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On the Minimum Safety Factor in Elastic Buckling of Fuel Rod

Hyung-Kyu Kim [a*], Jae-Yong Kim [a], Kyung-Ho Yoon [a], Young-Ho Lee [a], Kang-Hee Lee [a], Heung-Seok Kang [a], Kun-Woo Song [a]
[a]*Korea Atomic Energy Research Institute, 1045 Daedeokdaero Yuseong Daejeon 305-353 Korea*
[*]*Corresponding author: hkkim1@kaeri.re.kr*

1. Introduction

Elastic buckling of a thin tube is an instantaneous collapse phenomenon due to an external pressure. This should be prohibited for a PWR (Pressurized Water Reactor) fuel rod. There is an engineering formula of it; however, safety factor used to be applied to the calculation results since there will be uncertainty in the parameters of the formulae such as dimensional tolerances, environmental conditions and so forth.

It is a designer's responsibility to determine an appropriate safety factor that is acceptably economically conservative. Mechanical properties of a material are usually adopted from a material handbook. However, they are usually different from the measured values of the material actually used. A local dimension anomaly critically affects the elastic buckling.

Conventional safety factors against the elastic buckling seemed to be large (more than 3.5 [1]). However, the reason for this is rarely found. Engineering experience may be incorporated. Therefore, it is highly necessary to propose a minimum safety factor on the elastic buckling while accommodating the above mentioned uncertainties. It is so especially for the dual cooled fuel rod since it has never been used before.

The primary purpose of this work is to quantify the aforementioned uncertainties of the parameters in the elastic buckling formula, especially for an outer cladding of the currently studied dual cooled fuel rod. It is extended from the previous theoretical and experimental study [2].

2. Elastic Buckling Formula

From the theory of elasticity, a pressure at the onset of elastic buckling, p_{cr} is described as [3]

$$p_{cr} = \frac{E}{4(1-\nu^2)} \cdot \left(\frac{t}{r_m}\right)^3 = \frac{2E}{(1-\nu^2)} \cdot \left(\frac{t/D}{1-t/D}\right)^3 \qquad (1)$$

where E and ν are the elastic modulus and the Poisson ratio, respectively. t and r_m are the thickness and mean radius of the tube, respectively. D is the outer diameter of the tube. For conservatism, t, r_m and D are replaced with t_{min} (minimum thickness), $r_{m,max}$ (maximum mean radius) and D_{max} (miximum outer diameter) in order.

The safety factor (S) can be obtained as

$$S = \frac{p_{cr}}{p_D}, \quad p_D = p_o - p_i \geq 0 \qquad (2)$$

where, p_D is a design pressure, p_o and p_i are the external and internal pressure of the fuel cladding tube, respectively.

3. Required Safety Factor incorporating the Uncertainty of the Parameters in the Formula

3.1 On Dimensional Parameters

There are two dimension parameters (thickness and mean radius or outer diameter) and two elastic properties (elastic modulus and Poisson's ratio) in Eq. (1). Those are independent of each other so it is necessary to consider the uncertainty of each parameter independently. Then, the minimum required safety factor of the elastic buckling should be the sum of each parameter's required safety factor at the maximum uncertainty condition.

As for the uncertainty of the dimension parameters, ASTM Standard B 811 [4] can be consulted. It holds for a Zirconium alloy tube of nuclear grade for the thickness range of 5.1 ~ 16.5 mm (0.200 ~ 0.650 in.) and the outer diameter range of 0.25 ~ 0.89 mm (0.010 ~ 0.035 in). Since the outer diameter and thickness of the outer cladding of our dual cooled fuel rod are currently designed as 15.9 and 0.87 mm, respectively, ASTM B 811 can be used for it as well as the conventional solid fuel rod.

According to the ASTM Standard B 811, the permissible variations in dimension are ±0.05 mm (±0.002 in.) for the outer diameter and ±0.08 mm (±0.003 in.) for the thickness. As shown in Eq. (1), the critical buckling pressure decreases as the thickness decreases and/or the outer diameter increases. The smallest pressure case needs the largest safety factor. Therefore, a series of calculations were carried out as follows.

For the safety factor investigation in the case of the thickness uncertainty, the outer diameter was fixed to a certain value within 5.1 ~ 16.5 mm and the lowest permissible thickness was plugged into Eq. (1) to obtain a critical buckling pressure. Then, it was compared with the pressure evaluated for each nominal thickness. Similarly, in the case of the diameter uncertainty, the thickness was fixed within 0.25 ~ 0.89 mm and the largest permissible outer diameter was used in Eq. (1) to obtain a critical buckling pressure. Then, it was compared with the pressure evaluated for each nominal diameter. The results are given in Figs. 1 and 2.

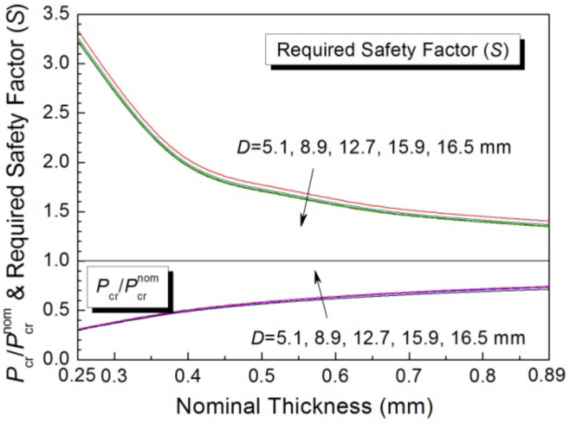

Fig. 1. Variation of critical buckling pressure and required safety factor corresponding to the cladding thickness.

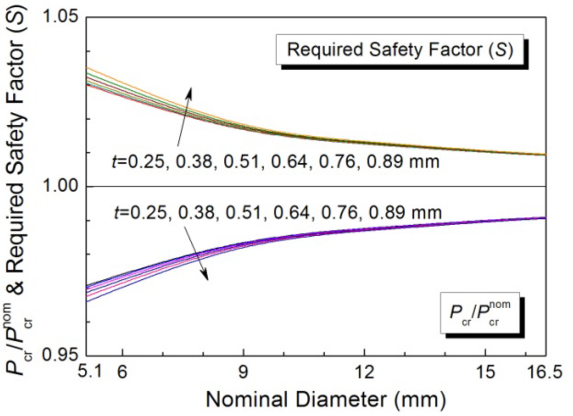

Fig. 2. Variation of critical buckling pressure and required safety factor corresponding to the cladding outer diameter.

From Fig. 1, the critical pressure increases as the thickness increases. The smaller the diameter, the larger (smaller) the required safety factor (critical pressure) is. However, the difference corresponding to the diameter variation is very small. The required safety factor is 3.23~3.34 when the thickness is 0.25 mm while it decreases considerably to 1.35 ~ 1.40 for a 0.89 mm thickness. To the contrary, Fig. 2 shows that the critical pressure and required safety factor are not very much altered in the case of the diameter variation. Overall, the required safety factor corresponding to the deviation of each diameter is at most 1.035.

3.2 On Mechanical Properties

The critical buckling pressure is linearly proportional to the elastic modulus in Eq. (1). For instance, the critical buckling pressure is overestimated by 10% if the elastic modulus in Eq. (1) is larger than an actual value by 10%. In this case, the minimum required safety factor should be 1.10. So it is highly necessary to actually measure the elastic modulus to evaluate the critical buckling pressure.

Therefore, the uncertainty during the elastic modulus measurement is considered in this study. Recently, the uncertainty during measuring the elastic properties was presented [5]. It is referred to here. It showed that the final combined uncertainty of the elastic modulus was ±1.66%. If an elastic modulus is smaller than the measured value by 1.66%, the required safety factor should be larger than 1.017.

The Poisson ratio (ν) for the Zirconium alloy tube is within the range of 0.25~0.37. The values of 0.25, 0.30 and 0.37 are often used. The term $1/(1-\nu^2)$ in Eq. (1) is almost linear with respect to ν when $0.25 \leq \nu \leq 0.37$, with the slope being around 0.76. Difference of the critical pressure between $\nu = 0.25$ and 0.37 is 8.6%. This means that the critical buckling pressure can be overestimated by 8.6% at most and the relevant required safety factor is 1.095. Resultantly, the overall required safety factor due to the uncertainty of the mechanical properties is 1.12.

3. Minimum Safety Factor for a Dual Cooled Fuel

Referring to the previous section, the required safety factors are 1.01 and 1.36 for the diameter and thickness variations, respectively. Resultantly, the minimum safety factor is 1.49 (≈1.5) after accommodating the mechanical property uncertainties. It is soundly concluded that the present design of our dual cooled fuel rod is safe enough to preclude the elastic buckling since the safety factor has been evaluated as 2.33 [2].

4. Conclusions

The minimum safety factor to prevent the elastic buckling of a fuel cladding tube was evaluated. It was found that the thickness deviation played the largest role in the safety factor determination. It was also found that currently designed dual cooled fuel rod would be safe against the elastic buckling.

ACKNOWLEDGMENT

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