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Effect of Bundle Junction Face and Misalignment on the Pressure Drops Across a Randomly Loaded and Aligned 12 Bundles in Candu Fuel Channel

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Abstract

The pressure drop of twelve fuel bundle string in the CANDU-6 fuel channel is equal to the sum of the eleven junction pressure losses, the bundle string entrance and exit pressure losses, the skin friction pressure loss, and other appendage pressure losses, where the junction loss is dependent on the bundle end faces and angular alignments of the junctions. The results of the single junction pressure drop tests in a short rig show that the most probable pressure drop of the eleven junctions was analytically equal to the eleven times of average pressure drop of all the possible single junction pressure drops, and also that the largest and smallest junction pressure drops across the eleven junctions probably occurred only with BA and BB type junctions, respectively, where A and B denote the bundle end sides with an end-plates on which a company monogram is stamped and unstamped, respectively.

1. Introduction

One of CANDU(CANadian Deuterium Uranium)-6 design requirements states that the pressure drop over each fuel bundle string must be compatible with the allowance provided by the primary coolant system. The pressure drop of twelve fuel bundle string in the CANDU-6 fuel channel is equal to the sum of the eleven junction pressure losses, the bundle string entrance and exit pressure losses, the skin friction pressure loss, and other appendage pressure losses, where the junction loss is dependent on the bundle end faces and angular alignments of the junctions. The maximum pressure drop between inlet and outlet headers at full power is shared by the feeders, end-fittings, the fuel channel and fuel. This gives a pressure drop allowance across the fuel bundle string. The fuel bundles must be designed such that when randomly aligned with respect to each other the most probable pressure drop over a string of 12 bundles must be less than this value.

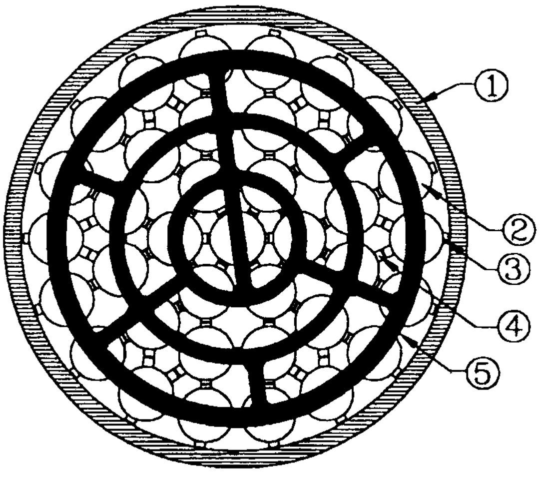
To measure the most probable pressure drop across a randomly loaded and aligned 12 bundles, it requires two type tests : bundle junction pressure drop tests and a bundle string pressure drop test [1]. The bundle junction pressure drop tests are performed in a short rig to determine the dependence of angular alignment and bundle junction face at the junction between a pair of bundles on the pressure drop, because the twelve fuel bundles are randomly loaded into the reactor fuel channels with random angular alignments. The information of pressure drop versus alignment is required for the bundle string pressure drop test. The bundle string pressure drop test is performed in a full-length test channel to measure the most probable pressure drop across a randomly loaded and aligned 12 bundles in the fuel channel. The bundles are loaded and aligned with specified bundle junction faces and alignment determined from the bundle junction pressure drop tests.

In this work, the effect of CANDU fuel bundle junction faces and misalignment on the pressure drops across the randomly loaded and aligned twelve fuel bundles in the fuel channel is studied with the test results of bundle junction pressure drops. It is primarily concerned to show that the bundle junction pressure drop test data are analytically combined with data from the full-length channel to produce the most probable pressure drop across the eleven junctions in the randomly loaded and aligned twelve bundles in the fuel channel, since the information of pressure drop versus alignment from the bundle junction pressure drop tests is required for the bundle string pressure drop test. It is also concerned to examine the effect of the bundle junction types on the most probable 11 junction pressure drop.

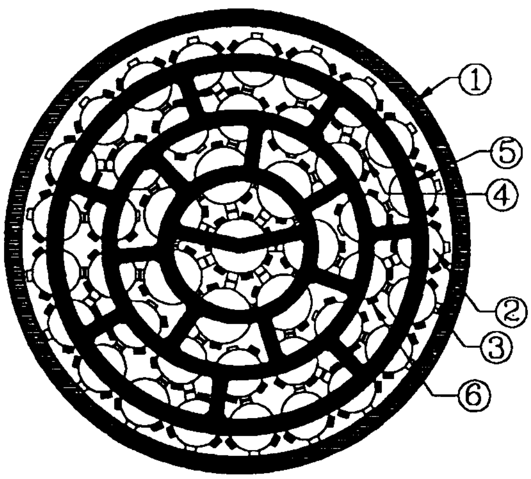
2. Description of Fuel Bundles, Facility and Method in Bundle Junction Pressure Drop Tests

2.1. Test Fuel Bundles

The fuel bundles used in the bundle junction pressure drop tests are CANDU-6 reactor standard 37-element and CANFLEX (CANDU FLEXible fuelling) 43-element fuel bundles. Fig. 1 shows the end views of the bundles inside pressure tube. The CANDU-6 standard and CANFLEX bundles are made of seven and eight components, respectively. Each fuel element contains natural UO_2 pellets in a Zircaloy-4 sheath. A graphite interlayer separates the sheath and the pellet to reduce pellet-sheath interaction. End-caps are resistance welded to the sheath extremities to seal the element. End-plates are welded to the end-caps to hold the elements in bundle configuration. Spacers are brazed to the elements at



(a) End View of CANDU-6 Standard Bundle Inside Pressure Tube



(b) End View of CANFLEX Bundle Inside Pressure Tube

Note : 1. Pressure tube 2. Fuel elements 3. Bearing pads 4. Inter element spacers 5. End plate 6. CHF enhancement pads

Fig. 1. End Views of CANDU-6 Standard 37-element and CANFLEX 43-element Bundles Inside Pressure Tube.

their mid-lengths to provide the desired inter-element separations. The bundle is spaced from the pressure tube by bearing pads brazed near the ends and at the middle of each outer element. Beryllium metal is alloyed with Zircaloy during brazing. The CANFLEX fuel bundle has additional pads attached on the elements at the two planes of their middle lengths between the bearing pads to provide the CHF (Critical Heat Flux) enhancement.

The CANFLEX fuel bundle is an CANDU advanced fuel bundle for CANDU-6 reactors, under joint development by KAERI (Korea Atomic Energy Research Institute) and AECL (Atomic Energy of Canada Limited) since February 1991 [2]. The major feature of the CANFLEX fuel bundle is an increase in the number of fuel elements, from 37 elements (13.1 mm O.D) in the standard CANDU-6 fuel bundle, to 43 elements of two different diameters. The 11.5 mm diameter elements in the outer two rings of the CANFLEX fuel bundle allow the peak element ratings in the bundle to be reduced by about 20% in comparison to the standard 37-element bundle. The 13.5 mm diameter elements in the inner two rings of the CANFLEX fuel bundle compensate for the fuel volume lost due to the smaller-diameter outer elements. Another important feature of CANFLEX bundle is the use of CHF-enhancing features on all elements in the CANFLEX fuel bundle. These will provide larger operating margins in existing CANDU reactors, thus permitting more flexibility in the use of fuel cycles with the CANDU-reactor on-power fuelling system.

2.2. Test Facility and Method

KAERI Cold Test Loop Facility [3] used in the bundle junction pressure drop tests consists of two pumps, a horizontal test rig, a light water storage tank and related piping. The two pumps as one small pump and one big pump are installed in parallel to be alternatively operated for the desired test flow rate. The desired flow rate is finally controlled by the valve at the upstream of the test rig. The test rig consists of end-fittings and transparent acrylic tube as schematically shown in Fig. 2. This acrylic tube is long enough to contain four CANDU-6 fuel bundle and the inside diameter is the same as that of CANDU-6 pressure tube. The two upstream bundles #1 and #2 are fastened each other and are fixed with a shaft fixed on the flange of the upstream end-fitting. The two downstream bundles #3 and #4 are also fastened each other and can be clockwise or counter-clockwise rotated with a rotative shaft fixed on a harmonic driving and stepping motor. In the rotational bundle junction pressure test, it allows a very small gap between the bundles #2 and #3 as possible as to make a contacting and frictional rotation of the bundle #3. The angular resolution of the stepping motor is 0.72°. So, 500 data are obtained in the one full rotation from 0° and 360°. The water flows into end-fitting side ports which are bolted to the inlet and outlet feeders and then flows through the hol es of a liner tube inside the end-fitting at the upstream. There are four pressure taps in the acrylic tube to measure the bundle and junction pressure drops as shown in Fig. 2. The pressure taps #1 and #4 measure the pressure drop across one bundle length section of the pair of fuel bundles #2 and #3, and the pressure taps #2 and #3 measure the effect of the bundle face and misalignment on the pressure drop across the bundle junction of the pair of fuel bundles #2 and #3. The inventory of the water storage tank is large enough to get constant temperature during bundle junction pressure drop tests.

When the fuel bundles with the bundle end faces shown in Fig. 1 are randomly loaded into the reactor with random angular alignments, there are four junction types, BA, AB, BB and AA of the possible bundle junction faces at the junction between the pair of bundles because of the two way loadings of one fuel bundle into the fuel channel as shown in Fig. 3. Let

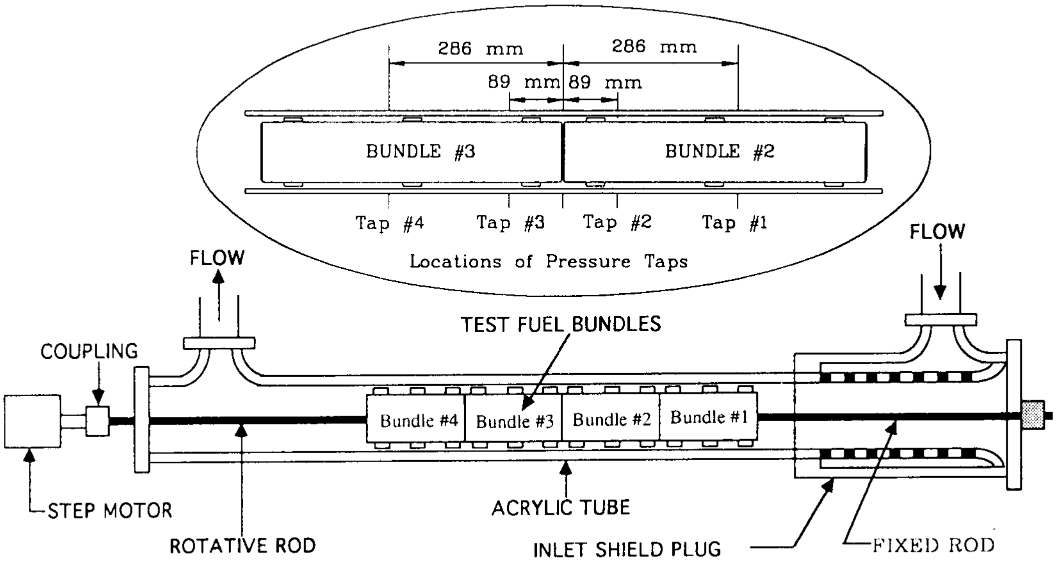


Fig. 2. CANDU Fuel Test Section of the KAERI Cold Test Loop

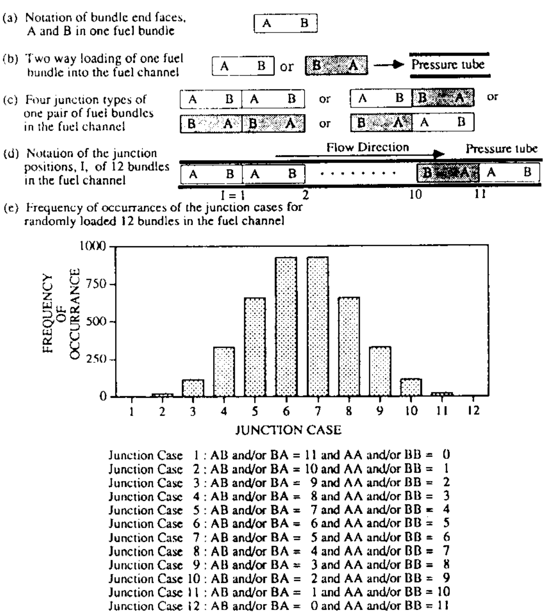


Fig. 3. Frequency of the Junction Type Occurrences

$\Delta P_{p,j,\theta,k}$ denote the pressure drop across a given bundle junction with a bundle junction position p (= 1, 2, 3, – – –, or 11) in the fuel channel, a junction type j (= BA, AB, BB or AA) and a bundle misalignment angle θ between 0° to 360° in a bundle rotated direction k (= CW (clockwise) or CCW (counter clockwise). In the point of analytical view, the pressure drop across the bundle junction with a bundle junction position i, the bundle junction type j = BA and the misalignment angle θ in the clockwise direction k = CW is the same as that with a bundle junction i, the bundle junction type j = BA and the misalignment angle $(360-\theta)$ in the counter clockwise direction k = CCW and is also the same as that with a bundle junction i, the bundle junction type j = AB and the misalignment angle θ in the counter clockwise direction k = CCW : $\Delta P_{p,j,\theta,k}$ (j = BA, $\theta=\theta_i$, k = CW) = $\Delta P_{p,j,\theta,k}$ (j = BA, $\theta=360-\theta_i$, k = CCW) = $\Delta P_{p,j,\theta,k}$ (j = AB, $\theta=\theta_i$, k = CCW). Similarly, it can see that $\Delta P_{p,j,\theta,k}$ (j = BB, $\theta=\theta_i$, k = CW) = $\Delta P_{p,j,\theta,k}$ (j = BB, $\theta=360-\theta_i$, k = CCW) = $\Delta P_{p,j,\theta,k}$ (j = AA, $\theta=\theta_i$, k = CCW). Therefore, the essential junction types to study the effect of the bundle junction face and misalignment on the bundle junction pressure drops can be selected as the two junction types of BA and BB.

To measure the effect of the bundle face and misalignment on the pressure drop across the bundle junction of the pair of fuel bundles #2 and #3, the bundle #2 is fixed to place the A side end-plate with company monogram stamp in the upstream and the B side end-plate with no company monogram stamp in the downstream and the bundle #3 is clockwise or counter-clockwise rotated by placing the A or B side end-plate at the junction between the pair of bundles #2 and #3 and so to perform the four types of bundle junction pressure drop tests to enhance the reliability of the magnitudes and signatures of the bundle junction pressure drops: a clockwise rotational pressure drop test for the BA junction, a counter-clockwise rotational pressure drop test for the BA junction, a clockwise rotational pressure drop test for the BB junction, a counter-clockwise rotational pressure drop test for the BB junction.

3. Test Results and Discussion

3.1. Test Results

Figs. 4 and 5 show the pressure drop signatures obtained from the four types of the CANDU-6 standard and CANFLEX bundle junction pressure drop tests, respectively. Finding the flow rate fluctuation of less than 1.0% in the measured pressure drops, the pressure drops in these figures are scaled to a constant flow rate of 23.9 kg/s in order to deal with them under the same condition and also to compensate the effect of flow rate fluctuations on the pressure drop variations. The equation used in the scaling is $\Delta P_{ref} = \Delta P_{exp}(M_{ref}/M_{exp})^2$ with the assumptions of constant coolant density and constant flow area in the room temperature, where ΔP_{ref} and ΔP_{exp} are the reference and experimental pressure drops, respectively, and M_{ref} (=23.9 kg/s) and M_{exp} are the reference and experimental flow rates, respectively. The uncertainty of the measured pressure drops is estimated to be less than ±2%, which is based on the uncertainties of the instrumentation for the pressure drop measurements.

3.2. Effect of Bundle Junction Faces and Misalignment on the Junction Pressure Drop

Reviewing the test results of bundle junction pressure drops shown in Figs. 4 and 5 with respect to the junction types, it is found that the signature of bundle junction pressure drops across the BA bundle junction is different from that across the BB bundle junction . For both the CANDU-6 standard and CANFLEX bundle junction press drop test results, the average pressure drop in the clockwise or counter cloc-

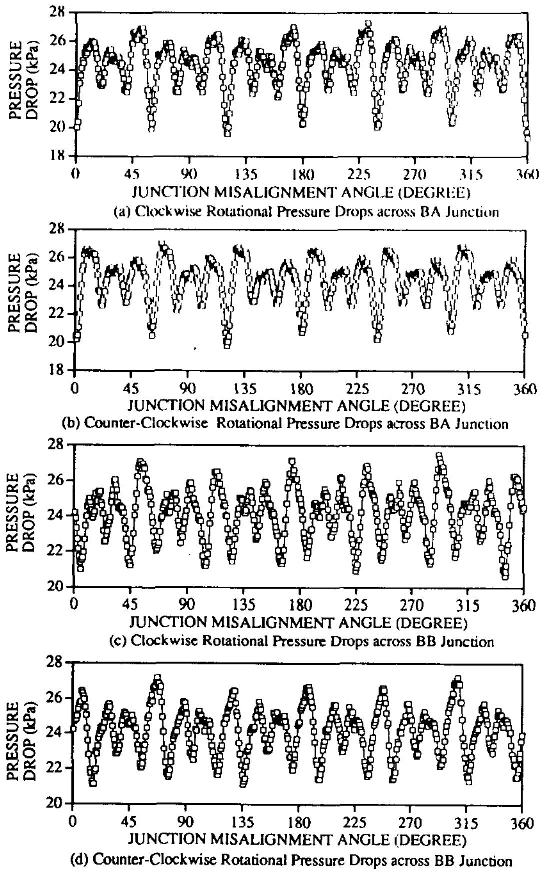


Fig. 4. CANDU Stanadard Bundle Junction BA and BB Type Rotational Pressure Drop Test Data (Scaled to the Flow Rate of 23.9 kg/s) Versus the Misalignment Angle

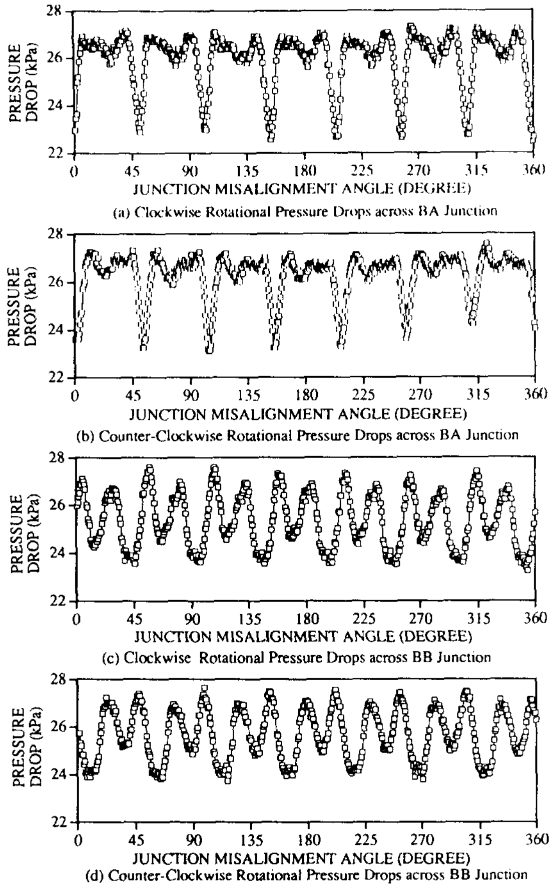


Fig. 5. CANFLEX Bundle BA and BB Type Rotational Junction Pressure Drop Test Data (Scaled to the Flow Rate of 23.9 kg/s) Versus the Misalignment Angle

kwise rotational signature of the bundle junction pressure drops across the BB junction is turned out to be slightly less than that across the BA junction as shown in Table 1.

The bundle junction pressure drop test results also reasonably show that, for the given junction type, the clockwise rotational pressure drop signature is symmetric to the counter clockwise rotational pressure drop signature at the angle of 360° and so support to hold the relationships of $\Delta P_{P,j,\theta,k}$ (j = BA, $\theta = \theta_i$, k = CW) = $\Delta P_{P,j,\theta,k}$ (j = BA, $\theta = 360 - \theta_i$, k = CCW) and $\Delta P_{P,j,\theta,k}$ (j = BB, $\theta = \theta_i$, k = CW) = $\Delta P_{P,j,\theta,k}$ (j = BB, $\theta = 360 - \theta_i$, k = CCW). Particularly, the CANDU-6 standard bundle junction pressure test results well agreed to the relationships because, for the bundle junction pressure drops across the BA or BB junction, the average pressure drop in the clockwise rotational signature is almost the same as that in the counter clockwise rotational signature as shown in Table 1. However, Table 1 indicates that, for the CANFLEX bundle BA or BB junction pressure drop signatures, the average value of the counter-clockwise bundle junction pressure drop signature is coincidentally about 1% larger than that of the clockwise bundle junction pressure drop signature, which can not be explainable, but considered to be happen by that the clockwise rotational bundle axis is not the same as the counter clockwise rotational bundle axis

Table 1. Average Junction Pressure Drops of CANDU-6 Standard and CANFLEX Bundles

Junction Face Type	Direction of Bundle Rotation	Average Junction Pressure of CANDU-6 Standard Bundles	Average Junction Pressure Drop of CANFLEX Bundles
BA	CW	24.44 kPa	25.99 kPa
	CCW	24.43 kPa	26.27 kPa
BB	CW	24.20 kPa	25.35 kPa
	CCW	24.18 kPa	25.68 kPa
Average Pressure Drop		24.31 kPa	25.82 kPa
11 x (Average Pressure Drop)		267.41 kPa	284.05 kPa

Note : CW = Clockwise ; CCW = Counter Clockwise during the bundle junction pressure tests.

The maximum pressure drop is appeared exists at a certain condition in all the CANDU-6 standard or CANFLEX bundle junction pressure drop signatures. But, the angular alignments at which the maximum pressure drop is appeared are different with the different junction types and angular alignment directions as shown in Figs. 4 and 5. Therefore, the bundle junction types and misalignment angles must be specified to measure the maximum pressure drop across the 12 bundles in a test channel.

3.3. Most Probable Pressure Drop Across the Eleven Junctions

For the two ways in loading one bundle into the fuel channel and so for the four junction types for the one pair of bundles (see Fig. 3), there exist 4096 ($=2\times2^{11}$) junction types for randomly loaded 12 bundles in the fuel channel. As mentioned in Section 2.2, if the bundle junction pressure drops are measured at every 0.72° bundle rotation, one test of bundle junction pressure drop with a given junction produces the pressure drops of 500 ($=360/0.72$) data and the total number of data for the eleven (11) junction pressure drops for randomly aligned 12 bundles is 4.8828125×10^{29} ($=500^{11}$). This total number of the eleven junction pressure drops for a randomly loaded and aligned 12 bundles is too very large one to generate them in a test channel or to deal them with a computer to find the most probable pressure drop. Therefore, it requires an analytical combination of the bundle junction pressure drop data with data from the full-length test channel to produce the most probable pressure drop across the eleven junctions in the randomly loaded and aligned twelve bundles in the CANDU fuel channel.

The most probable pressure drop across the randomly aligned twelve (12) bundles is defined as the string pressure drop which has maximum probability or frequency of occurrence. Here, the paragraph of "the randomly aligned twelve (12) bundles" is characterized as follows :

(1) bundle misalignment in the single junction of fuel bundle is random to have that all angles are equally probable at each junction,

(2) pressure drop at individual junction is independent of any event occurrence elsewhere in the channel,

(3) every junction in the fuel string has the same pressure drop verse misalignment angle signature, and

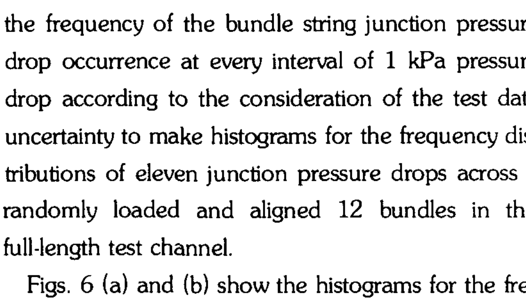
(4) flow is one dimensional single phase steady.

Based on this random characteristics on the most probable pressure drop across the 12 bundle string or the 11 junctions, the bundle junction pressure drop data can be analytically combined with the data from the full-length test channel to produce the most probable pressure drop across the randomly end-plate faced and aligned eleven junctions in the CANDU fuel channel by using the Monte Carlo method which randomly generate a certain large data of the bundle string junction pressure drops from the bundle junction pressure drop data.

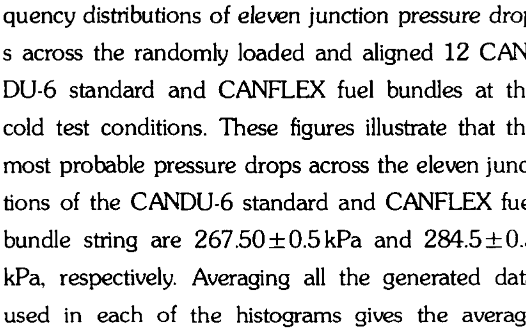
To find the most probable junction pressure drop for a randomly aligned and loaded 12 bundles at the cold test loop conditions, a computer program named with MONTE 3 [4] was made by using the Subroutine RANDU in "System/360 Scientific Subroutine Package (360A-CM-03X) Version Ⅲ Program Manual [5].

In the calculation of the most probable bundle junction pressure drop, first, the MONTE3 randomly selects one bundle junction type either BA or BB, one direction either clockwise or counter-clockwise bundle rotation and one of 500 pressure drop data for a randomly aligned bundle junction, and then, repeat and add the pressure drop for 11 times to obtain a bundle string junction pressure drop. Second, the MONTE 3 calculates the bundle string junction pressure drops for the randomly selected 300,000 bundle string. Third, the MONTE3 distinguishes and counts the frequency of the bundle string junction pressure drop occurrence at every interval of 1 kPa pressure drop according to the consideration of the test data uncertainty to make histograms for the frequency distributions of eleven junction pressure drops across a randomly loaded and aligned 12 bundles in the full-length test channel.

Figs. 6 (a) and (b) show the histograms for the frequency distributions of eleven junction pressure drops across the randomly loaded and aligned 12 CANDU-6 standard and CANFLEX fuel bundles at the cold test conditions. These figures illustrate that the most probable pressure drops across the eleven junctions of the CANDU-6 standard and CANFLEX fuel bundle string are 267.50±0.5 kPa and 284.5±0.5 kPa, respectively. Averaging all the generated data used in each of the histograms gives the average



(a) The Frequency Distribution of CANDU-6 37-Element Bundle 11 Junction Pressure Drops



(b) The Frequency Distribution of CANFLEX 43-Element Bundle 11 Junction Pressure Drops

Fig. 6. Frequency Distributions of 11 Junction Pressure Drops for Randomly Loaded and Aligned 12 CANDU-6 Standard 37-Element and CANFLEX 43-Element Fuel Bundles in a CANDU-6 Fuel Channel

pressure drops across the eleven junctions of the CANDU-6 standard and CANFLEX fuel bundle string are 267.06 kPa across the eleven junctions of the CANDU-6 standard bundle string and 284.06 kPa across the eleven junctions of the CANFLEX fuel bundle string. In the comparison between the most probable and average eleven junction pressure drops, it can be seen that the most probable 11 junction pressure drop $(DP)_{M11J}$ approached to the average 11 junction pressure drop $(\Delta P)_{A11J}$

Averaging all single junction pressure drop data used in the calculation of the frequency distribution of eleven junction pressure drops gives 24.31 kPa across the single junction of CANDU-6 fuel bundle and 25.82 kPa across the single junction of CANFLEX bundles. In comparison between average pressure drops across the single and eleven junctions, it is found that the 11 times of average pressure drop across the single junction is equal to the average 11 junction pressure drop and so to the most probable 11 junction pressure drop :

$$(\Delta P)_{M11J} \cong \Delta P)_{M11J} = 11\,\overline{\Delta P} \qquad (1)$$

where

$$(\Delta P) = [(\Delta P_{1,BA,CW})_{avg} + (\Delta P_{1,BA,CCW})_{avg} + (\Delta P_{1,BA,CCW})_{avg} + (\Delta P_{1,BB,CW})_{avg} + (\Delta P_{1,BB,CCW})_{avg}]/4 \qquad (2)$$

$(\Delta P_{1,j,k})_{avg}$ = the average pressure drop of the single junction pressure drop data.

Eq.(2) can be useful and recommended to experimentally confirm the average bundle junction pressure drop across all the possible junctions of the bundles loaded and aligned in the fuel channel. However, if the average value $(\Delta P_{1,j,CW})_{avg}$ of the clockwise bundle junction pressure drop test data is experimentally confirmed to be equal the average value $(\Delta P_{1,j,CCW})_{avg}$ of the counter clockwise bundle junction pressure drop test data,
Eq.(2) becomes

$$\overline{\Delta P} = [(\Delta P_{1,BA,CW})_{avg} + (\Delta P_{1,BA,CW})_{avg} \qquad (3)$$

In the point of experiment view rather than the point of analytical view, it is recognized that Eq.(2) is a more reliable equation to calculate the most probable 11 junction pressure drop, comparing with Eq.(3).

Once the average bundle junction pressure drop $\overline{\Delta P}$ is known, the junction type BA or BB and the misalignment angle can be found from the signature of pressure drop versus alignment in the bundle junction pressure drop tests to perform the most probable pressure drop across a randomly loaded and aligned 12 bundles. The bundle junction alignment angle to set up the most probable 12 bundle string tests can be found by tracing the average pressure drop value on all the individual single junction pressure drop signatures and by avoiding the pressure drop data which cross the average pressure drop value and have a relatively very sharp increase or decrease from the neighbour pressure drop data in the pressure drop signature.

3.4. Dependency of the Most Probable 11 Junction Pressure Drop on the Junction Type

When the 12 bundles are randomly loaded into the reactor, the most probable junction types in the fuel bundle string are the fuel string junction types 6 and 7 as shown in Fig. 3 (e). The fuel string junction type 6 has 6 junctions of the BA (and/or AB) type and 5 junctions of the BB (and/or AA) type . The fuel string junction type 7 has 5 junctions of the BA (and/or AB) type and 6 junctions of the BB (and/or AA) type. Here, as another interest, it is worthwhile to evaluate the effect of the junction types on the most probable 11 junction pressure drop. Fig. 7 shows the most probable and average 11 junction pressure drops for each of the junction type in the CANDU-6 standard and CANFLEX bundle string, which are calculated with the bundle junction pressure drop test data by using the MONTE 3 also. These figures illustrate that the pressure drop of the bundle string only with BA type junctions is mostly probable to be largest one, and the pressure drop of bundle string only with BB type junctions is mostly probable to be smallest one, comparing with the pressure drops of bundle strings with the mixed BA and BB junctions.

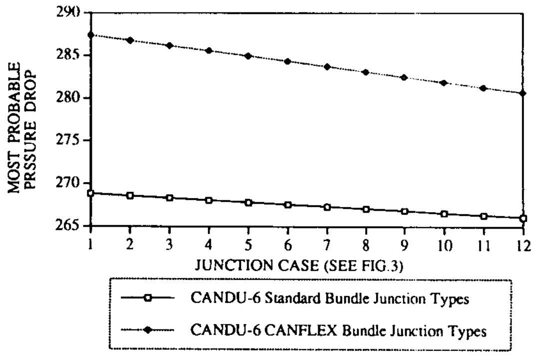


Fig. 7. The Variation of Most Probable Pressure Drops of the 11 Junctions with the Junction Cases

4. Conclusions

Based on the CANDU-6 standard and CANFLEX bundle junction pressure drops measured in KAERI Cold Test Loop, the effect of CANDU fuel bundle junction faces and misalignment on the pressure drops across the randomly loaded and aligned twelve fuel bundles in the fuel channel to obtain an analytical relationship between the single junction and 11 junction pressure drops and in addition to examine the most probable 11 junction pressure drop with respect to the junction types contained in the bundle string. Some conclusions can be made as follows :

1) It is found that the signature and average value of bundle junction pressure drops across the BA bundle junction are different from those across the BB bundle junction
2) It is recognized that the bundle junction types and misalignment angles must be specified to measure the pressure drop across the 12 bundles in a test channel.
3) It is found that the 11 times of average pressure

drops from all the possible single junction pressure drop test data is equal to the average 11 junction pressure drop. The average junction pressure drop $\overline{\Delta P}$ of all single junction pressure drops gives the information of the junction type BA or BB and the misalignment angle to perform the most probable bundle string pressure drop test.

4) It is recognized that the pressure drop of the bundle string only with BA type junctions is mostly probable to be largest one, and the pressure drop of bundle string only with BB type junctions is mostly probable to be smallest one, comparing with the pressure drops of bundle strings with the mixed BA and BB junctions.

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