The thermal–hydraulic characteristics for the CANadian Deuterium Uranium Flexible (CANFLEX)-burnable poison (BP) fuel channel, which is loaded with a BP at the center ring based on the CANFLEX-RU (recycled uranium) fuel channel, are evaluated and compared with that of standard 37-element and CANFLEX-NU (natural uranium) fuel channels. The distributions of fuel temperature and critical channel power for the CANFLEX-BP fuel channel are calculated using the NUclear Heat Transport CIRcuit Thermohydraulics Analysis Code (NUCIRC) code for various creep rate and burnup. CANFLEX-BP fuel channel has been revealed to have a lower fuel temperature compared with that of a standard 37-element fuel channel, especially for high power channels. The critical channel power of CANFLEX-BP fuel channel has increased by about 10%, relative to that of a standard 37-element fuel channel for 380 channels in a core, and has higher value relative to that of the CANFLEX-NU fuel channel except the channels in the outer core. This study has shown that the use of a BP is feasible to enhance the thermal performance by the axial heat flux distribution, as well as the improvement of the reactor physical safety characteristics, and thus the reactor safety can be improved by the use of BP in a CANDU reactor.

1. Introduction

The power coefficient is one of the most important physics parameters governing nuclear reactor safety and operational stability. The power coefficient of the nuclear reactor should be less than or equal to zero for stable operation of a power reactor. However, for the equilibrium CANadian Deuterium Uranium (CANDU) core, the power coefficient and the fuel temperature coefficient were reported to be slightly positive when newly developed Industry Standard Toolset reactor physics codes were used [1]. Therefore, it was necessary to find a new way to effectively decrease the positive power coefficient and the fuel temperature coefficient in order to enhance the safety and operational stability of a CANDU reactor. Recently, the application of burnable poison (BP) has been proposed to improve the power coefficient of the CANDU reactor.
reactor, and the optimal BP material and loading scheme have been obtained from the physics study for the CANDU reactor loaded with a CANFLEX-RU (CANDU Flexible-recycled uranium) fuel bundle [2]. It was shown that the use of BP is feasible to render the power coefficient of a CANDU reactor negative, and thus the reactor safety characteristics can be improved through the use of BP in a CANDU reactor.

However, a previous study has mainly focused on the safety characteristics related to the reactor physics by evaluating the power coefficient for the fuel channel using BP in the CANDU reactor. Together with the safety parameter related to the reactor physics, the thermal—hydraulic characteristics, including economic performance, should be evaluated in order to render the newly designed advanced fuel channel to be applicable to the reactor power plant. The critical channel power (CCP) is directly related to the thermal margin of the power plant, and a fuel channel with high CCP is desirable for an advanced fuel channel to maintain the full power level for the reactor power plant operation. In this study, the thermal—hydraulic characteristics related to the economic performance have been evaluated by analyzing the CCP for a fuel channel with a BP in a CANDU reactor. As shown in Fig. 1, the fuel channel with BP is selected as a CANFLEX-RU fuel bundle loaded with 11.0 wt.% $\text{Er}_2\text{O}_3$ in the central fuel rod (hereafter called CANFLEX-BP), which is revealed to be the most optimal design among the various loading schemes of BP in a previous study [2].

However, the fuel temperature coefficient is also an important safety-related parameter that is closely related to the power coefficient, and has been known to be largely dependent on the fuel temperature [3]. Hence, for an accurate evaluation of the safety-related physics parameters, including the fuel temperature coefficient, the fuel temperature distribution and its correlation with the coolant temperature should be accurately identified. Therefore, we have evaluated the fuel temperature distribution of a CANFLEX fuel bundle loaded with a BP and compared it with a standard 37-element fuel bundle and CANFLEX-NU (natural uranium) fuel bundle.

This study presents the results of a thermal—hydraulic analysis for the CANFLEX-BP fuel channel, which is known to have an improved power coefficient. In Section 2, the calculation conditions and numerical methods of fuel temperature calculation are briefly introduced. The fuel temperature characteristics for the standard 37-element, CANFLEX-NU, and CANFLEX-BP fuel channels with different axial and radial power distributions (RPDs) are analyzed in Section 3.1. To evaluate the thermal performance of the CANFLEX-BP fuel

![Fig. 1 – Configuration of fuel channels. (A) Standard 37-element fuel channel. (B) CANFLEX fuel channel with NU. (C) CANFLEX fuel channel with BP. BP, burnable poison; CANFLEX, CANadian Deuterium Uranium; NU, natural uranium.](image)
channel, the CCP is calculated in Section 3.2 and compared with the other fuel channels. Finally, a summary and conclusions are given in Section 4.

2. Numerical methods

A thermal–hydraulic analysis for a CANDU reactor loaded with standard 37-element or CANFLEX fuel channel was performed with the NUClear Heat Transport CIRcuit Thermohydraulics Analysis Code (NUCIRC) code, which predicts the fuel temperature and CCP for each fuel channel of a CANDU reactor, based on the given heat source and boundary conditions [4]. The calculations were performed under normal operating conditions with an inlet header temperature of 262 °C, an outlet header pressure of 9.99 MPa, and a header-to-header pressure drop of 1,282 kPa. For simulating the heat transport system of the CANDU reactor with the CANFLEX or 37-element fuel channel, the same NUCIRC input parameters are used, except for those related to the fuel channels, e.g., the form loss factor in the pressure drop model and the selection of critical heat flux (CHF) correlation are dependent on the bundle type in the fuel channel [5].

The fuel temperature for a CANDU reactor is mainly dependent on the fuel property, coolant temperature, and power generation in the fuel. The material properties, including a thermal conductivity, are given with the function of temperature from previous experimental literature [6]. The coolant temperatures are obtained with the NUCIRC code calculation, in which one-dimensional analyses are performed in an axial direction with the given bundle power. Because the coolant temperature has a one-dimensional distribution with the axial distance of the channel, the fuel rods on the same ring have the same temperature, and are dependent on the ring power distribution and coolant temperature in a channel. Hence, the fuel temperature for a representative fuel rod in each ring is first calculated, and the fuel temperature of a bundle is secured when considering the number of fuel rods of each ring.

\[
T_i = \frac{N_1 \times T_{f1} + N_2 \times T_{f2} + N_3 \times T_{f3} + N_4 \times T_{f4}}{N_{tot}},
\]

where \(T_f\) means the fuel temperature of a bundle, and \(N_1, N_2, N_3,\) and \(N_4\) denote the number of fuel rods in each ring, which is 1, 6, 12, and 18 for a standard 37-element fuel channel, and 1, 7, 14, and 21 for a CANFLEX fuel channel, respectively, and \(N_{tot}\) is the total number of fuel rods in a channel. Also, the averaged fuel temperature for each channel is secured by averaging the fuel temperatures of 12 bundles in the channel. The detailed calculation procedure for fuel temperature is well documented by Bae et al [7].

3. Results

3.1. Fuel temperature characteristics

The axial heat flux distribution for the standard 37-element, CANFLEX-NU, and CANFLEX-BP fuel channels are shown in Fig. 2. The power distributions are dependent on the fuel composition and the refueling scheme. The RU fuel bundle uses a four-bundle refueling scheme to meet the current CANDU fuel performance criteria, instead of the eight-bundle refueling scheme of the NU fuel bundle [8]. In this paper, the CANFLEX-NU and Standard-37 fuel channels have been supposed to use the eight-bundle refueling scheme, whereas the CANFLEX-BP fuel channels use the four-bundle refueling scheme.

The axial peak location of the CANFLEX-BP fuel channel tends to move upstream, whereas the standard 37-element and CANFLEX-NU fuel channels maintain a cosine shape. The axial heat flux distribution of the CANFLEX-BP fuel channel is caused by the use of the four-bundle refueling scheme of the RU fuel bundle in place of the eight-bundle refueling scheme of the NU fuel bundle. The axial heat flux distribution of a CANFLEX-BP fuel channel is optimized to increase the CCP of the CANadian Deuterium Uranium of type 6 (CANDU-6) reactor, because it decreases the local heat flux at the downstream of a channel where a dryout preferentially occurs.

Fig. 3 shows the relative ring-wise linear power distribution depending on the fuel burnup for CANFLEX-NU and CANFLEX-BP fuel bundles. Ring number 1 indicates the central fuel element, and ring number 4 stands for the outermost fuel ring. The relative linear power is the ratio of specific element power relative to the average element power, which is obtained from a HELIOS calculation [9]. Fig. 3 shows that the RPD of the CANFLEX-BP fuel continuously changes as the fuel burnup increases, whereas that of the CANFLEX-NU fuel remains the same throughout the fuel burnup. In the initial burnup conditions, the ring power of the CANFLEX-BP fuel bundles has the lowest value in the first fuel ring, because of the BP in the center fuel element. However, the RPD of the first fuel ring steadily increases as the BP is depleted. The linear power of the second ring is also rather low owing to thermal flux depression in the central region of the fuel bundle, and it increases gradually with the fuel burnup. Meanwhile, the change in linear power is quite small in the third ring for the whole lifetime. Therefore, in the initial burnup condition, the CANFLEX-BP fuel bundle has the highest value of linear power at the outermost ring among
the four rings, whereas the highest linear power region is changed to the second ring as the fuel burns.

The fuel temperature of each ring was compared among the standard 37-element, CANFLEX-NU, and CANFLEX-BP fuel channels at the mid-burnup condition, and the result is shown in Fig. 4. It is noted that, for the standard 37-element fuel channel, the minimum relative linear power occurs at the central element and increases monotonically with the ring number, whereas for the CANFLEX fuel channel, the third ring has the minimum linear power and a w-shape radial power profile is observed. Similarly with the radial power ratio of each fuel bundle, the CANFLEX fuel temperature in the third and fourth rings has a lower value compared with that of a standard 37-element. The CANFLEX-BP fuel channel has a similar temperature profile with the CANFLEX-NU fuel channel, except that the central rod fuel temperature is smaller by the loading of BP.

Figs. 5–7 show the fuel temperature distribution for 380 channels for the standard 37-element, CANFLEX-NU, and CANFLEX-BP fuel channels, respectively. The representative fuel temperatures for each ring are presented at the mid-burnup condition. For the case of the standard 37-element fuel channel, the fuel temperature of the first ring has the lowest value. As in the radial bundle power distribution, the fuel temperature steadily increases with the ring number, and the fuel temperature has the highest value at the fourth ring. It is shown in Fig. 5 that, for the high power channels near the center of the reactor, the difference in fuel temperature between the first and fourth rings is larger than that for the lower power channels at the peripheral region of reactor core. In addition, fuel temperature is shown to have nearly the same value for the center region of the reactor core, and linearly decreases as the distance from the core center increases.

For the case of a CANFLEX-NU fuel channel, the fuel temperature has the lowest value at the third ring, and has the maximum value at the fourth ring, which is in line with the radial bundle power distribution. It is shown in Fig. 6 that the fuel temperature of the fourth ring is largely decreased for the CANFLEX-NU fuel channel, compared with that of a standard 37-element fuel channel. In particular, for high power channels, it has a lower fuel temperature of about 100 °C and results...
in a decrease in the average fuel temperature of the CANFLEX NU fuel channel. It is shown in Fig. 7 that the fuel temperature of the CANFLEX-BP fuel channel has the lowest value at the first ring because of the BP loaded in the center fuel element, and has the maximum value at the fourth ring. The use of RU in the CANFLEX-BP fuel channel, except the first ring, increases the fuel temperature in the third and fourth rings, which results in an increase in the difference in fuel temperature among the four rings compared with that of the CANFLEX-NU fuel channel.

Fig. 8 shows the average fuel temperature distribution for 380 channels for the standard 37-element, CANFLEX-NU, and CANFLEX-BP fuel channels. It is shown in the figure that, although the fuel temperature for the CANFLEX-BP fuel channel has a slightly higher value compared with that of the CANFLEX-NU fuel channel, the CANFLEX-BP fuel channel has a lower fuel temperature compared with that of the standard 37-element fuel channel, especially for high power channels. The fuel temperature is closely related with the fuel temperature coefficient, which is one of the most important parameters in the reactivity-induced transient analysis. Because the fuel temperature coefficient tends to increase with the fuel temperature, and has an important impact on the safety characteristics at a high fuel temperature [2], the decreased fuel temperature of the CANFLEX-BP fuel channel for high power channels means that it can enhance the fuel safety and operational stability compared with the standard 37-element fuel channel.

Fig. 9 shows the fuel temperature variation for the CANFLEX-NU and CANFLEX-BP fuel channels at the initial, mid, and discharge burnup. It is shown in the figure that the fuel temperatures steadily increase with the fuel burnup, because of the deteriorated thermal conductivity of fuel and the increase in gap resistance. In particular, the increase in fuel temperature is noticeable during the period between the initial and mid burnup. Furthermore, the CANFLEX-BP fuel channels experience a larger increase of fuel temperature with the fuel burnup, relative to that of the CANFLEX-NU fuel channels, especially in the first and second rings, because of the presence of BP. The representative fuel temperatures in each ring are listed in Table 1 for a standard 37-element fuel channel, CANFLEX-NU, and CANFLEX-BP fuel channels at the initial, mid, and discharge burnup. For the entire period of burnup, the CANFLEX-BP fuel channel has decreased the maximum fuel temperature by about 50 °C, compared with that of the standard 37-element fuel channel, and the CANFLEX-NU fuel channel shows the lowest maximum fuel temperature among the three fuel channels.

Fig. 10 represents the fuel temperature of the standard 37-element, CANFLEX-NU, and CANFLEX-BP fuel channels with the function of bundle power for the 2,580 bundles in a core. As expected, the fuel temperatures steadily increase with the bundle power and have a temperature range of 270–980 °C for a bundle power of 50–1,000 kW. For the entire range of bundle power, the CANFLEX-BP fuel channel has a lower fuel temperature compared with that of the standard 37-element fuel channel, and has a slightly higher fuel temperature than the CANFLEX-NU fuel channel. The differences in fuel temperature among the fuel channels are negligible in the low bundle powers and increase as the bundle power increases. As remarked previously, the difference in fuel temperatures in the
region of high bundle power has greater meaning from the viewpoint of the safety characteristics related to the fuel temperature coefficient. It is shown in Fig. 10 that the fuel temperature of each fuel channel has two different values for the same bundle power, because the fuel temperature is dependent on the coolant temperature, as well as the bundle power. It was noted that the bundle power has a cosine shape in a channel, whereas the coolant temperature steadily increases along a channel. Hence, the fuel temperature has two different values for the same bundle power at the upstream and downstream of the channel. To exclude the effect of axial coolant temperature variation, the differences between the fuel temperature and coolant temperature are displayed in Fig. 11, with a function of bundle power. It is shown in the figure that the temperature difference between the fuel and coolant are well expressed with the second-order equation, with respect to the bundle power. Hence, the fuel temperature has the following relationship with respect to the coolant temperature and bundle power:

\[ T_f = T_c + AP + BP^2 \]  

(2)

where \( T_f \) is the effective fuel temperature in K, \( T_c \) is the effective coolant temperature in K, and \( P \) is the bundle thermal power in kW. Constants \( A \) and \( B \) are determined by the curve fitting into the second-order equation, and are listed in Table 2 for the standard 37-element, CANFLEX-NU, and CANFLEX-BP fuel channels at the initial, mid, and discharge burnup. Since the fuel temperature of the standard 37-element fuel channel has the highest value among the fuel channels, the constants \( A \) and \( B \) have the largest value for the standard fuel channel for the entire range of burnup. In addition, the constants \( A \) and \( B \) for the three fuel channels are shown to increase with burnup, which is in line with the fuel temperature characteristics. These correlations have error bands of ±15% and are applicable in the range of 100 < \( P < 800 \) kW.

### 3.2. CCP characteristics

CCP, which is defined as the channel power when a CHF occurs on the surface of a fuel rod, is an important parameter to evaluate the thermal margin of a fuel channel [11]. Fig. 12 shows the CCP distribution of the CANFLEX-BP fuel channel for 380 channels in a core, together with that of the standard 37-element and CANFLEX-NU fuel channels. Irrespective of the fuel bundle type, the high power channels in a central core have a larger CCP compared to the low power channels in the outer core, because the high power channels have a larger channel flow rate compared with that of the low power channels. It was also revealed from the figure that the CCP of CANFLEX type fuel channels (CANFLEX-NU and CANFLEX-BP) have a larger value compared to that of the standard 37 fuel channels owing to the CANFLEX design characteristics of a dual-sized 43-element bundle.

Fig. 13 shows the CCP ratio of a CANFLEX-BP fuel channel compared to that of the standard 37-element fuel channel in a core. The CCP of the CANFLEX-BP fuel channel has increased about 10% relative to that of the standard 37-element fuel channel for most of the channels in a core. The figure also shows that the relative ratio of the CCP are greater than 1.0 for the 15 and 30 EFPY (effective full power years), which reflects that the CANFLEX-BP fuel channels have sustained the relative increase of CCP for the whole operating period of a nuclear power plant.

### Table 1 – Constant value for fuel temperature prediction equation.

<table>
<thead>
<tr>
<th>Fuel channel</th>
<th>Burnup</th>
<th>Constant A</th>
<th>Constant B</th>
</tr>
</thead>
<tbody>
<tr>
<td>37-element</td>
<td>Fresh</td>
<td>0.4323</td>
<td>1.22E-04</td>
</tr>
<tr>
<td></td>
<td>Mid</td>
<td>0.4887</td>
<td>1.49E-04</td>
</tr>
<tr>
<td></td>
<td>Discharge</td>
<td>0.4956</td>
<td>1.66E-04</td>
</tr>
<tr>
<td>CANFLEX-NU</td>
<td>Fresh</td>
<td>0.3828</td>
<td>7.91E-05</td>
</tr>
<tr>
<td></td>
<td>Mid</td>
<td>0.4411</td>
<td>1.04E-04</td>
</tr>
<tr>
<td></td>
<td>Discharge</td>
<td>0.4556</td>
<td>1.12E-04</td>
</tr>
<tr>
<td>CANFLEX-BP</td>
<td>Fresh</td>
<td>0.3737</td>
<td>8.02E-05</td>
</tr>
<tr>
<td></td>
<td>Mid</td>
<td>0.4321</td>
<td>1.10E-04</td>
</tr>
<tr>
<td></td>
<td>Discharge</td>
<td>0.4510</td>
<td>1.23E-04</td>
</tr>
</tbody>
</table>

BP, burnable poison; CANFLEX, Canadian Deuterium Uranium Flexible; NU, natural uranium.
It was revealed that the CCP of the CANFLEX-BP fuel channel has an increased value for all channels compared to that of the CANFLEX-NU fuel channel, except the channels in the outer core for 30 EFPY. It is important to note that, although the CANFLEX-BP fuel channel was originally designed to enhance the reactor physical safety characteristics, it does not reduce the thermal performance of the fuel bundle, but rather the thermal performance is increased by the axial heat flux distribution of the CANFLEX-BP fuel channel when compared to that of the CANFLEX-NU bundle as well as the standard 37-element fuel channel. In addition, the relative increase of the CCP is noticeable for high power channels in the central core, which is closely related to the operating safety margin of the core [12].

The pressure tube diametral creep causes a bypass flow between the top of the bundle and the pressure tube, and reduces the effective heat transfer through the inner sub-channels of the bundle. Therefore, it is known that pressure tube creep will cause a reduction in CCP owing to the decrease in CHF [13]. Fig. 15 shows that the CCP decreases of the CANFLEX-BP fuel channel in the 3.3% crept and 5.1% crept channels in a core are about 12% and 20%, respectively. However, it shows that the CCP decreases for the 37-element bundle are about 15% and 23%, respectively, which are greater than those of the CANFLEX-BP fuel channel. This means that the CANFLEX-BP fuel channel is considerably less

### Table 2 — Fuel temperature comparison among fuel channels.

<table>
<thead>
<tr>
<th>Fuel channel</th>
<th>Burnup</th>
<th>Fuel Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Ring 1</td>
</tr>
<tr>
<td>37-element</td>
<td>Fresh</td>
<td>517.7</td>
</tr>
<tr>
<td></td>
<td>Mid</td>
<td>549.6</td>
</tr>
<tr>
<td></td>
<td>Discharge</td>
<td>561.8</td>
</tr>
<tr>
<td>CANFLEX-NU</td>
<td>Fresh</td>
<td>549.0</td>
</tr>
<tr>
<td></td>
<td>Mid</td>
<td>589.6</td>
</tr>
<tr>
<td></td>
<td>Discharge</td>
<td>604.0</td>
</tr>
<tr>
<td>CANFLEX-BP</td>
<td>Fresh</td>
<td>464.1</td>
</tr>
<tr>
<td></td>
<td>Mid</td>
<td>551.6</td>
</tr>
<tr>
<td></td>
<td>Discharge</td>
<td>615.8</td>
</tr>
</tbody>
</table>

BP, burnable poison; CANFLEX, CANadian Deuterium Uranium Flexible; CNU, natural uranium.

**Fig. 12** — Comparison of CCP among fuel channels. BP, burnable poison; CANFLEX, CANadian Deuterium Uranium Flexible; CCP, critical channel power; NU, natural uranium.

**Fig. 13** — CCP ratio of CANFLEX-BP fuel channel to 37-element fuel channel. BP, burnable poison; CANFLEX, CANadian Deuterium Uranium Flexible; CCP, critical channel power.

**Fig. 14** — CCP ratio of CANFLEX-BP to CANFLEX-NU fuel channel. BP, burnable poison; CANFLEX, CANadian Deuterium Uranium Flexible; CCP, critical channel power; NU, natural uranium.
sensitive to the CCP reduction, owing to the pressure tube creep, than the 37-element bundle. It was also found that the amount of CCP reduction due to the pressure tube creep increases in the outer-core region for both the standard 37-element and CANFLEX-BP fuel channels.

4. Discussion and conclusion

The CANFLEX-BP fuel channels have a lower fuel temperature compared with that of the standard 37-element fuel channel, especially for high power channels. Because the decreased fuel temperature brings about a decrease in the fuel temperature coefficient and power coefficient, the CANFLEX-BP fuel channel can enhance the safety and operational stability of the CANDU reactor, compared with the standard 37-element fuel channel. The radial fuel temperature distribution in a CANFLEX-BP fuel channel is in accordance with the relative power distribution having the minimum value at the center ring. The center and inner rings of the CANFLEX-BP fuel channels experience a larger increase of fuel temperature with the fuel burnup owing to the presence of BP. For the entire period of burnup, the maximum fuel temperature of the CANFLEX-BP fuel channel is decreased by about 50°C relative to that of the uncrept channel. Hence, the CANFLEX-BP fuel channel is less sensitive to the CCP reduction caused by pressure tube creep, relative to the 37-element fuel channel.

Conflicts of interest

No declared.

Acknowledgments

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea Government (Ministry of Science, ICT, and Future Planning) (No. NRF-2012M2A8A4025960).

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Fig. 15 – Critical channel power (CCP) ratio of the crept channel to the uncrept channel. BP, burnable poison; CANFLEX, CANadian Deuterium Uranium Flexible; NU, natural uranium.