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The Button effect of CANFLEX Bundle on the Critical Heat Flux and Critical Channel Power

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ABSTRACT

A CANFLEX(CANdu FLEXible fuelling) 43-element bundle has developed for a CANDU-6 reactor as an alternative of 37-element fuel bundle. The design has two diameter elements (11.5 and 13.5 mm) to reduce maximum element power rating and buttons to enhance the critical heat flux(CHF), compared with the standard 37-element bundle. The freon CHF experiments have performed for two series of CANFLEX bundles with and without buttons with a modelling fluid as refrigerant R-134a and axial uniform heat flux condition. Evaluating the effects of buttons of CANFLEX bundle on CHF and Critical Channel Power(CCP) with the experimental results, it is shown that the buttons enhance CCP as well as CHF.

All the CHF's for both the CANFLEX bundles are occurred at the end of fuel channel with the high dryout quality conditions. The CHF enhancement ratio are increased with increase of dryout quality for all flow conditions and also with increase of mass flux only for high pressure conditions. It indicates that the button is a useful design for CANDU operating condition because most CHF flow conditions for CANDU fuel bundle are ranged to high dryout quality conditions.

1. INTRODUCTION

In general, a fuel assembly consists of fuel elements, appendages such as spacer grids for LWR fuel and spacer pads for CANDU fuel and bottom/top plates for LWR fuel and end-plates for CANDU fuel to configure the assembly structure. Although the main feature of a CANDU fuel bundle is similar to a LWR fuel assembly, the CANDU spacing devices are different from LWR's because CANDU fuel bundle meets a pressure tube as a special flow tube in a CANDU reactor. Many studies for the effect of the LWR fuel spacing devices on CHF have been performed, but CHF effect of spacing devices for a CANDU type fuel bundle have not been well published. MacDonalds[1] evaluated spacing device techniques such as extra spacer planes, bearing pad planes, flow obstruction vanes, vortex generators, and etc. for enhancing the CHF in standard 37-element bundle. The techniques is appeared to be the most promising for the CHF enhancement even if pressure drop penalty is occurred due to two extra planes of spacers technique. Groeneveld et al.[2] collected a lot of papers on the thermalhydraulic effects of rod spacing devices in LWR, LMFBR and CANDU fuel assemblies. They indicated that the spacing devices can have large effects on CHF. The effects are usually positive. But, those are negative with ill-designed spacing devices. And also, the presence of spacers increased significantly bundle pressure drop. Most studies of spacing devices effects on flow fields are limited on the honeycomb type, egg-crate type, or flow swirler attached on spacer grids. The studies of spacers or bearing pads effects on CHF and pressure drop have performed mostly by AECL, and they have considered the additional spacer and bearing pad planes, and vortex generator, or flow obstruction vanes etc.. Groeneveld et al.[3] studied the effect of additional planes of spacers or bearing pads by the experiments, and showed that the significant increases of CHF were observed by using the additional spacer planes or installing the grid spacers instead of the conventional CANDU split spacers. The maximum observed increase of CHF was 139 % (under constant dryout quality condition) for the two grid spacer cases: the two spacer planes increase the friction pressure drop by approximately 100 %, compared with the friction pressure drop of standard 37-element bundle. But, in the CCP point of view, the analyses resulted that a flow increase of 1 % by decreasing bundle pressure drop would increase the CCP by approximately 0.76 %. It indicates that the optimum design of spacing devices should be considered the effect of a bundle pressure drop as well as CHF because maximum increase of CCP could be achieved with large CHF enhancement and small bundle pressure drop.

Hence, KAERI/AECL have jointly developed CANFLEX fuel as an advanced CANDU fuel bundle to reduce maximum element power rating and to increase CCP, where the CANFLEX bundle design has two element sizes and CHF enhancement buttons. To investigate the button effects of a CANFLEX bundle on CHF, pressure drop and CCP, the CHF experiments were performed using a modelling fluid as a refrigerant R-134a at AECL-CRL. Then CCP were analyzed by NUCIRC code for the un-buttoned and buttoned CANFLEX bundles.

2. CHF ENHANCEMENT DEVICES FOR CANFLEX BUNDLE

2.1 Thermalhydraulic Characteristics of Buttons

The CANFLEX button is designed to make small penalty of pressure drop and large CHF enhancement, compared to standard 37-element. It is the additional appendages attached on two axial planes on the CANFLEX bundle. The size is approximately less than the diameter of 3 mm. Since 1990's, AECL has invented the button design as the CHF enhancement devices by reviewing the effect of the additional appendages such as spacer planes and bearing pads on CHF and pressure drop[1,3]. The additional appendages give the rising of the pressure drop as well as CHF. Figure 1 shows a relationship between CHF curve and channel flow versus power characteristic curve. As shown in bottom part of Figure 1, the CHF curve is determined by the experiments for a specified bundle. The hydraulic characteristic curve in the upper part of Figure 1 represents the channel flow decreasing behaviour as increasing the channel power. In case of constant pumping power, channel flow is decreasing as increasing channel pressure drop according to the channel power increase. That is, the channel pressure loss by a fuel bundle is increasing as increasing the number of additional appendages, and then hydraulic characteristic curve goes down with the additional appendages, finally it makes CCP decrease.

In general, CHF is increasing as increasing the channel flow and then channel power increases. The more number of appendages makes flow disturbance and increases CHF of a rod bundle by reducing in-homogeneity of enthalpy and flow distribution among subchannels. Therefore, CHF curve shown in Figure 1 goes down and then the channel power can be increased. That is, the CHF enhancing appendages should be designed to small channel pressure drop and large CHF increase in order to achieve the CCP enhancement. Although the additional spacer planes of 37-element bundle increased CHF upto 100 % as compared to standard 37-element bundle, CCP was not proportionally increased with CHF increase[3]. Especially, increasing the more number of bearing pads could slightly increase the pressure drop and achieve little CHF enhancement, compared with the spacer pads. The CANFLEX bundle is characterized as the lower maximum element power rating and the flattened ring power distribution by using the two sized elements and CHF enhancement buttons, compared with standard 37-element bundle.

At the beginning stage of CANFLEX button design, the shape of button was a cube type, but has developed to the cylindrical or oval type in consideration of less pressure drop penalty. The final button design is fixed with the oval type, considering the fabrication difficulty and the results of the experimental sensitivity studies for several button shapes.

2.2 Test Section and CANFLEX Bundles

The CHF experiments for CANFLEX bundle have performed at MR-3a Test Loop in AECL(Atomic Energy Canada Limited)-CRL(Chalk-River Laboratory). The button effect of CANFLEX bundle on CHF and CCP were evaluated from the results of experiments and CANDU fuel channel analyses by NUCIRC code.

The cross-sectional view of CANFLEX bundle was used in the CHF experiments was shown in Figure 2. A string of twelve aligned CANFLEX bundles was placed in a pressure tube as shown in Figure 3. It has a heated length of about 6 m and divided up every 50 cm by simulated end-plates. Each bundle is composed of two diameter sized 43 elements, spacers, bearing pads and

CHF enhancing buttons.

Forty three heater rods of CANFLEX bundle is made of Inconel-718, electrically heated by a direct current to produce an axial uniform heat flux. It simulates the radial heat flux profile expected in a CANDU reactor fuelled with natural uranium fuel as shown in Figure 2. The bundle was eccentrically mounted by lift spring in a vertical flow tube to simulate the horizontal flow geometry existing in the CANDU reactor. The working fluid was the refrigerant R-134a. The movable thermocouples were equipped inside of all heater elements at the downstream three segments for CHF detection, and measure the post dryout temperatures.

Two series of CHF tests with the CANFLEX bundle (the first with buttons and the second without buttons(called a bare CANFLEX bundle)) were done. Total CHF data were obtained more than 140 points for un-buttoned and buttoned CANFLEX bundles.

3. RESULTS AND DISCUSSION

3.1 Buttons Effects on CHF

Two series of CHF tests with full string of CANFLEX bundles with button planes and without button planes were done, recently using refrigerant R-134a which allows much lower pressure and temperature than in water. The test conditions covered a range of water equivalent flows, inlet temperatures and pressures to the CANDU operating conditions. To evaluate the effects of buttons on a bundle, CHF enhancement ratio can be defined as followings;

$$R_{CHF} = \frac{CHF_{with\ button}}{CHF_{without\ button}} \qquad (1)$$

The R_{CHF} represents the ratio of the CANFLEX bundle CHF with buttons planes to the CHF without button planes.

The R_{CHF}'s is taken at three different pressures as shown in Figures 4, 5 and 6. R_{CHF}'s are varied with the flow conditions. The CHF enhancement ratio for the bundle with the button planes is approximately minimum 3 % and maximum 13 % as shown in the figures. At the pressure of 1.49 MPa, the CHF enhancement ratio is 1.1 at maximum, which corresponds to 10 % CHF increase by buttons. It is the lowest at high mass flux, 5.3 Mg/m^2s. The trend of increasing R_{CHF} as increasing mass flux was not found in these figures as expected for spacing devices of a LWR fuel assembly. The R_{CHF}'s are insignificantly decreasing as increasing inlet subcooling, which is different from LWR's. Usually, the mixing vane device[4] for a LWR fuel assembly makes CHF increase by tubulizing and swirling the flow and mixing inter-subchannel flow as increasing mass flux and inlet subcooling. But the different button effect on CHF from the ones of LWR fuel assembly is caused that the CANFLEX small sized buttons did not strongly affect on flow fields. The trend of decreasing R_{CHF} as increasing inlet subcooling is significant as increasing the pressure of 1.77 MPa to 2.04 MPa. The R_{CHF}'s are increasing as increasing mass flux for high pressures. For a given pressure of 2.04 MPa, the R_{CHF}'s are decreasing rapidly as increasing inlet subcooling and are increasing as increasing mass flux just below the inlet subcooling of 60 kJ/kg approximately as shown in figures.

The R_{CHF}'s versus dryout quality are plotted at three pressure conditions as shown in Figures 7, 8 and 9. The R_{CHF}'s are increasing as increasing the dryout quality for all the pressure conditions and also as increasing the mass flux except for pressure of 1.49 MPa as shown in Figure 7. In general, the rate of R_{CHF} increase for spacing devices of LWR fuel assembly is slow as increasing dryout quality[4], but the R_{CHF}'s for CANFLEX bundle with buttons is monotonically increasing as increasing dryout quality.

It indicates that the small sized buttons of CANFLEX bundle may attribute to mainly increases of turbulent intensity, not to disruption of liquid film and thinning the liquid film by strong swirling flow, which is different from the effect of LWR's mixing vanes on CHF.

These results indicated that the buttons of CANFLEX bundle can contribute to significant CHF increase in annular flow which has thinner liquid film rather than bubbly flow or slug flow and also increase at high pressure conditions.

3.2 Button Effect on CCP

In order to evaluate the CCP, the information of CHF enhancement and pressure drop for a specified bundle are needed. Using the pressure loss coefficient of button which was determined from experiments, the pressure drop by buttons in one channel was 7.2 % increase at the reference density and the flow rate of 781.0 kg/m^3, and 23.9 kg/s respectively for the CANDU-6 reactor.

Although the CHF enhancement by the button are different from the one flow condition to the other, the averaged CHF enhancement of 10 % was assumed for CCP analysis by using NUCIRC[5] which is the thermalhydraulic single channel analysis code for CANDU-6 fuel channel. The O-06 channel of Wolsong-2, which has the lowest minimum critical channel power ratio (MCPR), was selected for this evaluation.

Generally the boundary condition of header-to-header pressure drop of CANDU-6 reactor can be determined by the pressure distributions of I/O(Inlet/Outlet) feeder pipes, I/O end-fittings, and a fuel channel. Since the other terms except a fuel channel or fuel bundle string are fixed, the boundary conditions can be changed according to the pressure drop through the fuel channel. It affects channel flow rate, distributions of pressure drop, liquid enthalpy and quality.

First of all, the effect of buttons on boundary condition of I/O header pressure drop, was evaluated from the circuit analysis of PHT(Primary Heat Transport) system. Then the CCP was evaluated using the boundary conditions obtained from the above. The temperature and quality profiles for a CANFLEX bundle with and without button planes are compared as shown in Figure 10. The axial temperature and quality profile for CANFLEX bundle with button planes are little higher than those for the bundle without button planes. These are caused by the channel flow decrease due to pressure drop increase. Figure 11 shows that the CCP behaviour for both fuel bundles are comparable for the increasing channel power. As shown in Figure 11, the CCP increases 2.0 % due to button planes. Therefore, the CANFLEX bundle with the button planes has better CCP performance than that without button planes, where the effect of buttons on a channel pressure drop may deteriorate the CCP, but the larger enhancement of CHF makes CCP increase. The button for CANFLEX bundle is designed appropriately in CCP point of view.

4. CONCLUSION

As a CANDU advanced fuel bundle, the CANFLEX bundle with the special buttons was assessed in thermalhydraulic point of views by the experiments and the CCP analysis :

The buttons of the CANFLEX bundle make CHF enhancement ratio decrease as increasing the inlet subcooling and increase as increasing the channel exit quality. It also increases the system pressure. The CHF enhancement ratio by the button planes of CANFLEX bundle increases as increasing mass flux except the pressure of 1.49 MPa.

The CCP increases 2.0 % by the buttons, where the enhancement of CHF is relatively large contribution to the CCP, compared to the contribution of channel pressure drop.

In conclusion, the button for the CANFLEX bundle is designed appropriately in CCP point of view.

REFERENCES

1. I.P.L. MacDonald, Enhancement of Critical Heat Flux in CANDU 37-element Bundle, 6-th Annual Conf. of the Canadian Nuclear Society, 1985, June 2-5.
2. D.C. Groeneveld and W.W. Yousef, "Spacing Devices for Nuclear Fuel Bundles: A Survey of Their Effect on CHF, Post-CHF Heat Transfer and Pressure Drop", ANS/ASME Int. Topical Mtg., Nuclear Reactor Thermalhydraulics, Saratoga Springs, N.Y. Oct. 1980.
3. D.C. Groeneveld et al., "Analytical and Experimental Studies in Support of Fuel Channel Critical Power Improvements", Proceedings CNS Mtg. Toronto, June 9, 1989.
4. J.H. Park, J.S. Lee, and H.C. Suk, "The Effect of a Rod Bundle Mixing Vane on the Critical Heat Flux", KSME Vol. 18, No. 11, 1994.
5. M.F., Lightstone, NUCIRC MOD1.505 : A Computer Code for Nuclear Heat Transport Circuit Thermalhydraulic Analysis, User's Manual, TTR-516, 1993.

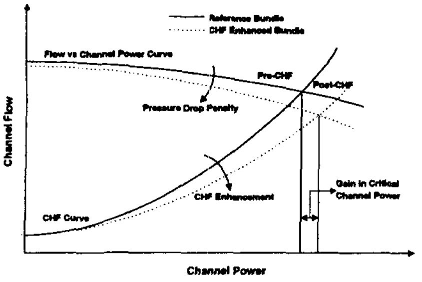

Fig. 1 Schematic of Flow and CHF Characteristics of Critical Channel Power

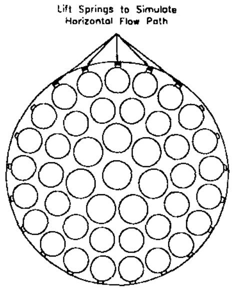

Fig. 2 Cross-Sectional View of CANFLEX Bundle

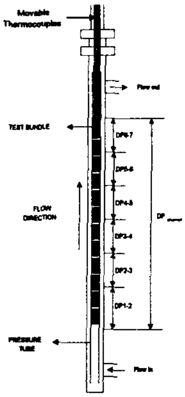

Fig. 3 Schematic Diagram for CHF Test Section

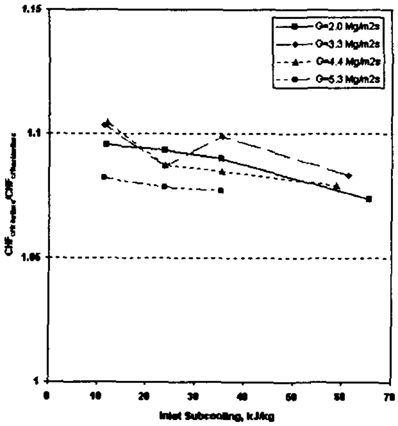

Fig. 4 The CHF Ratio of a CANFLEX bundle with buttons and without buttons According to Inlet Subcooling at Pressure 1.49 MPa

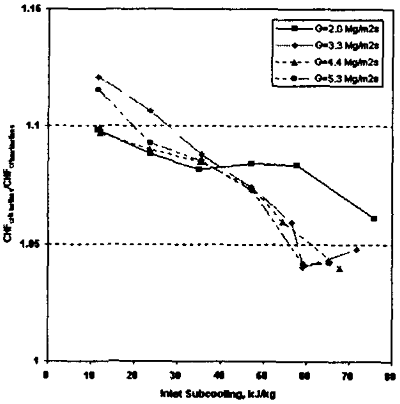

Fig. 5 The CHF Ratio of a CANFLEX bundle with buttons and without buttons According to Inlet Subcooling at Pressure 1.77 MPa

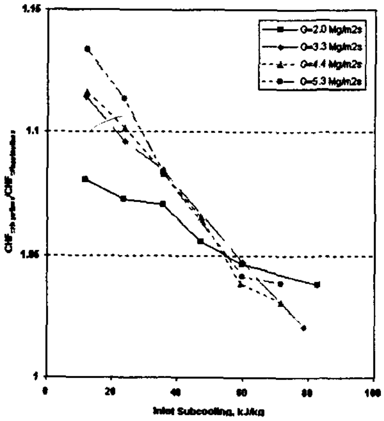

Fig. 6 The CHF Ratio of a CANFLEX bundle with buttons and without buttons According to Inlet Subcooling at Pressure 2.05 MPa

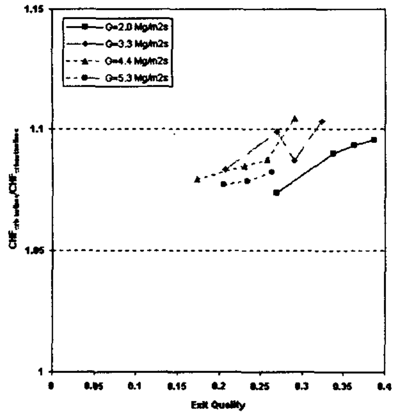

Fig. 7 The CHF Ratio of a CANFLEX bundle with buttons and without buttons According to Dryout Quality at Pressure 1.49 MPa

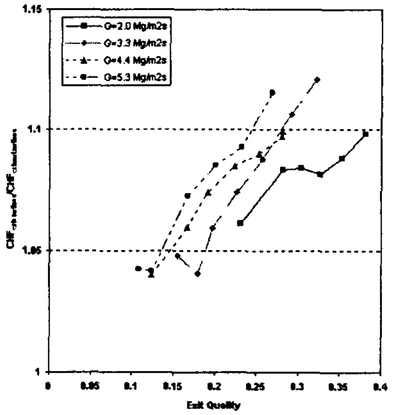

Fig. 8 The CHF Ratio of a CANFLEX bundle with buttons and without buttons According to Dryout Quality at Pressure 1.77 MPa

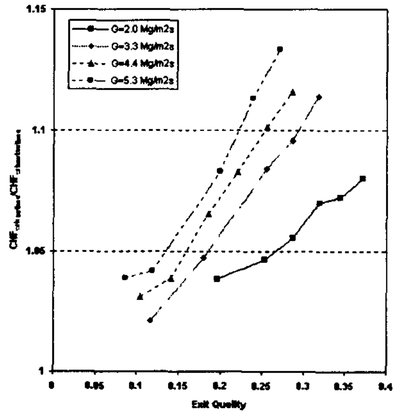

Fig. 9 The CHF Ratio of a CANFLEX bundle with buttons and without buttons According to Dryout Quality at Pressure 2.05 MPa

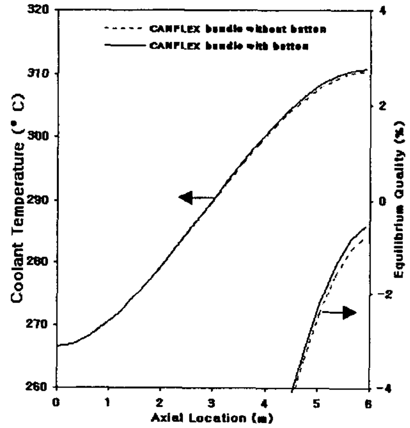

Fig. 10 Coolant temperature and quality profiles for CANFLEX bundle with buttons and without buttons along the channel axial positions

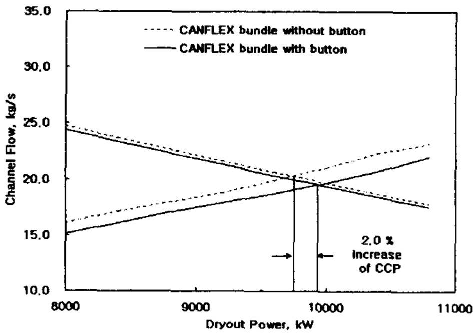

Fig. 11 CCP enhancement due to the averaged 10 % CHF enhancement by button