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Development of mechanical analysis module for simulation of SFR fuel rod behavior using finite element method

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1. Introduction

A Sodium cooled Fast Reactor (SFR) is a promising option to solve the spent fuel problems and, many efforts have been performed to develop the safe reactor and fuel. However, there are still many technical issues to commercialize a SFR. It is significant that one of issues is development of safe and economical SFR fuel because integrity of nuclear fuel is directly related with reactor's safety and economy. Since, Korean SFR developer decided to adapt metal fuel, current study focused on the metal fuel instead of oxide fuel.

The SFR metal fuel has been developed by Korea Atomic Energy Research Institute (KAERI) and many efforts focused on designing and manufacturing the metal fuel. Since a nuclear fuel is the first barrier to protect radioactive isotope release, the fuel's integrity must be secured during steady-state operation and accident condition within an acceptable range.

Whereas the design and evaluation methodologies, code systems and test procedures of a light water reactor fuel are sufficiently established, those of the SFR fuel needs more technical advances. In the view of regulatory point, there are still many challenging issues which are required to secure the safety of fuel and reactors. For this reason, the Korea Institute of Nuclear Safety (KINS) has launched the new project to develop the regulatory technology for SFR system including a fuel area.

The final goal of new project is the development of audit fuel performance code for SFR to support licensing issues. As the beginning step of audit code system development, widely known code systems for SFR fuel were reviewed [1]. The first reference code, LIFE-METAL, was developed by ANL and can cover steady-state and quasi steady-state operation of SFR metal fuel [2]. The principal performance models of LIFE-METAL are Fission Gas Release (FGR), fuel slug swelling, Fuel Cladding Chemical Interaction (FCCI) and constituent redistribution. For fuel rod mechanical analysis, the LIFE-METAL used an analytical modeling which can consider two dimensional stress-strain behavior of cladding under assumption that fuel slug is rigid body.

The ALFUS code was developed by CRIEPI and employs mechanistic model for fission gas release and swelling of fuel slug [3]. In the code system, a finite element method was introduced to analyze the fuel and cladding's mechanical behaviors.

The FEAST code is more advanced code system for SFR which adopted mechanistic FGR and swelling model but still use analytical model to simulate fuel and cladding mechanical behavior [4].

Based on the survey of the previous studies, fuel and cladding mechanical model should be improved. Analysis of mechanical behavior for fuel rod is crucial to evaluate overall rod's integrity. In addition, it is because contact between fuel slug and cladding or an over-pressure of rod internal pressure can cause rod failure during steady-state and other operation condition. The most of reference codes have simplified mechanical analysis model, so called "analytical model", because the detailed mechanical analysis requires large amount of calculation time and computing power. Even if the characteristics of "analytical model" are simple and fast running time, there are some limitations which can disturb the detailed modeling of nature. For instance, contact force between cracked slug and cladding shows much larger than non-cracked one due to the high stress concentration at crack tip. The analytical model cannot simulate the cracked slug model. To resolve the limitations, the finite element method (FEM) has been introduced to simulate the mechanical behavior of fuel rod. The ALFUS code adopts FEM modeling to solve mechanical behavior of fuel rod.

In this work, 2D FEM model, so called 'NUFORM2D', has been developed to simulate mechanical behavior of fuel and cladding in SFR. The model will be integrated into audit code system. To evaluate the developed model, a code-to-code benchmark was performed using the commercial FE package (ANSYS).

2. Development of mechanical analysis model using FEM

To develop mechanical analysis model in the FE solver, FORTRAN77 (IntelFORTRAN 2011 complier) was employed in WINDOW system. The FE module employs two-dimensional quadrilateral element that can reduce numerical error. Figure 1 shows calculation flow of the module. When the module is called by main program (fuel performance code), the calling subroutine should transfer fuel data at current state such as temperatures of nodes, the dimensions of fuel and cladding, pressure loading and so on. Node and element information of fuel and cladding should be also prepared as input file.

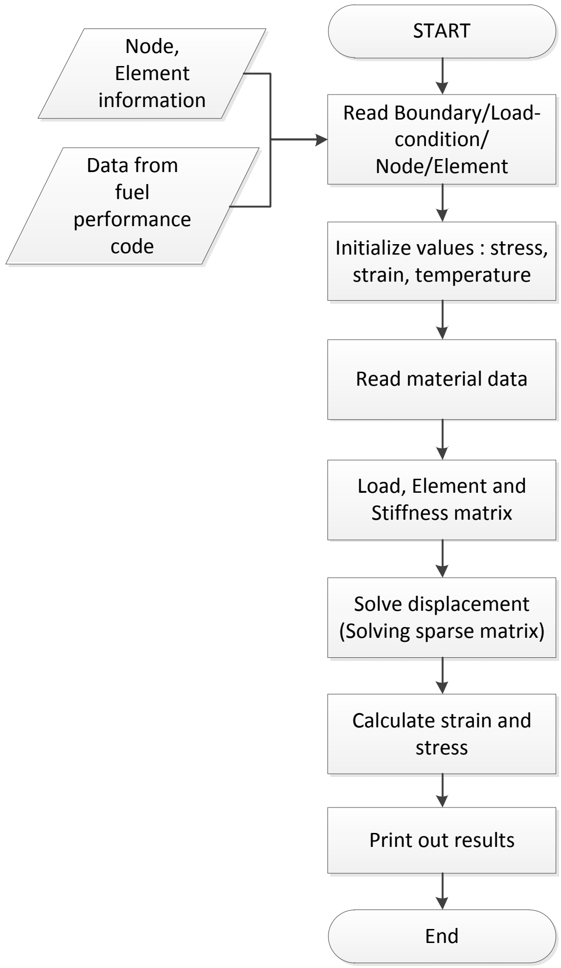


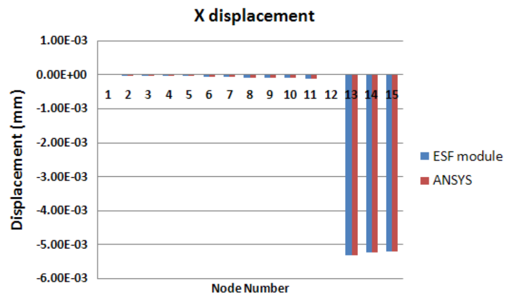
Fig. 1. Flowchart of NUFORM2D module

When the data for FE analysis is stored into the variables, stiffness and load matrix can be completed. To solve a global stiffness matrix effectively, the SKYLINE method [5] that is suitable for relatively small-size matrix was employed. After the matrix is resolved, we are able to obtain force and displacements of all integration points under the given conditions. To evaluate calculation results of stress and strain, the stress and strain should be recalculated using the solved force and displacement.

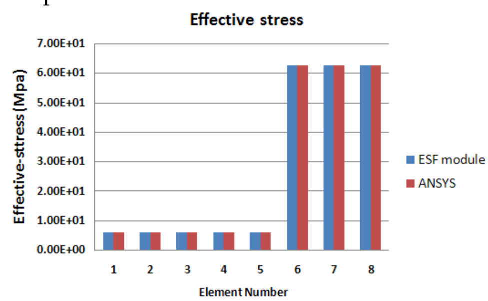
3. Simulation Results of the model

To evaluate the developed model, material properties should be defined. Because metal fuel and cladding properties are not available yet, mechanical material properties of oxide fuel and Zircaloy cladding (derived from MATPRO) have been applied. The assumptions are as follows: all materials were isotropic, and there is no mechanical contact (the contact module is under development) .

The boundary conditions for the structural analysis are as follows: coolant pressure, 15 MPa; gap pressure, 6 MPa; and the bottom nodes are symmetric. To verify the FE code, the displacements and effective stresses of the bottom nodes are compared with those of ANSYS. As shown in Figure 2, the displacements and effective stresses from the developed FE module are exactly equal to those of ANSYS. The comparison demonstrates that the NUFORM2D model was verified.



(a) Displacements



(b) Effective stress

Fig. 2 Comparison of simulation results

4. Conclusions

The project for the new fuel performance code development has been launched to evaluate the integrity and safety of SFR fuel in regulation aspects. Based on survey of the previous SFR fuel code system, the mechanical analysis module of the previous code should be improved to resolve limitations. This work develops the advanced mechanical analysis model of SFR fuel rod using finite element method, which is well matured in the mechanical field. The module has been implemented by FORTRAN77 to be called by main program. Comparison results between the developed module and commercial FE package demonstrates that the module is verified. For the future, mechanical contact model will be incorporated to simulate fuel-cladding mechanical interaction behavior.

Acknowledgement

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