Assessment of clad deformation model of MARS-KS against DIMAT separate effect test

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1. Introduction

MARS-KS simulates nuclear fuel with heat structure model, employing models for elastoplastic deformation of fuel clad and thermal expansion of fuel pellet, respectively[1]. However, since the employed model calculates plastic deformation of fuel clad through the rupture correlation[2], the code cannot implement rod deformation behavior depending on the characteristics of clad material, appropriately. For this, a new model has been developed to replace the current deformation model of MARS-KS[3]. Accordingly, this study aims at validating the developed rod deformation model. For this, the assessment has been conducted against DIMAT (Deformation In-situ Measurement Apparatus by image-analysis Technology) ballooning test[4]. Comparing the results with the current model of MARS-KS, the validity of the new model has been evaluated.

2. Methods and Results

2.1 Clad deformation model

The new model calculates clad deformation as:

$$\varepsilon_{clad,ij} = \varepsilon_{ij}^{el} + \varepsilon_{ij}^{th} + \varepsilon_{ij}^{p} \quad (1)$$

$$\varepsilon_{ij}^{el} = \frac{1}{E}[\sigma_\theta - \upsilon(\sigma_r + \sigma_z)] \quad (2)$$

$$\varepsilon_{ij}^{th} = \int \alpha \, dT \quad (3)$$

$$\varepsilon_{ij}^{p} = \varepsilon_{eff}^{p} + A_{eff}\exp\left(-\frac{Q}{RT}\right)\sigma_{eff}dt \quad (4)$$

where, ε_{ij}^{el},. ε_{ij}^{th}, ε_{ij}^{p} define elastic, thermal, and plastic strains of fuel clad, respectively. Through Eq. (1), the effective strain is calculated for circumferential deformation. For modeling rod ballooning, the change of plastic strain is modeled based on Norton thermal creep model[5]. For the burst criteria, the rupture strain data from NUREG-0630 is employed[2], and the rod burst is determined by comparing the calculated total hoop strain from Eq. (1) against the rupture data.

2.2 Overview of DIMAT test

DIMAT is a separate effect test designed for measuring the high temperature deformation of cladding. Fig. 1 depicts the cross-sectional view of the experimental setup. A fuel rod specimen is installed inside a quartz tube equipped with infrared lamps. To prevent oxidation on the outer surface of the cladding, the quartz tube is filled with argon gas, creating an inert atmosphere. The fuel rod specimen consists of Zr-4 cladding and alumina pellets. The internal pressure of the rod specimen is maintained by filling it with argon gas. The total heated length is 400mm, and a temperature gradient is established with respect to the center of the specimen. As illustrated in Fig. 2, before the transient test, the cladding is heated to typical PWR operating temperatures to establish steady-state conditions. Constant rod pressure is maintained by controlling the filled argon gas. The transient test is performed by increasing the power of the infrared lamps to heat the cladding surface. The heating rate of fuel clad is configured to be uniform by adjusting lamp power while maintaining the constant rod pressure. The real-time deformation behavior of cladding is measured by capturing the images. The experiment consists of 9 test cases set with three different rod pressure conditions (40, 60, and 80 bar) and three different heating rates for each (1, 14, and 28 K/s).

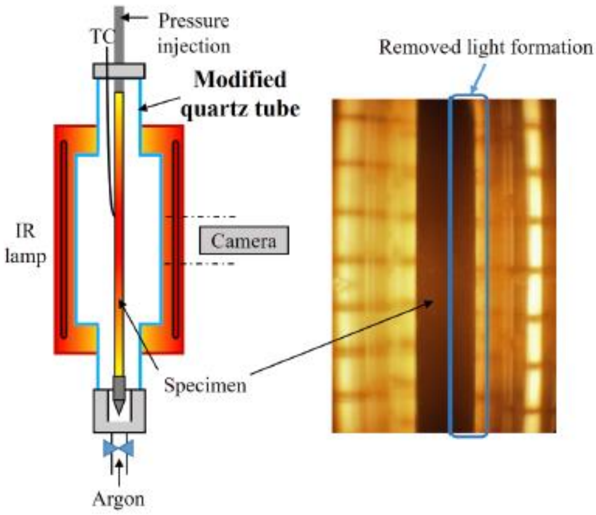


Fig. 1. Cross-sectional view of DIMAT test setup[4]

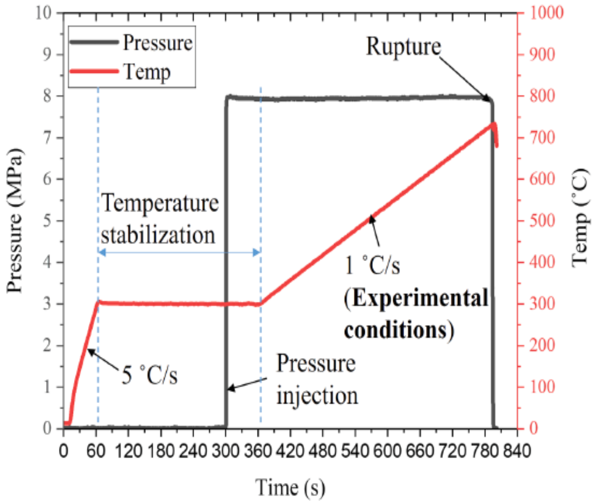


Fig. 2. Experimental procedure of DIMAT test[4]

2.3 Assessment model

Fig. 3 depicts the assessment model developed for DIMAT test. The fuel rod specimen was modeled with 26 axial nodes. The whole 400mm heated length of the specimen was modeled with 10mm uniform, except for the top and bottom of the specimen that featured uniform temperature distribution. To simulate the experimental boundary conditions, Time-dependent volume (TMDPVOL) components were modeled to each node of the fuel rod. This allowed for the same heating conditions of the experiment, where the cladding surface was heated by the infrared lamps. A dummy volume was modeled and connected to each TMDPVOLs, enabling the code to recognize the entire setup as a single system.

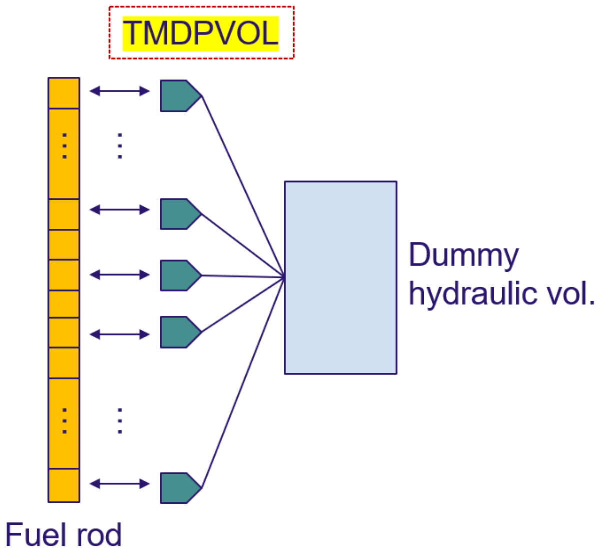
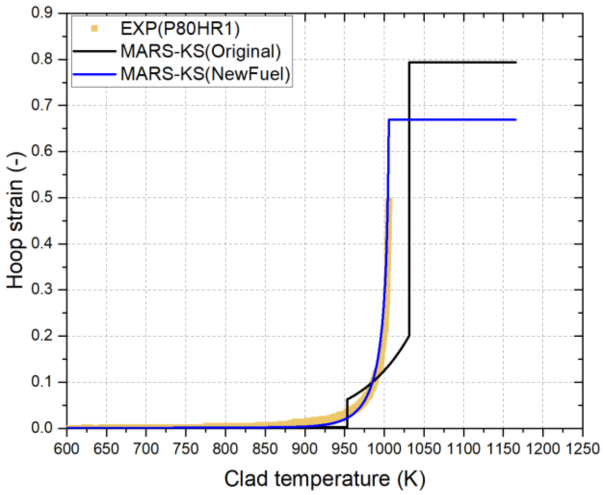


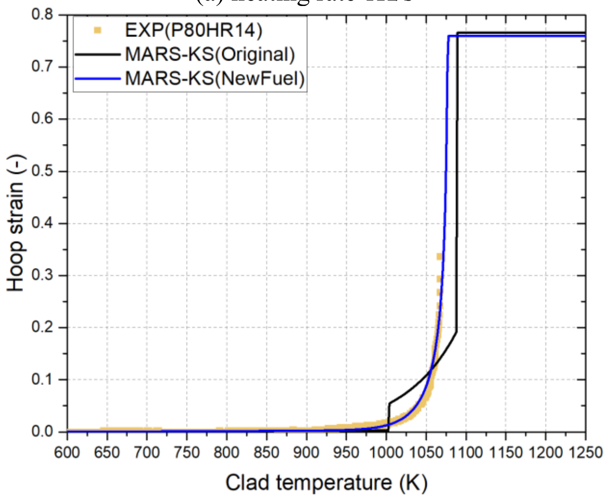
Fig. 3. MARS-KS assessment model for DIMAT test[4]

2.4 Assessment results

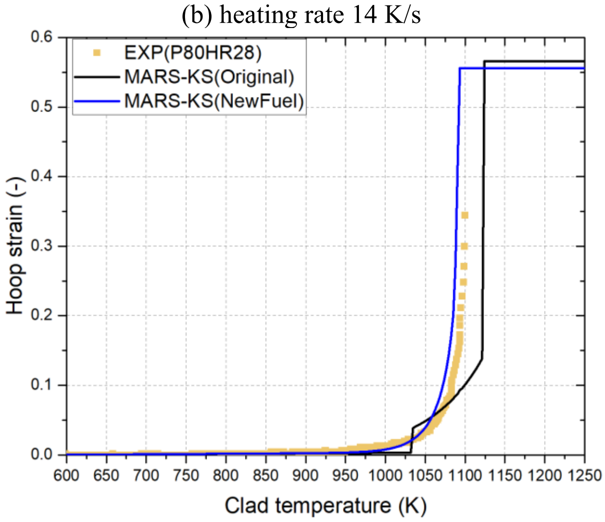
Fig. 4 to 6 show the calculation results for each test cases performed at 80, 60, and 40 bar, respectively. The results of the current rod deformation model of MARS-KS were also compared with the developed new model. As shown in the figures, the current deformation model of MARS-KS calculated different deformation behavior compared to the measured results in the experiment. While the measured results showed continuous creep deformation with increasing temperature, the current model resulted discontinuous deformation behavior. This result clearly revealed the limitation of current model, which calculates plastic deformation based on a rupture correlation. In contrast, the new model featured similar creep behaviors. In particular, for the test case at 80 bar, the model showed similar deformation behavior to the measured data. However, for the cases at 60 and 40 bars, the new model also failed to adequately predict the measured deformation behavior. It was revealed that all cases showing discrepancy against the measured data were those where the deformation occurred in the $\alpha+\beta$ transition region (1,083K < T ≤ 1,244K). Except for the 1K/s case at 60 bar where the deformation occurred at α-phase, the model predicted rod ballooning at lower temperatures than the measured data from the experiment. The poor prediction in the transition region was considered a limitation of the model as it assumed a linear phase transition by interpolating the creep parameters between α- and β-phases.



(a) heating rate 1K/s

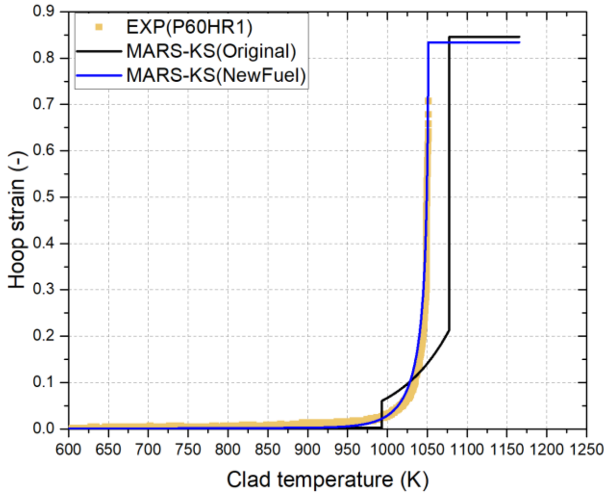


(b) heating rate 14 K/s

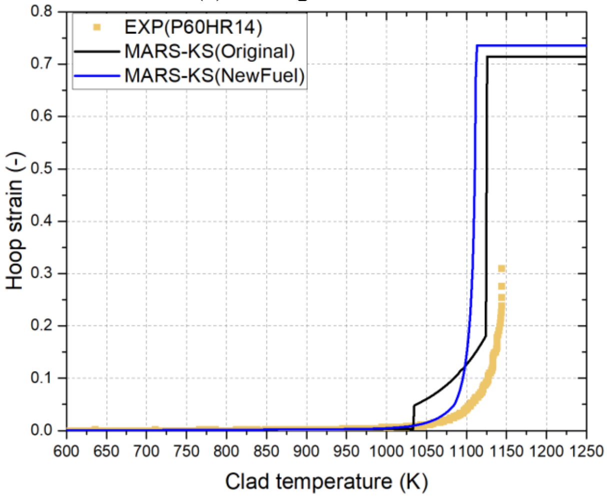


(c) heating rate 28 K/s

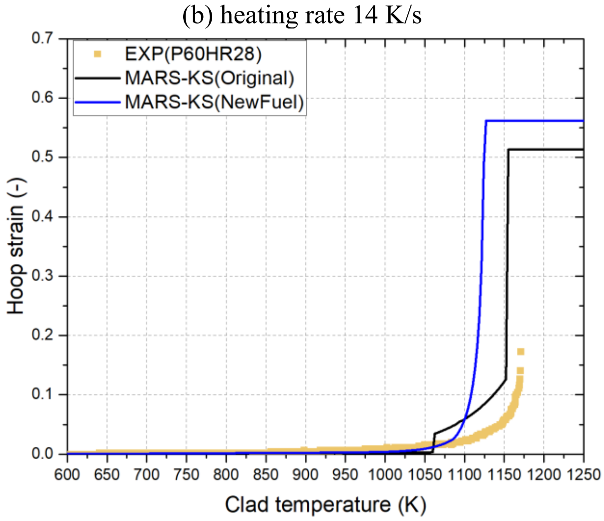
Fig. 4. Assessment results for DIMAT test case – 80 bar



(a) heating rate 1K/s

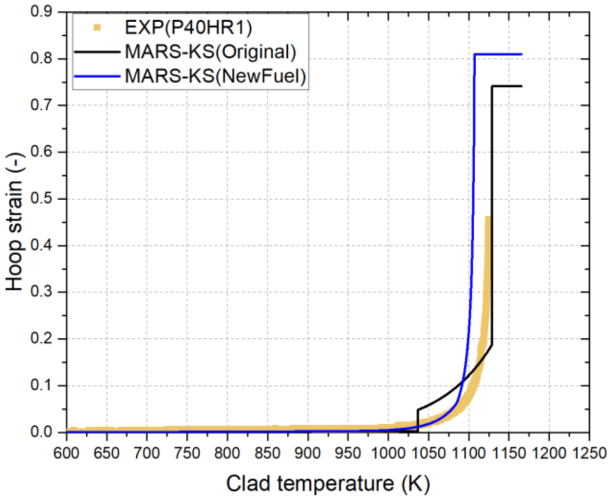


(b) heating rate 14 K/s

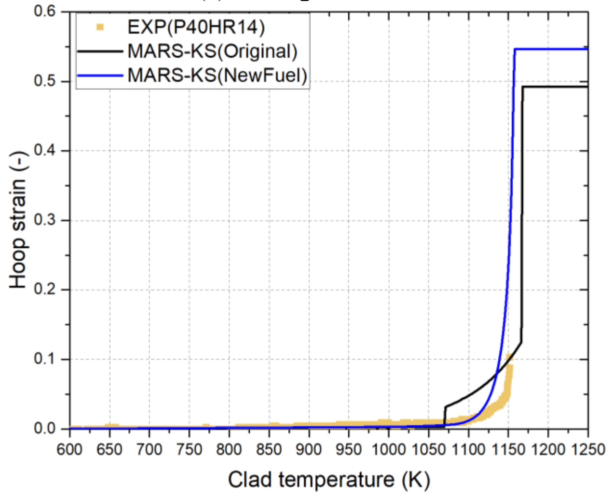


(c) heating rate 28 K/s

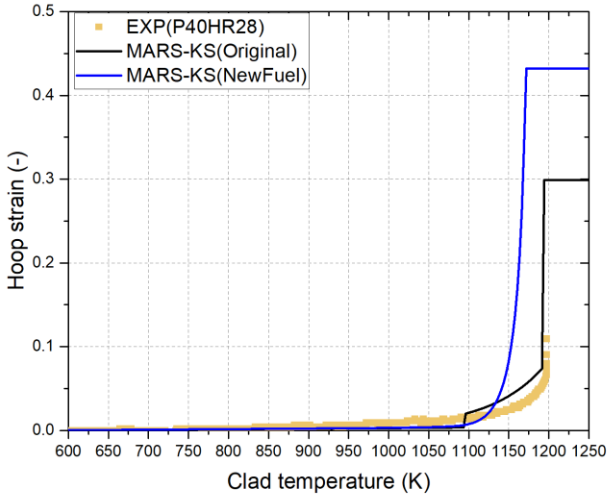
Fig. 5. Assessment results for DIMAT test case – 60 bar



(a) heating rate 1K/s



(b) heating rate 14 K/s



(c) heating rate 28 K/s

Fig. 6. Assessment results for DIMAT test case – 40 bar

3. Conclusions

In this study, the fuel clad deformation model of MARS-KS has been assessed against DIMAT ballooning test. Through the assessment, the improved performance of the developed new clad deformation model has been validated, comparing the results with the current model of MARS-KS. It was revealed from the assessment that the current model failed to predict the creep deformation behavior observed in the experiment, as it calculated discontinuous and unphysical deformation by rupture correlation. In contrast, the new model predicted similar creep behavior to the experiment. In particular, when the deformation occurred at α-phase region, the model featured similar results with the measured data. However, the model failed to predict the deformation behavior at the transition region. This was identified as a key limitation of the model, required to be improved. Since the model so simply interpolated the creep parameters between α- and β-phases linearly that it was unable to predict the non-linear transition behavior.

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