Critical Heat Flux, Single-Phase And Two-Phase Pressure Drop Methodologies For CANFLEX-NU With Crept And Uncrept Pressure Tubes

Richard Oduntan[1], Dan Quach, Carol Wong, Ab Tahir

Nuclear Safety Solutions (NSS) Ltd, 700 University Avenue, Toronto Canada.

ABSTRACT

Methodologies were developed for pressure drop (single and two-phase), Onset of Significant Void and local conditions Critical Heat Flux applicable to crept and uncrept fuel channels containing 43-element CANFLEX Natural Uranium (NU) fuel bundles. The correlations are based on the Stern Laboratory Incorporated experimental data for CANFLEX NU design. To obtain the coefficients for the different correlations developed, the Gauss-Newton method for unconstrained optimization problems was employed. Excellent agreement was obtained between experimental data and the predictions of the developed correlations.

1.0 INTRODUCTION AND BACKGROUND

1.1 Background

The 43-element CANFLEX[2] fuel bundle design utilizing either natural uranium (NU) or slightly enriched uranium is being considered as replacement for 37-element fuel bundle design in CANDU reactors for the purpose of improving safety margin for Large Break Loss of Coolant Accidents (LBLOCA) and mitigating the effects of Heat Transport System (HTS) aging with respect to Critical Heat Flux (CHF) and Critical Channel Power (CCP). One of the effects of CANDU HTS aging is pressure tube diametral creep, which has been demonstrated experimentally to affect the fuel channel pressure drop and fuel cooling characteristics [1].

Pressure tube diametral creep increases the fuel channel's available coolant flow area

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[1] Richard Oduntan is now with Ontario Power Generation (Pickering A Nuclear Generating Station)

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

thereby reducing the channel resistance to flow. The increased flow is not distributed uniformly through the fuel bundle cross-section as the bundle tends to settle to the bottom of the fuel channel, leaving a crescent-shaped space above.

To be able to predict CHF and CCP over the life of the fuel channel, it is important to derive pressure drop (single phase and two-phase) and CHF correlations that incorporate the effects of pressure tube diametral creep. This paper presents the development of methodologies for CHF and pressure drop correlations applicable to CANFLEX-NU fuel with crept and uncrept pressure tubes. The coefficients of the correlations were developed based on the full scale 43-element CHF and pressure drop experiments carried out at the Stern Laboratories Inc [1].

The paper is organized in four Sections. Section 2 details the modeling approach for pressure drop (single-phase and two-phase flow) while Section 3 describes CHF and dryout power modeling. Conclusions are provided in Section 4.

2.0 PRESSURE DROP MODEL DEVELOPMENT

As shown in Figure 1, the pressure-drop phenomenon in a channel flow is modelled using a control volume approach that assumes a one-dimensional horizontal flow[3]. For horizontal channels, the gravitational term is neglected. The thermal hydraulic characteristics at each pressure tap location for both the crept and uncrept fuel channels are taken as bundle cross-sectional average values. Thus, pressure drop is calculated using the following equation:

$$\Delta P_{\text{Model}} = \Delta P_a + \Phi_m^2 \Delta P_{sp} \qquad \text{[E-1]}$$

where:

ΔP_a - the acceleration pressure drop in kPa

Φ_m^2 - the model two-phase multiplier

ΔP_{sp} - the single-phase pressure drop in kPa

The acceleration pressure term is a significant component of the total pressure-drop for boiling flows or for flows with non-uniform, cross-sectional flow areas, and is given as:

$$\Delta P_a = \frac{-\dot{m}_{in}^2}{A_{f_{average}}}\left(\left(\frac{1}{\rho_{TP} A_f}\right)_u - \left(\frac{1}{\rho_{TP} A_f}\right)_d\right) \qquad \text{[E-2]}$$

[3] As the flow decreases the assumption of a one-dimensional flow becomes less valid, and the predictions outside the lower range of the flow may result in poor predictions.

where:

$\dot{m}_{in}$ = the inlet mass flow rate in kg/s
A_f = the flow area in m^2
ρ_{TP} = the two-phase mixture density in kg/m^3

the subscripts *u* and *d* signify the upstream and downstream locations of the control volume (see Figure 1) and $A_{f_{average}}$ is the arithmetic mean of A_{f_u} and A_{f_d}. The acceleration pressure-drop term is significant for crept channel pressure drop calculations even under single-phase conditions due to the area changes that occur along the channel length. Equation [E-2] is computed using the inlet and outlet flow areas, which are creep level dependent. For flow under single-phase conditions, the value of the single-phase liquid densities at the inlet and outlet of each section are used instead of the two-phase density, ρ_{TP}.

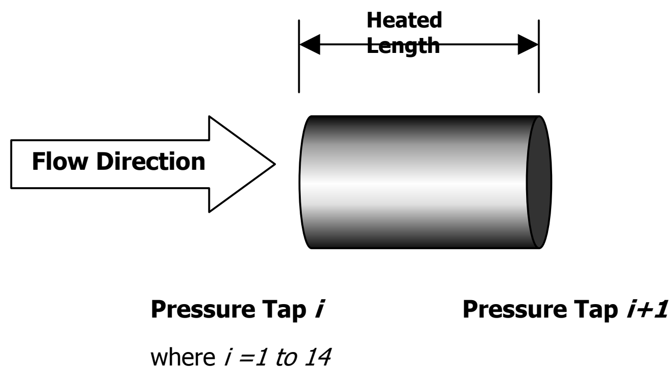


Figure1: Control Volume Used

The two-phase mixture density used in Equation [E-2] is defined as follows:

$$\frac{1}{\rho_{TP}} = \frac{X_{CAL}}{\rho_g} + \frac{(1 - X_{CAL})}{\rho_l} \qquad \text{[E-3]}$$

Where:

X_{CAL} = the cross-sectional averaged quality as given in Equation [E-5]

ρ_g = the gas-phase density in kg/m^3

ρ_l = the liquid-phase density in kg/m^3

The two-phase mixture density is computed at the inlet and outlet of a control volume. For calculations at the inlet of the control volume, the gas and liquid-phase densities are computed using the inlet temperature and pressure. Similarly, the outlet of the control volume uses the outlet temperature and pressure to evaluate gas and liquid-phase densities.

The two-phase mixture density is dependent on the cross-sectional averaged quality X_{CAL} which is the quality within the phase transition region of the boiling flow. This quality is a function of the vapour weight quality which has been used extensively for two-phase multiplier predictions in systems with round tubes. Vapour weight quality is defined as:

$$X_{VW} = \frac{X - X_{OSV}\ (e^{\frac{X}{X_{OSV}}-1})}{1 - X_{OSV}\ e^{(\frac{X}{X_{OSV}}-1)}} \qquad \text{[E-4]}$$

where:

$$X = \frac{h - h_f}{h_{fg}} \text{ (thermodynamic quality)}$$

h = the local enthalpy in kJ/kg using the local (i.e at a node) pressure and temperature

h_f = the saturated liquid enthalpy in kJ/kg based on local pressure and temperature

h_{fg} = the latent heat of vaporisation in kJ/kg based on the local pressure and temperature

X_{OSV} = the thermodynamic quality at Onset of Significant Void (OSV) as given in Equation [E-6]

It should be noted that two-phase flow boiling in fuel bundle geometries has some distinct features that differ from the behaviour observed under similar conditions in round tubes. Specifically these are:

- The radial flux distribution causes unequal power transfer to the fluid in a given cross section.

- The flow is segmented into separate subchannels, with imperfect mixing between all regions.

As a result, flow and enthalpies are unevenly distributed among the subchannels at a bundle cross-section. These phenomena and the effects of pressure tube creep can be modelled using the cross-sectional averaged quality (X_{CAL}) defined as:

$$X_{CAL} = X_{VW} + \frac{X_{OSV}}{2\, e^{\lambda + \left(\frac{2X}{X_{OSV}}\right)^2}} \qquad \text{[E-5]}$$

where:

$$\lambda = \left(\frac{D_{PT_{crept}} - D_{PT_{nominal}}}{D_{nominal}} \right) \times 100\%$$

$D_{PT_{crept}}$ = the crept pressure tube diameter in m evaluated at the control volume mid-point

$D_{PT_{nominal}}$ = the nominal pressure tube diameter in m

A constraint on X_{CAL} is that it is set to zero for all cases when OSV has not been reached. The thermodynamic quality at the onset of significant void (OSV) for both uncrept and crept pressure tubes can be empirically correlated as follows:

$$X_{OSV} = \left(-C \left(\frac{A_{f\,nominal}}{A_{f\,crept}} \right)^{E_5} \right) Bo_{local} \qquad \text{[E-6]}$$

where:

$A_{f\,nominal}$ = the nominal flow area in m^2 evaluated at the control volume mid-point

$A_{f\,crept}$ = the crept flow area in m^2 evaluated at the control volume mid-point

Bo_{local} = the local boiling number as given in Equation [E-7]

C and E are correlation coefficients.

The area ratio is used to account for the effects of creep where the crept area at the location of OSV and the local Boiling number are evaluated at the centre of each control volume. The local Boiling number is given as:

$$Bo_{local} = \frac{q_{local}}{G_{local}\ h_{fg}} \qquad \text{[E-7]}$$

where q_{local} is the local heat flux in kW/m^2. The local coolant mass flux G_{local} is evaluated at the centre of each control volume using the average channel flow area as follows:

$$G_{local} = \frac{\dot{m}_{in}}{A_{f_{average}}} \qquad \text{[E-8]}$$

To predict the single-phase component of Equation [E-1] for uncrept and crept pressure tubes the following relationship is used:

$$\Delta P_{sp} = \left(f\frac{L}{D_H} + \left(\frac{A_{f_{nominal}}}{A_{f_{crept}}}\right)^2 \sum K \right) \frac{G^2_{local}}{2\rho_l} \qquad \text{[E-9]}$$

where:

f = the skin friction factor
L = the bundle length in m
D_H = the equivalent hydraulic diameter in m evaluated at the control volume midpoint
ΣK = the sum of form losses as given in Equation [E-10]
ρ_l = the fluid density in kg/m^3 evaluated at the control volume midpoint

The skin friction factor for fully turbulent flow is computed using the implicit Colebrook-White correlation evaluated using the local Reynolds number and local hydraulic diameter.

$$\sum K_{crept} = \sum K_{bundle} \left(\frac{A_{f_{nominal}}}{A_{f_{crept}}}\right)^{B_1} \qquad \text{[E-10]}$$

where:

Re_{local} = the local Reynolds number evaluated at the control volume mid-point

$D_{H_{local}}$ = the hydraulic diameter in m evaluated at the control volume mid-point
$D_{PT_{local}}$ = the local pressure tube diameter in m evaluated at the control volume mid-point
$D_{element}$ = the element diameter in m evaluated at the control volume mid-point
μ = the fluid viscosity in kg/m/s evaluated at the control volume mid-point
ε = the relative roughness evaluated at the control volume mid-point
B_1 is a correlation coefficient.

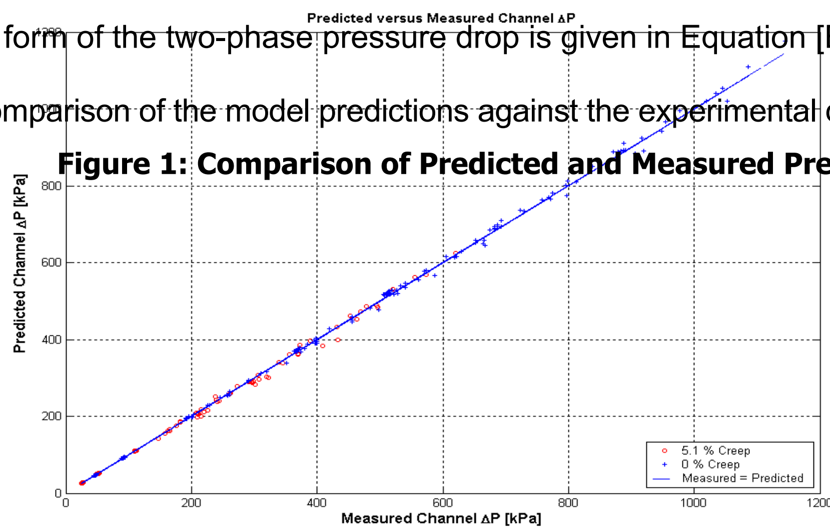
The form loss coefficient ΣK in Equation [E-9] corresponds to the losses associated with the junction planes, spacer planes and bearing pads. These flow obstructions are expected to represent a smaller percentage of the flow area for crept channels. Thus, the form loss coefficient is expected to decrease with increasing diametral creep, and the phenomenon is modelled using a flow area ratio squared.

To evaluate the friction and form loss pressure drop in boiling flows, a two-phase multiplier is used. The frictional and form loss pressure-drops are calculated assuming single-phase flow with the fluid properties evaluated using the liquid saturation properties. The two-phase pressure drop is computed using the two-phase multiplier as follows:

$$\Phi_m^2 = B_4\left(1+\left(\frac{\rho_l}{\rho_g}\right)^{B_5}\left(\frac{Re}{10^5}\right)^{B_6} X_{CAL}(1-X_{CAL})\right)\frac{\rho_l}{\rho_{TP}} \qquad \text{[E-11]}$$

Where:

X_{CAL} = the cross-sectional averaged quality as given in Equation [E-5]
ρ_g = the gas-phase density in kg/m^3
ρ_l = the liquid-phase density in kg/m^3
ρ_{TP} = the two-phase density
B_4, B_5, B_6 are correlation coefficients.



The form of the two-phase pressure drop is given in Equation [E-1].

A comparison of the model predictions against the experimental data is shown in Figure 1.

Figure 1: Comparison of Predicted and Measured Pressure Drop Data

3.0 CHF MODEL DEVELOPMENT

The local conditions CHF approach assumes that CHF is a function of only local fluid conditions along a flow channel. Assuming adequate mixing across the fuel channel cross-section, a local conditions CHF correlation can therefore be expressed as functions of cross-sectional average fluid property.

The local CHF (q_{CHF}) is defined as follows:

$$q_{CHF} = \frac{\varphi \cdot Power_{DO}}{A_{Heated}} \qquad \text{[E-12]}$$

Where:

φ = The axial flux factor (normalised by the average channel flux)

$Power_{DO}$ = The power at dryout in kW

A_{Heated} = The heated surface area (m^2)

For CANFLEX-NU design, the heated area is as follows:

$$A_{Heated} = \left(35\,\pi\,D_{se} + 8\pi\,D_{le}\right)L_{heated} \qquad \text{[E-13]}$$

Where:

D_{le} = element diameter (rings 1 and 2) (m)
D_{se} = element diameter (rings 3 & 4) (m)
L_{heated} = bundle string heated length (m)

The thermodynamic quality at dryout location is calculated as follows:

$$\chi_{DO} = \frac{h_{local} - h_f}{h_{fg}} \qquad \text{[E-14]}$$

Where:

$$h_{local} = \frac{Power_{DO} \cdot \int_{x=0}^{x=x_{DO}} \varphi \cdot dx}{\dot{m}_{in}} + h_{in} \qquad \text{[E-15]}$$

h_{local} = enthalpy at dryout location (kJ/kg)

h_f = saturated liquid enthalpy at dryout location (kJ/kg)

h_{fg} = latent heat of vaporisation at dryout location (kJ/kg)

h_{in} = inlet enthalpy based on inlet pressure and temperature (kJ/kg)

$\dot{m}_{in}$ = the inlet mass flow rate in kg/s

X_{DO} = dryout location

To ensure applicability to both light and heavy water coolants, a CHF correlation of the following form is proposed:

$$\frac{q_{CHF}}{G \cdot h_{fg}} = C_1 \left(1-\chi_{DO}\right)^{C_2} \left(w_B \cdot \frac{\rho_1}{\rho_g} \right)^{C_3} \varphi^{C_4} \times \frac{1}{CF} \quad \text{[E-16]}$$

Where CF = $C_5 D_{Hnom}{}^2 + C_6 D_{Hnom} - (C_5 + C_6 - 1)$ [E-17]

and

$$w_B = \left(\frac{G_{local}{}^2 \cdot D_H}{\sigma \cdot \rho_1} \right) \quad \text{[E-18]}$$

CF = creep factor

χ_{DO} = the thermodynamic quality at dryout

D_H = the local hydraulic diameter in m

D_{Hnon} = the local hydraulic diameter at dryout normalized by the nominal hydraulic diameter

σ = the local surface tension in N/m

ρ_1 = the local saturated liquid density in kg/m^3

ρ_g = the local saturated vapour density in kg/m^3

φ = the axial flux factor (normalized by the average channel flux)

G = local coolant mass flux (kg/m^{2}s)

C_1, C_2, C_3, C_4, C_5 and C_6 are correlation coefficients.

A comparison of the model predictions against Stern Lab CHF data is as shown in Figure 2,

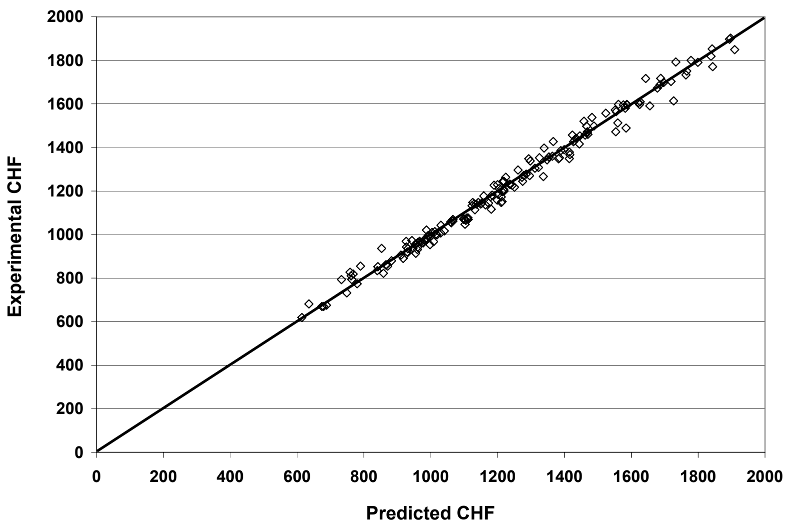


Figure 2: Comparison of Predicted and Measured CHF Data

3.1 Dryout Power

Incipient dryout occurs in the fuel channel when the heat flux predicted by CHF correlation at any location along the channel equals the heat flux calculated from the local bundle power and the heated area. The channel power corresponding to this onset of dryout is known as the dryout power. By accounting for heat balance, incipient dryout can be simulated using an iterative procedure, starting with an initial guess of the dryout power. Given the bundle string geometrical dimensions, CHF, OSV, single-phase and two-phase pressure drop correlations as derived in the foregoing Sections, local thermalhydraulics parameters required to predict dryout power are calculated at given nodes along the channel using the following inputs from the experimental data:

(i) Channel Inlet Pressure (kPa) (ii) Channel Inlet Temperature (^{o}C)

(iii) Axial Heat Flux Distribution (iv) Pressure Tube Diameter Creep Profiles and

(v) Channel Mass Flow Rate (kg/s)

A comparison of the predictions of dryout power against the experimental data using the derived correlations is shown in Figure 3.

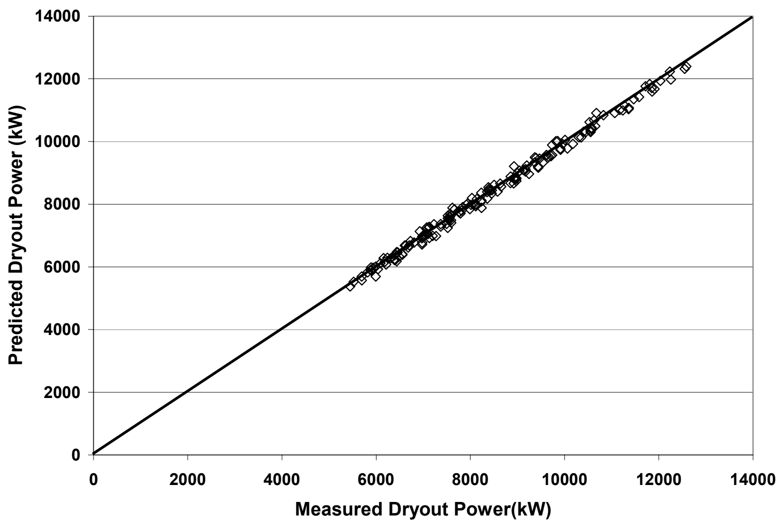


Figure 3: Comparison of Predicted and Measured Dryout Power

4.0 CONCLUSIONS

Methodologies were developed for pressure drop (single and two-phase), Onset of Significant Void (OSV) and local conditions Critical Heat Flux (CHF) applicable to crept and uncrept fuel channels containing 43-element CANFLEX Natural Uranium (NU) fuel bundles. Excellent agreement was obtained between experimental data and correlations prediction of pressure drop, CHF and dryout powers.

REFERENCE

R.A FORTMAN, R.C. HAYES and G.I. HADALLER, “Critical Heat Flux and Post-Dryout Tests of CANFLEX Bundles in Water (Mark IV Design with High Bearing Pads)”, Stan Lab Internal Report No. SL-124, September 2001.