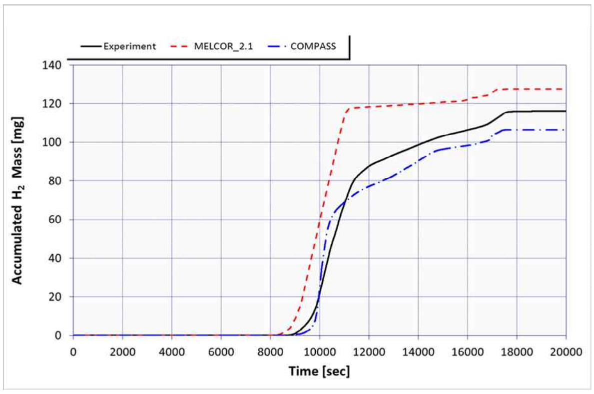
Figure 8 shows the shroud temperature evolution at 200mm and 800mm from the bottom of fuel bundle. Similarly with the fuel temperature, MELCOR shows the steep temperature increase around 10,000sec by the exothermic oxidation for the case of 200mm location and it has slightly higher temperature rather than experimental data. While, COMPASS shows mild temperature increase around 10,000sec and it has slightly lower temperature compared with the experimental data. For the case of 800mm location, while COMPASS are nearly good agreement with the experimental data, MELCOR are predicting the notable higher value for the shroud temperature.

The hydrogen generation by oxidation reaction is the one of important phenomena in severe accident analyses. Figure 9 shows the calculated results and the experimental data for the hydrogen generation rate and the accumulated hydrogen mass. It is shown from the figure that COMPASS and MELCOR are well predicting the hydrogen generation rate in the experiment, although MELCOR are showing that oxidation reaction is started at a slightly earlier time. The accumulated hydrogen mass calculated COMPASS is slightly lower than the experimental data, while MELCOR are predicting a little bit higher hydrogen mass compared with the experimental data. However, the increasing slope of accumulated hydrogen mass as well as the final accumulated hydrogen mass still shows a good agreement between the numerical results and experimental data.

The total mass distribution and melting mass migration are important variables in the core degradation process. Figure 10 shows the mass distribution along the vertical location of fuel bundle for the initial and the final state of experiment. Solid lines denote the mass distribution at the final state and dotted lines are the initial mass distribution of experiment and numerical simulation. The black line is experimental data and blue line is COMPASS results and red line is MELCOR results. It is shown from the figure that the mass in the upper region has been relocated to the lower region of test section. While COMPASS are showing a little bit smaller mass relocation, MELCOR shows a notable larger mass relocation compared with the experimental data. In the PHEBUS experiment, since the inlet steam flow from the bottom of test section is very small, the debris bed is difficult to be formed in this experiment, compared with the high flow rate condition having a stronger shattering and turbulence. Hence, in the COMPASS simulation of PHEBUS experiment, the material relocation by a slumping (which simulate the debris bed formation) is set to have a limited value and the most of material relocation is done by material melting mechanism. However, the solid material melting temperature is necessary to have sensitivity study, because the relocated mass in COMPASS simulation is smaller than the experimental data.

While, in the MELCOR simulation, the debris bed formation has been set to occur below the minimum metallic Zircaloy thickness, which results a lot of solid material to be relocated to the lower region in a form of debris bed, which is also showing the necessity for have a sensitivity study for the condition of the debris bed formation.





(a) Hydrogen mass flow rate (b) Accumulated hydrogen mass

Fig. 9 Hydrogen mass flow rate and accumulated hydrogen mass

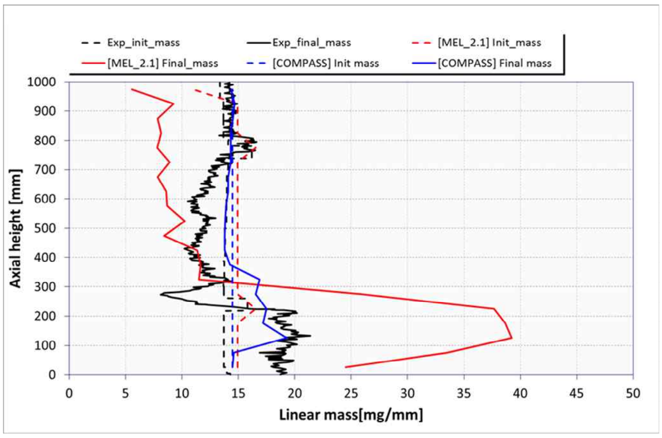


Fig. 10 Initial and final mass distribution

IV. Conclusion

For the purpose of COMPASS code validation, the numerical simulation for PHEBUS FPT3 experiment has been conducted. The temperature of the main component has been secured by using COMPASS code for a fuel, cladding, control rod and surrounding structure. And they are compared with that of experimental data as well as MELCOR simulation results. Although the MELCOR simulation results are showing a little bit difference with the experimental data, especially for the shroud temperature, it can be concluded that COMPASS and MELCOR codes are well predicting the experimental data.

MELCOR are showing that an oxidational reaction starts a little bit earlier time and has the slightly higher value of the accumulated hydrogen mass, while COMPASS code predicts the slightly lower value of the accumulated hydrogen mass. COMPASS are predicting a little bit smaller mass relocation compared with the experimental data, while MELCOR has much larger mass relocation. In the future, the sensitivity study is necessary for the condition of debris bed formation as well as the material melting temperature considering the eutectic material.

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