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Benchmarking of PHEBUS FPT0 experiment by using CINEMA and MELCOR code

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1. Introduction

Code for INtegrated severe accident Management and Analysis (CINEMA) has been under development in Republic of Korea to establish an independent capability in analyzing the postulated severe accident phenomena in light water reactors (LWRs). The CINEMA code is structured with several stand-alone modules, such as CSPACE, SACAP, and SIRIUS, which can simulate not only both in and ex-vessel phenomena but also behavior of fission product (FP) [1, 2].

It is of noteworthy to describe the function of each module in the CINEMA. First, CSPACE module is an integrated module embracing the COMPASS and SPACE-SAM codes. Each code analyzes the core degradation and thermal-hydraulic behavior of a system, respectively. SACAP module calculates severe accident phenomena and corresponding thermal-hydraulic behaviors in the containment building. To assess the coolability of corium after failure of reactor pressure vessel (RPV), a model for fuel-coolant interaction and steam explosion are included. Finally, SIRIUS module calculates overall behavior of released fission products from the reactor core. Through the physical coupling of the aforementioned module, therefore, the complex progress of severe accident can be analyzed in detail through the CINEMA code.

To improve the models in the newly developed code, various verification and validation studies are underway. Particularly, meaningful validation studies have been conducted with the COMPASS module to accurately simulate the core degradation process [3]. This study also focuses on the improvement of the COMPASS module as a part of the validation.

In this study, PHEBUS Fission Product Test (FPT) conducted by CEA/IPSN and JRC was selected for the target experiment [4]. The purpose of FPT experiment was to analyze the progress of core degradation and corresponding FP behavior in the reactor circuit and containment building. In the experiment, the process of core degradation was analyzed in detail by measuring the temperature change of each component in the reactor core. These experimental results were reasonable in evaluating the degradation model in COMPASS module.

Specifically, the core degradation behavior of FPT0 was simulated by using the CINEMA code in the current study. For validation, the experimental data of the temperature history and hydrogen generation were compared with the CINEMA code results. Additionally, the MELCOR code simulation results were also performed and compared for more to figure out the code to code characteristics.

2. Methodology

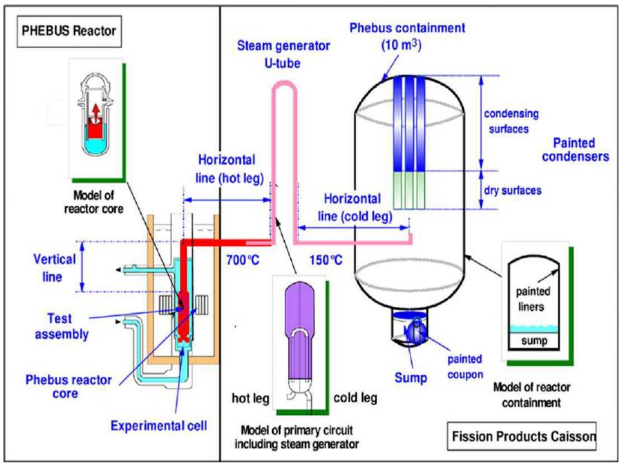

Fig 1. Schematic of PHEBUS FPT experiment [3, 5]

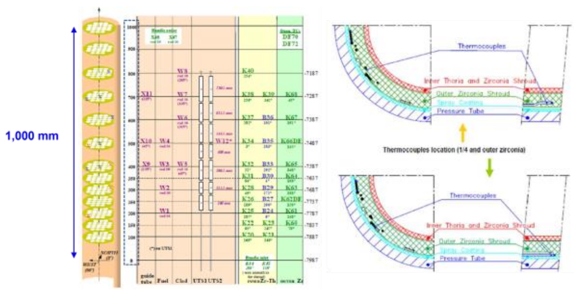

Fig 2. Location of thermocouples in the experiment [3, 5]

Figure 1 shows the schematic of PHEBUS FPT [3, 5]. Overall degradation process was analyzed based on several thermocouples, which were axially installed in the fuel bundle and shroud region to measure the temperature change of fuel, cladding, and inner/outer shroud as shown in Figure 2 [3]. In addition, the generation rate and total mass of hydrogen during core degradation were analyzed. Five cases of experiment were conducted according to the experimental conditions, among which FPT0 was selected as a reference case.

2.1. FHEBUS FPT0 experiment

4.5% enriched UO_2 fuel irradiated for 9 days up to burn-up of 0.23 GWd/tU was used in the experiment [6]. The cladding material is Ag-In-Cd (80:15:5), and it was surrounded by a Zircaloy guide tube. Figure 3 shows each phase during the transition in the experiment. Steam of 165 ℃ and 2.5 MPa was injected into reactor core through the tube 2,300 s to oxidize the fuel before heat-up for emulating the oxidized fuel in the reactor core of PWR. After oxidation phase, bundle power was gradually increased, such that the fuel temperature started to increase. The cladding was oxidized by existing steam, which accelerated the accident progress so that the core structure melted.

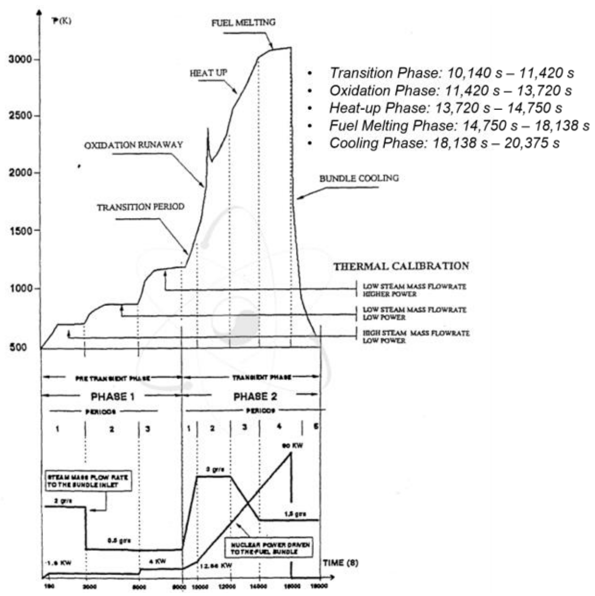

Fig 3. The progress of FPT0 experiment during the transition

2.2. Input modeling by CINEMA and MELCOR for FPT0

Figure 4 shows the nodalization of CINEMA input for FPT0. The input includes core components, U-tube, containment, and a connected line between those. Therefore, released fission products and generated hydrogen during core degradation were finally transferred to the containment compartment. The core region consisted of 25 axial levels and 2 radial rings. The lower plenum, core support plate, 22 active fuel rods, and core outlet were modeled in each radial ring. The length of active fuel region is 1.0 m, and diameters of each radial ring are 0.02133 m and 0.0365 m, respectively. As the same with the number of active fuel rod, shroud region was modeled to be 22 axial nodes.

Likewise, 22 active fuel regions were modeled in core region of MELCOR input as shown in Figure 5. However, two more axial levels were assigned because the lower plenum was divided into two compartments and core inlet compartment was additionally modeled. Based on the experimental condition, power history and steam mass flow rate were modeled in each input as shown in Figure 6 [6].

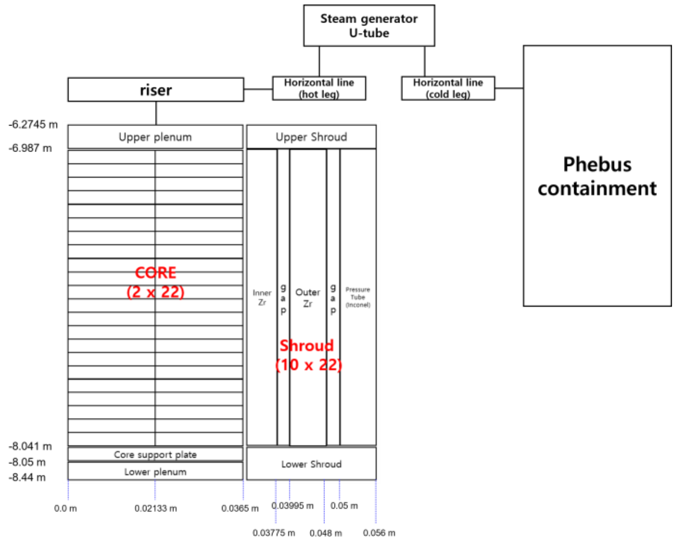

Fig 4. Nodalization of CINEMA input for FPT0 experiment

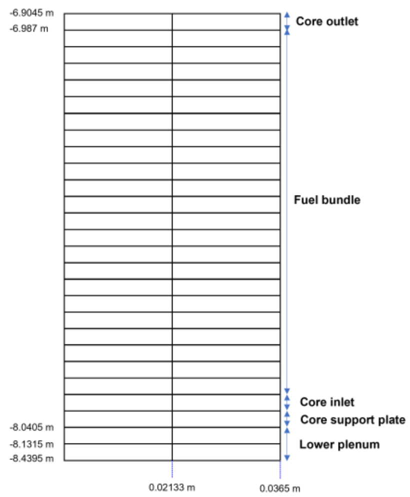

Fig 5. Nodalization of core region of MELCOR input for FPT0 experiment

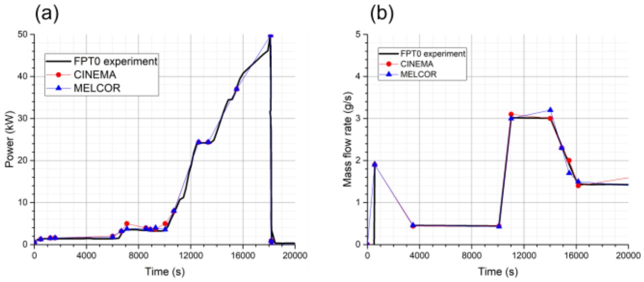

Fig 6. Modeling of (a) bundle power, and (b) mass flow rate of injected steam in CINEMA and MELCOR codes

3. Result and Discussion

Figure 7 shows the comparison of temperature history of inner fuel at 400 mm, 700 mm, 800 mm of both codes with experimental results. The first oxidation phase started at 9,200 s in MELCOR simulation, which was faster than that of experiment (11,800 s). In CINEMA simulation, on the other hand, the oxidation started at 11,000 s, which agrees more to the experimental result. Although oxidation temperature is same, 1,173 K, the reason of different initiation time was presumed to be due to heat transfer mechanism. Compared to MELCOR simulation, in CINEMA simulation, the heat generated in the core was more transferred to the outer region. Therefore, in MELCOR simulation, the fuel temperature rose higher so that oxidation occurred faster.

In this phase, fuel temperature increased up to 2,240 K. However, peak temperature due to oxidation was 1,890 K in CINEMA simulation, which was relatively low. However, MELCOR predicted the peak temperature as 2,390 K, which was higher than CINEMA calculation. In particular, the massive relocation of the degraded fuel occurred at 16,000 s in MELCOR because an UO_2 eutectic model was applied and apparently it captured the more degradation.

Figure 8 shows the temperature history of outer fuel at 400 mm, 600 mm. In Figure 8(a), the outer fuel temperature rapidly decreased at 15,000 s. The reason for this different trend could be because the thermocouple at this location was failed by the relocated corium melting from the upper region in actual experiment [6].

The relatively low peak temperature of the CINEMA calculation in Figures 7 and 8 may be attributed to the influence of oxidation model. Figure 9 shows the generation rate and accumulated mass of hydrogen. When Zircaloy was oxidized, the calculated value of maximum generation rate was 0.1 g/s, whereas it was 0.24 g/s in the experiment. As a result, the accumulated hydrogen mass was 77.4 g, which is only 61.1 % of the experiment. As a result, the temperature in the latter part was predicted lower than that of the experiment. For MELCOR result, on the other hand, although maximum generation rate was 0.06 g/s, a total mass of generated hydrogen is 110 g, which is much higher. This is because oxidation was continuously occurring for a long time, 3,000 s, at a maximum rate. Therefore, it was judged that the temperature trend can be predicted more reasonably if the oxidation model in CINEMA code is further improved.

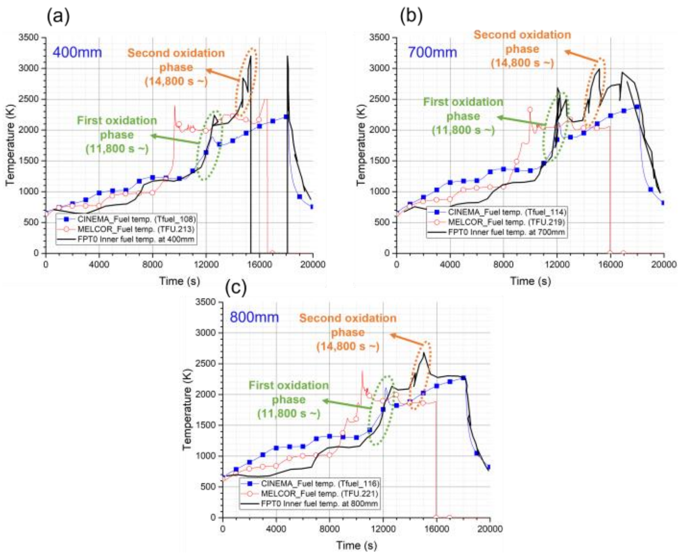

Fig 7. Inner fuel temperature at (a) 400 mm, (b) 700 mm, and (c) 800 mm

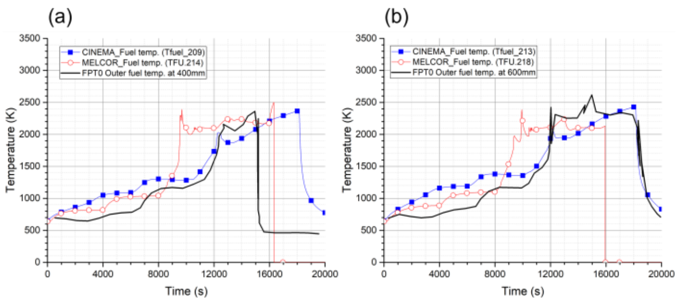

Fig 8. Outer fuel temperature at (a) 400 mm, and (b) 600 mm

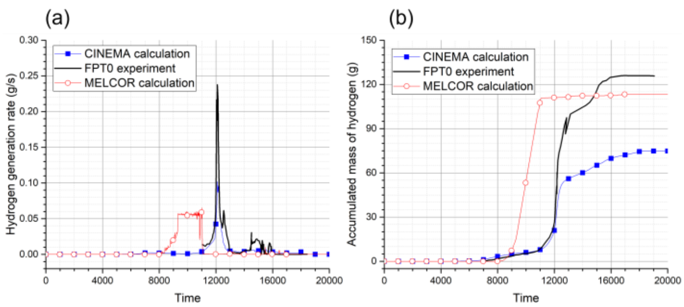

Fig 9. (a) generation rate, and (b) accumulated mass of hydrogen

4. Conclusions

In this study, the validation study for CINEMA code was conducted. Code simulation for PHEBUS FPT0 experiment was performed, which was compared with experimental results and MELCOR simulation results. The temperature history of inner/outer fuel and corresponding hydrogen generation were analyzed, and a required model was proposed for further improvement in core degradation modeling. The major findings and future works in this study can be summarized as follows.

(1) Compared to MELCOR simulation results, overall trend of temperature history predicted by CINEMA code agrees better with that of experiment. In particular, the time of temperature peak due to oxidation was predicted reasonably. Based on these results, it was judged that CINEMA code predicted the process of core degradation more reasonably.

(2) Still, the oxidation model in CINEMA code needs to be improved. When Zircaloy is oxidized, the calculated value of maximum hydrogen generation rate was 0.1 g/s, which is only 41.1 % of the experiment. Corresponding total mass of generated hydrogen was 77.4 g, which is 61.1 % of the experiment, and temperature peak was relatively low. This trend could be due to the core temperature history. The oxidation can be affected by temperature because the reaction can occur actively in high temperature region. Therefore, overall heat transfer mechanism should be analyzed. Generally, because the oxidation and subsequent hydrogen generation were evaluated conservatively in severe accident analysis, it was judged that the improvement process is required. It will be our important future works.

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