Evaluation of Creep-Based Deformation Model in FRAPTRAN-KATF for In-situ Cladding Ballooning Measurement Data

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1. Introduction

The prediction of cladding ballooning and burst under accident conditions, such as a large break loss-of-coolant accident (LBLOCA), can be applied to the evaluation of the blockage ratio of the flow channel in a reactor core which affects the long-term cooling performance. It also provides information about the cladding deformation, which is a key parameter of fuel relocation analysis in FFRD (Fuel Fragmentation, Relocation and Dispersal) .

FRAPTRAN [1], a code used by the NRC to evaluate the performance of nuclear fuel under accident conditions, uses the BALON2 [2] algorithm to evaluate the large deformation of cladding at high temperatures. However, there is a discontinuity in the process of switching from the small deformation analysis module FRACAS-I to BALON2 when a certain criterion is reached. Although this methodology improved the accuracy of the prediction to some extent, it is inadequate for predicting the secondary deformation that does not predict the actual deformation.

To overcome this, KAERI has introduced a methodology that applies a large-deformation creep model to replace BALON2. In order to verify the application of this large-deformation creep model, an evaluation for the real-time deformation measurement data which were measured by the high-temperature cladding in-situ deformation measurement device, DIMAT [3,4] was performed using FRAPTRAN-KATF [5], and the results are described in this paper.

2. Creep Model for Cladding Ballooning

The deformation of cladding in the out-of-pile can be divided into elastic, thermal, and plastic deformation. At constant temperature and stress, the steady-state creep deformation rate of the cladding can be obtained from the following Arrhenius equation for the effective stress and effective strain, which can be used to calculated the plastic deformation.

$$\dot{\epsilon}_{eff} = A_{eff} exp\left(-\frac{Q}{RT}\right)\sigma_{eff}^{n}$$

Where, $\dot{\epsilon}$ is the steady-state creep strain rate, ϵ is the strain, A is the structure parameter, Q is the activation energy, R is the gas constant, T is the absolute temperature, σ is the stress, and n is the stress index. Representative coefficients for these equations were given for the axial direction by Rosinger et al. [6] as shown in Table 1.

Table 1. Axial creep parameter by Rosinger et al. [6]

Phase	T (K)	Az	Q	n
α	900 ~ 1085	19400	320000	5.89
β	1248 ~ 1873	7.9	142000	3.78

Since FRAPTRAN calculates the relation between the effective stress and strain for plastic deformation, the following effective structure parameter can be obtained from the axial parameters.

$$A_{eff} = (F + G)^{\frac{n+1}{2}} / A_z$$

Where F and G are anisotropy coefficients and A_z is the axial structure parameter. Therefore, the increment of strain during a time step is given by

$$\mathrm{d}\epsilon_{eff} = A_{eff} exp\left(-\frac{Q}{RT}\right)\sigma_{eff} \cdot dt$$

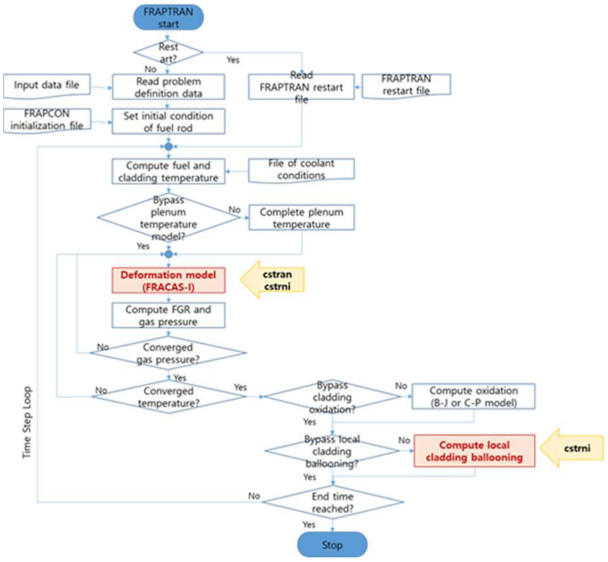

Fig. 1 Flowchart of deformation in FRAPTRAN

The calculation flowchart of FRAPTRAN is shown in Fig. 1. The strain of cladding is calculated in FRACAS-I and BALON2 module, and it is recommended to apply BALON2 module for large deformations such as LOCA. Yadav et al. [7] applied a creep model within the BALON2 module, but in this study, the creep model was implemented for global strain prediction without using the BALON2 module, which considers localized deformation. By the procedure of FRAPTRAN, the effective stress of present step is obtained based on the strain of the previous step, and the increment of the calculated strain is used in the next time step.

3. Analysis Results

The temperature is the main parameter of the creep model for calculating the deformation. Therefore, the temperature distribution along the axial direction was measured in the experiment and this measured axial distribution was used in this analysis. The simulated rod used in this analysis has the following geometries.

Table 2. Geometry of the simulated rod

Parameter	Value
Pellet OD	8.42 mm
Clad OD	9.5 mm
Clad thickness	0.57 mm
Gap between pellet and clad	0.075 mm
Heating length	400 mm

Three deformation models were applied to calculate experiment matrix for internal pressures of 4, 6, 8 MPa, and heating rates 1, 14, 28 K/s. The analysis results for the nine experiments are shown in Fig. 2. The maximum strain in the axial direction occurs at the most centrally located node number 10 among the 19 axial nodes, as given by the boundary conditions. The deformation model noball=0 is the traditional methodology of FRAPTRAN, where the strain calculation model is applied differently from FRACAS-I to BALON2 depending on certain criteria, which is the permanent hoop strain of 5%. This two-step methodology is also applied to option noball=3, which applies a creep model for deformation based on the stresses calculated within BALON2. Therefore, the behavior of options 0 and 3 is the same up to the inflection point, and the difference in behavior is due to the different models applied for subsequent deformations. However, option noball = 2 applies one creep model to the deformation, so the cladding tends to deform without inflection point as shown in the experimental data.

Option 3 is the most similar to the experiment in terms of rupture time as it shows a lower strain again after the switch of the creep model. However, it is important to recognize that this is a distortion of the physics. The case of applying the one creep model for all nodes and the entire deformation (noball=2) shows similar results to the experiments and closer to the rupture time compared to the default option (noball=0) in all experimental conditions.

4. Conclusions

A module based on the creep model for predicting the cladding ballooning of cladding tubes under accident conditions was implemented in FRAPTRAN-KATF, a nuclear fuel performance code for accident conditions. In this study, the evaluation of the performance was carried out for in-situ high-temperature deformation experimental data using Zr-4 cladding by DIMAT, and nine transient experiments were utilized. The results of the analysis using the creep model show that, unlike the default model option, the inflection point does not occur and the behavior of strain and stress is well simulated. The creep model is able to simulate the axial deformation shape, which is beyond the limitation that the default model of BALON2 considers a specific node that have reached a certain limit for deformation. For all the experimental conditions, the creep model results in a slightly different rupture criterion than the default BALON2 option, and the rupture time is more similar to the experiments in the calculation used the creep model.

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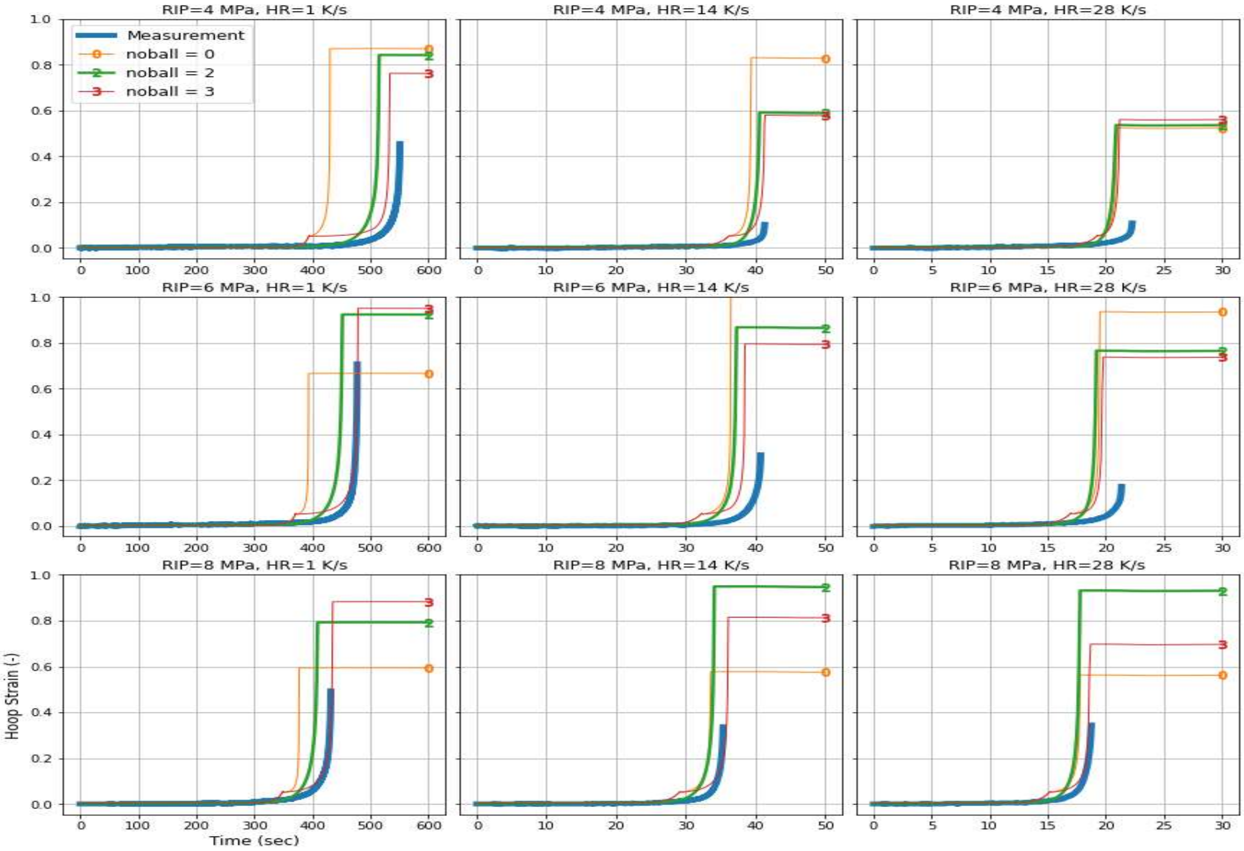

Fig. 2 Analysis results with the creep deformation model of FRAPTRAN-KATF