Validation of OPERA3D PCMI Analysis Code

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1. Introduction

Nuclear power plant consists of many complicated systems, and one of the important objects of all the systems is maintaining nuclear fuel integrity. However, it is inevitable to experience PCMI (Pellet Cladding Mechanical Interaction) phenomena at current operating reactors and next generation reactors for advanced safety and economics as well. To evaluate PCMI behavior, many studies are on-going to develop 3-dimentional fuel performance evaluation codes [1, 2]. Moreover, these codes are essential to set the safety limits for the best estimated PCMI phenomena aimed for high burnup fuel. This report will describe introduction of validation of OPERA3D code, and validation results that are directly related with PCMI phenomena.

2. Development of OPERA3D Code

OPERA3D (Optimized PCI Evaluation and Load-following using 3-Dimensional FEM) is a 3-dimensional Pressurized Water Reactor (PWR) fuel rod performance analysis code for normal operation and Anticipated Operational Occurrences (AOO). This code has been developed under collaboration between KEPCO Nuclear Fuel (KNF) and Candu Energy Inc. [3]. The calculation flow of OPERA3D is illustrated in Figure 1.

OPERA3D performs various calculations for the PWR fuel behavior parameters. The fuel behavior includes temperature, gap conductance at the interface between pellet and cladding, fission gas release, rod internal pressure, pellet microstructural changes, pellet deformation (swelling, densification, elastic and creep), pellet cracking and healing, cladding oxidation and hydriding, and cladding stress and strain.

In the finite element model, one fuel rod is divided into several segments in the axial direction. Although one axial segment contains one pellet or more, all pellets in the same segment are considered to have the same geometry and the same thermal mechanical properties. Therefore, one pellet per segment is analyzed in the OPERA3D code with 3D thermal-mechanical models.

3. OPERA3D code Validation

Validation activities were defined with validation plan and all the validation experiment cases were defined to validate each key output parameters which have close relationship with governing phenomena of the fuel rod. The key output parameters are fuel centerline temperature, fission gas release, internal gas pressure, void volume in the fuel rod, clad strain, water side oxidation thickness. Moreover, all the validation cases were designed to validate various operating condition and design geometry of fuel rod [3]. Among these key output parameters, fuel centerline temperature and clad strain are directly related with PCMI phenomena.

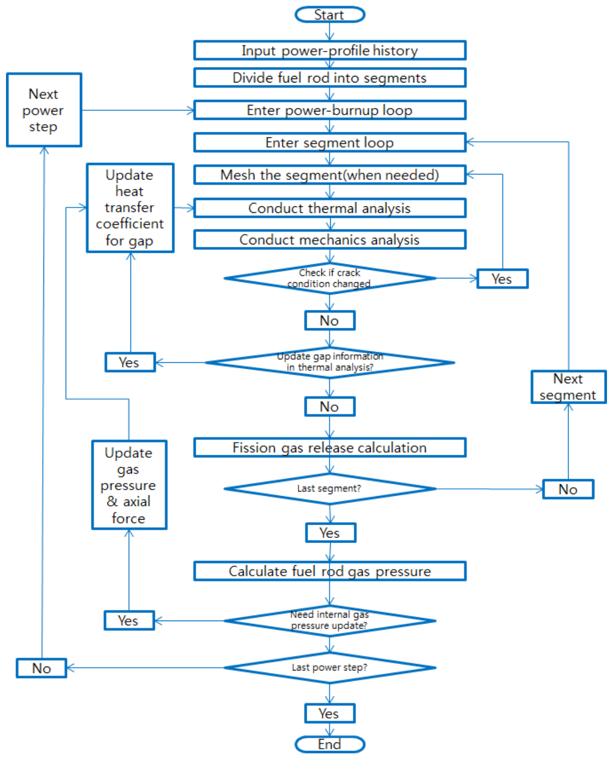

Fig. 1 Calculation flow of OPERA3D

The fuel temperature calculation result for the IFA562 Rod 16 measurement data [4] is shown in Figure 2. The overall profile between measurement and prediction shows very similar result. The average bias, the standard error of the relative bias, and the relative standard deviation are -7%, 0.3%, and 4%, respectively.

Also, the fuel temperature calculation result for the IFA562 Rod 18 measurement data [4] is shown in Figure 3. The differences between rod 16 and 18 are pellet and clad roughness, and initial filling gas (xenon and helium). The overall profile between measurement and prediction shows very similar result with measurement. The average bias, the standard error of the relative bias, and the relative standard deviation are -5%, 0.4%, and 5%, respectively.

In addition, it is shown in Figure 4 that the OPERA3D fuel clad strain validation result is in good agreement with the measured clad outer diameter of a fuel rod irradiated for three cycles in a commercial PWR plant. Since, OPERA3D prediction has only 7 axial nodes to reduce calculation time, the predicted clad outer diameter profile shows much smoother than measurement data. However, the overall profile between measurement and prediction shows similar result. Including this data, the averaged residual error, standard error, and the standard deviation at the middle part of fuel rod are 0.01766 mm, 0.1589 mm, and 0.027 mm, respectively.

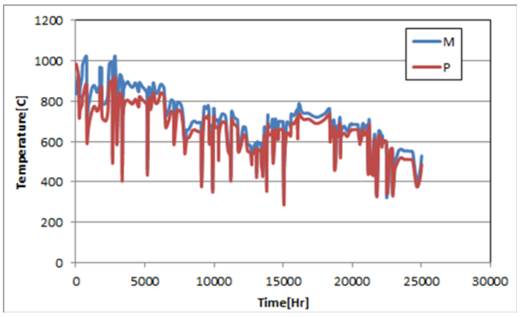

Fig. 2. Comparison between centerline temperature of IFA 562 rod 16 measurement and OPERA3D prediction during power ramp

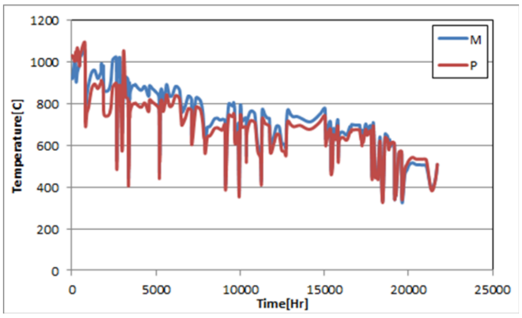

Fig. 3. Comparison between centerline temperature of IFA562 rod 18 measurement and OPERA3D prediction during power ramp

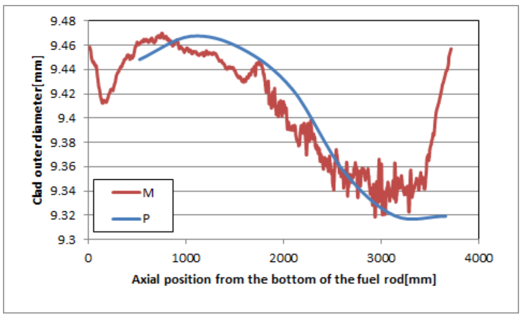

Fig. 4 Comparison between clad outer diameter measurement and OPERA3D prediction

Figure 5 shows 3D profile on fuel rod element displacement result of commercial plant case calculation at the middle of the axial nodes. Contact between pellet and clad is found with contact pressure. Friction was considered with 0.5 of friction coefficient. However, the amount of contact pressure is not enough to cause hazardous PCMI phenomena on the inside of clad surface. Moreover, it shows slight deformation but slight hourglass shaping of fuel pellet can be seen with OPERA3D FEM nodalization model as shown in Figure 5.

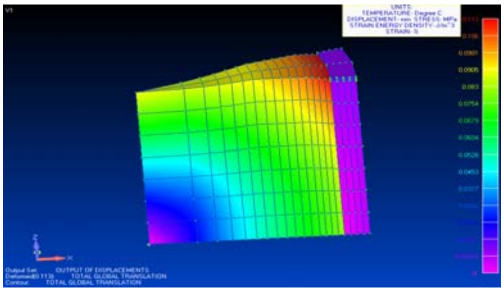

Fig. 5 3D profile on fuel rod element displacement result of calculation at the middle of the axial node

4. Conclusion

OPERA3D was developed for the PCMI analysis and validated using the in-pile measurement data. Fuel centerline temperature and clad strain calculation results shows close expectations with measurement data. Moreover, 3D FEM fuel model of OPERA3D shows slight hourglassing behavior of fuel pellet in contact case. Further optimization will be conducted for future application of OPERA3D code.

5. Acknowledgement

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REFERENCES

[1] M. Suzuki, H. Uetsuka and H. Saitou, Analysis of mechanical load on cladding induced by fuel swelling during power ramp in high burn-up rod by fuel performance code FEMAXI-6, Nuclear engineering and design, Vol. 229, No. 1, pp. 1-14, 2004.

[2] G. Thouvenin, J. M. Ricaud, B. Michel, D. Plancq and P. Thevenin, ALCYONE: the PLEIADES fuel performance code dedicated to multidimensional PWR studies, Top_Fuel 2006 International meeting on LWR fuel performance, pp. 38-42, 2006.

[3] H. T. Han, J.M. Choi, C.D. Jung, J. S. Yoo, “Development of fuel performance analysis code in KEPCO NF”, 18th PBNC conference, 2012 March.

[4] OECD Halden reactor project group, “Final report on the in-pile results from the pellet roughness test in RIG IFA-562”, HWR-245, 1989 November.