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EFFECT OF RADIAL HEAT FLUX DISTRIBUTION ON PRESSURE DROPS

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ABSTRACT

Pressure drop data were obtained with CANFLEX bundle strings that simulated the radial heat flux distributions (RFDs) of natural uranium (NU) and 1.6 % slightly enriched uranium (SEU) fuel. The experiments were conducted using an axially uniform-heated CANFLEX bundle simulator installed in the vertical test station of the MR-3 heat transfer loop at Chalk River Laboratories. Pressure taps were attached at various locations along the channel and were connected to differential-pressure cells to measure the pressure drop. The measurements covered single-phase and boiling flow with channel powers up to the critical value. Pressure-drop parameters, such as friction factor, onset of significant void and two-phase multiplier, have been evaluated from the pressure drop measurements. Comparisons of these parameters between the CANFLEX bundle strings of NU and 1.6% SEU fuel RFDs are presented. Overall, the RFD effect on single and two-phase pressure-drop parameters is small.

1. INTRODUCTION

The design of the CANFLEX® (CANDU® Flexible)[1] bundle allows the use of various levels of fuel enrichment in a CANDU reactor. AECL is currently considering the use of slightly enriched uranium (SEU) fuel for the CANFLEX bundle. The CANFLEX bundle with 1.6% SEU fuel has a steeper RFD than that of the CANFLEX bundle with NU fuel. It is anticipated that the effect of RFD on the single-phase pressure drop characteristics of the CANFLEX SEU fuel bundle will be small, since single-phase pressure drop depends mainly on the surface roughness and bundle geometry. However, the RFD may have some impact on the initiation of boiling and may impact the two-phase pressure drop.

Pressure-drop experiments were conducted using an axially uniform-heated CANFLEX bundle simulator installed in the vertical section of the MR-3 heat transfer loop at AECL Chalk River Laboratories. These experiments were performed to provide pressure-drop data for a CANFLEX bundle simulating the radial power profile of NU fuel and 1.6 % SEU fuel

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[1] CANFLEX® is a registered trademark of Atomic Energy of Canada Limited (AECL) and the Korean Atomic Energy Research Institute (KAERI).
CANDU® is a registered trademark of AECL.

at water-equivalent high pressure and high flow conditions. The data were applied to evaluate the pressure-drop parameters, such as friction factor, onset of significant void, and two-phase multiplier, for the CANFLEX bundle. The calculated parameters for the 1.6% SEU fuel RFD bundle were compared against those for the NU fuel RFD bundle to examine the effect of RFD. The objectives of this paper are to present the comparison results of various pressure-drop parameters between CANFLEX bundles of NU and 1.6% SEU fuel RFDs, and quantify the impact of RFD on single-phase and two-phase pressure drops.

2. EXPERIMENTS

The pressure-drop experiment was performed using an axially uniformly-heated CANFLEX bundle simulator installed in the vertical section of the MR-3 loop. Figure 1 shows a schematic diagram of the MR-3 heat transfer loop.

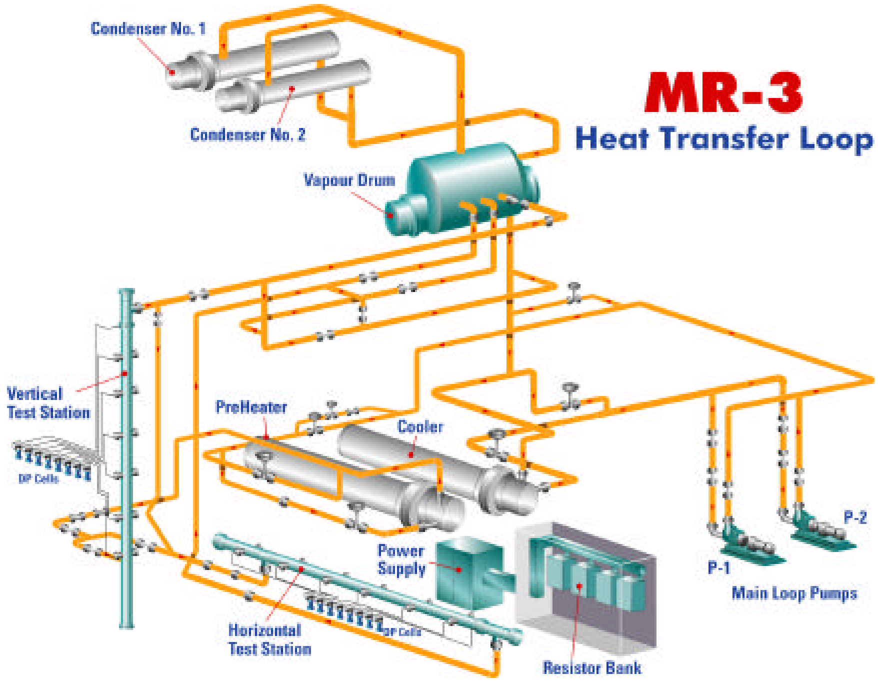

Figure 1. Schematic Diagram of MR-3 Loop

2.1 Test Section

The test section simulated a string of 12 aligned CANFLEX bundles, including bundle junctions and appendages (i.e. spacers, bearing pads, and buttons). The CANFLEX bundle consisted of 43 elements with two different outer diameters. The bundle string was mounted inside a fibreglass flow tube of 103.4 mm in inside diameter, and was cooled with an upward flow of Freon (R-134a). Seven pressure taps were installed to provide pressure distributions along the flow tube. The axial heat-flux distribution along the bundle string is uniform.

2.2 Radial Heat-Flux Distribution Profile

The radial power distribution of the bundle string simulated the NU fuel profile, using tubes of different wall thicknesses at various rings. An external resistor bank was attached to various rings of elements in the bundle string to facilitate changing of the radial power profile. The resistors were adjusted to provide the simulation of the 1.6% SEU fuel RFD. Figure 2 presents the radial power and heat-flux ratios at each ring of the bundle simulator for both NU and 1.6% SEU fuels. The RFDs in Figure 2 corresponds to that of fresh fuel [1].

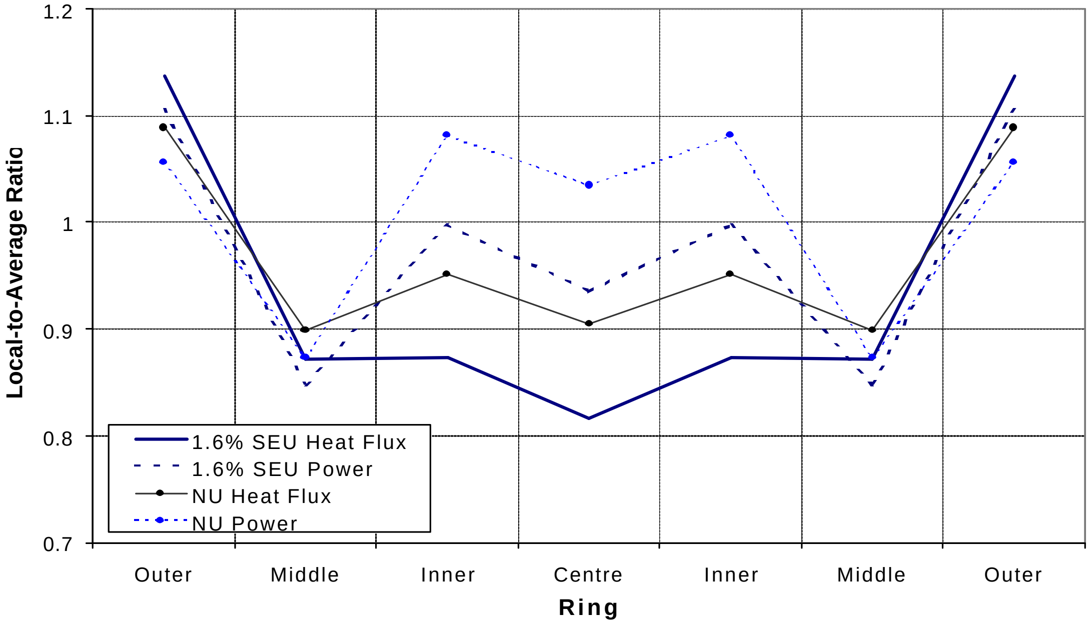

Figure 2. Radial Power and Heat-Flux Ratios for the CANFLEX NU and 1.6% SEU Fuel Bundles.

2.3 Instrumentation

Loop and bundle simulator instrumentation included absolute and differential pressure transducers, thermocouples, and resistor temperature devices (RTDs). Test-section mass flow rates were measured with two in-series flow meters, and individual ring powers were provided using the current shunts and a custom-designed electronic instrument. The test-section power was calculated using the voltage drop and the current through all rings.

2.4 Test Conditions

The test conditions covered in the pressure-drop experiments are shown in Table 1. The water-equivalent values for the test conditions were calculated using fluid-to-fluid modelling parameters for critical heat flux (CHF) [2].

Table 1: Freon Test Conditions

	Freon Conditions	**Water-Equivalent Conditions**
Outlet Pressure (MPa)	1.76 to 2.43	10.6 to 14.2
Mass Flow Rate ($kg{\cdot}s^{-1}$)	12.0 to 21.6	16.7 to 30.4
Inlet Fluid Temperature (ºC)	26.85 to 67.58	218.1 to 319.6

3. RESULTS AND ANALYSIS

Pressure-drop measurements at various measuring stations along the channel were obtained for single-phase (no boiling) and boiling flows at the outlet of the heated bundle string. These measurements were used to calculate the single-phase friction factor, onset of significant void, and two-phase multiplier for the CANFLEX bundle strings of NU and 1.6% SEU fuel RFD.

3.1 Single-Phase Pressure Drop due to Friction

The single-phase pressure drop due to friction is calculated from

$$\begin{aligned}\Delta P_{SP,\,f} &= \Delta P_{SP,\,t} - \Delta P_{SP,\,a} - \Delta P_{SP,\,g} \\ &= \Delta P_{SP,\,t} - G^2 \Delta\left(\frac{1}{\rho_b}\right) - \rho_b g \sin\theta \ \Delta z\end{aligned} \tag{1}$$

where ΔP with the subscripts “SP”, “f”, “t”, “a” and “g” refer to the single-phase, friction, total, acceleration, and gravity, G is the mass flux in $kg.m^{-2}.s^{-1}$, Δz is the axial distance over the node in metres, ρ_b is the bulk fluid density in $kg.m^{-3}$, g is the gravitational constant ($9.806\ m{\cdot}s^{-2}$) and θ is the angle of the channel orientation with respect to the horizontal.

The pressure-drop measurement is expressed in terms of the single-phase equivalent friction factor, defined as

$$\begin{aligned}f_{equiv.} &= \Delta P_{SP,\,f} \frac{D_{hy}}{\Delta z} \frac{2\rho_b}{G^2} \\ &= f_{bundle} + \Sigma K_i \frac{D_{hy}}{\Delta z}\end{aligned} \tag{2}$$

where f_{bundle} is the friction factor at the unobstructed element region, and K_i are the loss factors of appendages (i.e. bundle junctions, spacer planes, and bearing pad planes.

Figure 3 presents the experimental friction factors as a function of Reynolds number for one of the measuring sections in the channel with the NU and 1.6% SEU RFD bundles. The friction factor decreases with Reynolds number. The decreasing trend is more noticeable at low Reynolds number, but becomes gradual with increasing Reynolds number. Overall, the friction factors evaluated in various measuring sections for the CANFLEX 1.6% SEU and NU bundles exhibit a similar decreasing trend with increasing Reynolds numbers confirming that the effect of RFD on single-phase pressure drop over the CANFLEX bundle is small.

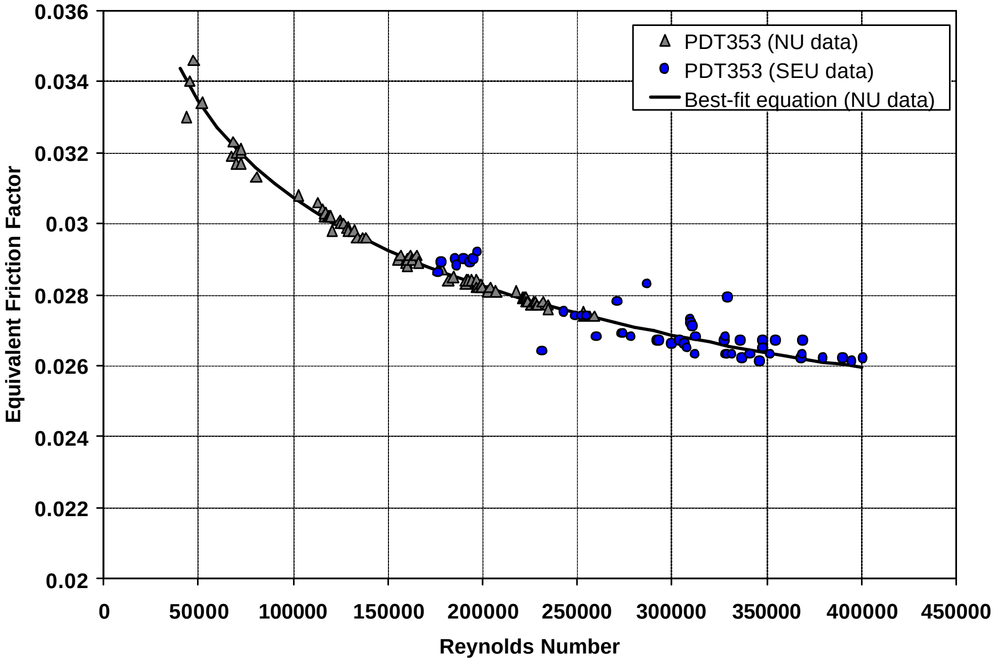

Figure 3: Variation of Friction Factors with Reynolds Number at one of the Measuring Sections

Equations were introduced to represent the friction-factor values for the NU fuel RFD, and compared against those for the 1.6% SEU fuel RFD. The friction factor equation is expressed in the form of

$$f_{equiv.} = a\,\mathrm{Re}^{-b} \tag{3}$$

The constants, a and b, were determined using the method of least squares for the single-phase friction factors at various measuring sections along the channel. Figure 4 shows the friction-factor ratio between measured 1.6% SEU and $f_{equiv.}$ NU RFDs. All ratios are close to one over the current range of Reynolds numbers (the mean ratio is 1.003). This shows that the effect of RFD on single-phase friction factor, and hence pressure drop, is small for the CANFLEX bundle.

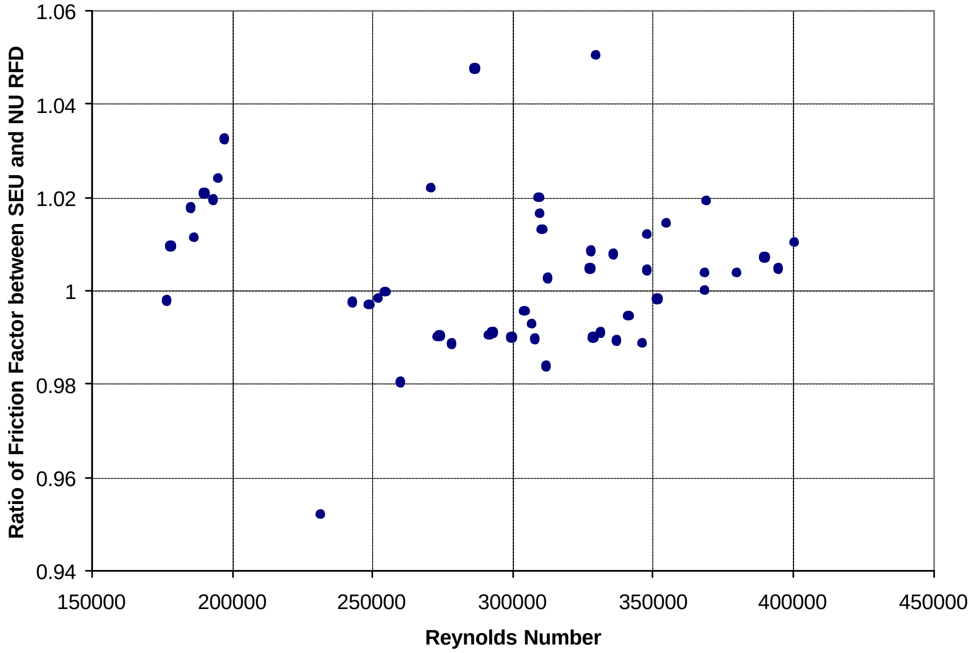

Figure 4: Ratio of Friction Factor between SEU and NU RFDs with Reynolds Number at one of the Measuring Sections

3.2 Onset of Significant Void

The onset of significant void (OSV) is considered as the transition point between single-phase and two-phase pressure drop. It occurs at a thermodynamic quality slightly higher than that corresponding to the onset of nucleate boiling (ONB) at the same inlet-flow conditions. The impact of near-wall boiling at ONB on pressure drop is minor and hence the pressure drop between ONB and OSV is often evaluated with the single-phase calculation. The variation of pressure drop becomes noticeable beyond OSV, and hence the two-phase calculation is applied.

The OSV point in a heated channel is often determined empirically from the pressure drop data. Saha and Zuber [3] introduced an OSV correlation for tubes, based mainly on the boiling number for high-flow conditions. Snoek [4] extended the Saha and Zuber equation to a 37-element bundle. He observed a strong effect of inlet subcooling on the OSV point.

The OSV point in the CANFLEX bundle is located using the axial pressure distribution, established from the pressure-drop measurements, along the channel. Figure 5 illustrates the axial pressure distribution for one of the cases. A linear line was introduced for the single-phase pressure-drop region at the inlet end of the bundle and a parabolic curve was used to represent the two-phase pressure-drop region at the outlet end of the bundle. The OSV point is considered at the intersecting point of the linear line and the parabolic curve. It is about 4400 mm from the inlet end of the bundle string in the illustrated case.

Figure 6 presents the variation of the thermodynamic quality at the OSV point with the boiling number for the NU and 1.6% SEU fuel RFDs. The thermodynamic quality is evaluated from a heat balance, and the boiling number is defined as

$$Bo = \frac{q}{G\,H_{fg}} \tag{4}$$

where q is the local heat flux in $W.m^{-2}$ and H_{fg} is the latent heat of vaporization in $J.kg^{-1}$. The OSV quality generally decreases with increasing boiling number (see Figure 6). The decreasing trend appears to begin at boiling numbers close to $15 \cdot 10^{-5}$. This differs from the trend observed among tube data, where the decreasing trend begins at boiling numbers close to 0. The difference is due to the enthalpy imbalance within the bundle and the vapour generated in several subchannels does not have a significant impact on the overall pressure distribution. Furthermore, the OSV quality represented the cross-sectional average value and is lower than the local quality at the high-enthalpy subchannel. The scatter among data is relatively large. Nevertheless, the OSV points for the 1.6% SEU fuel RFD follow closely those for the NU fuel RFD. This implies that the effect of RFD on the OSV point is minor.

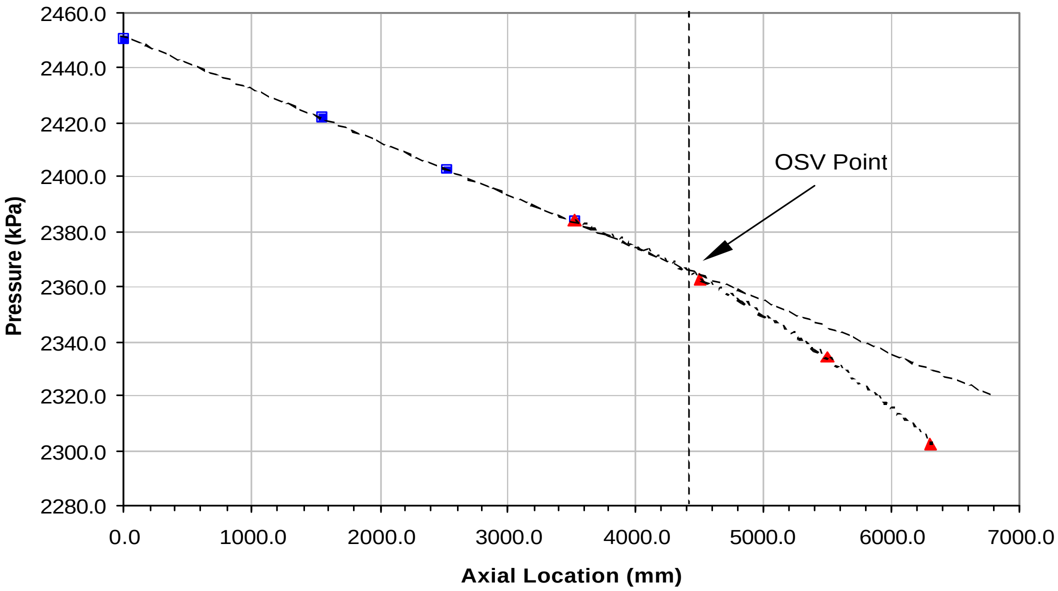

Figure 5. Axial Pressure Distribution and the Establishment of the OSV point.

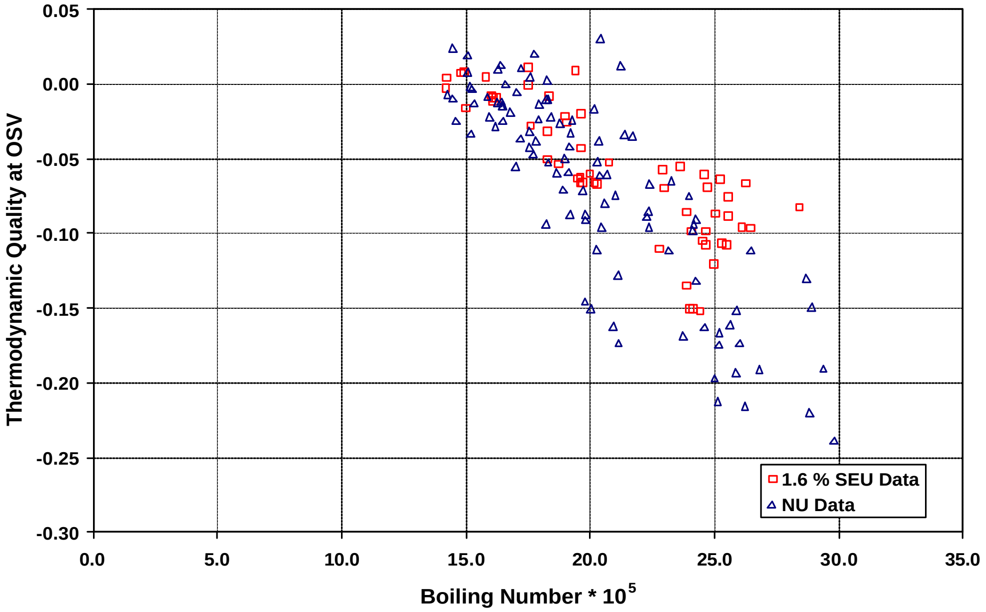

Figure 6: Variation of Thermodynamic Quality at OSV with Boiling Number

3.3 Two-Phase Pressure Drop due to Friction

The two-phase pressure drop due to friction is calculated from

$$\begin{aligned}\Delta P_{TP,\,f} &= \Delta P_{TP,\,t} - \Delta P_{TP,\,a} - \Delta P_{TP,\,g} \\ &= \Delta P_{SP,\,t} - G^2 \Delta\left(\frac{x_a{}^2}{\alpha\rho_g} + \frac{(1-x_a)^2}{(1-\alpha)\rho_f}\right) - (\alpha\rho_g + (1-\alpha)\rho_f)\, g \sin\theta\ \Delta z\end{aligned} \tag{5}$$

where ρ_f is the saturated liquid density in kg.m^{-3}, ρ_g is the saturated vapour density in kg.m^{-3}, x_a is the vapour-weight quality evaluated with the Saha and Zuber correlation [3], and α is the void fraction calculated with the Massena correlation [5].

The two-phase pressure drop is expressed in terms of the two-phase multiplier, defined as

$$\phi_{TP}^2 = \frac{\Delta P_{TP,\,f}}{\Delta P_{SP,\,f}} \tag{6}$$

The single-phase pressure drop is calculated using Equation (1) with the equivalent friction factor evaluated using Equation (2). Figure 7 illustrates the variation of two-phase multipliers with thermodynamic quality (average value over the measuring section) over various pressures fixed at a mass flux of 5.3 Mgm^{-2}s^{-1}. The two-phase multipliers for both the 1.6% SEU and NU fuel RFD increases with increasing quality and increasing pressure. At a particular pressure, the experimental two-phase multipliers for both the 1.6% SEU and NU bundles, appear to consolidate into a single line, and increase with increasing thermodynamic quality. Within the current range of test conditions, the effect of pressure on the two-phase multiplier is relatively small.

Figure 8 illustrates the ratio of two-phase multipliers between 1.6% SEU and NU fuel RFDs for various pressures and mass fluxes. All ratios are close to 1 within the range of thermodynamic quality tested. This shows that the effect of RFD on two-phase multiplier, and hence two-phase pressure drop, is minor for the CANFLEX bundle.

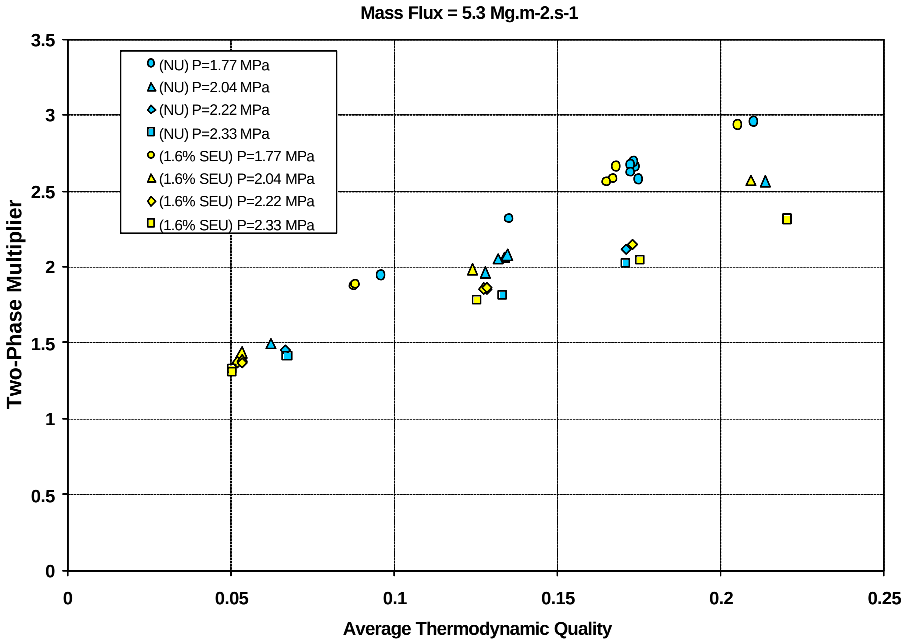

Figure 7. Variation of Two-Phase Friction Multipliers with Thermodynamic Quality and Pressure.

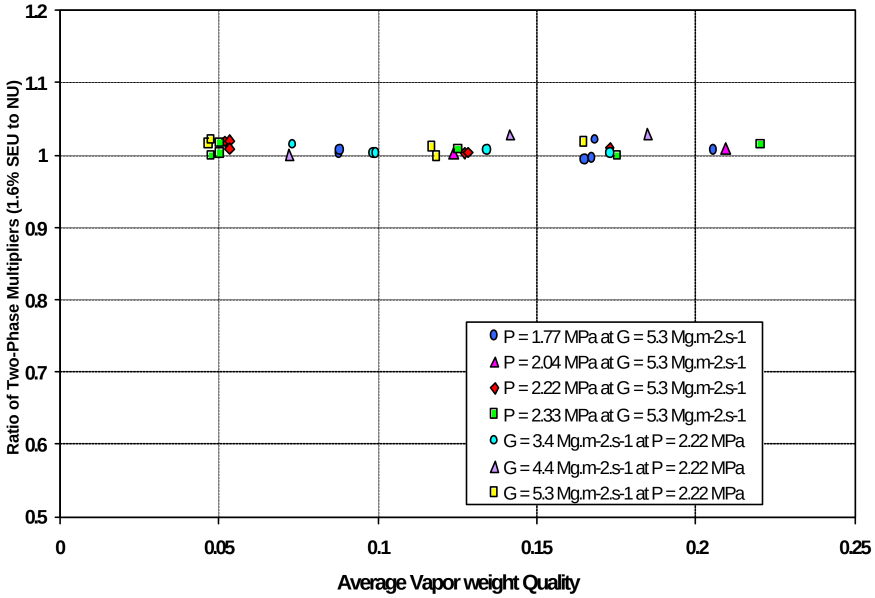

Figure 8. Two-phase Multiplier Ratios between 1.6% SEU and NU Fuel RFDs at Various Mass Fluxes and Pressures.

4. CONCLUSIONS

- The pressure-drop data obtained with a CANFLEX bundle string simulating the RFDs of 1.6% SEU and NU fuel have been analyzed.
- The friction factors for both the 1.6% SEU and NU fuel RFD follow the consistent decreasing trend with increasing Reynolds number. The effect of RFD on friction factor is small.
- The OSV point has been established for the CANFLEX bundle at test conditions. The thermodynamic quality at OSV decreases with boiling number. No significant differences in OSV quality was noticed between the 1.6% SEU and NU fuel RFDs.
- The two-phase multipliers for both the 1.6% SEU and NU fuel RFD increases with increasing quality and increasing pressure. There appears to be no effect of RFD on two-phase multiplier for the CANFLEX bundle.
- Based on the analysis, the effect of RFD on single and two-phase pressure drops is negligible for the CANFLEX bundle.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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