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Inner Ring Modification of a Standard 37-element Fuel bundle

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1. Introduction

A CANDU-6 reactor has 380 fuel channels of a pressure tube type, which creates an independent flow passage and 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 of the pressure tube owing to more open space in its top section than the 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.

During the last decades, there have been several studies to overcome the CHF deterioration owing to the creep pressure tube. One of the studies to enhance the CHF was the development of a CANFLEX-NU fuel bundle, which is composed of two pin sizes and attached the CHF enhancement buttons to 43 element fuels [1]. However, it has not been commercialized yet.

Recently, the modification of a standard 37-element fuel (37M fuel) was suggested by Ontario Power Generation (OPG) in Canada to enhance the CHF of a creep pressure tube. The main idea of the 37M fuel is the size reduction of a center rod to enhance the CHF. The small size of the center rod among 37 elements makes a larger flow area of the center subchannels of a standard 37-element (37S fuel). The CHF experiments of the 37M fuel were done in Stern Laboratory. It may be known that the CHF enhancement was obtained for the un-crept and crept channels, but any information of the specific CHF results for the 37M fuel have been not published yet. Even if the 37M fuel has a higher CHF performance than the 37S fuel bundle, it can have 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.

In particular, a 37S fuel bundle has been used in commercial CANDU reactors for over 40 years as a reference fuel bundle. Most CHF of a 37S fuel bundle were occurred at the elements in the inner ring at high flows, but at the element in the outer ring at low flows [2]. It could be noted that the 37-element fuel has a relatively small flow area and high flow resistance at the peripheral subchannels of its 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 [3]. It shows 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 37S fuel bundle with the modified inner ring radius. 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 37S 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, a subchannel analysis was performed using the ASSERT code [4], 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.

A 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 Figure 1.

This paper proposed an increase of the inner ring radius instead of reducing the center rod diameter. Hence, the peripheral subchannel area adjacent to the center rod can be enlarged and finally enhance the CHF of a fuel bundle without any adverse impact on safety as well as fabrication cost. A schematic view of the increase in inner ring radius is shown in Figure 2.

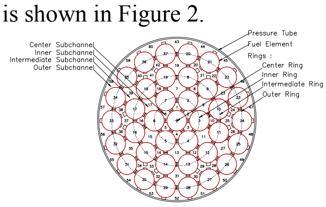

Figure 1. Cross-sectional view of standard 37-element fuel

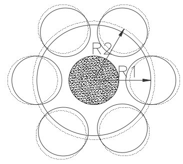

Figure 2. Schematic diagram of inner ring radius increase

R_1 and R_2 in Figure 2 represent the inner ring radii of the standard and modification of a 37-element fuel bundle, respectively. The minimum gap size between elements of the inner and intermediate ring of the 37S fuel bundle was designed as 1.8mm. The allowable maximum inner ring radius can be found as 15.4mm from the Fuel Design Manual [5]. For the present study, the inner ring radii were considered to be from 14.88mm to 15.38mm with 0.1 mm step increases.

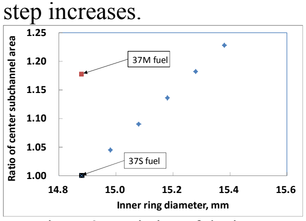

Figure 3. Variation of the inner subchannel area according to increasing

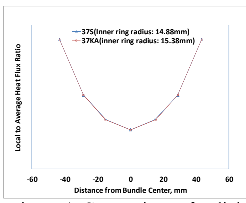

Figure 4. Comparison of radial heat flux ratios of the 37S fuel

an inner ring radius and inner ring modification

The increasing ratio of the flow area of the center subchannels with respect to the 37S fuel is shown in Figure 3. Also the center subchannel area of the 37M fuel is equivalent to that of a 15.18mm inner ring radius, as shown in Figure 3. The radial heat flux distribution for the present calculation is shown in Figure 4.

3. Results and Discussion

Subchannel analyses were performed for a 37S fuel bundle with/without an 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℃, which are equivalent to in-reactor conditions, and the inlet mass flows were 20kg/s, 24kg/s, and 28kg/s, in consideration of a reference flow, 24kg/s, noted in the Fuel Design Manual [5]. The inner ring radius of the 37S fuel bundle is increased from 14.88mm to 15.38mm in 0.1mm step.

Figure 5 shows the subchannel and rod identification for the subchannel analysis of the ASSERT code. It was found that all CHF occurrences of the 37S fuel bundle, which has a 14.88mm inner ring radius, were located at the peripheral subchannel around the center rod, rod #7 and subchannel #1. These results are similar to the previous CHF experiment of the 37S fuel bundle at high flow [2].

The axial positions of the CHF occurrences are located before the spacer of the 10^{th} or 11^{th} bundle for all flow conditions. It is 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 37S fuel bundle with/without the inner ring modification were calculated and compared under the mass flow conditions. The ratio of dryout power of the 37S fuel bundle to that with the ring radius modification is defined as follows;

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

R_{en} was plotted in terms of the various inner ring radii as shown in Figures 6, 7, and 8 for the mass flow conditions of 20kg/s, 24kg/s, and 28kg/s, respectively. As shown in Figures 6, 7, and 8, R_{en} is not sensitive to the inlet temperature conditions. However, R_{en} is revealed differently according to the increasing mass flows.

For the mass flow of 20kg/s, R_{en} is increasing as the inner ring radius increases, and is the maximum at 14.98mm of the inner ring radius. The first CHF occurrence for the 37S fuel bundle was located at rod #7 and subchannel #1, but it was moved to the peripheral subchannels of rod #32 as the inner ring radius increase, as shown in Figure 6. It was found that the maximum dryout enhancement was 1.4% for 20kg/s of the mass flow and 14.98mm of the inner ring radius.

For the mass flow of 24kg/s in Figure 7, R_{en} has a similar trend at 20kg/s of the mass flow condition, but the subchannel locations of the CHF occurrences were changed the subchannels from the center to the intermediate and return to the inner or from the center to the inner, subchannel #12 for a further increase of the inner ring radius. The maximum R_{en} is increased to 1.02 at 15.08mm of the inner ring radius.

For the mass flow of 28kg/s, the maximum dryout enhancement was ~5% at 15.08mm of the inner ring radius. It was noted that the dryout power for the lager flow area of the center subchannels can be enhanced more than that for the low mass flow conditions. As shown in Figure 8, the locations of the CHF occurrences at 28kg/s of the mass flow were moved from the center subchannels, #1 or #4 to the inner or intermediate subchannels, like those at 24kg/s of the mass flow condition.

The dryout enhancement ratio for 15.08mm of the inner ring radius was plotted versus the mass flow in Figure 9. As shown in Figure 9, the mass flow is higher, and more dryout power enhancement can be obtained for the larger center subchannel area by increasing the inner ring radius.

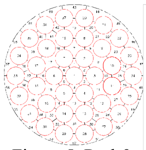

Figure 5. Rod & subchannel id. of 37-element fuel

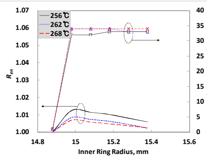

Figure 6. Ratio of dryout power enhancement at 20kg/s

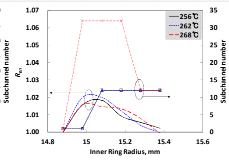

Figure 7. Ratio of dryout power enhancement at 24kg/s

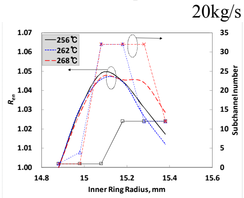

Figure 8. Ratio of dryout power enhancement at 28kg/s

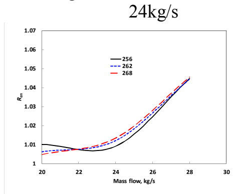

Figure 9. Ratio of dryout power enhancement for mass flow at 15.08mm

4. Conclusion

From the present study, it was revealed that the inner ring radius modification is a very effective way for the CHF enhancement and can increase the dryout power of the 37S fuel without any adverse impact on the safety margin or fuel fabrication cost. Also, 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 increases, the location of the first CHF occurrence can be moved to the other sub-channels. Also the maximum enhancement of the dryout power was 4.5% at a 15.08mm inner ring radius compared to the 37S fuel for a un-creep pressure tube.

Further study will be necessary for the creep pressure tubes, such as 3.3% and 5.1% creep to achieve the maximum dryout power enhancement to overcome the aging effects of CANDU fuel channels.

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