Comparison of Fuel Temperature Characteristics between Standard 37-element and CANFLEX Fuel Bundles

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1. Introduction

The CANFLEX fuel has been developed for the CANDU-6 reactor as an alternative to the standard 37-element fuel bundle and it is comprised of dual-size 43 fuel elements. The fuel temperature coefficient (FTC) is an important safety parameter and it is dependent on the fuel temperature. For an accurate evaluation of the safety-related physics parameters including FTC, the fuel temperature distribution and its correlation with the coolant temperature should be accurately identified. Although the thermal characteristics of the CANFLEX bundle were already analyzed, the related information is not fully available with the recent code systems at the moment. Therefore, we have re-evaluated the fuel temperature distribution of a CANFLEX-loaded CANDU core by using the NUCIRC [1] code.

2. Numerical methods

The calculation of fuel temperature was performed with an inlet header temperature of 262°C, an outlet header pressure of 9.96 MPa, and a header-to-header pressure drop of 1271 kPa at 90 MWh/kgU burnup. The CANFLEX bundle is comprised of 4 fuel rings. In the present calculation, a fuel temperature was calculated only for a representative fuel element in each ring. It is reasonably assumed that the coolant temperature is uniform at a specific axial location and the heat generation rates are same for all fuel elements of each ring, and all the fuel elements in each ring have the same fuel temperature.

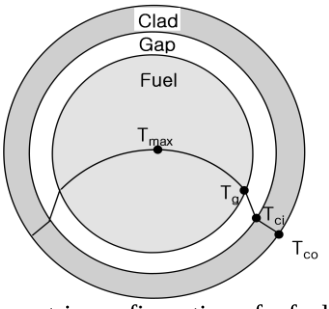

Fig.1 Geometric configuration of a fuel element

The schematic of the one-dimensional fuel element is sketched in Fig. 1. The coolant temperature is firstly obtained from the relation between the enthalpy rise of coolant and bundle power input in one-dimensional analysis and then the fuel temperature is calculated by considering the heat transfer from the fuel to coolant.

The Seider and Tate equation [2] was used to the heat transfer coefficient of fuel element to a coolant:

$$\frac{h_{coolant}\, D_e}{k_{coolant}} = 0.023 Re^{0.8} Pr^{0.4} \left(\frac{\mu_w}{\mu}\right)^{0.14} \quad (1)$$

where $k_{coolant}$ = coolant conductivity, D_e = equivalent diameter of fuel element.

The heat conduction in the cladding is simply analyzed by solving the source-free heat conduction equation.

Regarding heat transfer in the gap between cladding and fuel pellet, it is assumed that the gap consists of an annular space occupied by gases. The heat transfer coefficient in a gap is represented by[3]:

$$h_{g,open} = \frac{k_{eff}}{\delta_{eff}} + \frac{\sigma T_g^3}{\frac{1}{\epsilon_f} + \frac{1}{\epsilon_c} - 1} \quad (2)$$

which reflects conduction through an annular space and radiation from the fuel. Here, ϵ_f, ϵ_c is surface emissivities of the fuel and cladding, σ is Stefan-Boltzman constant. The gas composition is gradually altered with burnup by the addition of gaseous fission product. Hence, the effective gap width, δ_{eff}, is different with the real gap width because of the temperature discontinuities at the gas-solid surface. In eq. (2), the effective gap thickness and effective conductivity are given by:

$$\delta_{eff} = \delta_g + \delta_{jump\ 1} + \delta_{jump\ 2} \quad (3)$$

$$k_{eff} = (k_1)^{x_1} (k_2)^{x_2} \quad (4)$$

where x_1 and x_2 are the mole fractions of helium and xenon, respectively.

Since thermal expansions of the fuel and cladding are often different, the pellet-cladding contact occurs at the interface, which results in reduced thermal resistance in a gap. The contact area is proportional to the surface contact pressure between the fuel and cladding. Thus the contact-related heat transfer coefficient can be given by:

$$h_{contact} = C \frac{2k_f k_c}{k_f + k_c} \frac{p_i}{H\sqrt{\delta_g}} \quad (5)$$

where C = a constant; p_i = surface contact pressure; H = Meyer's hardness number of the softer material.

Consequently, the total gap conductance upon contact is given by:

$$h_g = h_{g,open} + h_{contact} \quad (6)$$

In order to determine the temperature profile within the fuel rod, the following energy transport

equation in a fuel rod is solved:

$$\frac{1}{r}\frac{d}{dr}\left(k(T)\frac{dT}{dr}\right) + q'''(r) = 0 \quad (7)$$

Thermal conductivity of UO_2, k(T), was interpolated from the experimental conductivity data. And, the heat generation rate in a fuel rod, q''', was obtained from physics calculation for fuel rods and burnup [4].

Table.1 Fuel temperature comparison

	Standard 37-element		CANFLEX	
	Relative linear power	Fuel temperature (°C)	Relative linear power	Fuel temperature (°C)
Ring #1	0.775	561.79	1.021	603.95
Ring #2	0.811	576.60	1.072	622.27
Ring #3	0.915	619.98	0.871	566.35
Ring #4	1.132	716.88	1.061	637.22
Core Average	1.00	658.51	1.00	611.56

3. Results and discussion

Table 1 shows the relative linear power and fuel temperature of each fuel element. In Table 1, Ring#1 indicates the central fuel element and Ring#4 stands for the outer-most fuel ring. Relative linear power is the ratio of specific element power relative to the average element power, which is obtained from HELIOS calculation. For the standard 37-element, the minimum relative linear power occurs at the central element and it increases monotonically with the ring number. For the CANFLEX fuel, the 3rd ring has the minimum linear power and a w-shape radial power profile is observed. Since the relative linear power mainly affects the fuel temperature, the fuel temperature shows a similar profile as in the linear power. That is, the fuel temperature in the 3rd and 4th rings is lower for CANFLEX compared to 37-element. It is noted that, since the number of elements is larger at outer ring, the total volume averaged fuel temperature in a core is about 47 °C lower with the CANFLEX fuel.

Figures 2 and 3 show an fuel temperature distribution over 380 channels in the whole core. It is noted that the fuel temperature difference between CANFLEX and 37-fuels is more distinct in the higher power region of the core. Especially, the 4th ring, which has the maximum fuel temperature among elements, shows about 100°C temperature difference between the two fuel designs in the high power region. In general, a lower fuel temperature results in a lower fuel temperature coefficient. Therefore, it is expected that the CANFLEX fuel design can slightly improve the fuel temperature coefficient of the CANDU reactor.

Generally, fuel temperature is mostly governed by the coolant temperature and bundle power. Hence, the correlation to predict fuel temperature can be represented as follows:

$$T_{fuel} = T_{coolant} + AP + BP^2 \quad (8)$$

where P is a bundle power.

In the present study, the correlation was determined by the least-square method with 2880 data set for a full power core. For the 37-element design, the constant A and B were found to be 0.491 and 2.064×10^{-4}. For CANFLEX, A and B were calculated to be 0.502 and 1.563×10^{-4}, respectively. The prediction error of the correlations is ±5% and applicable in the rage of $50 < P < 800kW$.

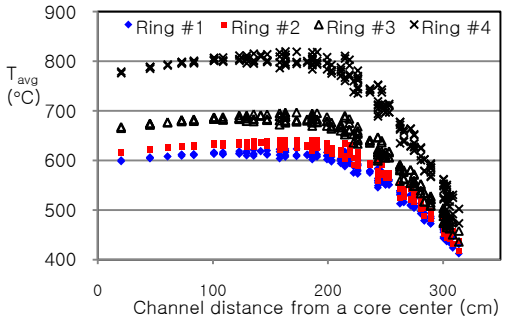

Fig.2 Fuel temperature in 37-element.

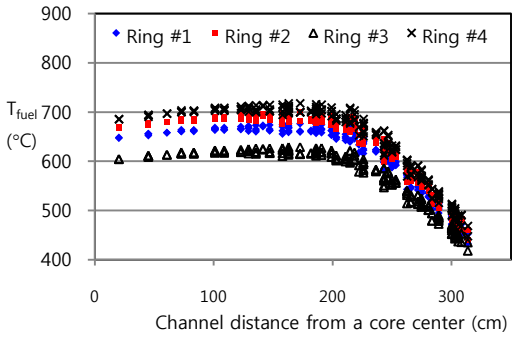

Fig.3 Fuel temperature in CANFLEX.

ACKNOWLEDGMENT

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