Diameter Evaluation Methodology for Un-measured Pressure Tubes of CANDU Reactor

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1. Introduction

Pressure tubes are the main components of the CANDU reactor and serve as the fuel channel as well as the coolant pressure boundary of the primary heat transport system. Pressure tubes have degraded not only material properties such as fracture toughness, deuterium ingress, mechanical characteristics but also deformation, wear, crack and fracture under the severe operating conditions of a high neutron flux, high temperature and pressure inside the pressure tube.

KAERI has been carrying out R&D project regarding the development of the diameter evaluation methodology for aged pressure tubes in order to overcome the safety issue such as a reduction of the operational margin in terms of the regional over-power trip set point owing to the diametrical expansion of the pressure tube.

Many studies [1-12] have been done to evaluate the diameter expansion of the pressure tube and KAERI recently presented new rules [13-14], so called JY2019 model, to assess the diametrical expansion for measured pressure tubes which have experiences to be measured its diameter at least once. JY2019 model evaluated the diameter expansion based on the measured data and flux distribution from each measured pressure tube. However, the percentage of the measured pressure tubes is only about 3% compared to the whole pressure tubes in the CANDU reactor, thus JY2019 model should extend to the un-measured pressure tubes.

In this paper, we extended JY2019 model to the un-measured pressure tubes so that it can cover un-measured pressure tubes as well as measured pressure tubes. Evaluation results from extended JY2019 model for un-measured pressure tubes showed very reasonable results compared to the measured pressure tubes.

2. Development of JY2019 Model

2.1 JY2019 Model for Measured Pressure Tubes

Basic concept of the pressure tube diameter modeling is that the diameter can be expressed as a combination of neutron flux and temperature effects such as equation (1) and equations (2) and (3) show the detailed modeling of flux and temperature effect.

$$\%creep\_rate_{MEA} = \%creep\_rate_{FLUX} + creep\_rate_{TEMP} \quad (1)$$

$\%creep\_rate_{MEA}$: Measured diameter strain-rate
$\%creep\_rate_{FLUX}$: Flux effect on dia. expansion
$\%creep\_rate_{TEMP}$: Temp. effect on dia. expansion

$$\%creep\_rate_{FLUX} = F_1 \times \%creep\_rate_{flux} \quad (2)$$
$$\%creep\_rate_{TEMP} = T_1 \times (BD\ location) + T_2 \quad (3)$$

Here, F_1, T_1 and T_2 are the scaling factors which determine the each contribution of neutron flux and temperature on the pressure tube diameter expansion. *%creep_rate*$_{MEA}$ is the strain-rate value derived from the measurement data for each pressure tube and *%creep_rate*$_{flux}$ is the normalized neutron flux distribution for each fuel channel. Procedures for deriving both *%creep_rate*$_{MEA}$ and *%creep_rate*$_{flux}$ are explained in the reference 9 and 12.

New 4 rules were derived to determine F_1, T_1 and T_2 [13-14] as follows.

- Rule 1: **Determination of F_1**

$F_1 = 0.5x\{(\%creep\_rate_{MEA})_{at\ BD6}+(\%creep\_rate_{MEA})_{at\ BD7}\} / \{(\%creep\_rate_{flux})_{at\ BD6} + (\%creep\_rate_{flux})_{at\ BD7}\}$

- Rule 2: **Determination of T_1**

$T_1=\{(\%creep\_rate_{MEA}-\%creep\_rate_{FLUX})_{at\ BD6} - (\%creep\_rate_{MEA}-\%creep\_rate_{FLUX})_{at\ BD1}\}/\{\Delta X_{BD1-BD6}\}$

- Rule 3: **Determination of T_2**

$T2 = (\%creep\_rate_{MEA} - \%creep\_rate_{FLUX})_{at\ BD1}$

- Rule 4: **$\%creep\_rate_{TEMP}$ at Bundle 10, 11 and 12**

$(\%creep\_rate_{TEMP})_{at\ BD10} = (\%creep\_rate_{TEMP})_{at\ BD9}$
$(\%creep\_rate_{TEMP})_{at\ BD11} = (\%creep\_rate_{TEMP})_{at\ BD8}$
$(\%creep\_rate_{TEMP})_{at\ BD12} = (\%creep\_rate_{TEMP})_{at\ BD4}$

Fig. 1 shows the diameter evaluation result for the measured pressure tube of Wolsong 3 O14 channel. The result from JY2019 model is very close to the measured data.

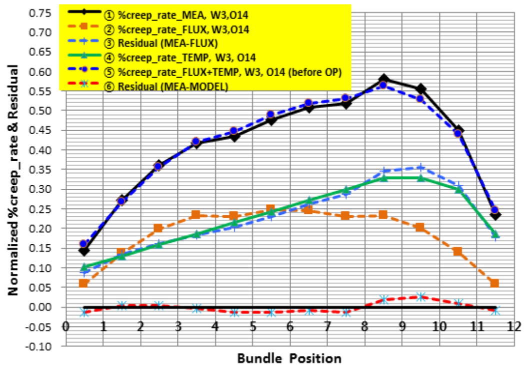

Fig. 1. Diameter prediction results for the measured pressure tube, Wolsong 3 O14 channel.

2.2 JY2019 Model for Un-measured Pressure Tubes

Fig. 2 shows the whole procedure of JY 2019 model for measured and un-measured pressure tubes. Because un-measured pressure tubes don't have their measured diameter data, we can't derive the scaling factors, F_1, T_1 and T_2 for un-measured pressure tubes. Thus, we derived scaling factors F_1, T_1 and T_2 for un-measured pressure tubes from the pre-determined scaling factors for measured pressure tubes through optimization process by minimizing the residuals between the measured data and the evaluated results from JY2019 model for measured pressure tubes.

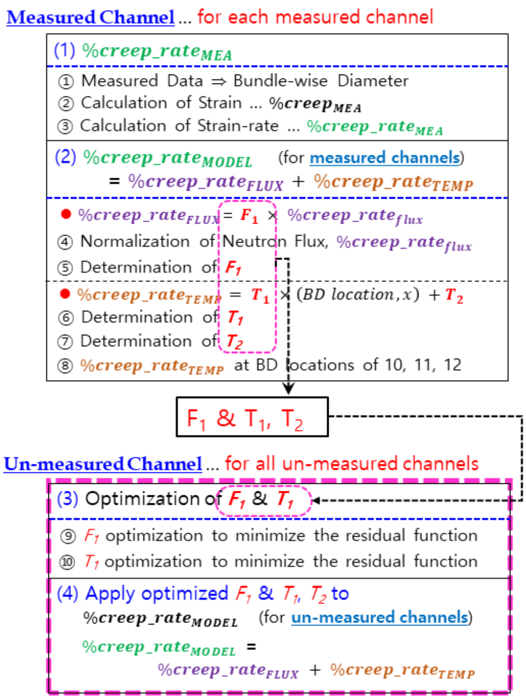

Fig. 2. Procedure of JY2019 model for un-measured pressure tubes

Following two residual functions were applied at optimization process to derive the scaling factors for un-measured pressure tubes.

$$average|4pt\,diff| = \frac{1}{n}[\sum_{CH=1}^{n}\frac{1}{4}\sum_{BD=7}^{10}(|\%creep\_rate_{mea} - \%creep\_rate_{model}|)]$$

$$average|max.\,diff| = \frac{1}{n}[\sum_{CH=1}^{n}\max(|\%creep\_rate_{mea} - \%creep\_rate_{model}|_{BD_i},\ i = 1 \ldots 12)]$$

The first residual function means the average residuals between measured data and evaluated results at the locations of bundle 7 ~ bundle 10 for all measured pressure tubes. The second residual function implies the average residuals at the location of the maximum deformation for all measured pressure tubes. Figs. 3 and 4 shows the sensitivity analysis results of the two residual functions expressed as the second order polynomials regarding the variation of T1 and F1. The scaling factors for un-measured pressure tubes were determined by differentiating the 2[nd] order polynomials and find the adequate values where the differentiation functions were zeros.

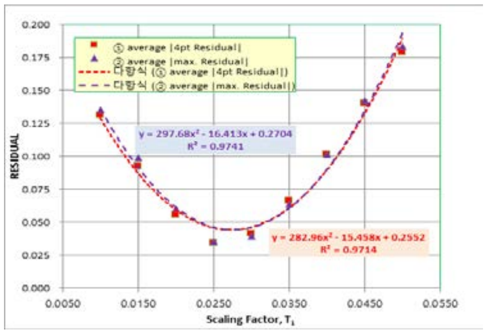

Fig. 3. Sensitivity results for the 1st residual function by the variation of T_1.

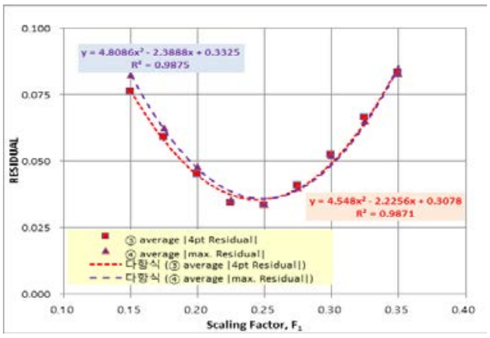

Fig. 4. Sensitivity results for the 2nd residual function by the variation of F_1.

3. Evaluation Results for Un-measured PTs

3.1 Selection of the un-measured pressure tubes

In order to apply newly derived scaling factors for un-measured pressure tube through the optimization procedure, un-measured fuel channels were selected as shown in Table I based on the channel power.

Table I: Selection of Un-measured Pressure Tubes

Channel	Channel Power (MW)	Altitude
W10	4.0	Low
B10	5.0	High
G05	6.0	Medium High
S10	6.6	Medium Low
O06	7.0	Medium

3.2 Diameter Evaluation Results

Figs. 5 ~ 7 show the evaluation results for W10, G05, and O06 channels' pressure tubes. Results from JY2019 model represented by blue curve is more conservative than results from RC1980, which is the Canadian's model represented by purple curve, for low power channel. But, in the case of high power channel, RC1980 evaluated the diameter more conserve than JY2019 model except inlet region.

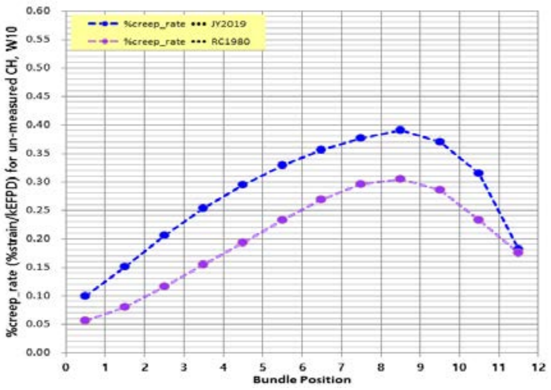

Fig. 5. Evaluation results for W10 channel.

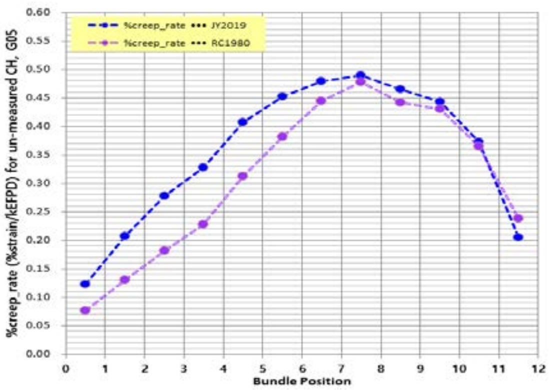

Fig. 6. Evaluation results for G05channel.

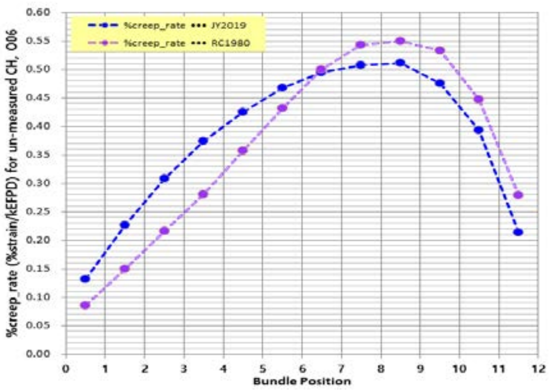

Fig. 7. Evaluation results for W06 channel.

4. Conclusions

In this paper, we extended JY2019 model to the un-measured pressure tubes so that it can cover un-measured pressure tubes as well as measured pressure tubes. Evaluation results from extended JY2019 model for un-measured pressure tubes showed very reasonable results compared to the results from currently used RC1980 model.

ACKNOWLEDGEMENTS

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