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Consideration of Subchannel Area of a 37-element Fuel to Enhance CHF

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ABSTRACT – A CANDU-6 reactor has 380 fuel channels of a pressure tube type, which provides an independent flow passage, and each pressure tube contains 12 fuel bundles horizontally. The CHF of a CANDU fuel bundle in a horizontal fuel channel is one of the important parameters determining the thermalhydraulic safety margin as well as the trip set point of the Regional Overpower Protection (ROP) system. Hence, the CHF enhancement of a CANDU fuel bundle has been an issue for a long time and can be affected by the geometric configuration of the fuel elements as well as several appendages such as the end-plates, bearing pads, and spacers attached to the fuel elements. This paper considers the modification of the inner ring radius of a standard 37-element fuel bundle to enhance the CHF, since the CHFs of a standard 37-element fuel bundle preferably occur at the peripheral subchannels of the center rod, owing to the relative small flow area or high flow resistance under high flow conditions or the normal operating conditions of a CANDU reactor. Subchannel analysis techniques using the ASSERT-PV code were applied to investigate the local CHF characteristics according to the inner ring radius variation for the original diameter of the pressure tube. It was found that the modification of the inner ring radius is very effective in enhancing the dryout power of the fuel bundle under the reactor operating conditions through an enthalpy re-distribution of the subchannels and change in the local locations of the first CHF occurrences.

1. Introduction

A CANDU-6 reactor has 380 fuel channels of a pressure tube type, which creates an independent flow passage where the fuel bundles rest horizontally. Most of the aging effects for a CANDU operating performance originate from a horizontal creep pressure tube. As the operating years of a CANDU reactor proceeds, a pressure tube experiences high neutron irradiation damage under high temperature and pressure. It is expanded radially as well as axially during its life time, resulting in a creep of the pressure tube, which allows a by-pass flow on the top section inside the pressure tube owing to more open space in its top section than bottom section. Hence, the creep pressure tube deteriorates the CHF (Critical Heat Flux) of the fuel channel and finally worsens the reactor operating performance and thermal margin. This is known to be a very important phenomenon of a CHF for a horizontal pressure tube owing to the aging effects.

During the last three decades, many papers have been published to enhance the CHF and/or Critical Channel Power (CCP), which is determined by the dryout and hydraulic characteristic curves of the primary heat transfer system of a CANDU reactor [1, 2, 3, 4]. In the late 1970s, a turbulent promoter was invented to increase the turbulent intensity surrounding the fuel elements in a fuel channel [1]. The axial positions or number of bearing pad planes were changed, or the number of spacer pad planes were increased to enhance the CHF by means of increasing the turbulent intensity or flow mixing within a fuel passage [2]. These attempts provided a CHF increase, but an adverse effect on the CCP existed to worsen the hydraulic characteristics of the primary heat transfer system when increasing the pressure drop of the fuel channel.

On the other hand, the Korea Atomic Energy Research Institute (KAERI) and Atomic Energy Canada Limited (AECL) have developed the CANFLEX fuel jointly since 1991. The CANFLEX fuel was designed to mainly recover the ROP margin reduction caused by the aging of the pressure tubes. Using two pin sizes and CHF enhancement buttons of the CANFLEX fuel, it was known that the CANFLEX fuel can achieve remarkable CHF enhancement for the aging of the pressure tubes [6, 7]. However, it has not been commercialized yet, owing to a more complex design and higher fabrication cost than those of a standard 37-element fuel bundle.

In particular, a 37-element fuel bundle has been used in commercial CANDU reactors for over 40 years as a reference fuel bundle. Most of the first CHF of a 37-element fuel bundle were occurred at the center subchannels adjacent to the center rod at high flows [9], or under reactor conditions of which the reference flow rate is 24kg/s [8]. This causes the 37-element fuel to have a relatively small flow area and high flow resistance at the peripheral subchannels of the center rod compared to the other subchannels. The configuration of a fuel bundle is one of the important factors affecting the local CHF occurrence. Recently, the diameter effect of each rod located in the center, inner, intermediate, and outer rings of the 37-element fuel bundle has been studied [10]. It was shown that the dryout power of a fuel bundle has a tendency to increase as the size of the rod diameter decreases. However, a decrease of the rod size of a fuel bundle increases the coolant volume in a fuel channel. Finally, it can deteriorate the safety margin by increasing the coolant void reactivity, etc.

This paper introduces the modification of a ring radius, especially an inner ring radius, to increase the CHF. Also, the dryout power and CHF occurrence were analyzed for a standard 37-element fuel bundle with the modified inner ring radius. In addition, the effects of the inner ring radius variation on the subchannel enthalpy distribution and dryout power of the proposed modification were examined, and the results were compared to those of the standard 37-element fuel bundle.

2. Subchannel Modeling

For the sensitivity studies of the effect of an inner ring radius on the CHF or dryout power of a fuel bundle, the subchannel analysis was performed using the ASSERT code [11] (Carver, 1995), which was transferred from AECL to KAERI under a Technology Transfer Arrangement (TCA) between KAERI/AECL. It is known that the subchannel analysis technique is a very useful tool to precisely investigate the thermal-hydraulic behavior of a fuel bundle in a nuclear reactor. In the present study, the subchannel analysis for a horizontal flow has been performed with a variation of the inner ring radius of a fuel bundle.

2.1 Geometry of a Fuel Bundle

Standard 37-element fuel is composed of 37 fuel elements and 4 rings, a center ring, an inner ring, an intermediate ring, and an outer ring, and several appendages such as bearing pads, spacer pads, and end-plates to configure a bundle structure, as shown in Fig. 1. In addition, each ring radius is summarized in Table 1.

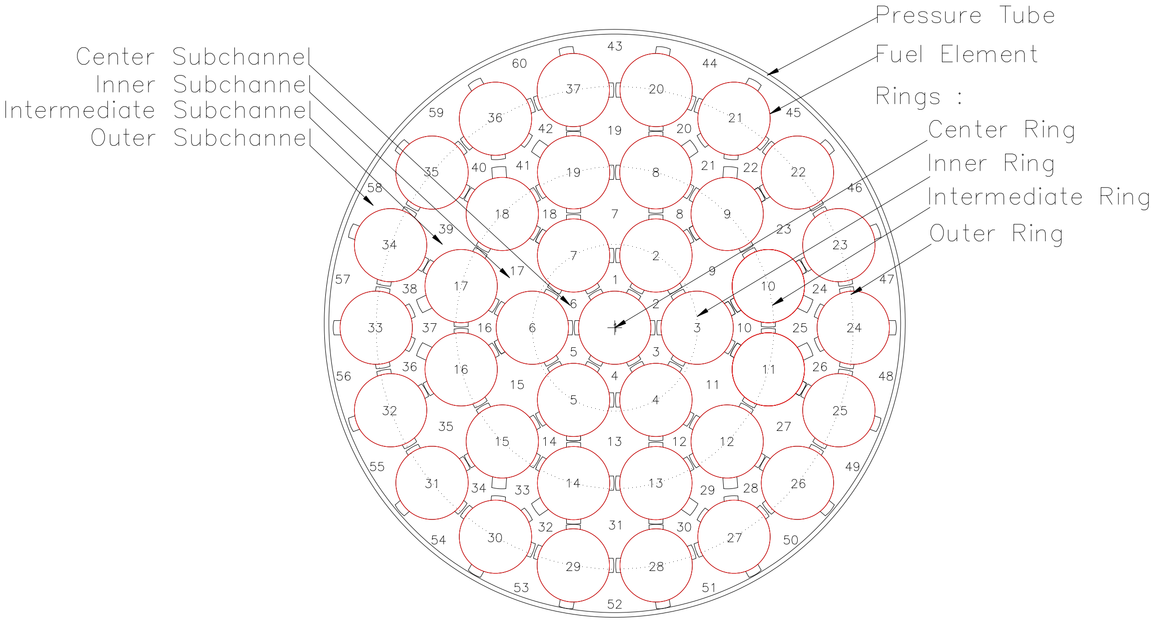

Fig. 1. Cross-sectional view of standard 37-element fuel

Table 1. Ring radii of the standard 37-element fuel

Ring Identification	Ring radius, mm	No. of elements
Center	0.0	1
Inner	14.88	6
Intermediate	28.75	12
Outer	43.33	18

From the previous CHF experiments, it is known that most of the first CHFs of a standard 37-element fuel occurred at the peripheral subchannels of a center rod at a high flow [9]. This was caused by the relatively small flow area of the center subchannels or higher resistance than the other subchannels.

Recently, the modification of standard 37-element fuel was suggested by the Ontario Power Generation (OPG) in Canada. The main idea of the modified 37-element fuel (37M fuel) is a size reduction of the center rod to enhance the CHF. The small size of the center rod among the 37 elements makes a larger flow area and lower flow resistance of the center subchannels of a standard 37-element fuel bundle. The CHF experiments of the 37M fuel were performed at Stern Laboratory in Canada. It is known that the CHF enhancement was obtained for the un-crept and crept channels, but no information of the specific CHF results for the 37M fuel have been published yet. However, even if the 37M fuel has a higher CHF performance than the standard 37-element fuel bundle, it could have the adverse effects on safety, in which the large flow area of the fuel bundle can increase the coolant void reactivity, and the small size of the center rod can also increase the linear element power of the other rods to achieve the same bundle power.

To overcome the negative safety effects owing to the small size of the center rod of the 37M fuel, an increase of the inner ring radius is introduced, instead of reducing the center rod diameter. Hence, the peripheral subchannel area adjacent to the center rod can be enlarged by increasing the inner ring radius, and it may finally enhance the CHF of a fuel bundle without any adverse impact on safety or fabrication costs.

A schematic view of the increase in inner ring radius is shown in Fig. 2. R1 and R2 in Fig. 2 represent the inner ring radii of the standard, and a modification of a 37-element fuel bundle, respectively. For the present study, the inner ring radii were considered to be from 14.88 mm to 15.38 mm with a 0.1 mm step increase, considering the interference gap between the inner and intermediate elements [8]. The increasing ratio of the flow area of the center subchannels with respect to the standard 37-element fuel bundle is shown in Fig. 3. The subchannel area adjacent to the center rod of the 37M fuel is equivalent to that of 15.18 mm inner ring radius, as shown in Fig. 3.

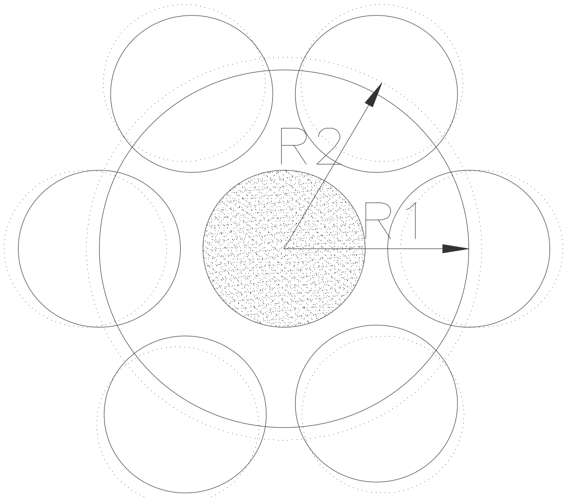

Fig. 2. Schematic diagram of flow area increase around a center rod

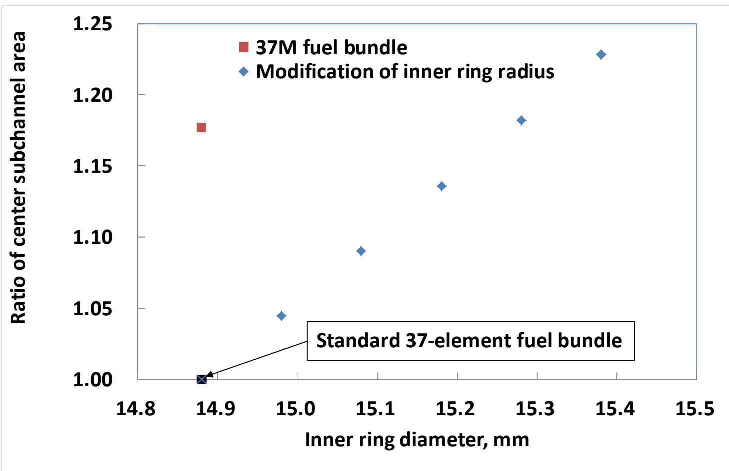

Fig. 3. Variation of the inner subchannel area according to increasing an inner ring radius

2.2 Modeling of AFD and RFD

A CANDU-6 core is composed of 380 fuel channels, and each fuel channel accommodates 12 fuel bundles resting horizontally. Hence, the CHF of a fuel bundle can be affected by the radial flux profile (RFD) of a fuel bundle, as well as the axial flux profile (AFD) in a fuel channel. Figs. 4 and

5 show the typical RFD and AFD of a standard 37-element fuel bundle in a fuel channel, respectively [8]. For a subchannel analysis of the standard 37-element fuel bundle and its inner ring radius modification, the same AFD and RFD can be used because the change of the inner ring radius does not affect the AFD and RFD, except that the radial position of the inner ring is different, as shown in Fig. 4.

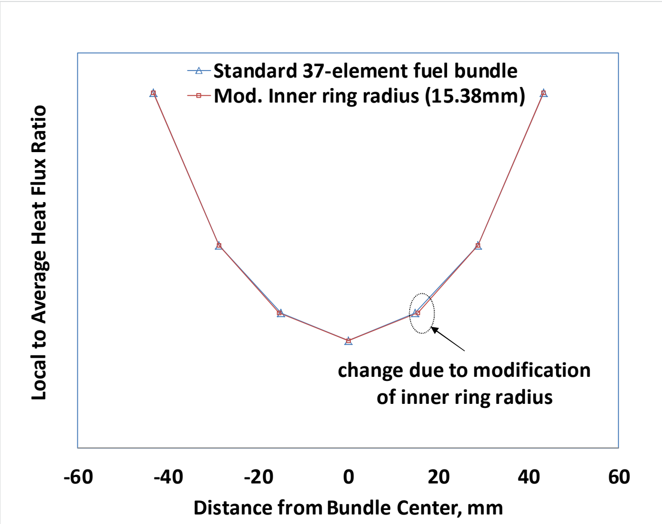

Fig. 4. Comparison of radial heat flux ratios of the standard 37-element fuel bundle and modification of its inner ring radius

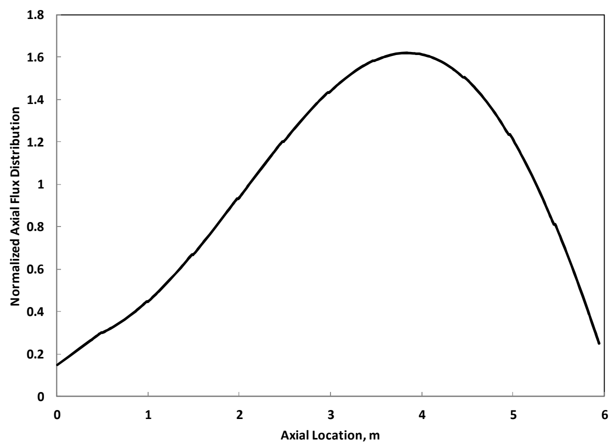

Fig. 5. Normalized axial heat flux distribution for a fuel channel

3. Results and discussion

Subchannel analyses were performed for a standard 37-element fuel bundle with/without the inner ring radius modification using the ASSERT code. To examine the dryout enhancement of the modified inner ring radius, the inlet temperatures were selected as 256℃, 262℃, and 268℃, and the inlet mass flow were selected as 20kg/s, 24kg/s, and 28kg/s, which are the representative conditions of the normal operating conditions of a CANDU-6 reactor [8]. The inner ring radius of the standard 37-element fuel bundle is increased from 14.88 mm to 15.38 mm in 0.1 mm steps.

Fig. 6 shows the subchannel and rod identification for the subchannel analysis of the ASSERT code. The results of the rod and adjacent subchannel number for the first CHF occurrences are summarized in Table 2. As summarized in Table 2, it was found that all CHF occurrences of the standard 37-element fuel bundle, which has a 14.88 mm inner ring radius, were located at the peripheral subchannel around the center rod, subchannel #1. These results are the same as the previous CHF experiment of a standard 37-element fuel bundle under a high flow [9].

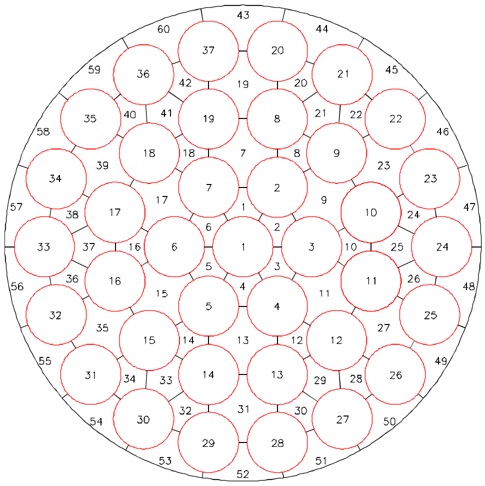

Fig. 6. Rod and subchannel identifications of 37-element fuel bundle

Table 2. Axial and radial locations of CHF occurrences under various inlet temperatures and mass flows

Temperature, ℃	Flow Rate, kg/s	Axial Location, cm	Rod No	Channel No
256	20	508.5	7	1
262	20	508.5	7	1
268	20	503.4	7	1
256	24	466.3	7	1
262	24	466.3	7	1
268	24	466.3	7	1
256	28	459.0	7	1
262	28	466.3	7	1
268	28	459.0	7	1

The axial positions of the CHF occurrences are located before the spacer of the 11th bundle for 20 kg/s and of the 10th bundle for 24kg/s and 28kg/s. It was revealed that the location of the CHF occurrences are moved to the upstream of the fuel channel as the mass flow increases, while those locations were not changed by the inlet temperature conditions.

The dryout powers of the standard 37-element fuel bundle with/without the inner ring modification were calculated and compared for the various mass flow conditions. The ratio of the dryout power with a ring radius modification to without a modification of the standard 37-element fuel bundle is defined as follows:

$$R_{en} = \frac{Dryout\ power\ with\ ring\ radius\ modification}{Dryout\ power\ without\ modification}$$

R_{en} were plotted in terms of the various inner ring radii, as shown in Figs. 7, 8, and 9 for the mass flow conditions of 20kg/s, 24kg/s, and 28kg/s, respectively. As shown in Figs. 7, 8, and 9, R_{en} is not sensitive to the variation of the inlet temperature conditions. However R_{en} is revealed differently according to an increasing in the mass flow.

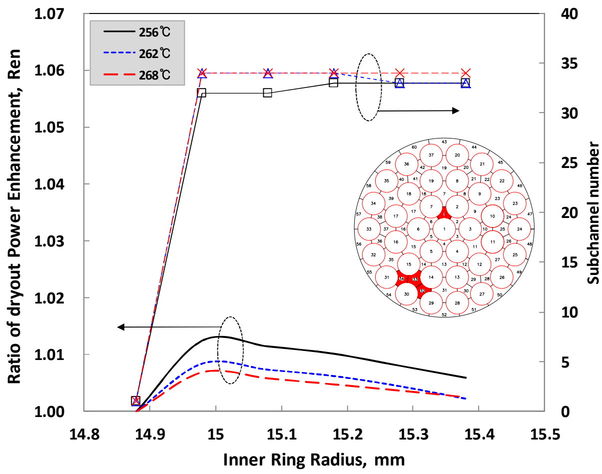

Fig. 7. R_{en} variation and the first CHF occurrence subchannel according to inner ring radius increases at 20kg/s

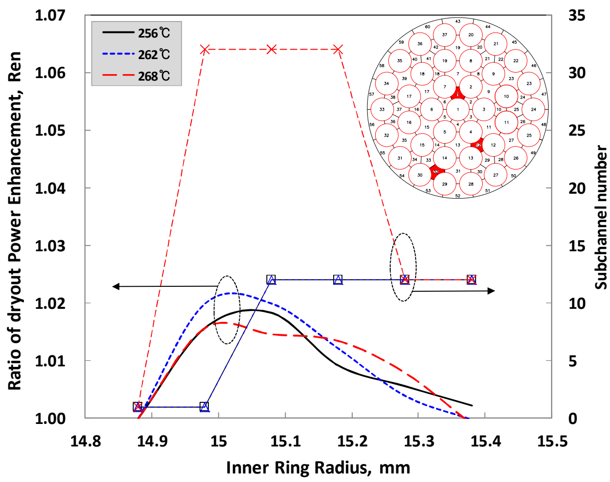

Fig. 8. R_{en} variation and the first CHF occurrence subchannel according to inner ring radius increases at 24kg/s

For the mass flow of 20kg/s, R_{en} increases as the inner ring radius increases and is the maximum at 14.98 mm of the inner ring radius. The first CHF occurrence for the standard 37-element fuel bundle was located at subchannel #1, but was moved to the peripheral subchannels, #32, #33, or #34 as the inner ring radius increases, as shown in Fig. 7. It was found that the maximum dryout enhancement was 1.4% for a 20kg/s mass flow and 14.98 mm in inner ring radius.

For a mass flow of 24kg/s, R_{en} has a similar trend at 20kg/s of the mass flow condition, but the subchannel location of the first CHF occurrence for 268℃ was changed from the center subchannel #1 to subchannel # 32, and returned to the intermediate subchannel #12, for a further increase of the inner ring radius, as shown in Fig. 8. For 256℃ and 262℃, however , the subchannel locations of the first CHF occurrence were moved from center subchannel #1 to the inner subchannel #12. The maximum R_{en} is increased to 1.02 at 14.98 mm of the inner ring radii.

For a mass flow of 28kg/s, the maximum dryout enhancement was 4.5% at a 15.08 mm inner ring radius. It was noted that the dryout power for the high flow conditions can be enhanced more than that for the low mass flow conditions. As shown in Fig. 9, the locations of the first CHF occurrence at a 28kg/s mass flow were moved from the center subchannels #1 or #4 to the inner or intermediate subchannels, #12 or #32 subchannels, like those at a 24kg/s mass flow condition.

The low CPR (Critical Power Ratio) fuel channels among the 380 fuel channels of CANDU-6 reactor are located mostly in the vicinity of the reactor center [12] which has the high flow and high power conditions rather than in the outer region of the reactor core which have low flow and low power. It is noted that the increase of the inner ring radius is very effective to enhance the dryout power of the low CPR fuel channels in a CANDU-6 reactor.

The dryout enhancement ratio for a 15.08 mm inner ring radius was plotted versus the mass flow rates in Fig. 10. As shown in Fig. 10, the R_{en} is increasing monotonically as increasing the mass flow. The maximum R_{en} was 1.045 at 28 kg/s of the mass flow and it became less sensitive to the inlet temperature variation as increasing the mass flow.

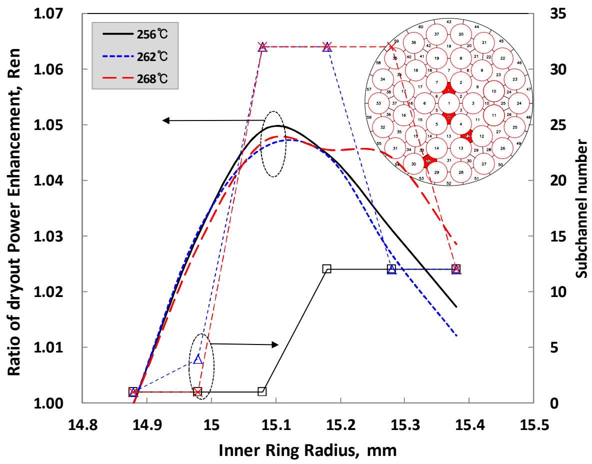

Fig. 9. R_{en} variation and the first CHF occurrence subchannel according to inner ring radius increases at 28kg/s

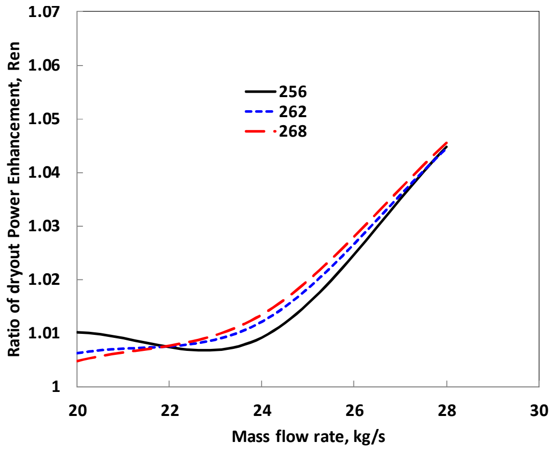

Fig. 10. R_{en} variations according to mass flow increase (@15.08mm inner ring radius)

4. Conclusions

A subchannel analysis was performed to investigate the effect of the inner ring radius modification of the standard 37-element fuel bundle on the dryout power. It was revealed that the inner ring radius modification is a very efficient way for the CHF enhancement and can increase the dryout power of the standard 37-element fuel bundle without any adverse impact on the safety margin or fuel fabrication cost. In addition, the enhancement of the dryout power is strongly dependent on the mass flow condition, but weakly dependent on the inlet temperature of the coolant. As the inner ring radius is increasing, the location of the first CHF occurrence can be moved from the center subchannel to the other subchannels. On the other hand, the maximum enhancement of the dryout power was 4.5% at a 15.08 mm inner ring radius compared to the standard 37-element fuel bundle, which has a 14.88 mm inner ring radius. It is noted that the increase of the inner ring radius is very effective to enhance the dryout power of the low CPR fuel channels in a CANDU-6 reactor.

Since the present study was performed for the uncrept pressure tube, further study for the crept pressure tube will be necessary to overcome the power de-rating due to the pressure tube aging.

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