High Temperature Fuel Rod Bundle Analysis of QUENCH-06 Experiment Using CINEMA

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1. Introduction

In nuclear power plants, severe accident has been one of the most concerns to maintain the nuclear safety. Therefore, various severe accident analysis codes were developed such as MELCOR and MAAP. The Korean nuclear industry has used above severe accident analysis codes to simulate severe accident. CINEMA (Code for Integrated Severe Accident Evaluation and Management) was developed to avoid using severe accident analysis code developed by a foreign vendor which can be an obstacle to the future Korean nuclear reactor exports.

The primary objective of the CINEMA is to simulate the whole progress of severe accident. As a result, the CINEMA code includes both in-vessel and ex-vessel models for the severe accident scenarios, and also has ability to predict the behavior of fission products. In-vessel phenomena is simulated by CSPACE module, ex-vessel phenomena by SACAP module, fission products behavior is tracked by SIRIUS module, and the modules are integrated by master program to completely analyze total severe accident process. CSPACE was developed from the coupling of the thermal hydraulic analysis code SPACE and the core meltdown analysis code COMPASS especially.

Since severe accidents progress with various complex phenomena, severe accident analysis code should be validated carefully. In this study, CINEMA code is validated with the QUENCH-06 experiment. QUENCH-06 includes overheated fuel cooling with non-condensable gas, fuel cladding oxidation by steam, hydrogen generation, cladding failure and slumping, water injection to the degraded core. QUENCH-06 is modelled with CINEMA and the calculation results were compared to the both experimental results and RELAP/SCDAP code calculation results.

2. Modelling of QUENCH-06 experiment

2.1 QUENCH-06

QUENCH-06 has been chosen as the OECD's ISP-45, used for the validation and evaluation of severe accident analysis models and software. The experimental facilities and test bundles are shown in Fig. 1. and Fig. 2. The bundle is fixed by five grid spacers and has a 5 x 5 structure made up of 21 fuel simulation rods and 4 corner rods. The 20 rods around the core of the bundle are heated by electricity except the unheated central rod. Total length of the rod is approximately 2.5 m, and its heated length is around 1 m. The cladding is a zirconium-4 alloy with an outer diameter of 10.75 mm and a wall thickness of 0.725 mm. Central tungsten heater has an outer diameter of 6 mm. Shroud is consist of a 2.38 mm thick zirconium alloy, a 37 mm thick Ar gas filled ZrO2 fiber insulation layer, and an annular stainless steel cooling jacket. The upper part (1000 mm ~ 1300 mm) of the shroud is only filled with Ar gas without ZrO2 fiber.

For the QUENCH-06 case, system pressure of the test section is around 2 bar. 3 g/sec of argon and 3 g/sec of steam is constantly injected to the bottom of the test section until the quenching phase start. The electrical power over rod bundle gradually increase from 4 kW to 10.5 kW during the first stage of the experiment. The stage is called heat-up phase and last until 1965 sec. After the heat-up phase, steady pre-oxidation phase last until 6011 sec. During the phase, fuel and cladding temperature is maintained almost constantly with 11 kW of electrical power input. Transient phase, which accompany with increase of the electric power up to 18 kW, comes next. After the transient phase, water injection starts at around 7180 sec to cool down the test section.

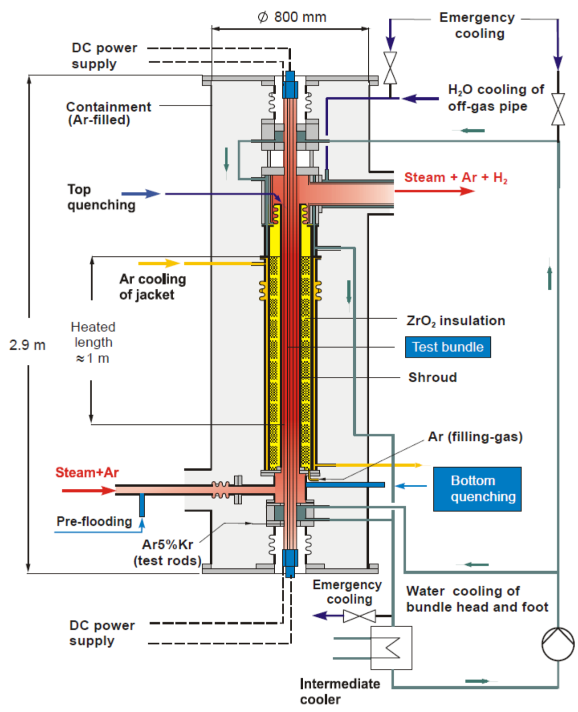

Fig. 1. QUENCH test section

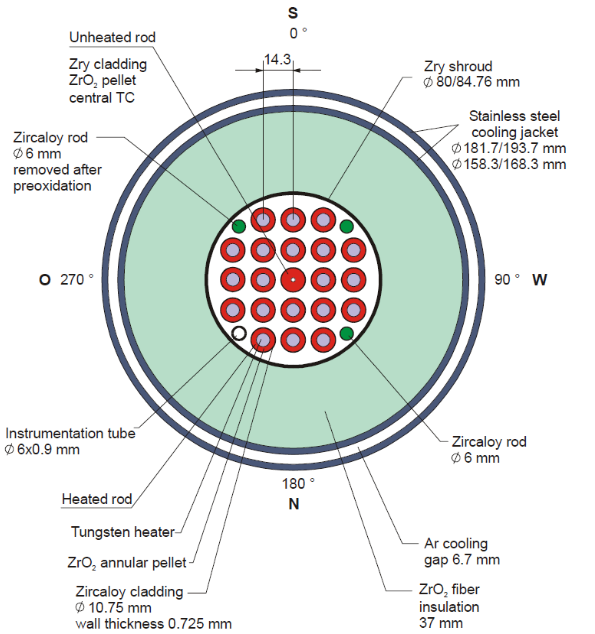

Fig. 2. Cross-sectional view of the QUENCH rod bundle

2.2 CINEMA Input Model

Fig. 3. Shows the CINEMA code nodalization for the QUENCH-06 simulation. SAM-225 is a lower plenum that receives argon, steam and quench water injection with the length of 0.175 m. SAM-226 is for the 0.2 m height upper plenum which receives top side argon injection from C104 and connected to the outlet C108. Boundary conditions were allocated on C101, C103, and C105 which correspond to steam, argon, water injection respectively.

Heated section was described by SAM nodes which are designed for the coupling of COMPASS and SPACE-SAM. SAM-181 to 196 were assigned for the 8 inner heated rods and 203 to 218 were for the 12 outer rods. The nodes have 0.1 m length each which means the total height of simulated rod bundle is 1.6 m (-0.3 m to 1.3 m).

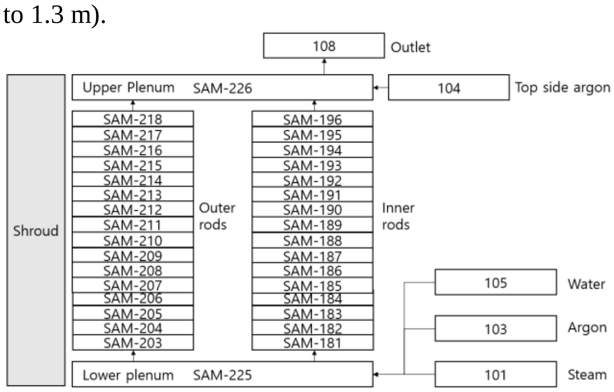

Fig. 3. Nodalization of QUENCH-06 test section with CINEMA

3. CINEMA Results and Discussion

Main concerns of the QUENCH-06 is temperature profile through the test section and hydrogen production due to the cladding oxidation. Fig. 4 shows the cladding temperature of outer rods and shroud temperature at the 350 mm height. CINEMA resulted in higher temperature compared to the experimental results but this is similar tendency to the RELAP5/SCDAP results on Fig. 5. They pointed out that the reason of over-estimation at lower parts is oriented from lack of the knowledge of filled argon gas behavior in ZrO2 fiber which leads to the bigger heat transfer coefficient compared to actual material property.

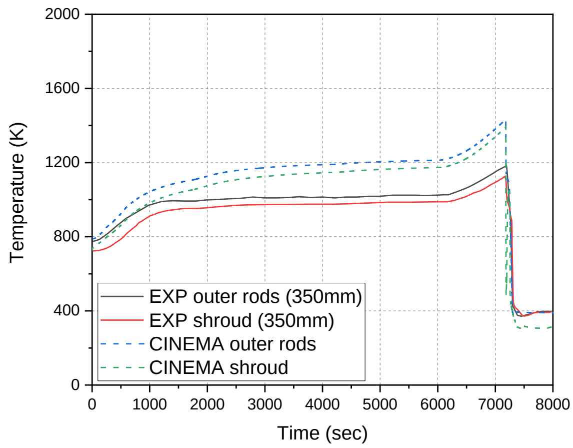

Fig. 4. Bundle temperatures at 350 mm (Experiment and CINEMA code results)

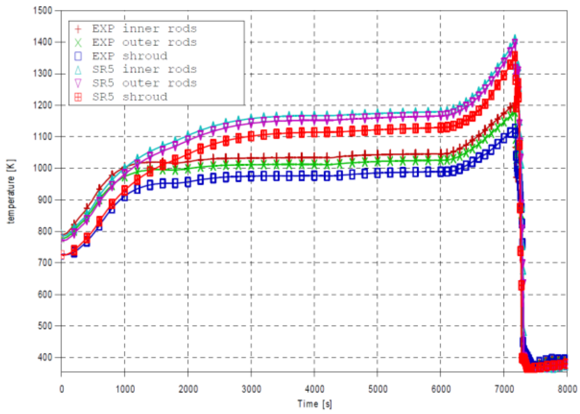

Fig. 5. Bundle temperatures at 350 mm from RELAP5/SCDAP results

Fig. 6 and Fig. 7 shows the bundle temperature at the 750 mm and 950 mm height respectively. CINEMA expected the almost identical peak cladding temperature at 750 mm height as shown in Fig. 6. However, second peak temperature right after the quench water injection did not estimated well by CINEMA because CINEMA does not have model to consider the effect of shattering which leads to the second peak of the cladding temperature. During the reflood of degraded fuel cladding, brittle cladding is shattered by the thermal shock and thus, exposed fresh metal oxidize immediately releasing a lot of heat.

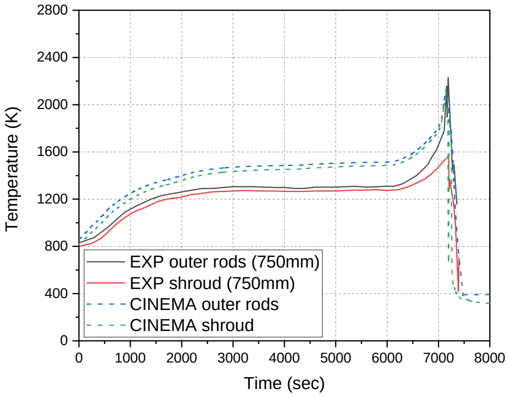

Fig. 6. Bundle temperatures at 750 mm (Experiment and CINEMA code results)

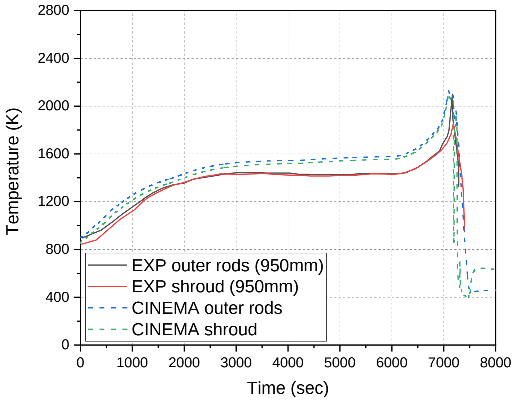

Fig. 7. Bundle temperatures at 950 mm (Experiment and CINEMA code results)

Accurate estimation of hydrogen generation stem from the cladding oxidation is a trait which severe accident analysis code should attain. Therefore, the prediction performance over hydrogen generation of CINEMA code was validated against QUENCH-06. As shown on Fig. 8, CINEMA over estimating the hydrogen generation through the oxidation phase and transient phase. CINEMA is using Cathcart model for 1173K to 1850K and Baker-Just model for the cladding temperature over 1850K. SCDAP/RELAP is using Cathcart model for 1239K to 1853K and Urbanic and Heidrick model for the cladding temperature over 1853K. The cause of the overestimation is the inability of CINEMA to reflect high heat transfer coefficient at the upper part of the shroud. During the experiment, high shroud temperature over 1000K leads to the argon circulation within the shroud and transfer huge amount heat from the subchannel to the outer cooling jacket. This suppress the bundle temperature rises over 1000 mm height and as a consequence, hydrogen generation is suppressed on the region. However, CINEMA is not capable of describe the phenomena. Although the heat generation at upper part is reduced to consider the shroud heat transfer enhancement, this was not enough to maintain upper region bundle temperature as an experimental level.

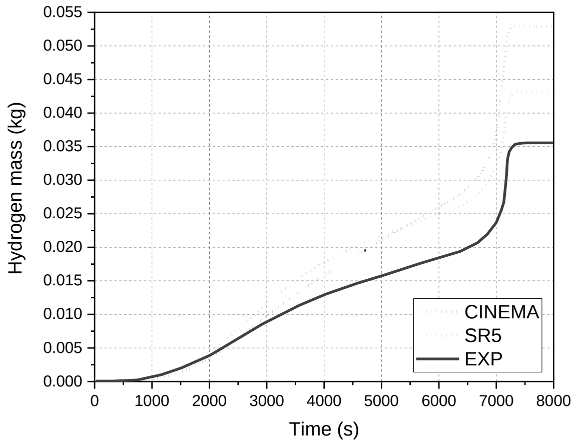

Fig. 8. Total hydrogen mass produced during the QUENCH-06

4. Conclusions

CINEMA code is validated by the QUENCH-06 experiment to verify calculation capability over high temperature rod bundle. The calculation results had good agreement with the experiment overall which indicates the CINEMA code is capable of analyzing the rod behavior during the core degradation and reflood phase. Although CINEMA is slightly overestimating the bundle temperatures in the lower part of the test section, same amount of overestimation was observed in RELAP5/SCDAP calculation due to the underestimation of the thermal conductivity of argon-filled ZrO2 fiber. Also, CINEMA's oxidation model, which is the combination of Cathcart-Pawel model and Baker-Just model, leads to the accurate prediction of the peak temperature throughout the test section. Hydrogen generation rate is overestimated in CINEMA simulation but the overestimation caused by higher bundle temperature at the upper part of the shroud. In the experiment, upper bundle temperature is suppressed by high heat loss rate across the upper shroud. With the appropriate consideration of upper shroud heat transfer rate and shattering effect during the quench water injection, hydrogen generation rate will be accurately estimated by CINEMA. In conclusion, CINEMA well predicts high temperature rod bundle behavior and proved the capability of analyzing the fuel rod degradation and reflood phenomena.

5. Acknowledgments

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