The Effect of a CANDU Fuel Bundle Geometric Variation on Thermal Hydraulic Performance

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Abstract

The effect of fuel bundle geometry using the subchannel code ASSERT has been evaluated to enhance the thermalhydraulic performance. Based on the configuration of a standard 37-element fuel bundle, the element diameter in center ring has been changed while those of other rings are kept as the original size.

1. Introduction

The fuel channel in service at high temperature and pressure undergoes the increase of diameter due to the pressure tube creep resulting from neutron irradiation damage. It is well known that a crept pressure tube leads to a bypass flow through the upper peripheral region of a bundle and it results in a decrease of dryout power. Together with the diametral creep of a pressure tube, the thermal performance of a fuel channel is largely affected by the configuration of a rod bundle in a pressure tube. With a view to designing the advanced fuel channel having a larger safety margin, it is important to reveal the effect of the geometric configuration on the thermalhydraulic characteristics of a fuel channel.

The literature scan reveals that the design of the new fuel channel has been focused on improving fuel bundle performance and has received a great deal of attention from nuclear reactor designers. The considered new fuel channel is the one having a different configuration of a rod bundle [1, 2] or a different composition of fuel with a standard 37 element fuel bundle [3]. Full scale bundle experiments have shown the improvement in dryout power for the new designed fuel bundle as compared with the 37-element bundle. The thermalhydraulic performance of the new designed fuel bundle has also been evaluated by the single channel analysis using NUCIRC code [4]. Although the experimental work and the single channel analysis is useful for comparing the thermal performance between the 37-element bundle and the new designed one, they have the limitation to reveal the detailed thermal-hydraulic characteristics for the local flow field, which is essential for the design of the advanced fuel channel.

The subchannel technique is known to be very useful for investigating the thermal behavior of a fuel assembly in nuclear power reactors. The subchannel analysis of a fuel bundle normally provides the detailed thermalhydraulic information of a local flow field which can be utilized in assessing the thermal margin of a fuel channel. The assessment of the thermal behavior of a fuel bundle using subchannel analysis computer code strongly depends on the modeling methods of the mass, momentum and energy exchange between subchannels. Among those, the transverse interchange model is the most important one. Since the fuel channel of the CANDU reactor is horizontal, the equilibrium void profile may be quite different from that of a vertical flow in the LWR fuel bundle.

Literature scans show that numerous studies have been conducted to model the transverse interchange mechanism. Tye et al. [5] have examined the influence of the constitutive relations in

the intersubchannel transfer mechanism on the prediction of the subchannel code for horizontal flows. It was found that the buoyancy drift model based on the correlation of Wallis [6] results in better agreement between the predictions and the experimental results. Calucci et al. [7] developed the generalized relationship for the two-phase intersubchannel turbulent mixing and lateral buoyancy drift in horizontal flows and it is implemented in a subchannel thermalhydraulic code. Park [8] conducted the subchannel analysis for the CANFLEX fuel bundle having a different composition of fuel with a 37 elements fuel bundle. The local thermalhydraulics parameters at the exit plane are compared and have shown that the subchannel analysis for a horizontal flow is very informative in developing the new fuel for a CANDU reactor.
In the present study, the subchannel analysis for a horizontal flow has been performed with a variation of the geometric configuration of a rod bundle by adopting smaller center rod. Based on the standard 37 elements fuel bundle, which consists of center, inner, intermediate (middle) and outer rings, the element size of center ring was moderated while the element sizes of other rings remained. The thermal character of the standard 37 elements fuel bundle in an uncrept and crept channel are first analyzed by comparing the thermalhydraulic parameters of each subchannel. To evaluate the overall thermal performance of modified fuel channel, the dryout power is compared for a range of creep ratio between the 37 elements fuel channel and the modified fuel channel. The suggested geometry produces the maximum dryout power, which is one of the principal thermalhydraulic parameters in establishing operating and safety margins for the new fuel.
The objective of this study is to examine the thermalhydraulic characteristics in a fuel channel having the different geometric configuration of a rod bundle and to scrutinize the effect of the modification of element size on the thermal performance of a horizontal fuel channel.

2. Theoretical Development

In this study, the ASSERT-PV code [9] was used for the subchannel analysis of a horizontal flow in an uncrept and crept fuel channel. ASSERT is a subchannel thermalhydraulics code developed by AECL (Atomic Energy of Canada Limited) for the thermalhydraulic assessment of CANDU fuel. The code can predict the flow and phase distributions in subchannels of a fuel bundle, and provide detailed distributions of the critical heat flux (CHF), post-dryout heat transfer and fuel sheath temperature throughout the fuel bundle. Unlike conventional subchannel codes such as COBRA, which are designed primarily to model a vertical fuel bundle and use a homogeneous mixture model of two-phase flow, ASSERT uses a drift-flux model that permits the phase to have unequal velocities. ASSERT includes gravity terms that may make it possible to analyze separation tendencies which could occur in a horizontal flow. Hence, ASSERT is the ideal computational tool for assessing the effect on the dryout power of changes in bundle geometry, such as changes in element diameters that are considered in the present study. During its developmental stage, the computational results of the ASSERT code were validated against the real scale 37-element bundle experimental data [10].

ASSERT is, at the level of the individual subchannels, a one-dimensional two-phase flow code. However, the flow in a fuel bundle has a three-dimensional nature. The three-dimensional representation of a fuel bundle is arrived at by including the effects of the crossflow as source terms in the 1D form of the conservation equations of mass, axial momentum and energy, and by the addition of a transverse momentum equation.

In this study, Wallis's model [6] was used for the buoyancy drift velocity and the turbulent mixing coefficient was set to 0.01 instead of the default value of 0.05, based on the result of previous study [11], which shows that the subchannel model used in the ASSERT code well predicts the experimental results. The present calculation was performed under the normal operating condition of a CANDU reactor with an inlet fluid temperature of 256°C, an outlet header pressure of 10.0 Mpa and mass flux of 20.0 kg/s. In the real nuclear power plant, the boundary conditions such as the mass flow rate and inlet temperature are affected by the plant aging effect such as the degradation of steam generator or the creep of pressure tube, etc. However, since the present study are focused on the geometric effect of fuel channel including the creep of pressure tube, the constant boundary condition are used for the uncrept and crept fuel channel.

The numerical solution of ASSERT is obtained by solving the energy and the state equations using a block iterative method which is used to calculate the mixture and phase enthalpies for all subchannels using the current estimates of flow. Once the solution of energy equation converges, flows and pressure gradients at that axial position can be obtained from a direct matrix solution of the crossflow equations. With this information, axial flows and pressures can be calculated. The channel is successively swept from the inlet to the exit, until it converges.

The CHF prediction in the ASSERT code is performed subsequently to flow distribution calculation by using one of the CHF correlations such as BAW-2, W-3, Whalley's, or AECL's CHF table. In this study, AECL's CHF look-up table was used for all simulations. The more detailed information for the numerical method in ASSERT code, including the governing equation and two-phase flow correlations, are well represented in Ref. [5, 9].

Table.1 Ring power ratios for standard and modified fuel bundle

	Center ring	Inner ring	Middle ring	Outer ring
Standard fuel	0.775	0.811	0.915	1.132
Center ring modified	0.653	0.816	0.918	1.135
Inner ring modified	0.812	0.703	0.938	1.151
Middle ring modified	0.825	0.866	0.810	1.181
Outer ring modified	0.853	0.893	1.012	1.036

As like the reference fuel bundle, the volumetric heat generation rate of a fuel is identical for all elements in a modified fuel bundle. However, for the same power in a reactor, the volumetric heat generation rate of a modified fuel bundle is different from that of the reference fuel bundle due to the change of total fuel amount in a bundle. And, the radial power distribution is changed with the variation of geometric configuration of a rod bundle. For a given power, the radial power distributions for the fuel elements have been obtained from the physics calculation using the RFSP code [12] and listed in Table. 1 for the modified fuel bundle having 11mm element diameter.

In subchannel analysis, the complex geometry of the rod bundle is divided into smaller sections. Since gravity is perpendicular to the direction of the channel flow in a CANDU reactor, at least half of the bundle should be modeled for the subchannel analysis. Figure 1 shows the present subchannel model for the standard 37 elements fuel bundle, together with the element and subchannel numbers. The subchannel model for the standard fuel bundle includes 19 powered elements and 34 subchannels.

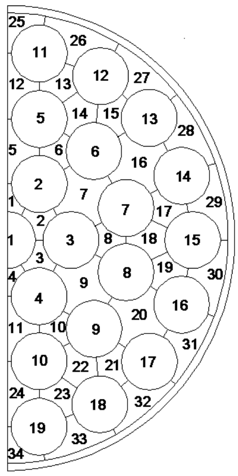

Figure 1 Subchannel models of standard fuel bundle.

The pressure tube creep is reflected in the ASSERT code by changing the geometric data such as the subchannel flow area, gap size, and wetted perimeter along the axial location. The axial power distribution and the radial creep distribution along the rod bundle are represented in Ref. [13]. In a rod bundle having a total length of 5.96m, the maximum diametric creep is located 4.3m from the inlet for the 3.3% crept channel, and 4.8m from the inlet for the 5.1% crept channel.

For the standard 37 element fuel bundle, the diameter of each rod is 10.13mm and the gap size between the neighboring element rings is taken to be 1.5 mm and 1.6 mm for the gaps between the same ring elements. For a modified fuel bundle which has a center rod of a smaller diameter, the heights of spacer pad have been adjusted to fit the gaps between the center ring and inner ring.

The ASSERT code returns a CHF assessment by means of the CHF ratio (CHFR), which is the ratio of the computed CHF flux to actual flux at axial node. ASSERT predicts the incipient CHF when the minimum CHFR (MCHFR) in the entire calculation domain has the value of 1.0. Since it is difficult to arrive at this condition exactly, the linear interpolation between two cases that compute $1.0 - \varepsilon < \text{MCHFR} < 1.0 + \varepsilon$ is normally used. In this study, $\varepsilon = 0.05$ was used.

3. Results

3.1 Numerical results for a crept fuel channel

Figure 2 shows the variation of dryout power of each ring in a bundle with respect to the creep rate. In the same manner of securing the dryout power of a fuel bundle, the dryout power of each ring (or each element) has been obtaind by adjusting the channel power until the MCHFR of each ring (or each element) has the value of 1.0.

It is revealed from the figure that the dryout power of each ring tends to decrease with the creep rate since the bypass flow through the most outer subchannel in the upper region increases with the creep rate. Hence, the dryout power in a fuel bundle, which is the minimum dryout power among four rings, decreases in a 3.3%, 5.1% crept channel, respectively, as much as 5.2%, 7.5% compared with that in an uncrept fuel channel. Although the present prediction for the dryout power in a fuel bundle has the uncertainties on the subchannel model and the CHF correlation, the present result shows the coincident result with that of the previous experimental study [13].

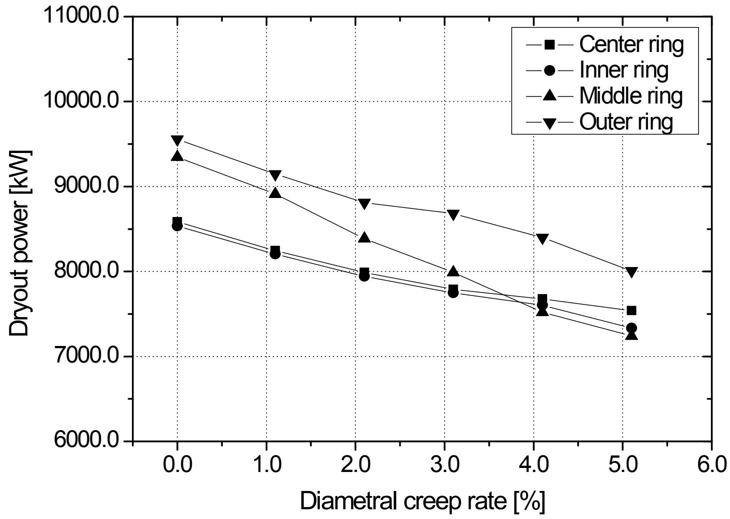

Figure 2 Dryout power versus creep rate for a standard fuel bundle.

In an uncrept channel, the first dryout in a fuel bundle is anticipated to occur at the center or inner rings since it has the minimum dryout power among four rings in a bundle. An inspection of Fig. 2 reveals that the dryout power of the middle ring is mostly dependent on the creep rate and shows the largest decrease with the creep rate. By the result, the dryout power in a fuel bundle has occurred at the elements in the middle ring for the range of creep rate over 4.0%. The present results for the locations of dryout power are in accord with the previous experimental study [5], which showed that the location of the first dryout for the experiment was on a rod in the inner or middle ring.

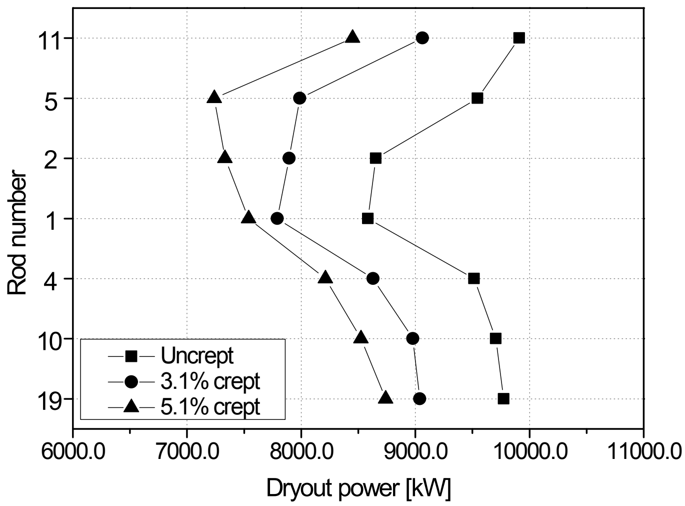

Figure 3 Comparison of dryout power at central-positioned rods of standard fuel bundle.

In order to scrutinize the effect of the creep rate on the local flow fields in a fuel bundle, the thermal-hydraulic characteristics for each element and each subchannel has been examined. Figure 3 shows the dryout power of each element for various creep rates. Of the 19 elements in a fuel bundle, the elements on a vertical centerline has been considered since these elements experience the largest variation of property such as enthalpy, void fraction in a fuel bundle and may well represent the variation of the dryout power of all the elements in a fuel bundle. In an uncrept channel, the elements of the center ring and upper inner ring are shown to have the minimum dryout power. As the creep rate increases, the dryout power of each element decreases for all the elements. The close inspection of the figure reveals that the elements in the upper half region in a bundle experience the larger decrease of dryout power with the creep rate rather than the elements in the lower half region in a bundle. It is noted that the buoyancy drift always acts in such a way as to transfer the void towards the physically higher subchannel. Hence, the property variation occured mostly in the upper region in a bundle and the effect of the creep rate on the dryout power definitely appeared on the elements in this region. In acutal, the element of number 5 in a middle ring has the largest decrease of dryout power with a creep rate and it brings forth the first dryout in a 5.1% crept channel to occur at the middle ring in a fuel bundle, as revealed in Fig. 2. It is noted that the elements of the outer ring in the upper region has the slight variation of dryout power with a creep rate, compared with the elements of other rings in the upper region, since the bypass flow through these subchannels increases with a creep rate.

3.2 Numerical results for a modified fuel channel

In the design of the advanced fuel bundle, the ultimate target is to make for a fuel channel to have better dryout power and greater safety margin. For this purpose, the effect of element diameter on the flow character and thermal margin has been examined. Based on the configuration of a standard fuel bundle, the element diameters in a center ring of a bundle have been changed while the element diameters of other rings retained their original size. By the limitation of the space in a pressure tube, only the cases where elements in center ring have a smaller diameter than the original size are considered. For the modified fuel bundle having a smaller center rod, the heights of spacer pad and bearing pad should also be adjusted to fit gaps between neighboring elements and it was reflected in the computation by the change of form loss factor for the appendages.

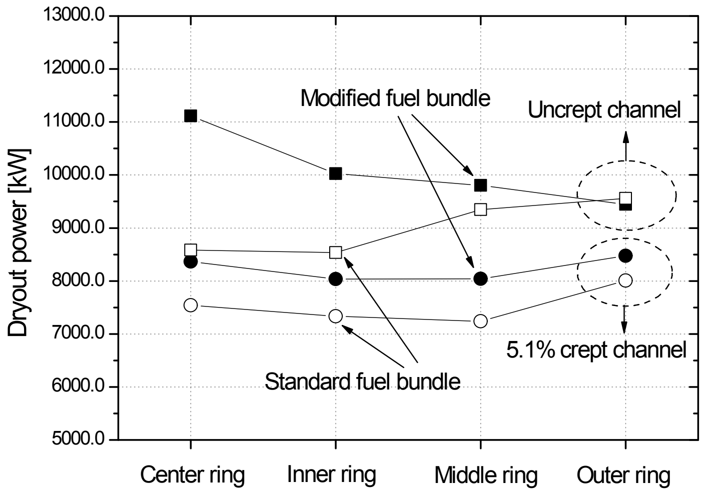

Figure 4 Dryout power at each ring of modified fuel bundle.
(Hollow and solid denote a standard and modified fuel bundle, respectively; Rectangular symbol is uncrept fuel channel and circle symbol is 5.1% crept fuel channel)

Figure 4 shows the dryout power of each ring for a modified fuel bundle. The dryout power of each ring for a standard fuel bundle is also plotted in the same figure for the comparisons. The open and solid symbol denotes the value for a standard and a modified fuel bundle, respectively. The dryout power in an uncrept and 5.1% crept fuel channel is shown, respectively, by the rectangular and circular symbol. As the basic case of a modified fuel bundle, the diameter of center ring is modified and the element diameter in center ring was changed to 11.0mm from the original value of 13.08mm. From the figure, it is revealed that, by the modification of element diameter, the dryout power of each ring is substantially affected and the location of ring where the first dryout occurs is also changed. For an uncrept fuel bundle, the location of ring where the first dryout occurs is changed from the inner ring to outer ring by the modification of element diameter.

For the case where the diameter of center ring decreased (see Fig. 4), the flow rate in the subchannels near the center ring is increased, which results in the increase of dryout power at the elements in the center and inner ring. As shown in Fig. 2, in an uncrept channel, the first dryout has occurred on the elements in the center or inner ring for a standard fuel bundle. Hence, in an uncrept channel, the large increase of dryout power of a center and inner ring results in the increase of the minimum dryout power of a bundle in a modified fuel channel

As shown in Fig. 4, for an uncrept channel, the dryout powers of middle and outer ring remain nearly unaffected by the modification of a center ring. It is interesting to note that, for a 5.1% crept channel, together with the dryout powers of center and inner ring, the dryout powers of middle and outer ring are also increased by the modification of the center ring although the coolant flow passage in the subchannels near the middle and outer ring does not increase. As shown in Fig. 2, in a 5.1% crept channel, the first dryout occurs on a middle ring for a standard fuel channel. Hence, the increase of dryout power of the middle ring brings forth the increase of the minimum dryout power of a bundle in a modified fuel channel. As the element diameter of the center ring is modified, the dryout power in a fuel bundle is improved by about 11.0% for both the uncrept and 5.1% crept channels, compared with a standard fuel bundle.

The effect of the modification of element diameter on the thermal characteristics in a fuel bundle has been scrutinized in detail by comparing the dryout powers of elements and the local properties of subchannels between a standard and modified fuel channels. Figure 5 shows the dryout powers of the elements which are on a vertical centerline in a fuel bundles. Basically, the case in which a center ring is modified has been considered.

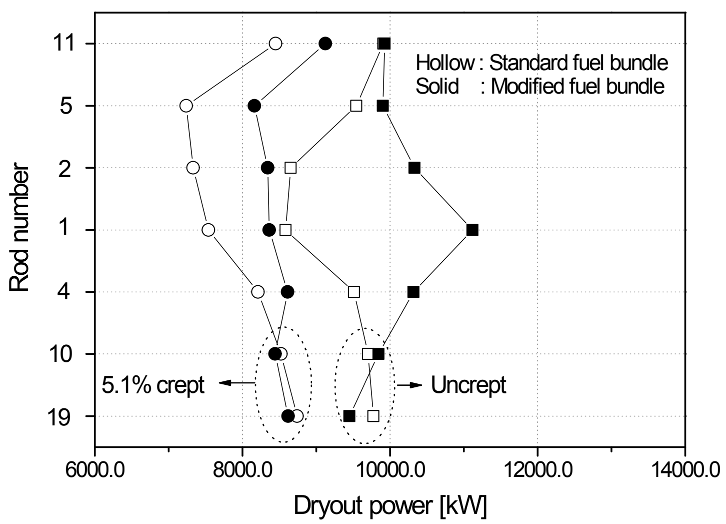

Figure 5 Comparison of dryout power at central-positioned rods.
(Hollow and solid denote a standard and modified fuel bundle, respectively)

It is revealed from the figure that, in an uncrept channel, the elements in the center ring and upper inner ring have an enormous increase of dryout power by the modification of the center ring. The effect of the modification of the center ring is transferred towards the physically higher elements due to the buoyancy drift effect. Hence, the effect of modification of the center ring is more pronounced at the elements in the upper region of a bundle rather than at the elements in the lower region of a bundle as shown in Fig. 5. Especially, in a 5.1% crept channel, the dryout power of elements in the upper half region of a bundle are significantly affected by the modification of the center ring.

It is noted that, in the upper region of a bundle, the property variation in a vertical direction is steeper for a 5.1% crept channel rather than an uncrept channel. Hence, the net effect of void diffusion and buoyancy void drift is more pronounced in a 5.1% crept channel. Consequently, in a 5.1% crept channel, the modification of center ring brings forth the large property variation of subchannels in the upper region of a bundle and it results in a significant increase of dryout power of elements in this region in a 5.1% crept channel.

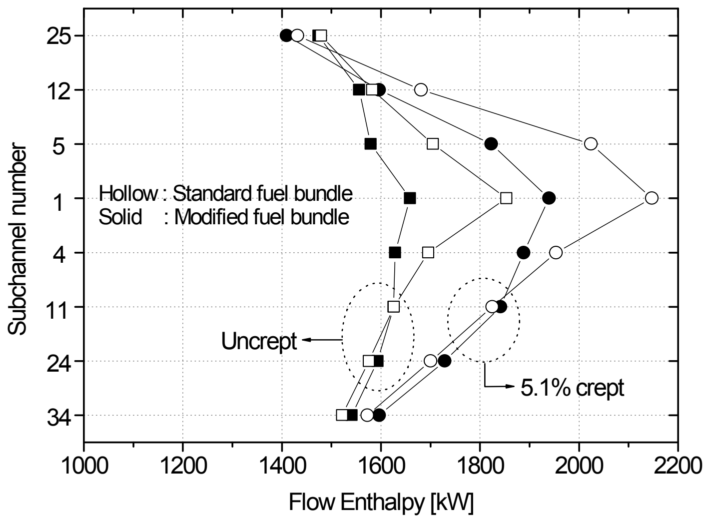

Figure 6 Flow enthalpy at central-positioned subchannels of modified fuel bundle.

Figure 6 shows the flow enthalpy distribution at the subchannels on the vertical centerline for a modified fuel bundle. The decrease of enthalpy is the largest at the upper center subchannel by the increased flow rate in this region, which is in line with the result of dryout power variation. Although the enthalpy at the subchannels in the upper half region in a fuel bundle is decreased by the modification of the center ring for both the uncrept and 5.1% crept channels, the enthalpy decrease in the upper half region is more definitely shown in a 5.1% crept channel, which reflects the pronounced buoyancy effect in a 5.1% crept channel.

Figure 7 shows the void fraction at subchannels on a vertical centerline for a standard and modified fuel channels. It is revealed from the figure that the void fraction at subchannels in the upper half region of a bundle is largely decreased by the modification of the center ring, which reflects the buoyancy effect in a horizontal fuel bundle. It is noted that the increased flow rate at the subchannels between the center and inner rings in a modified fuel bundle results in the decrease of void fraction at these subchannels, while it makes the void fraction at subchannels in other region to increase due to the decreased flow rate. Hence, the subchannels in the lower region of a bundle have a slight increase of void fraction as shown in Fig. 7.

The above findings assert that, by the modification of the element diameter in center ring, the local flow and thermal characteristics in a fuel bundle are substantially affected and it causes the significant change of the dryout power in a fuel bundle. Hence, it is an important issue to decide the optimal size of an element in center ring with a view to designing the advanced fuel bundle. A series of computations were made by altering the size of the elements in center ring, and the results are shown in Fig. 8. For the considered size of element diameter, the dryout power of a fuel bundle has a tendency to increase as the size of the element diameter decreases. However, an inspection of Fig. 8 reveals that, as the element diameter is further decreased beyond a certain value, the increase rate of dryout power in a fuel bundle is decreased. In actual, in the case where the center ring is modified, the dryout power of a bundle shows the negligible change for the further decrease of the element diameter below 11mm.

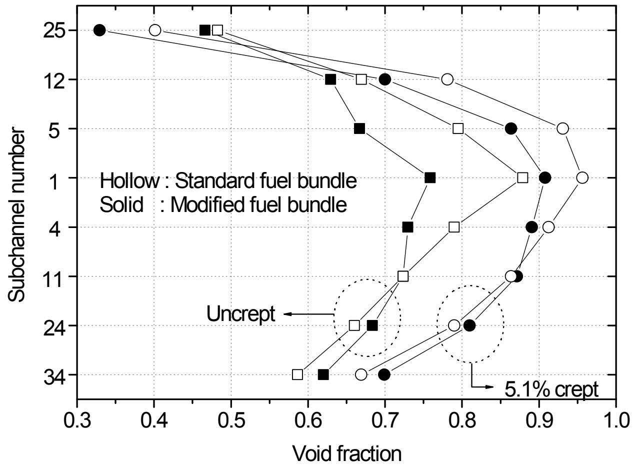

Figure 7 Void fraction at central-positioned subchannels of modified fuel bundle.

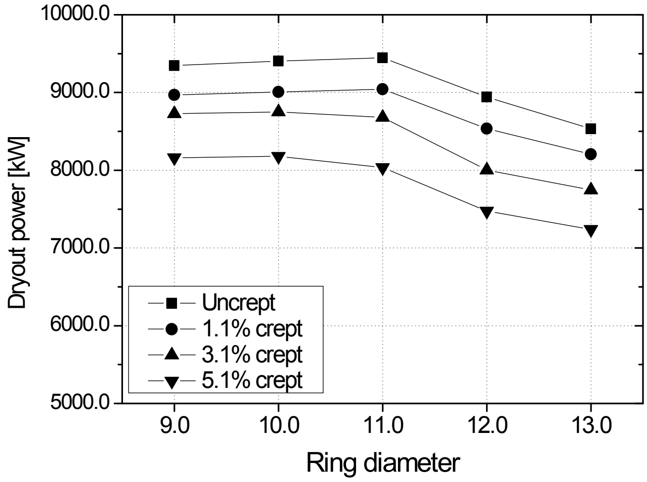

Figure 8 The effect of diameter of modified fuel bundle on the dryout power.

4. Conclusion

The subchannel analysis for a horizontal CANDU fuel bundle reveals that the variation of thermal characteristics with a creep rate is significant for the subchannels in the upper region in a bundle due to the buoyancy drift effect. And, it results in the largest decrease of dryout power with a creep rate for the elements in this region.

It is revealed that the dryout power of a fuel bundle is increased by the modification of an element size. For an uncrept channel, the dryout power is largely increased for the elements near the modified ring. In a 5.1% crept channel, the increase of dryout power by the modification is noticeable for the elements in the upper region of a bundle.

A series of computations for a fuel bundle with a different size of element diameter reveal that the dryout power of a fuel bundle has a tendency to increase as the size of the element diameter decreases. However, as the size of the element diameter is further decreased beyond a certain value, the increase rate of dryout power in a fuel bundle is reduced.

The modification of the element diameter enhances the operating performance by increasing the dryout power of a fuel bundle. The present numerical simulations are expected to be applicable to design the advanced fuel bundle.

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6. References

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