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The CCP Assessment of CANDU-6 Channel Loaded with CANFLEX-NU Fuel Bundle

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Abstract

The thermal margin of CANDU-6 reactor is estimated by the CCP, which is dependent on fuel channel hydraulics and the CHF of fuel bundle. This paper intents to describe the characteristics of CCP behavior for the CANDU-6 channel in which CANFLEX-NU fuel bundles are assumed to be loaded. Also, it includes the thermal margin evaluation of the CANDU-6 channel loaded with a mixed CANFLEX-NU and 37-element fuel bundles as a simulation of the partial loading of CANFLEX-NU fuel bundle in the CANDU-6 reactor. For the mixed fuel channels, the effects of axial flux distribution(AFD) on CCP were investigated by using the AFD tilted in the downstream. The CCP of CANFLEX-NU fuel bundle was found to be improved by the CHF enhancement, despite of the slight flow decrease, in case of both full and partial loading, compared with those of a standard 37-element fuel bundle.

1. Introduction

CANFLEX(CANDU Flexible Fuelling) is a 43-element CANDU bundle, which is being developed jointly by KAERI and AECL, to facilitate the use of various advanced fuel cycles in CANDU reactors through the provision of enhanced operating margins in the bundle design[1]. CANFLEX uses dual sized rods and critical heat flux(CHF) enhancement appendages(buttons) as shown in Figure 1. The CANFLEX-NU(Natural Uranium) bundle program is now nearing completion. Now, the fuel design report[2] was submitted to KINS to get the government design approval which is needed prior to the fuel bundle irradiation in a reactor power.

This paper described the thermal margin assessment of CANDU-6 channel in which CANFLEX-NU fuel bundles were assumed to be fully or partially loaded. It also investigated how the CANFLEX-NU fuel bundle will affect the channel flow distribution and thermal margin of CANDU-6. The thermal margin of CANDU reactor is determined by critical channel power(CCP)[3], which is dependent on fuel channel hydraulics and the CHF of the bundle.

Fuel channel hydraulics means the variation of channel flow with respect to increasing channel power under the fixed primary heat transport system(PHTS) pump capacity. Fuel channel hydraulics is dependent on the bundle pressure drop. K-factor of the pressure drop model[4] was obtained as the most probable form loss factor of fuel bundle. The CHF is the thermal capacity of fuel sheath dryout at a flow for a given bundle geometry, inlet temperature and pressure. In the prediction of the CHF of CANFLEX-NU fuel bundle, the CHF enhancement factor[5], which was derived from AECL-CRL Freon loop test data, was applied to the CHF bundle lookup table[6] of 37-element bundle. The calculations utilized the NUCIRC[4] of CANDU-6 single channel steady state thermalhydraulic(T/H) analysis code, applied with the K-factor and the CHF enhancement factor.

Based on the 8 bundle shift refueling method, the recursive scenario[7] was taken for the mixed fuel channel model in order to simulate the partial loading of CANFLEX-NU fuel bundles into a CANDU-6 channel. The lowest CPR(Critical Power Ratio) channel(O-6) loaded with a mixed CANFLEX-NU bundles and 37-element bundles was selected for the evaluation of CCP. The CCP of the mixed fuel channel were calculated under the constant header-to-header pressure drop as well as under the constant flow condition. The CPR of the tilted axial power in the downstream was also compared with that of normal axial power distribution.

2. Analysis Method

2.1 Boundary Conditions

The calculations were performed by taking the constant header-to-header pressure drop, the fixed reactor inlet header temperature and outlet header pressure conditions which were same with those of a standard 37-element bundle.

The change of fuel channel pressure drop will affect the PHTS pump operation and vary the header-to-header pressure drop condition. The header-to-header pressure drop takes place at fuel channels, feeder pipes and end fittings. The ratio of fuel string pressure drop to the header-to-header pressure drop is about 10~25% at orificed channels and 50~60% at non-orificed channels. According to a sensitivity analysis, if the fuel string pressure drop of CANFLEX-NU fuel bundle were increased by 2.7% than the 37-element bundle, it would increase 0.6% header-to-header pressure drop. The increased header-to-header pressure drop will give 0.6% channel flow and 0.3% CCP more than the results of the constant header-to-header pressure drop condition. Thus, it was found that the CCP assessment of CANFLEX-NU fuel bundle using the constant header-to-header pressure drop condition would be conservative.

2.2 Pressure Drop Model

To use K-factor model of NUCRIC code, the form loss factor should be derived from the most probable pressure drop of 12 fuel bundle string. From loss is composed of loss by bundle appendages such as bearing pads, spacers and button, loss by 11 junctions of the fuel bundle string and loss by channel entrance and exit.

$$\Delta P_{form} = \Delta P_{obstacles} + \Delta P_{junctions} + \Delta P_{entrance} + \Delta P_{exit} = K \cdot \frac{\rho v^2}{2} \quad (1)$$

In the above, K is total form loss factor of fuel channel.

According to the results of the bundle junction rotational pressure drop test[8] in KAERI cold test loop, it was found that the alignment angles for the most probable pressure drop were 28° and 31° of the CANFLEX and 37-element bundles, respectively. The most probable pressure drop test[9] was performed in KAERI hot test loop with aligning 12 fuel bundles. Form loss factors[10] of CANFLEX-NU and 37-element bundle were derived as 9.6 and 12.6 respectively, which were assumed to be constant due to the high flow and the fully developed turbulent flow in the Reynolds number region of reactor operating ranges.

2.3 CHF Prediction Model

The bundle CHF lookup table[6] was developed, based on the various water CHF test data of the mockup bundles with the uniform and cosine axial heat flux distributions. It covers broad flow range and predicts CHF using input parameters of pressure, mass flux and quality based on flow area averaged conditions. The bundle CHF lookup table was developed mainly to apply for the 37-element NU bundle. The application method to the CANFLEX fuel bundle was suggested by the reference[11] in which two correction factors for the CANFLEX fuel bundle were used. The first is CHF enhancement factor to consider the geometrical difference effect between 37-element bundle and CANFLEX fuel bundle, and the second is RFD factor to consider the radial flux distribution variation due to the burnup or fuel composition change from the natural uranium to the enriched uranium. In the present analysis, RFD effect is not considered, because the composition of CANFLEX bundle is natural uranium.

The CHF test of CANFLEX-NU fuel bundle was carried out in AECL-CRL MR-3a loop with Freon-22 coolant and uniform heat flux. As the parameter of CHF ratio between 37-element and

CANFLEX-NU bundle, LDP(Linear Dryout Power) factor[5], $K_{enhancement}$, was suggested to compare the linear dryout powers of two bundles by using the experimental data. $K_{enhancement}$ was expressed as the function of pressure, mass flow and dryout quality as the following.

$$K_{enhancement} = \frac{a \cdot (1-x_c)^{bP_w} + c \cdot W_w^{\,d}}{(1-x_c)^{eP_w} + f \cdot W_w^{\,g}} \qquad (2)$$

Where, X_c is dryout quality, P_w is pressure(MPa), W_w is mass flow(kg/s) and a, b, c, d, e, f, g are constant numbers.

2.3 Mixed Fuel Channel Model

To establish the mixed fuel channel model, the following assumptions were used: (i) the mixed fuel channel will not affect the header-to-header pressure drop, (ii) the pressure drop of mixed fuel string channel is given by the sum of the most probable pressure drop of each bundle and 1.0% of this sum due to one mixed junction in the bundle string, (iii) dryout takes place at the downstream fuel bundle, thus the CHF correlation of downstream bundle is used to determine dryout power, and (iv) the normal axial peak power takes place at 3.0 m location from the channel inlet, and the tilted axial peak power is assumed to take place at 3.6 m location, in order to compare the effect of axial power distribution on dryout power.

The normal and tilted AFD were used of the axial power distributions, provided by the assumption (iv), as shown in Figure 2. According to the 8 bundle shift refueling scheme[12] of CANDU-6 reactor, the mixed fuel channel models given in Table 1 were selected. Because the thermal margin of the mixed fuel channel is dependent on the downstream bundles, 37-element bundle on the process of CASE I→ CASE II and CANFLEX bundle on the process of CASE III→CASE IV should be reference bundle for the derivation of the most probable form loss factor and the application of CHF correlation.

3. Results

For the full loading of CANFLEX-NU fuel bundles in the CANDU-6 reactor, Figure 3 showed the channel flow distributions with respect to the percentage of channel number within radius from core center. More than 50% channels had the high flow rate above 24 kg/s and flow rates of the 50% outer channels were rapidly decreased as increasing core radius. The maximum channel flow was decreased about 1.8% due to the increase of the most probable fuel channel pressure drop, but overall flow conditions were very similar to those of a standard 37-element bundle. The five major T/H characteristics channels of 380 fuel channels were selected as the highest power(N-6), the highest flow(L-5), the highest exit quality(O-11), the lowest power/lowest flow(V-6) and the lowest CPR(O-6) channels. All the characteristics channels except the lowest flow(V-6) channel were located within the region of 50% core radius as shown in Figure 3. With the investigations of the effects of fuel channel hydraulics and the CHF of the bundle in the five major T/H characteristics channels, the CCP of CANFLEX-NU fuel bundle was negligibly small affected by flow decrease and dominantly increased by CHF enhancement as shown in Figure 4. The CCP of the lowest CPR channel O-6 was about 5.0% more than 37-element bundle.

Figure 5 showed the dryout power curve of the mixed fuel channel which was determined only by CHF correlation. The dryout power of CANFLEX-NU bundle located at downstream was increased by about 11.4% under the constant 19.0 kg/s channel flow condition, compared with that of the 37-element bundle, as shown in Table 1. The dryout power of the tilted AFD was about 3.6% less than the normal AFD. In the case of the downstream tilted AFD, dryout occurred at the low channel power because the local heat flux was increased at CHF onset location.

In the Table 1 summarized for the mixed fuel channel analysis, the dryout results under the constant header-to-header pressure drop condition mean the CCP of the mixed fuel channel which was determined by both channel pressure drop characteristics curve and CHF curve. The channel flow of the mixed fuel channel was about 1.2% less in case of the normal AFD and about 0.8% less in case of the tilted AFD, compared with that of the full loading of 37-element bundle in the channel. The downstream tilted AFD made the channel flow increase more than the normal AFD, which was caused by the fact that two phase pressure drop was decreased by moving the location of boiling onset to downstream.

In the CASE II and CASE IV, both mixed channel models had the identical channel flow but applied the different CHF correlation with respect to the downstream bundle type. In the CASE II with 37-element bundles in the downstream, the CPR was 1.403 and 1.413 respectively according to the axial power distributions. These results showed the about 0.4% less than CASE I with the full loading of the 37-element bundle in the channel, which was caused by the fact that the channel flow of the mixed fuel channel was about 1.2% decreased. In the CASE IV with CANFLEX-NU fuel bundles in the downstream, the CPR was 1.476 and 1.502 respectively according to the axial power distributions. These results showed the about 4.8% and 5.9% respectively more than CASE I, which was caused by the fact that dryout power was increased due to the CHF enhancement, despite of flow decrease.

4. Conclusion

The CCP assessments of CANFLEX-NU fuel bundles in the CANDU-6 reactor give the following conclusions, compared with those of a standard 37-element bundle in case of both full and partial loading of CANFLEX-NU fuel bundles in the reactor.

- CANFLEX-NU fuel bundle will be hydraulically compatible with CANDU-6 PHTS because the flow distributions are very similar to those of 37-element bundle.
- As an interim result, the CCP of CANFLEX-NU fuel bundle is about 5.0% increased, which is mainly dominated by the CHF enhancement but negligibly affected by the flow decrease.
- The tilted AFD will decrease the CCP under the fixed flow condition due to the increase of local heat flux at CHF onset location, however it can increase the CCP under the constant header-to-header pressure drop condition due to the shorter boiling length than that of the normal AFD.
- CANFLEX-NU fuel bundle will not affect ROP trip set point because of CCP improvement in case of both full and partial loading.

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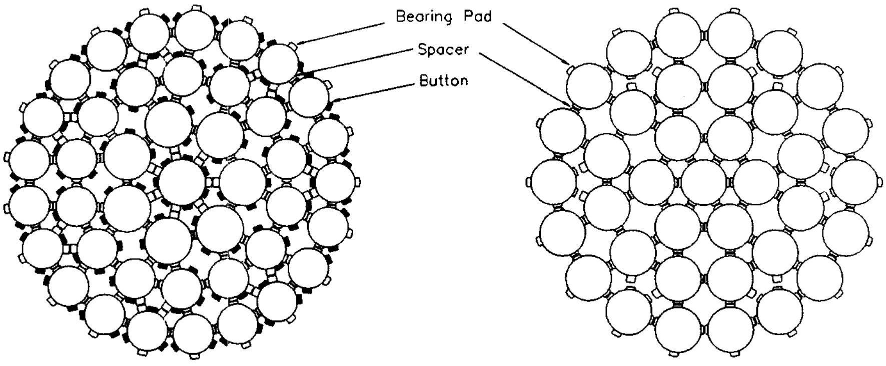

(a) CANFLEX-NU Fuel Bundle (b) 37-element Bundle

Figure 1 Cross Sectional View of CANFLEX-NU and 37-element Bundle

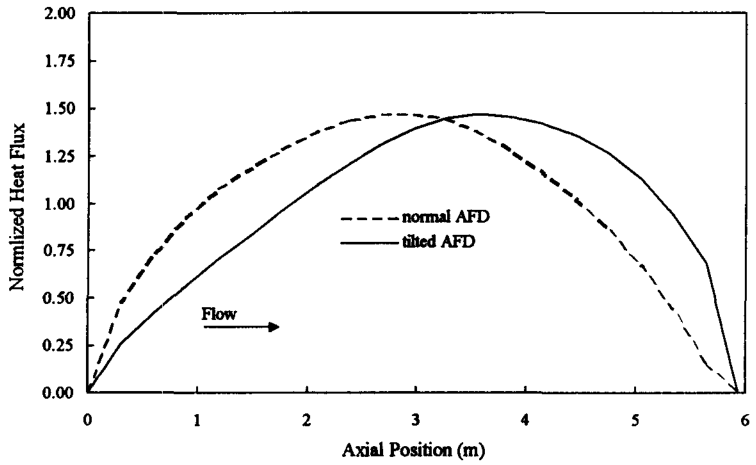

Figure 2 The Normal and Tilted AFD for the Mixed Fuel Channel Analysis

Table 1 The Dryout Power Results of the Mixed Fuel Channels

Bundle String Model	Power (kW)	Constant Head to Head Pressure Drop Condition				Constant Channel Flow Condition			
		Flow(kg/s)		CCP(kW)	CPR	CCF(kg/s)		CCP(kW)	CPR
CASE I 12 No. of 37-element	6553	normal	25.8	9227	1.408	normal	19.0	9249	1.411
		tilted	26.1	9292	1.418	tilted	19.0	8929	1.363
CASE II Upstream : 4 No. of CANFLEX Downstream : 8 No. of 37-element	6549	normal	25.5	9185	1.403	normal	19.0	9251	1.413
		tilted	25.9	9254	1.413	tilted	19.0	8930	1.364
CASE III 12 No. of CANFLEX	6540	normal	25.5	9649	1.475	normal	19.0	10303	1.575
		tilted	25.8	9819	1.501	tilted	19.0	9939	1.520
CASE IV Upstream : 8 No. of 37-element Downstream : 4 No. of CANFLEX	6549	normal	25.5	9668	1.476	normal	19.0	10304	1.573
		tilted	25.9	9838	1.502	tilted	19.0	9940	1.518

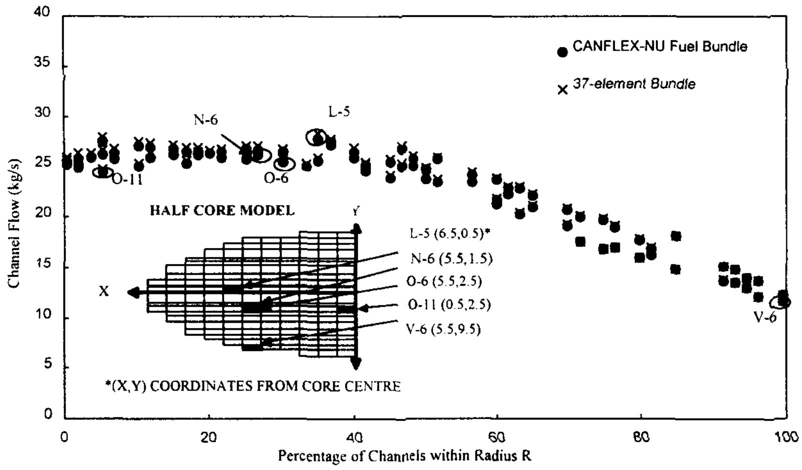

Figure 3 The Channel Flow Distributions at Full Reactor Power

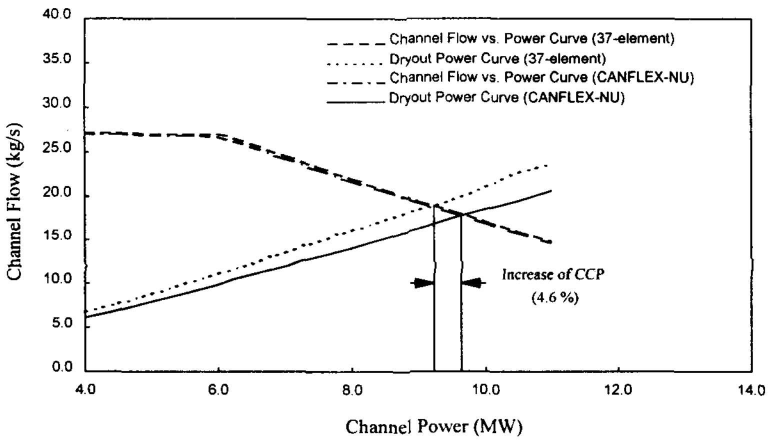

Figure 4 The CCP Characteristics of O-6 Channel with CANFLEX-NU Fuel Bundle

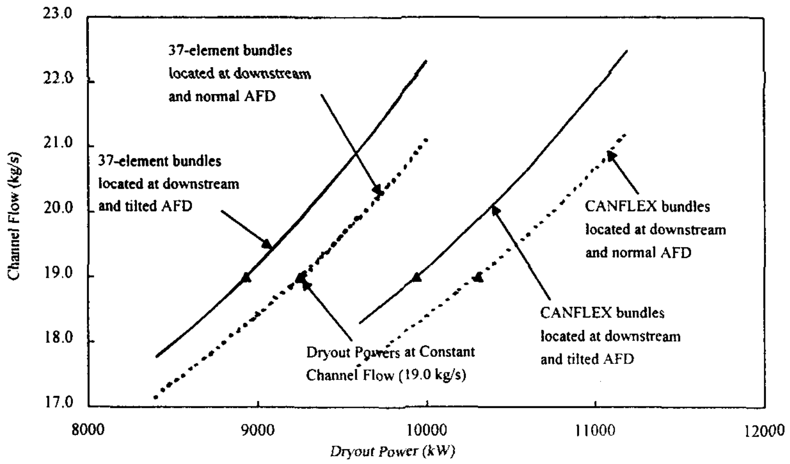

Figure 5 The Dryout Power Curves of the Mixed Fuel Channel with Normal and Tilted AFD