UNENE Graduate Course Reactor Thermal-Hydraulics Design and Analysis

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Pressure Drop

Dr. Amad Abdul-Razzak
Dr. Laurence Leung
Dr. Nik Popov

Outline

- Background
- Conservation equations
- Single-phase pressure gradient
- Onset of significant void
- Two-phase pressure gradient
- Summary

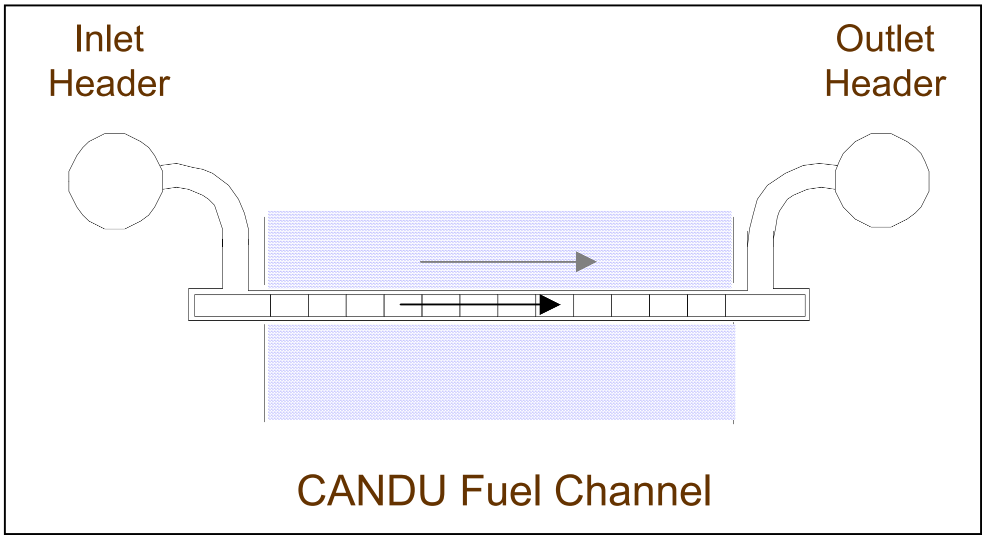
Introduction

- A pumped system is often employed for flow mediums circulation and transportation
- All piping components in the flow system reduce the system pressure
- Pressure reduction can be minimized but is not always feasible
- Pump capacity must be matched properly with the system requirements
- For design calculations, the pump size has a large impact on the system cost.

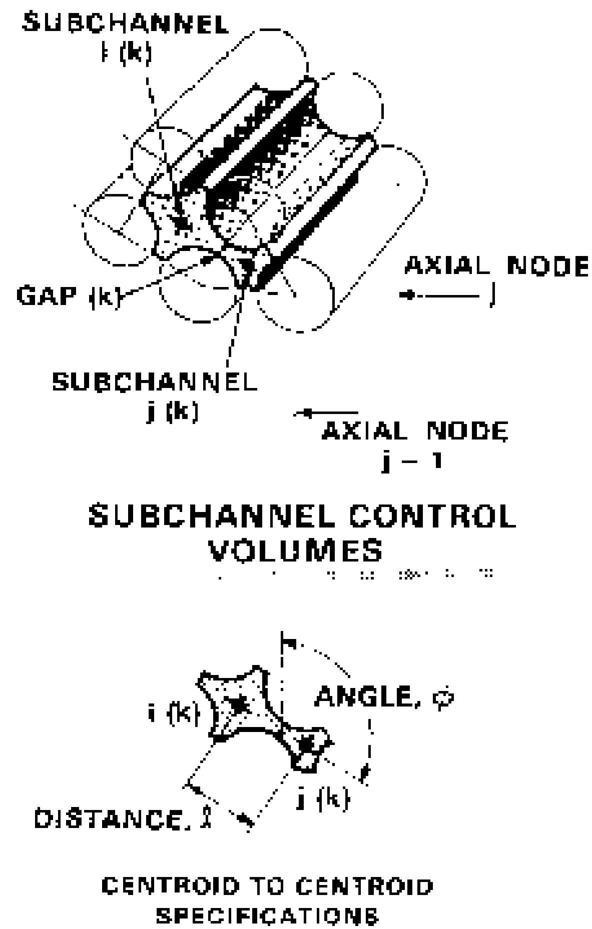
Applications

- General applications:
  - Optimize pump capacity requirement
  - Optimize pump energy requirement
- CANDU nuclear reactor applications:
  - Determine coolant-flow rate in primary circuit
  - Determine local conditions in bundles and subchannels
  - Determine flow rate across parallel interconnected subchannels in fuel bundles

CANDU Applications



CANDU Fuel Channel

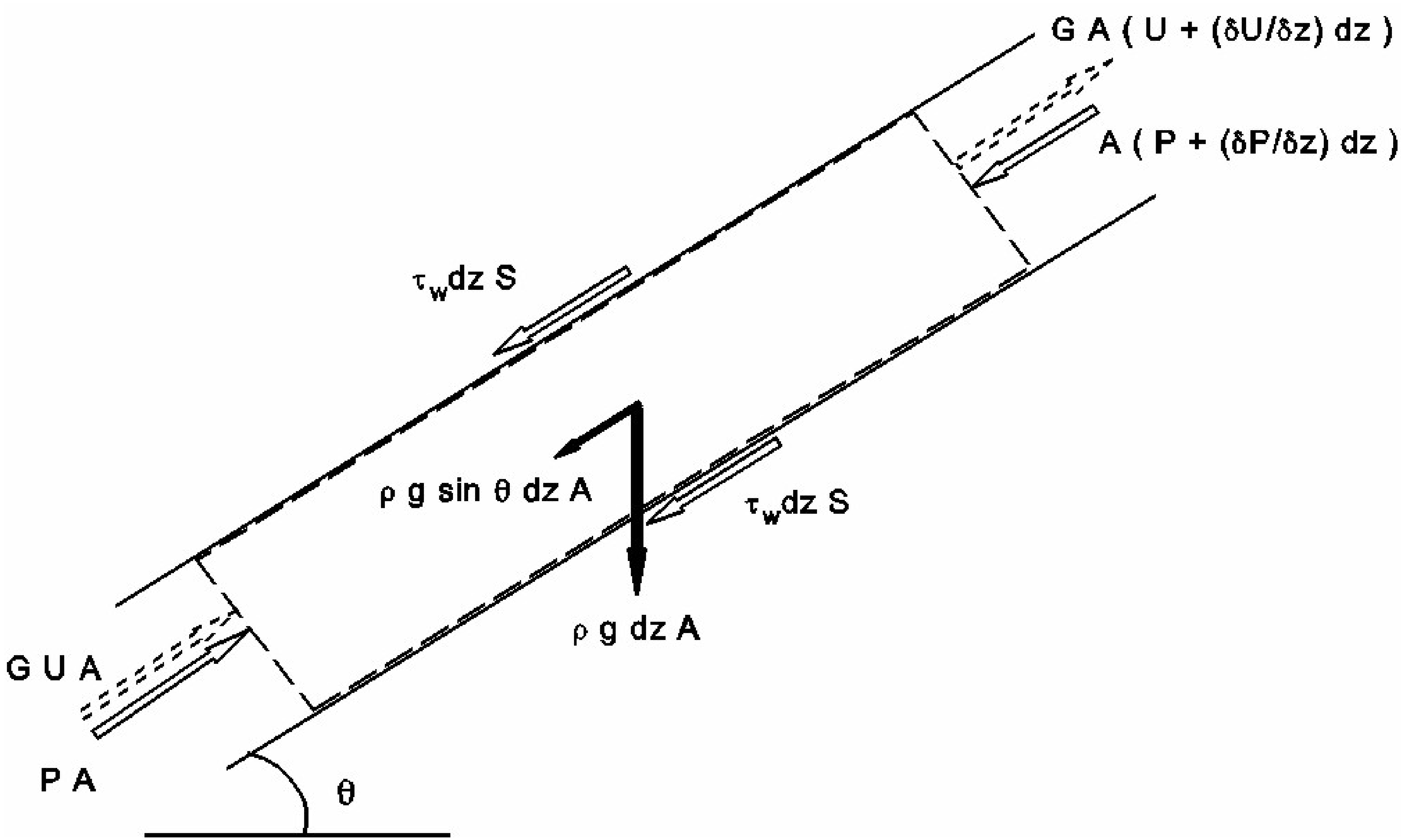


Partial Setup of Nodes In Subchannel Code - ASSERT

Conservation Equations

- Mass-balance (continuity) equation
- Momentum-balance equation
- Energy-balance equation
- Cases:
  - Steady-state flow in channel of uniform flow area in axial direction
- Assumptions
  - Negligible variation of fluid properties over the control volume
  - Homogeneous or separated flow

Force-Momentum Balance within a Control Volume



Basic Equations for Homogeneous-Flow Assumption

$$\int_A \left(P - \left(P + \frac{dP}{dz}\delta z \right) \right) dA = \int_S \tau_w \delta z\, dS + \int_A \frac{d}{dz}(G\, u_m)\, \delta z\, dA + \int_A \rho_H\, g \sin\theta\, \delta z\, dA$$

$$\frac{1}{\rho_H} = \frac{x_a \rho_l + (1 - x_a)\rho_g}{\rho_g\, \rho_l}$$

$$-\frac{dP}{dz} = \frac{S}{A}\tau_w + \frac{d}{dz}\left(\frac{G^2}{\rho_H} \right) + \rho_H\, g \sin\theta$$

$$-\frac{dP}{dz} = \frac{S}{A}\tau_w + G^2 \frac{d}{dz}\left(\frac{x_a}{\rho_g} + \frac{(1-x_a)}{\rho_l} \right) + \rho_H\, g \sin\theta$$

$$-\frac{dP}{dz} = -\left(\left(\frac{dP}{dz} \right)_f + \left(\frac{dP}{dz} \right)_a + \left(\frac{dP}{dz} \right)_g \right)$$

Basic Equations for Separated-Flow Assumption

$$\int_A \left(P - \left(P + \frac{dP}{dz}\delta z \right) \right) dA = \int_S \tau_w \delta z \, dS + \int_A \frac{d}{dz}\left(G_l u_l + G_g u_g \right) \delta z \, dA + \int_A \rho_{tp} \, g \sin\theta \, \delta z \, dA$$

$$\rho_{tp} = \alpha \rho_g + (1-\alpha)\rho_l$$

$$-\frac{dP}{dz} = \frac{S}{A}\tau_w + \frac{d}{dz}\left((1-\alpha) G_l u_l + \alpha G_g u_g \right) + (\alpha \rho_g + (1-\alpha)\rho_l) g \sin\theta$$

$$-\frac{dP}{dz} = \frac{S}{A}\tau_w + G^2 \frac{d}{dz}\left(\frac{x_a^2}{\alpha \, \rho_g} + \frac{(1-x_a)^2}{(1-\alpha)\,\rho_l} \right) + (\alpha \rho_g + (1-\alpha)\rho_l) g \sin\theta$$

$$-\frac{dP}{dz} = -\left(\left(\frac{dP}{dz} \right)_f + \left(\frac{dP}{dz} \right)_a + \left(\frac{dP}{dz} \right)_g \right)$$

Pressure Gradients

- Friction
  - Between fluid and channel wall
  - Primarily affected by tube diameter, velocity gradient and viscosity
- Acceleration
  - Change in fluid momentum between locations
  - Significant in channel with varying flow area and fluid temperature
- Gravity
  - Change in hydrostatic head
  - Only in vertical channel
- Others
  - Flow blockages: valves, orifices, bundle junction, appendages, etc.
  - Change in flow direction: elbows, etc.
  - Change in flow area: sudden contraction, sudden expansion, etc.

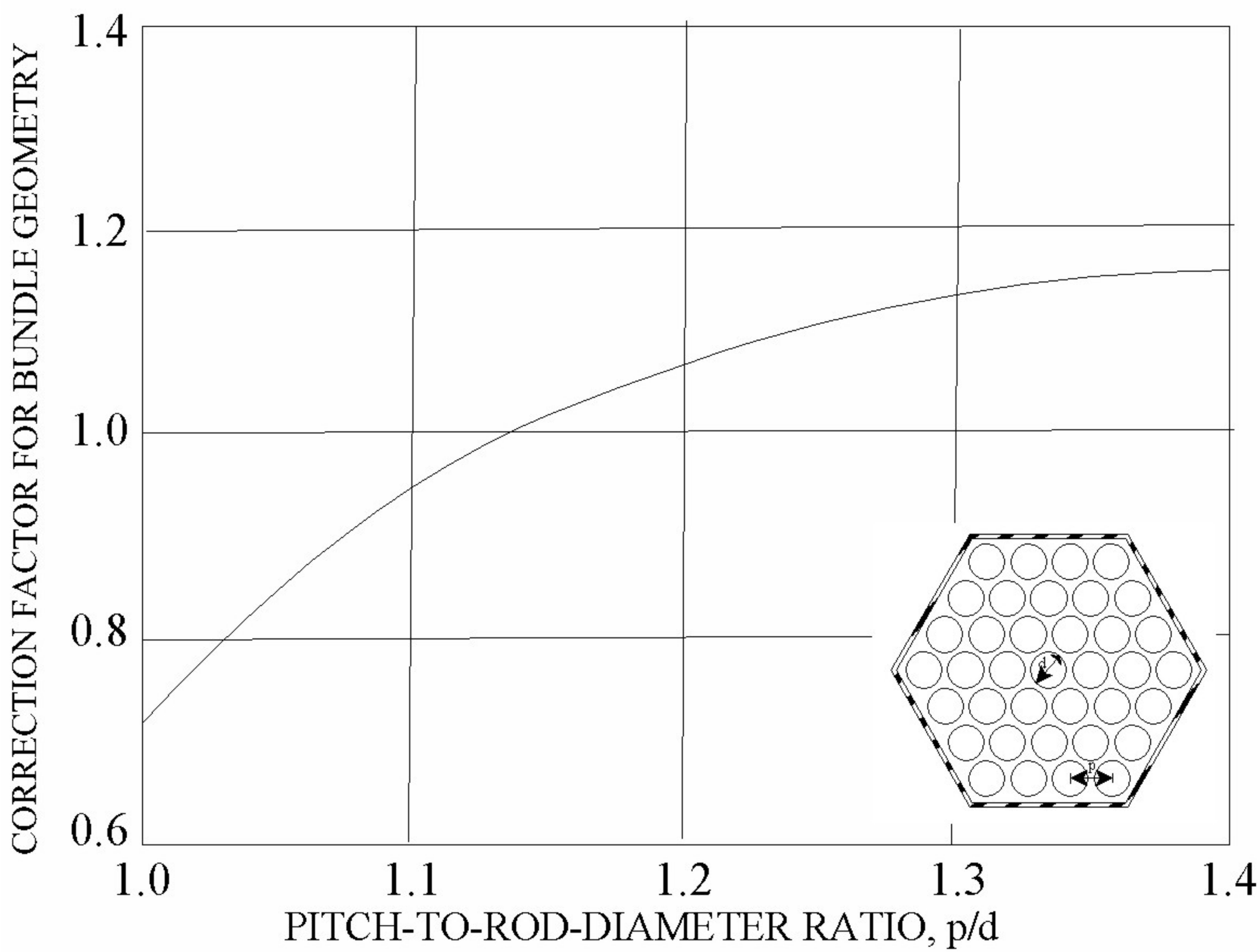
SP Pressure-Drop Equations

- Friction $$\Delta P_{sp,\,fric} = \frac{f\,\Delta L\; G^2}{D_{hy}\; 2\rho_l}$$
- Acceleration $$\Delta P_{sp,\,acc.} = G^2 \Delta \upsilon_l$$
- Gravity $$\Delta P_{sp,g} = \rho_b\, g \sin\theta\, \Delta z$$
- Form $$\Delta P_{sp,\,local} = K_{local} \frac{G^2}{2\rho_l}$$

Single-Phase Friction Factor

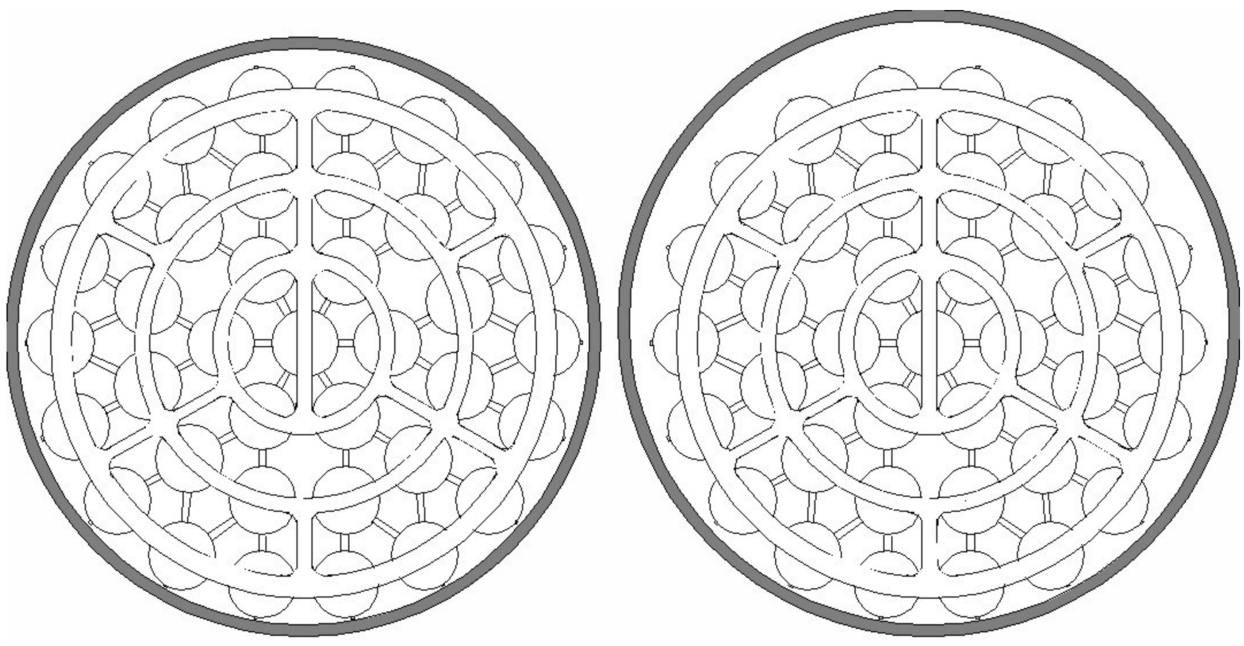
- Tubes
  - Colebrook-White equation $$\frac{1}{\sqrt{f_{tube}}} = -2\log\left(\frac{\varepsilon / D_{tube}}{3.7} + \frac{2.51}{\sqrt{f_{tube}}\,\mathrm{Re}}\right)$$
- Bundles
  - Based on hydraulic-equivalent diameter approach with the tube-based equation
  - Correction for geometry effect (differences between tubes and bundles)
  - Correction for eccentricity effect (differences between concentric and eccentricity bundles) in crept channels
  - Correction for channel shape effect (converging and diverging channels) in crept channels
  - Correction for surface heating effect

Bundle Correction Factor

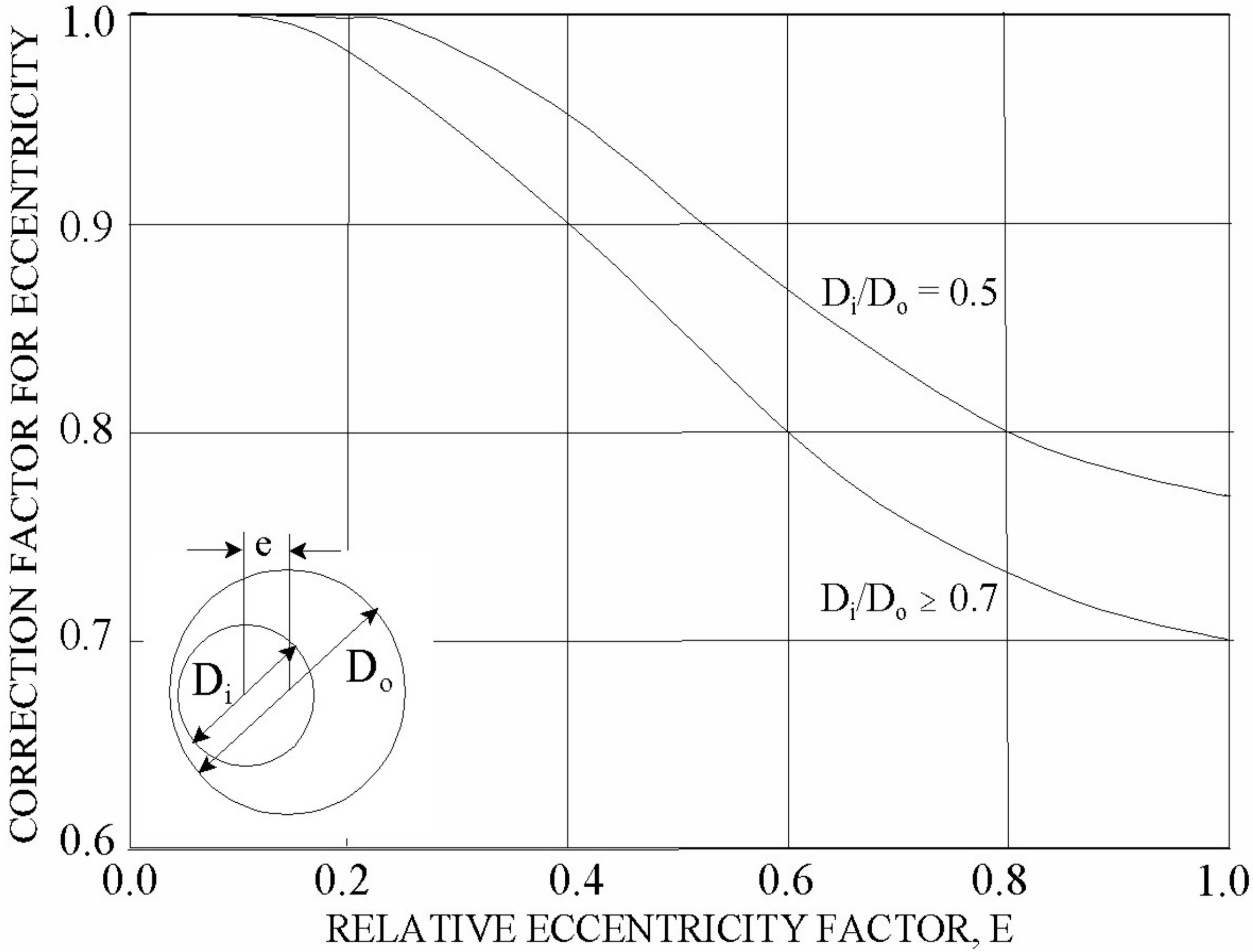


Eccentricity Effect

- More fluid tends to flow in the open region (less resistance)
- Non-uniform velocity distribution



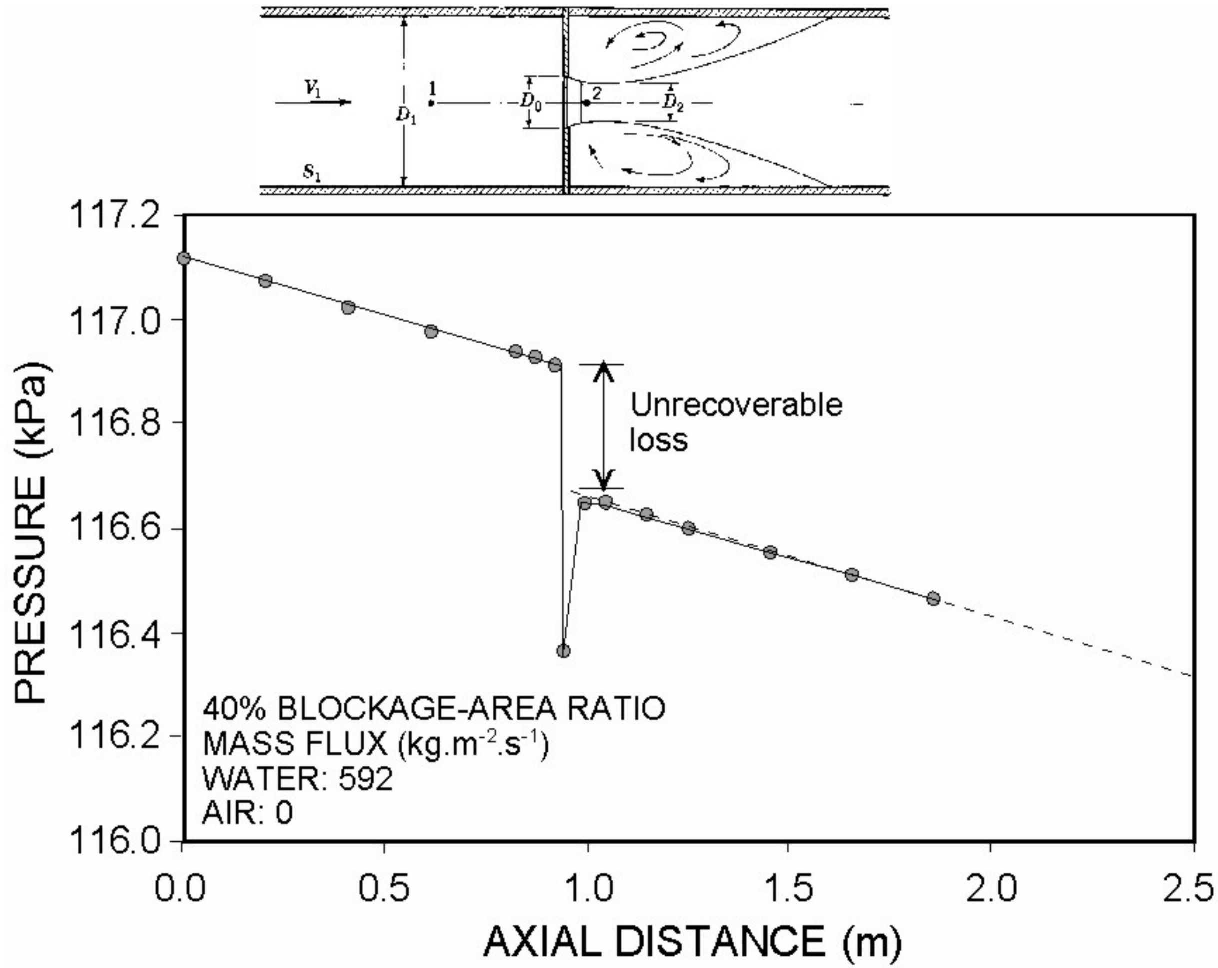
Eccentricity Correction Factor



Single-Phase Loss Coefficients

- Sudden contraction
  - Based on flow-area ratio $K_{cont.} = 0.5\left(1 - \frac{A_f}{A_o}\right)^{3/4}$
- Sudden expansion
  - Based on flow-area ratio $K_{\exp.} = \left(1 - \frac{A_f}{A_o}\right)^{2}$
- Bends
  - Based on angle
- Junction and appendages in bundles
  - Based on data obtained with production bundles
  - Correction for eccentricity effect

Single-Phase Pressure Distribution over a Square-Edged Orifice

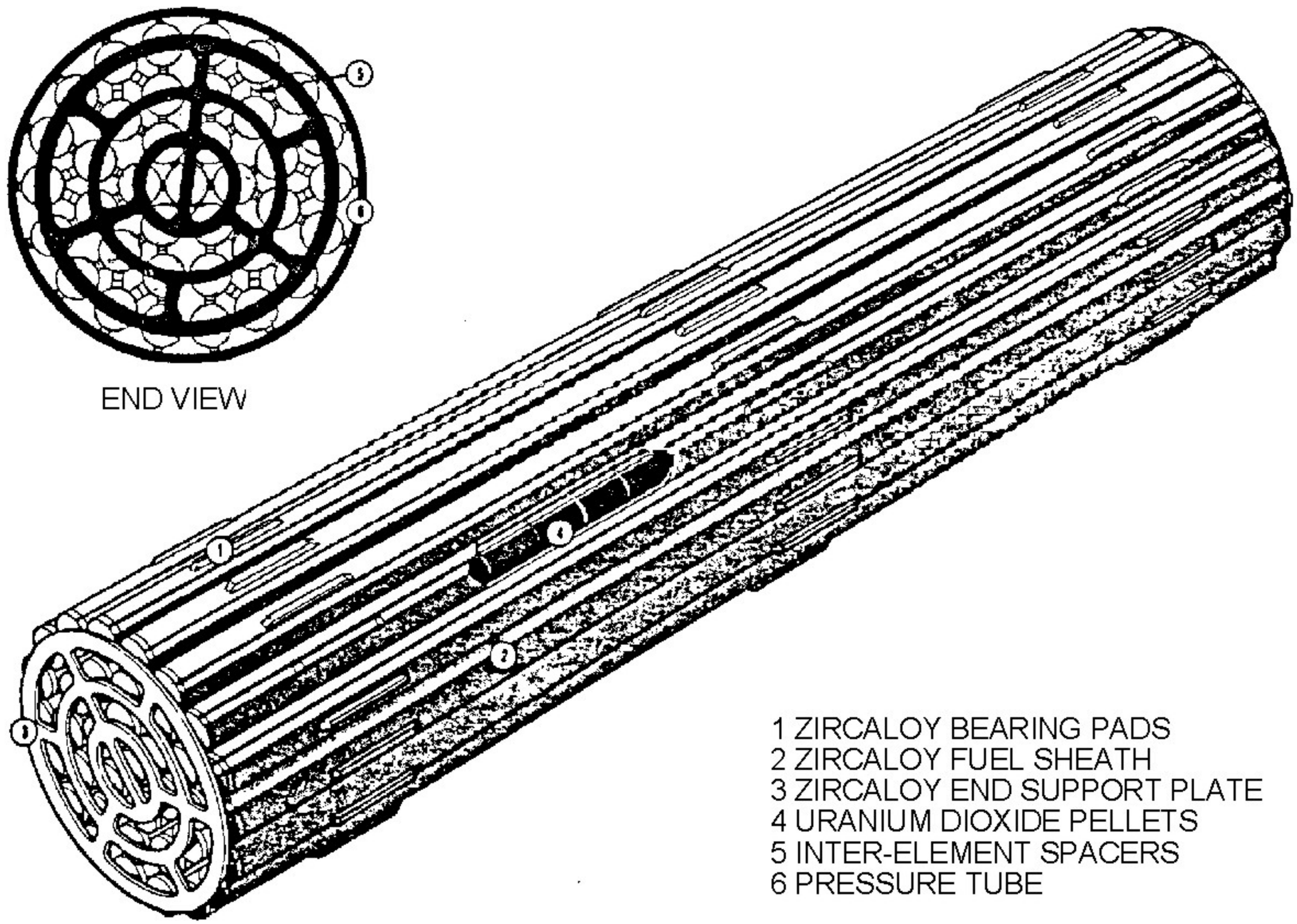


Fuel String Pressure Drop

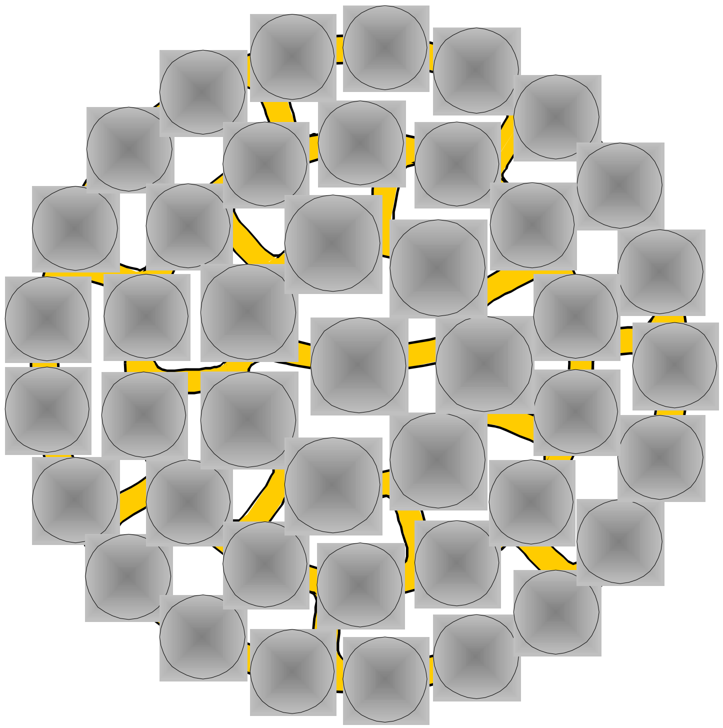
- Part of the overall pressure drop between headers
- Separated into single-phase and two-phase regions
- Pressure-drop components
  - Friction
  - Bundle junction, spacers, buttons, and bearing pad planes
  - Acceleration
  - End fittings
- Simplified evaluation approach for bundles
  - Combined friction and form losses into a bundle loss coefficient

$$\Delta P_{sp,\,Bundle} = K_{Bundle}\frac{G^2}{2\rho_l} = \left(\frac{f_{Bundle}L_{Bundle}}{D_{hy}} + K_{junction} + K_{appendage}\right)\frac{G^2}{2\rho_l}$$

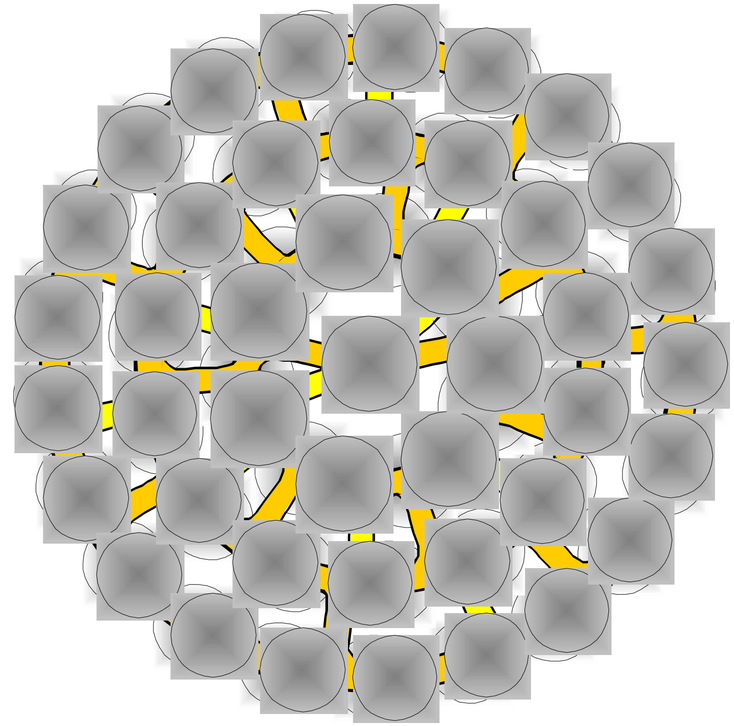
Appendages in a CANDU Fuel Bundle



Bundle Junction Alignment

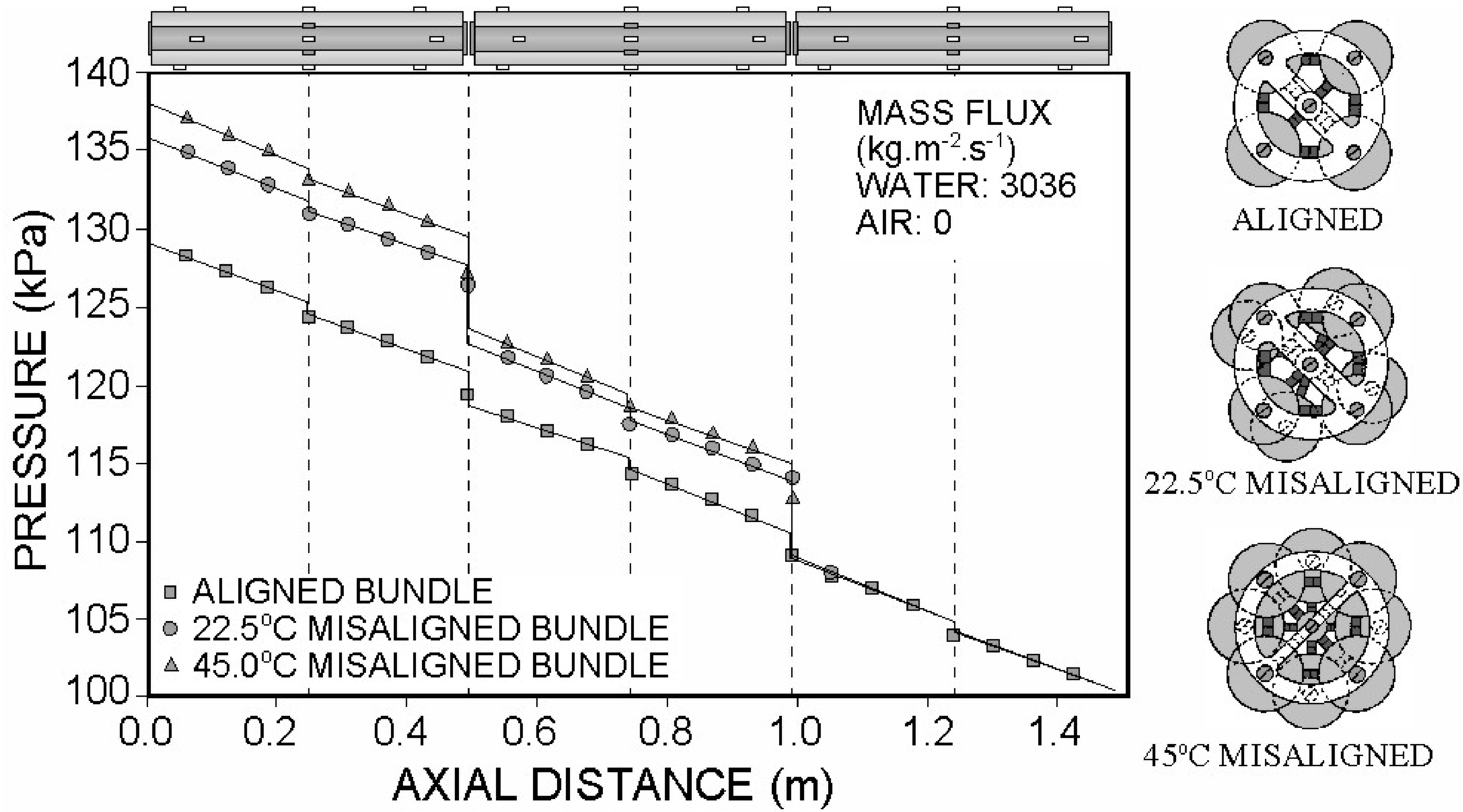


Aligned Bundles

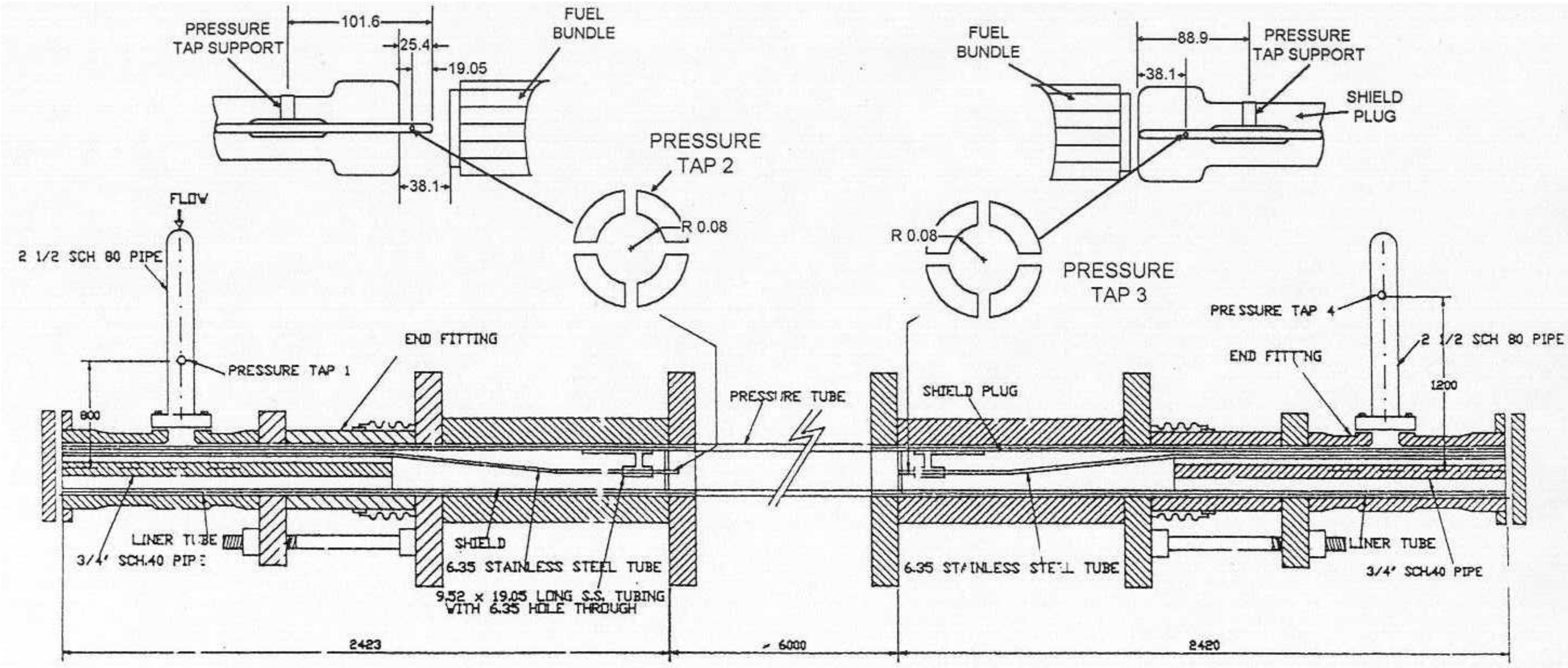


Misaligned Bundles

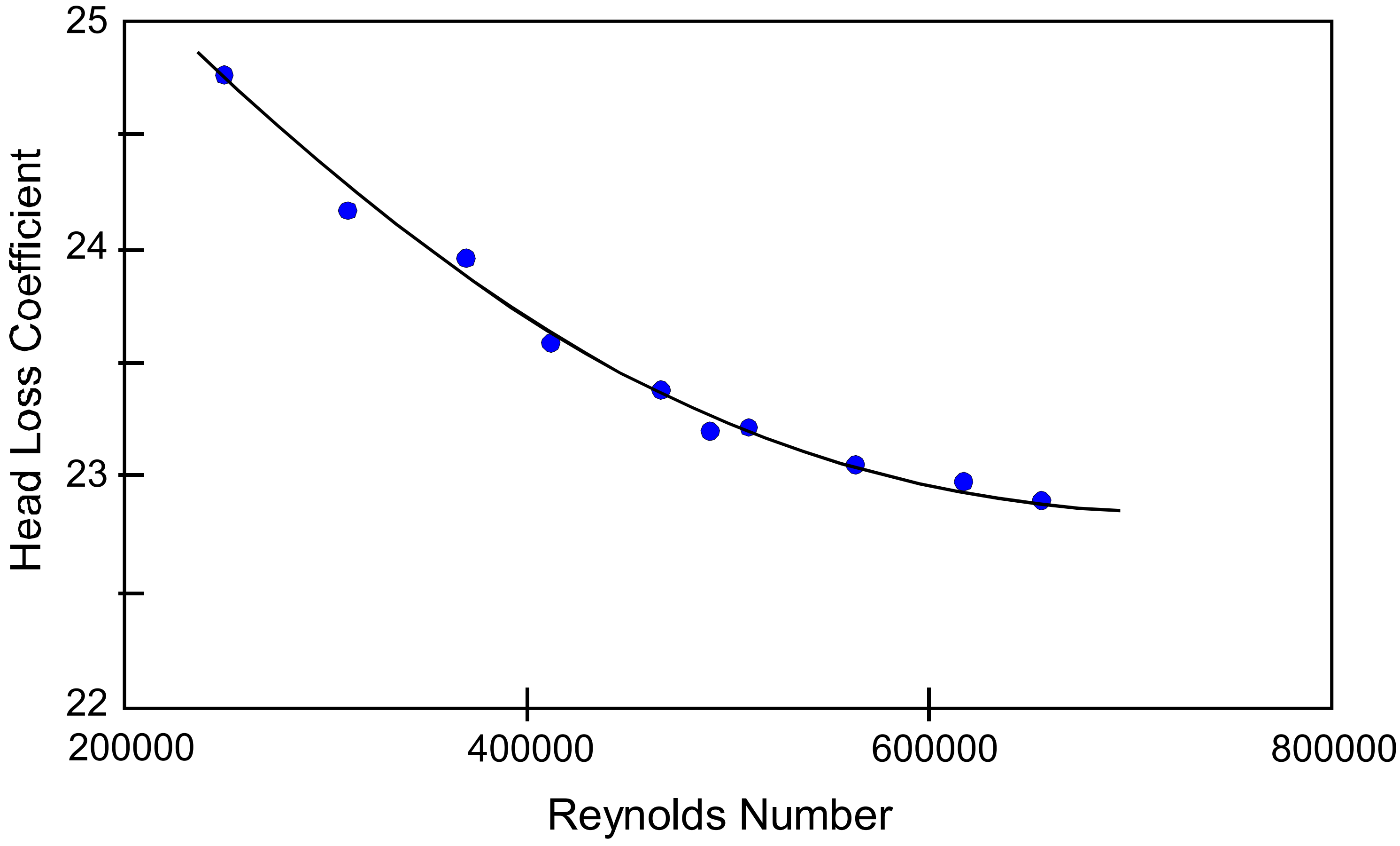
Single-Phase Pressure Distributions over Aligned and Misaligned Bundles



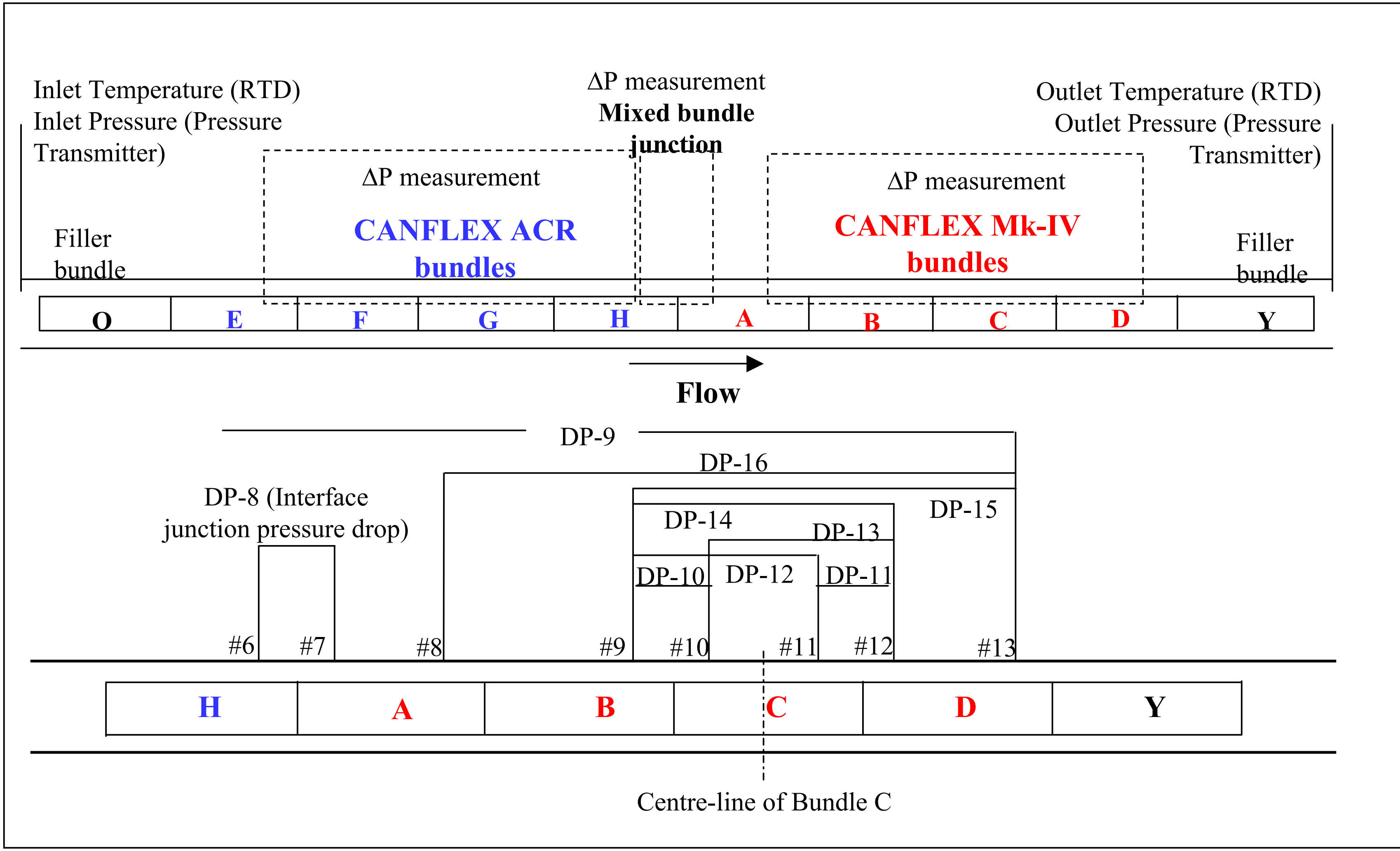
Water Pressure Drop Test Station



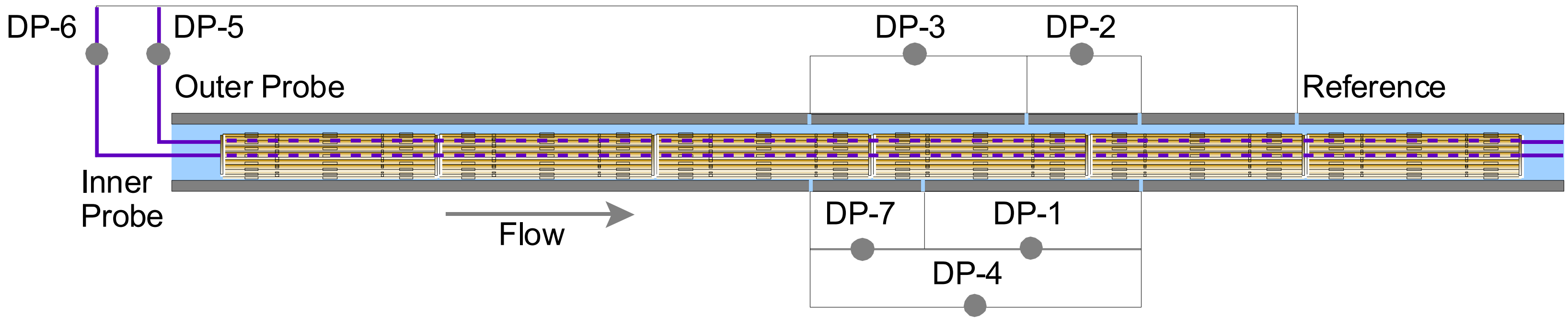
Water Pressure Drop Test Results

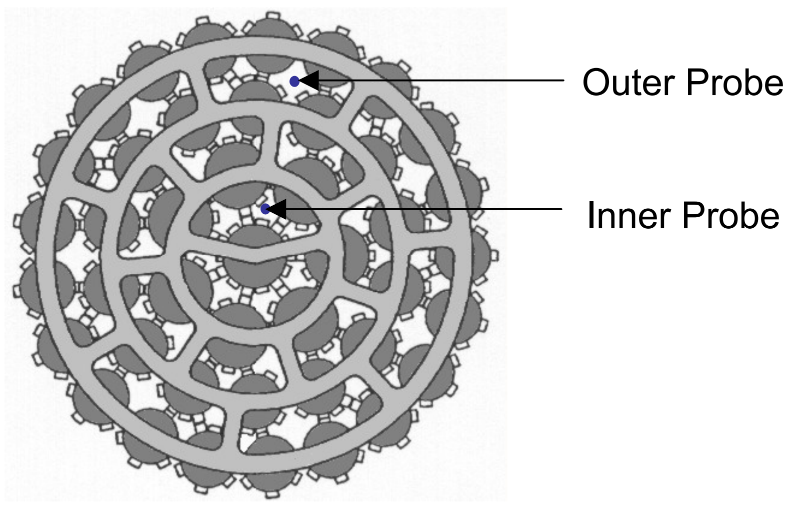


Freon Pressure Drop Test Station

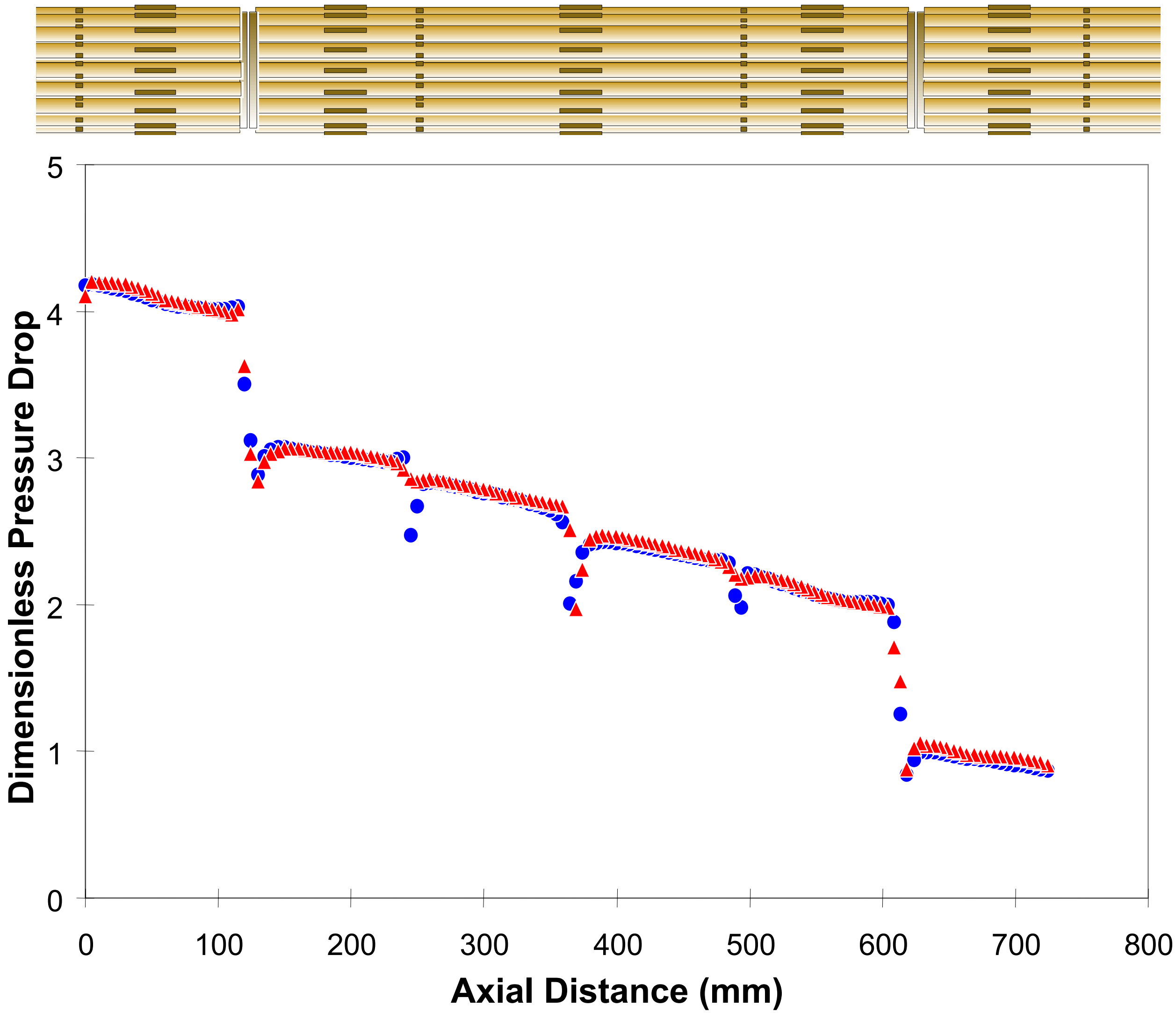


Hydraulic Characterization Test

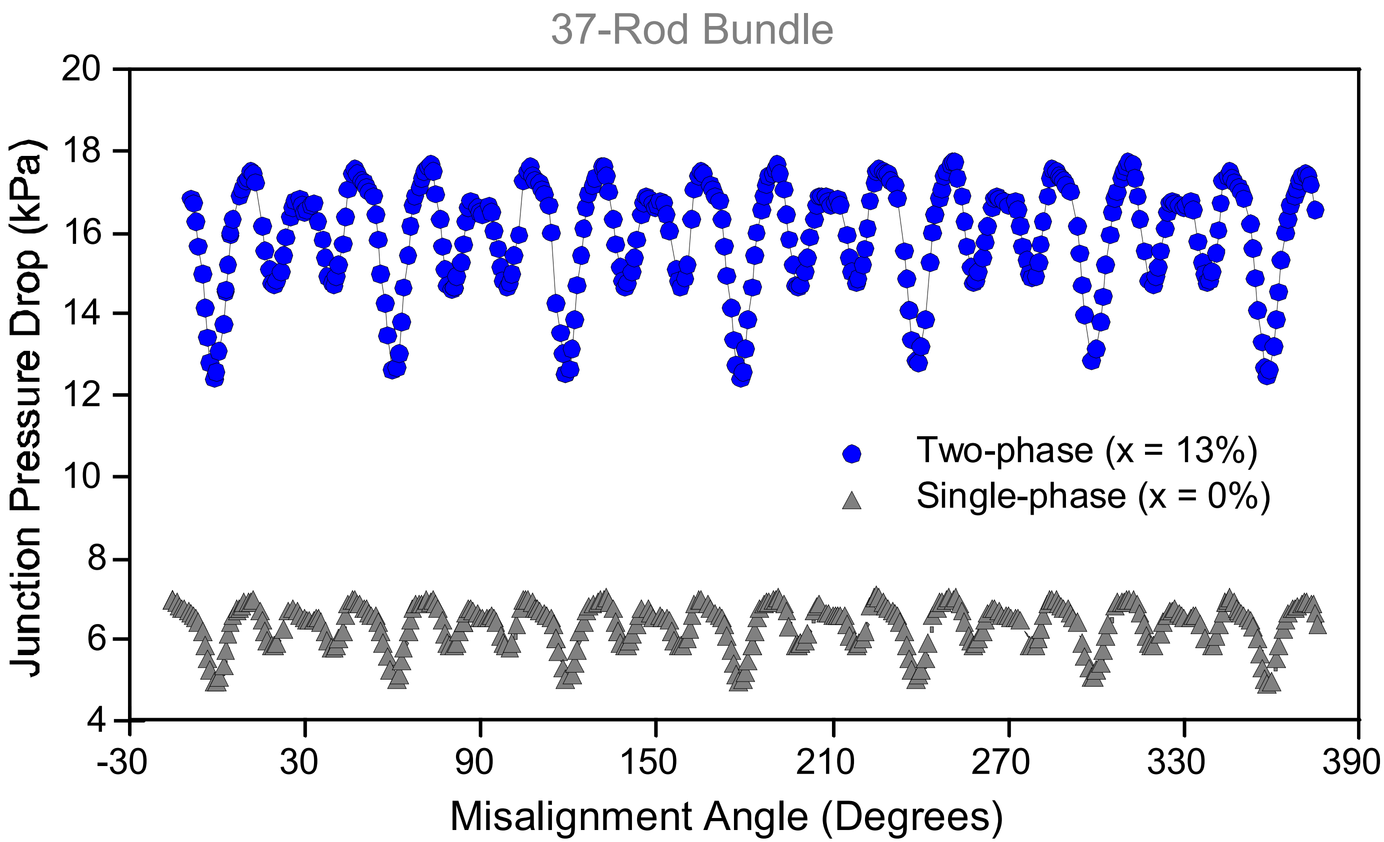




Freon Pressure Drop Test Results



Misaligned Junction Signatures



Sutradhar, Proc. 6th Int. Conf. on CANDU Fuel, Niagara Falls, Canada, September 26-30, 1999.

Onset of Significant Void (OSV)

- Determined from axial pressure distributions along the full-scale bundle simulator in reference and aged channels
- A linear relation over the single-phase region in uncrept channel and a parabolic equation over the two-phase region
- The intersecting point of these two equations is considered as the OSV

Axial Pressure Distribution

OSV Correlations

- Saha-Zuber correlation for tubes
  - Peclet number (G D Cp / k) < 70,000

$$x_{OSV} = -0.0022 \frac{q\, D\, C_{pf}}{k_f\, H_{fg}}$$

  - Peclet number ≥ 70,000

$$x_{OSV} = -154 \frac{q}{G\, H_{fg}}$$

- Modified Saha-Zuber correlation for bundles
  - Update empirical coefficients using full-scale bundle data
  - Proprietary information

TP Frictional Pressure Drop

- The two-phase frictional pressure drop is calculated with

$$\Delta P_{f,\,TP} = \phi_L^2\ \Delta P_{f,\,L} \quad \text{or} \quad \Delta P_{f,\,TP} = \phi_{LO}^2\ \Delta P_{f,\,LO}$$

$$\phi_{LO}^2 = \phi_L^2 (1 - x_a)^{2-b} \quad \text{where } f = a\ Re^{-b}$$

$\phi_L^2 - \Delta P_{f,\,L}$ based on only single – phase liquid in the channel

$\phi_{LO}^2 - \Delta P_{f,\,LO}$ based on total flow as single – phase liquid

Two-Phase Multiplier

- Two-phase multipliers, ϕ^2_L or ϕ^2_{LO}, are empirical factors based on experimental data
- Expressed in the form of graphs or correlations (large uncertainty due to scatter among data)
- Depends mainly on quality and pressure
- Mass-flux effect primarily observed at low flows (flow-regime dependent)
- Surface heating has a strong impact (near-wall effect) on two-phase multiplier in tubes and annuli, but not in bundles (compensating effect)

Homogeneous Two-Phase Multiplier

- The simplest form

$$\phi_{LO}^2 = \frac{f_{TP}}{f_l}\frac{\rho_l}{\rho_{TP}} = \left(1 + x_a\left(\frac{\rho_l - \rho_g}{\rho_g}\right)\right)\left(\frac{\mu_l}{\mu_{TP}}\right)^{-b}$$

$$\frac{1}{\mu_{TP}} = \frac{x_a}{\mu_g} + \frac{1 - x_a}{\mu_l}$$ McAdam et al.

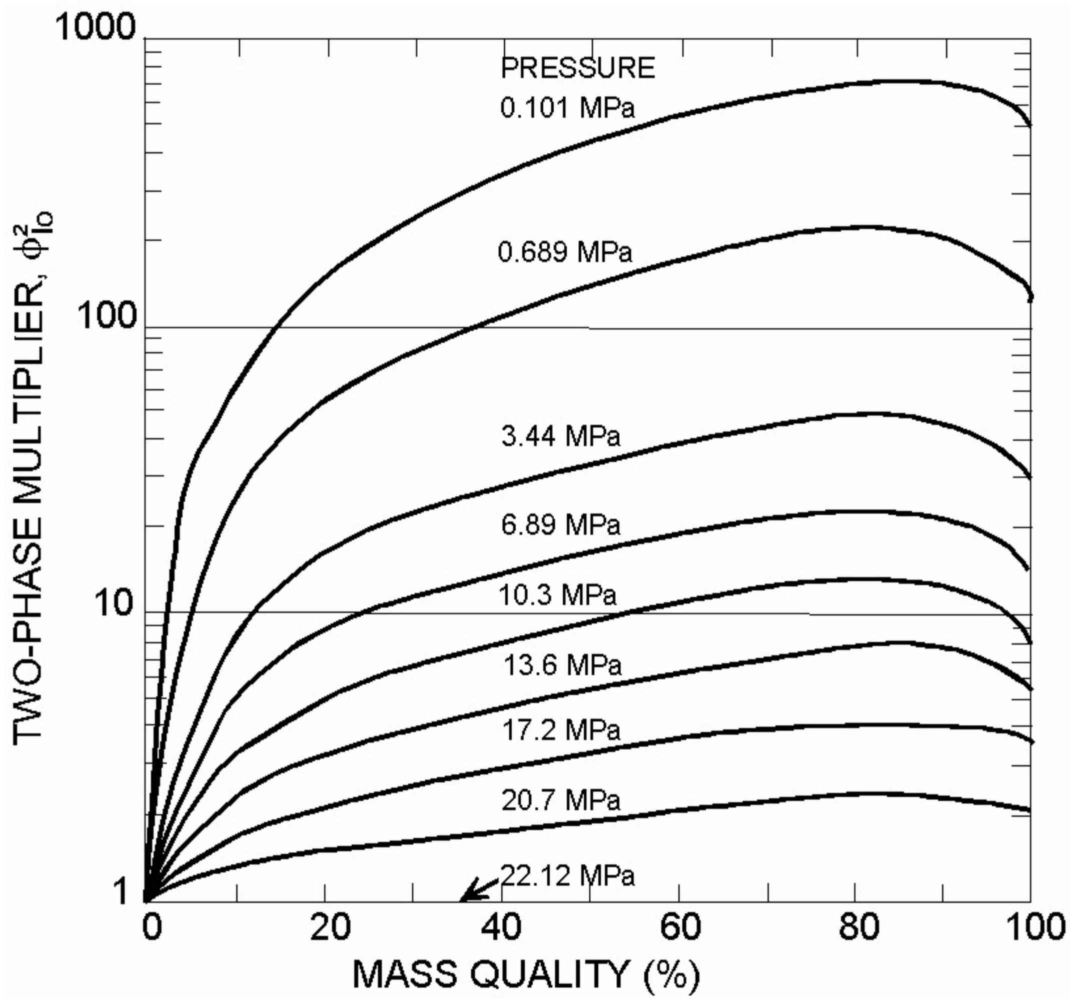
$$\mu_{TP} = x_a \mu_g + (1 - x_a)\,\mu_l$$ Cicchitti et al.

$$\mu_{TP} = \rho_{TP}\left(\frac{x_a\,\mu_g}{\rho_g} + \frac{(1 - x_a)\,\mu_l}{\rho_l}\right)$$ Dukler et al.

$$\mu_{TP} = f(\text{flow} - \text{pattern})$$ Beattie

TP Multiplier in Separated Flow

Martinelli and Nelson Graph



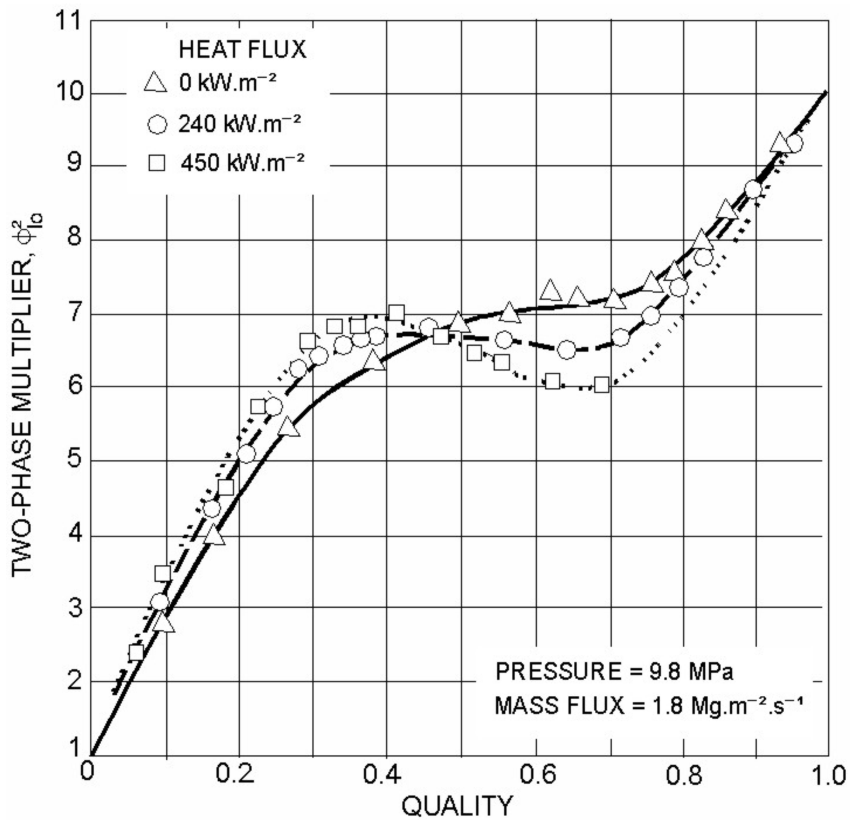
Friedel Correlation

- Complex formulation
- Based on over 25,000 data points
- Uncertainty: ±26%, ±32% and ±25% for single-component upward, horizontal and downward flow
- Recommended by many studies

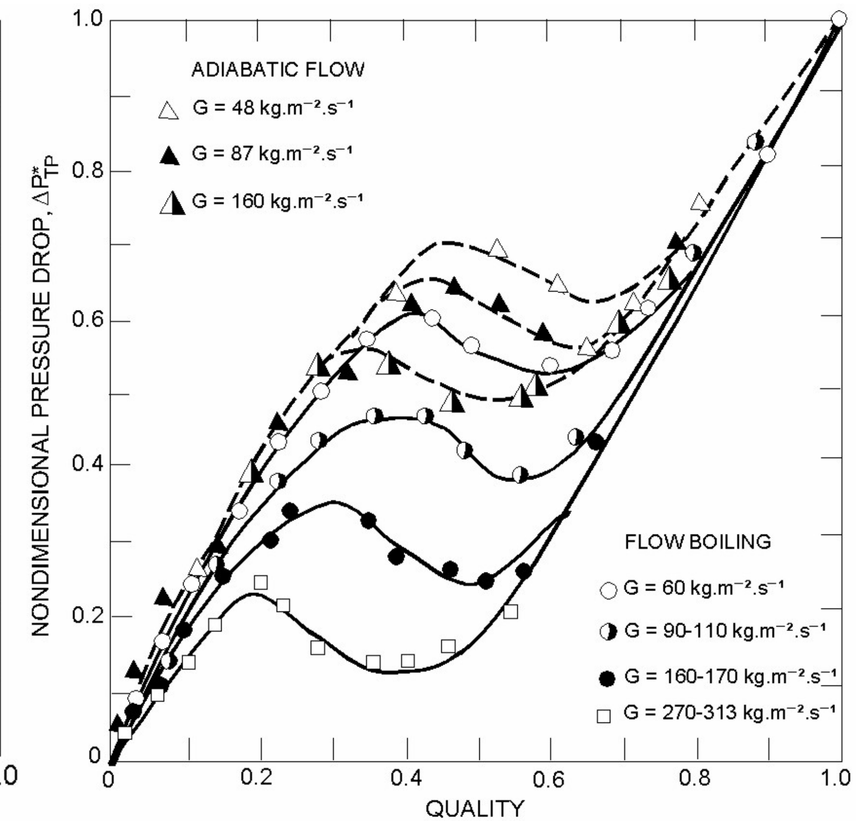
Surface-Heating Effect

- Changes in near-wall velocity gradient due to bubble formation, hence two-phase pressure drop
- Sharp variations due to liquid-film thinning, liquid-surface contact or vapour-surface contact
- Depends strongly on critical heat flux

Effect of Surface Heating

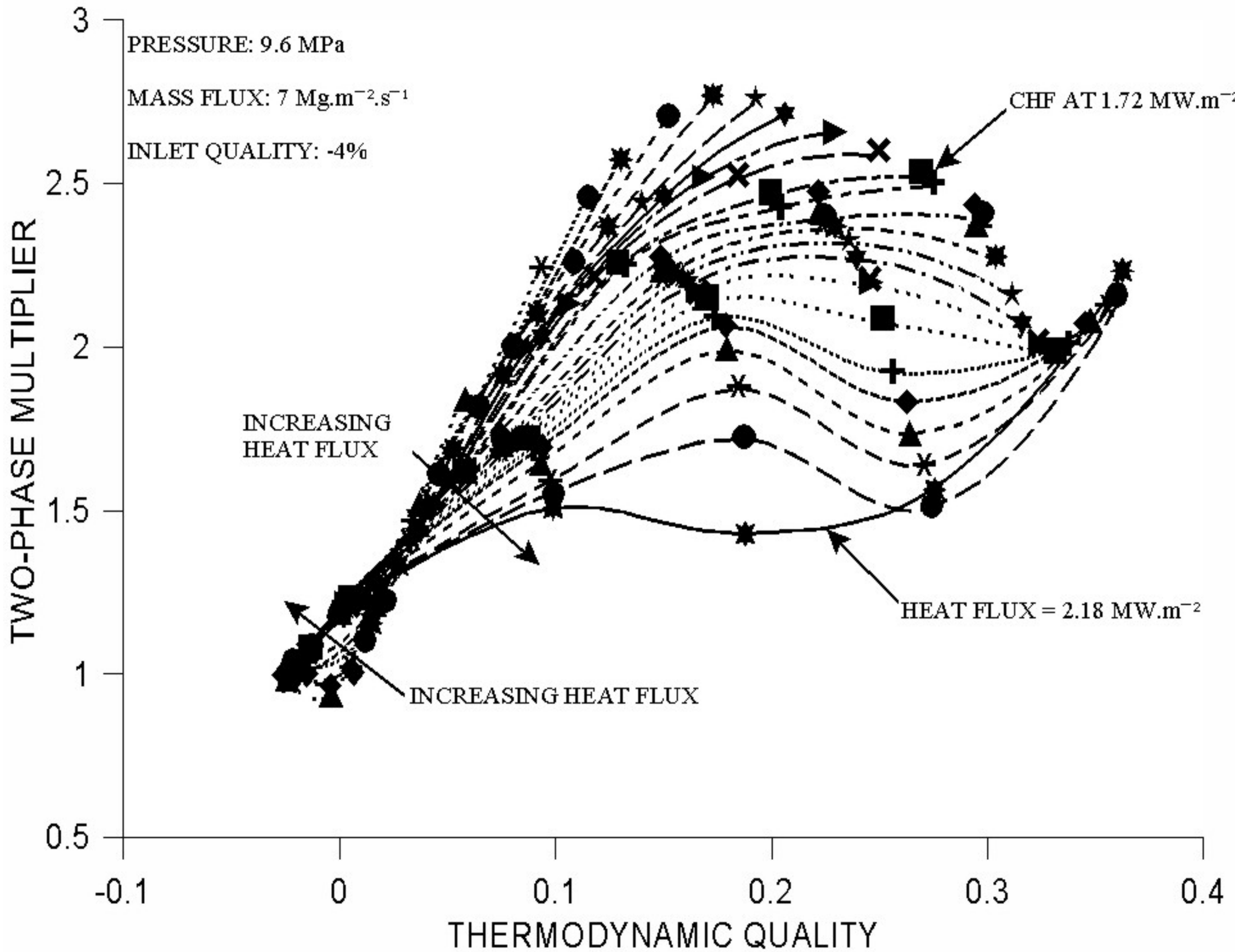


Water Flow

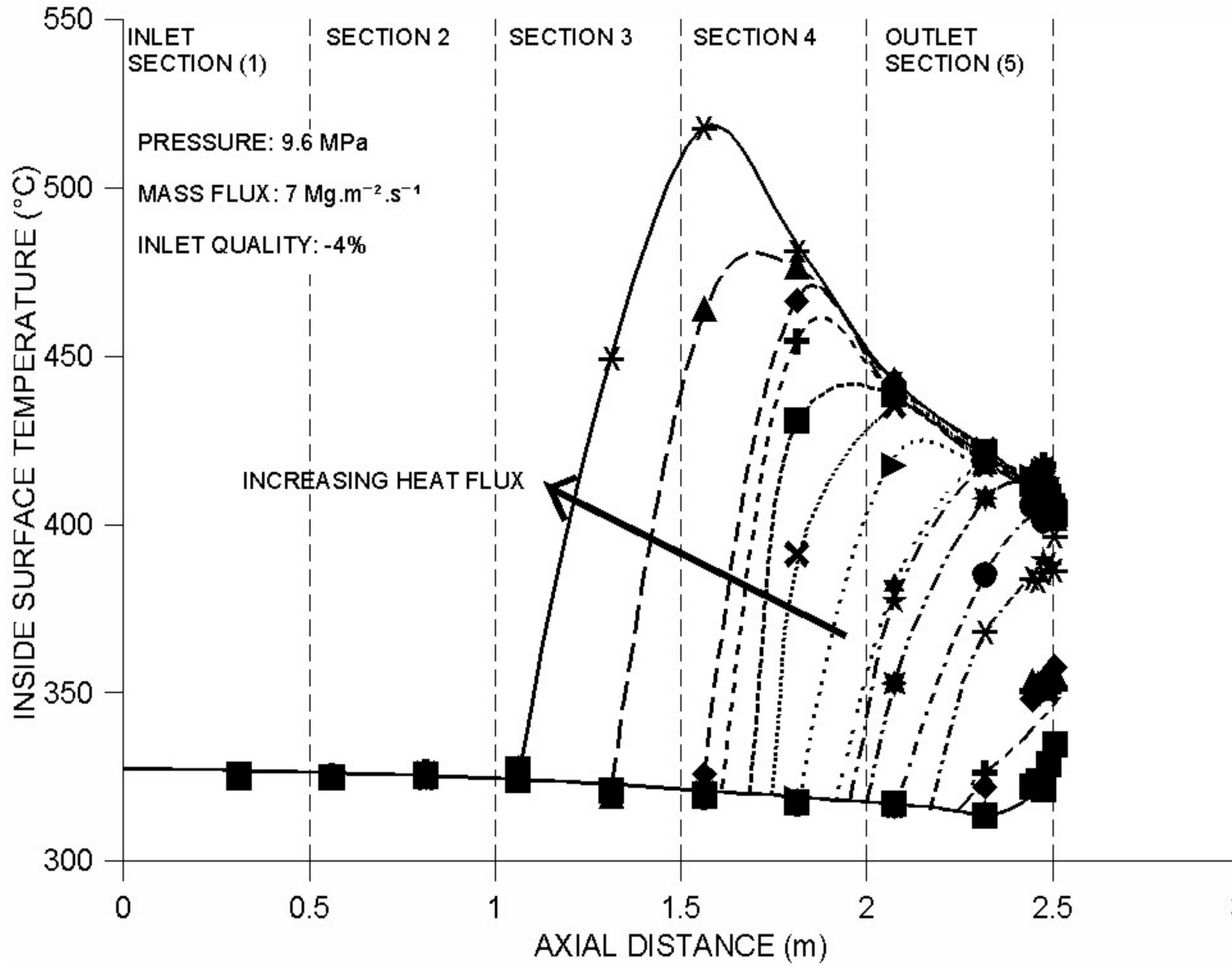


Helium Flow

Two-Phase Multipliers in Pre- and Post-Dryout Regions



Corresponding Surface-Temperature Variations



Local Pressure Drop

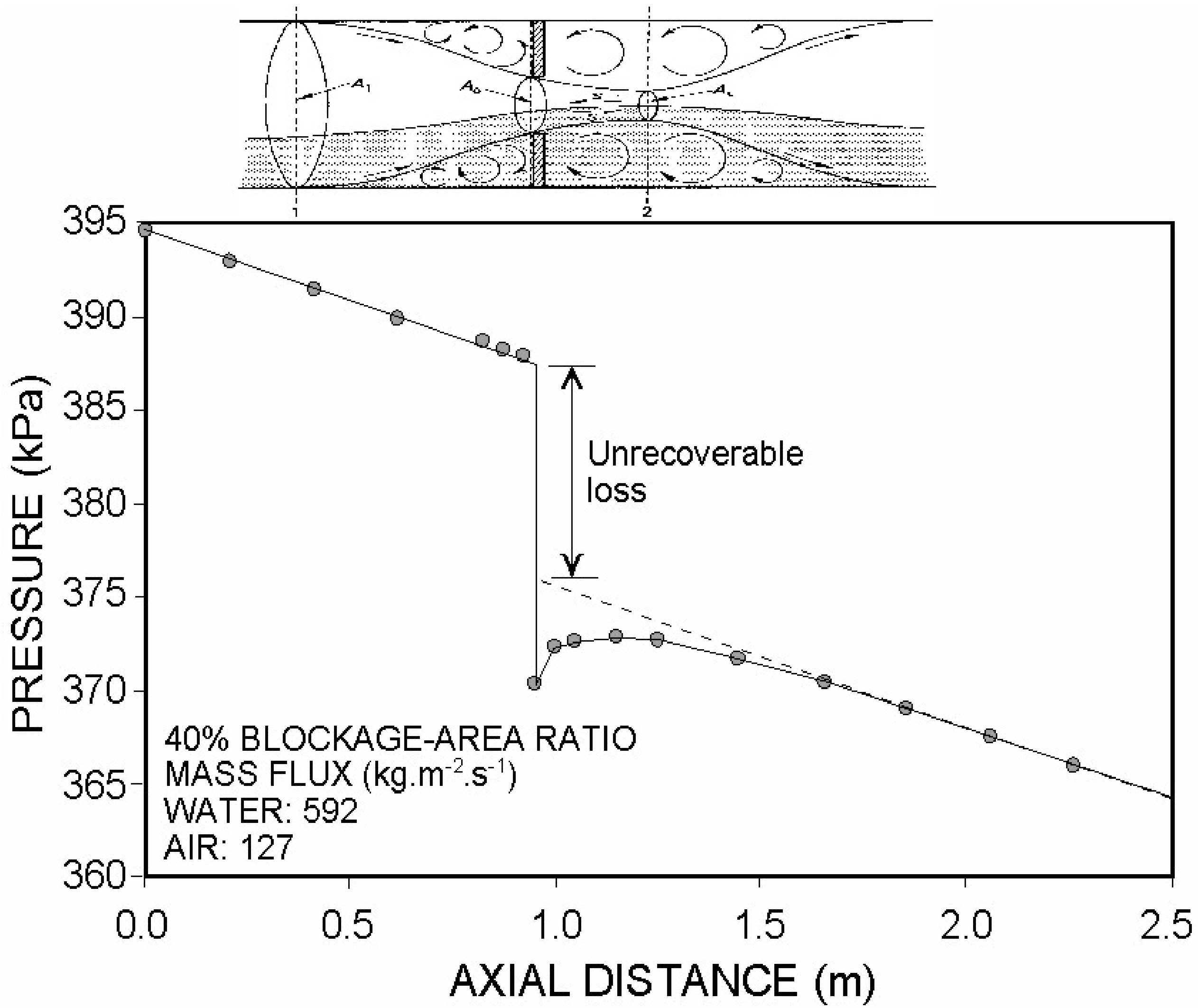
- Two-phase local pressure drop is calculated with

$$\Delta P_{local,\,TP} = \phi^2_{LO,\,local}\,\Delta P_{local,\,SP}$$

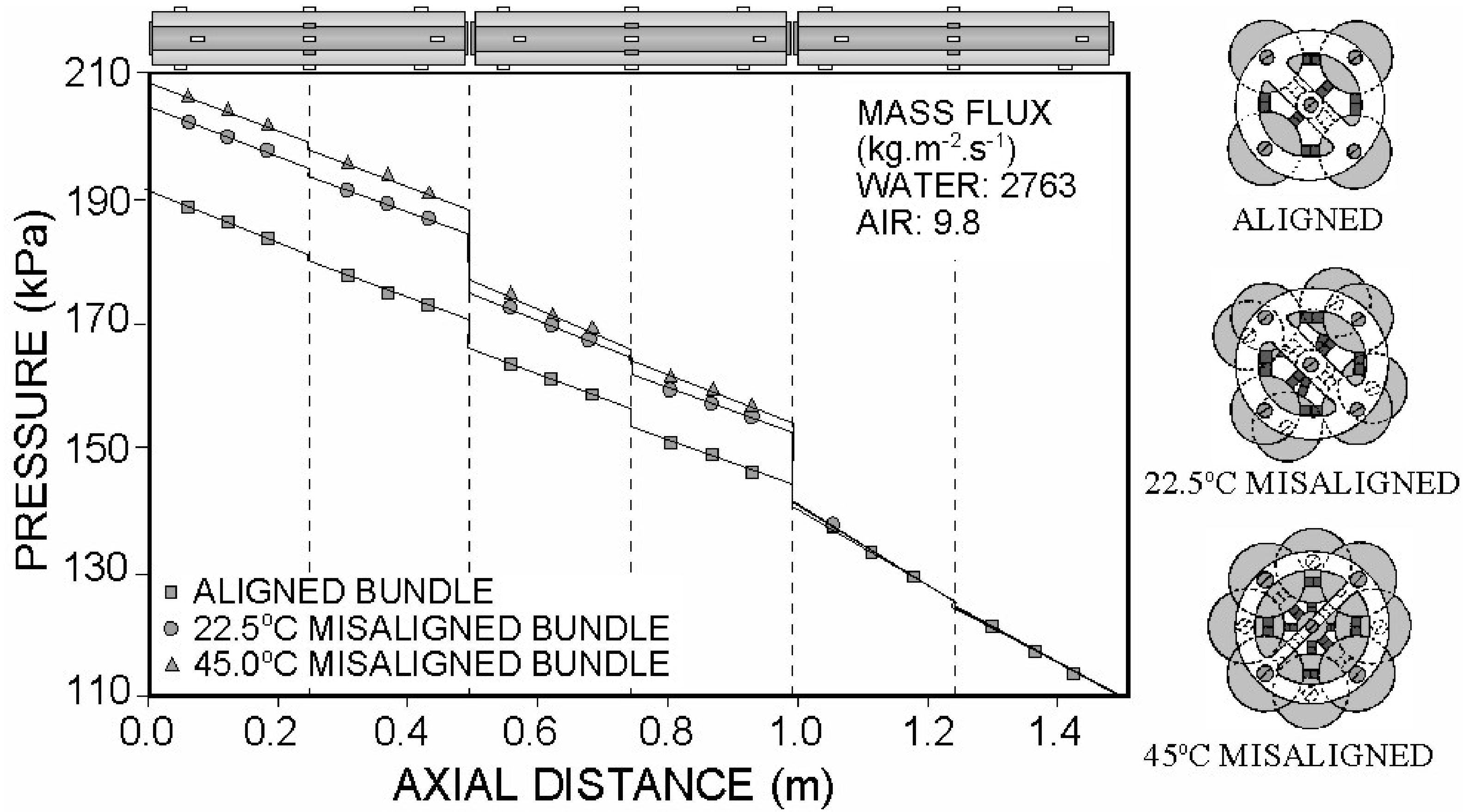
$$\phi^2_{LO,\,local} = 1 + x_a\left(\frac{\rho_l - \rho_g}{\rho_g}\right)$$

Homongeneous two – phase multiplier

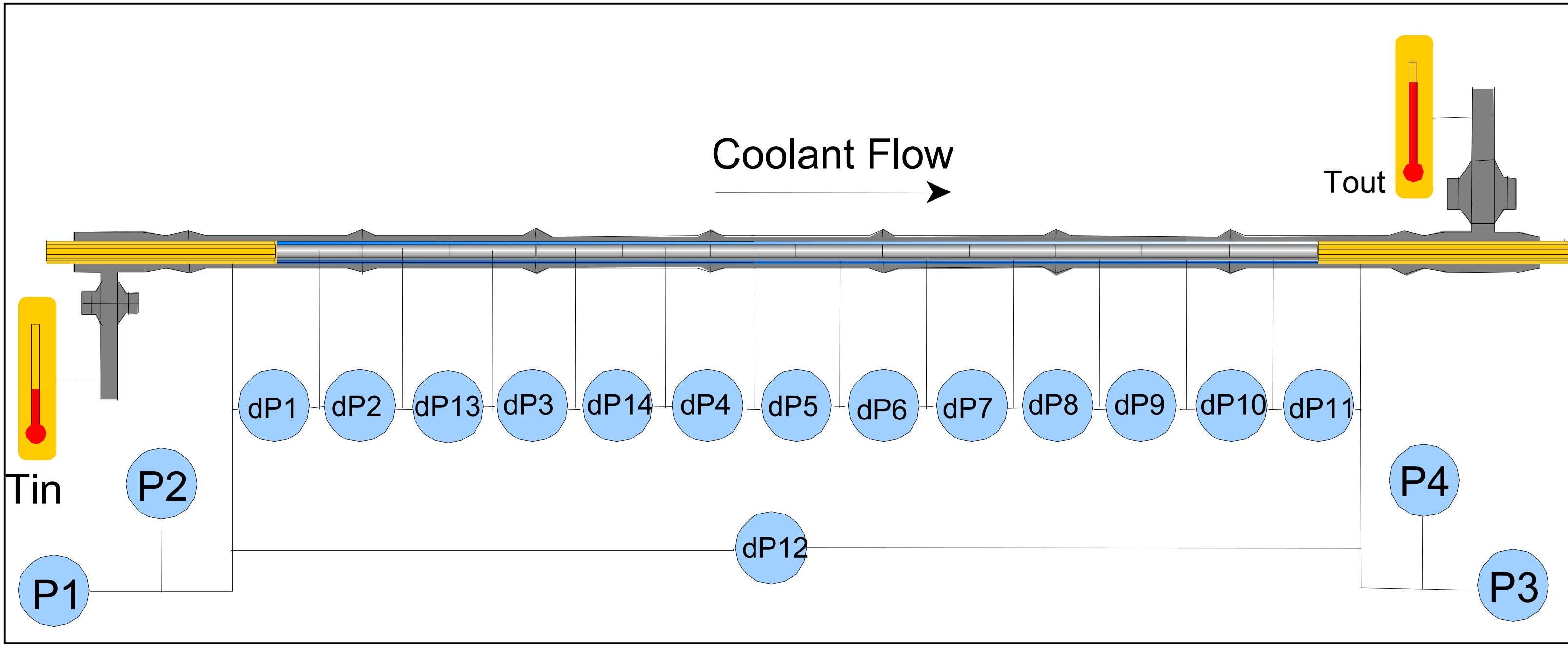
Two-Phase Pressure Distribution over a Square-Edged Orifice



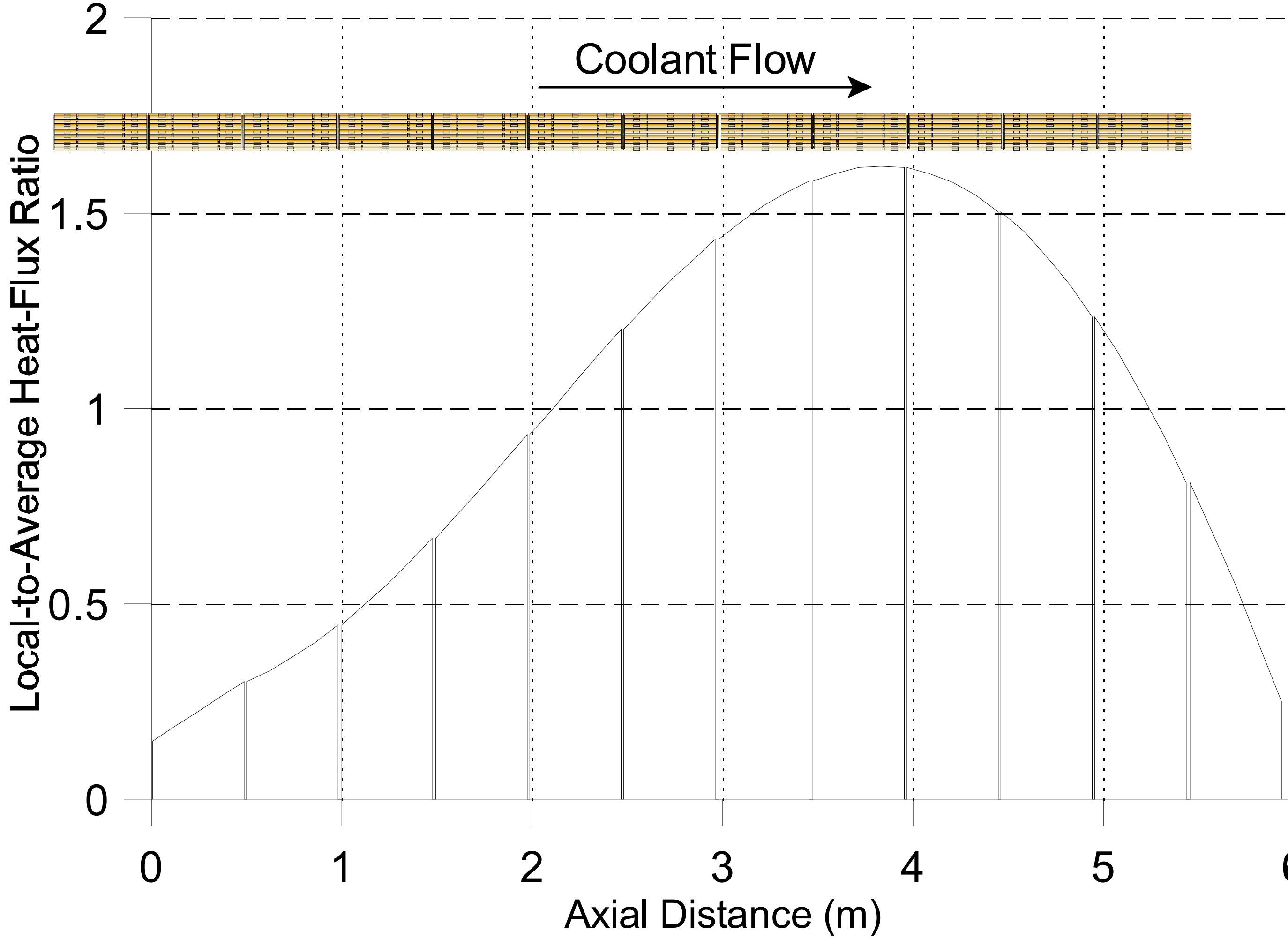
Two-Phase Pressure Distributions over Aligned and Misaligned Bundles



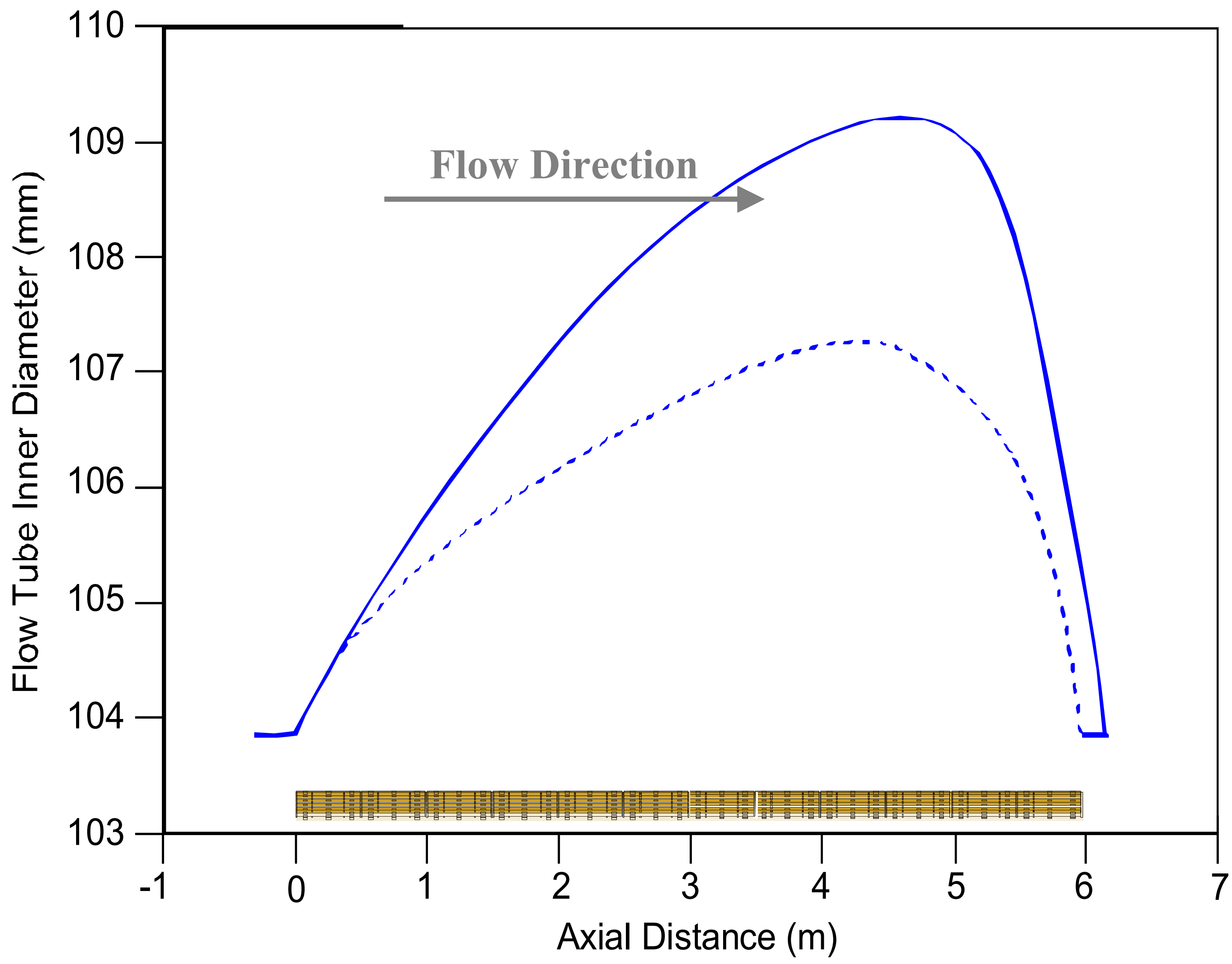
High Pressure Water Test Station



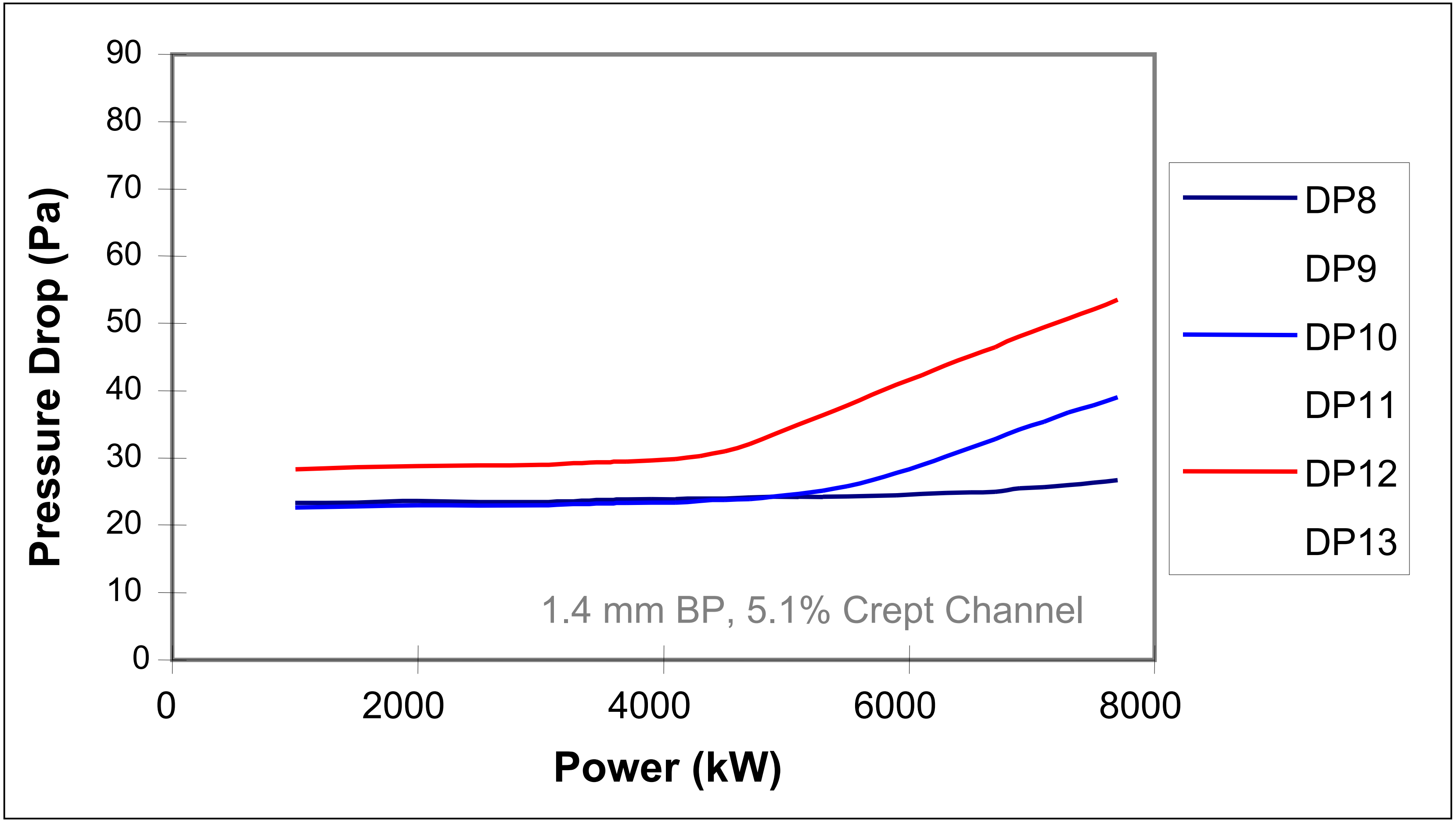
Axial Power Profile in Water Tests



Axial Flow Tube Diameter Variation

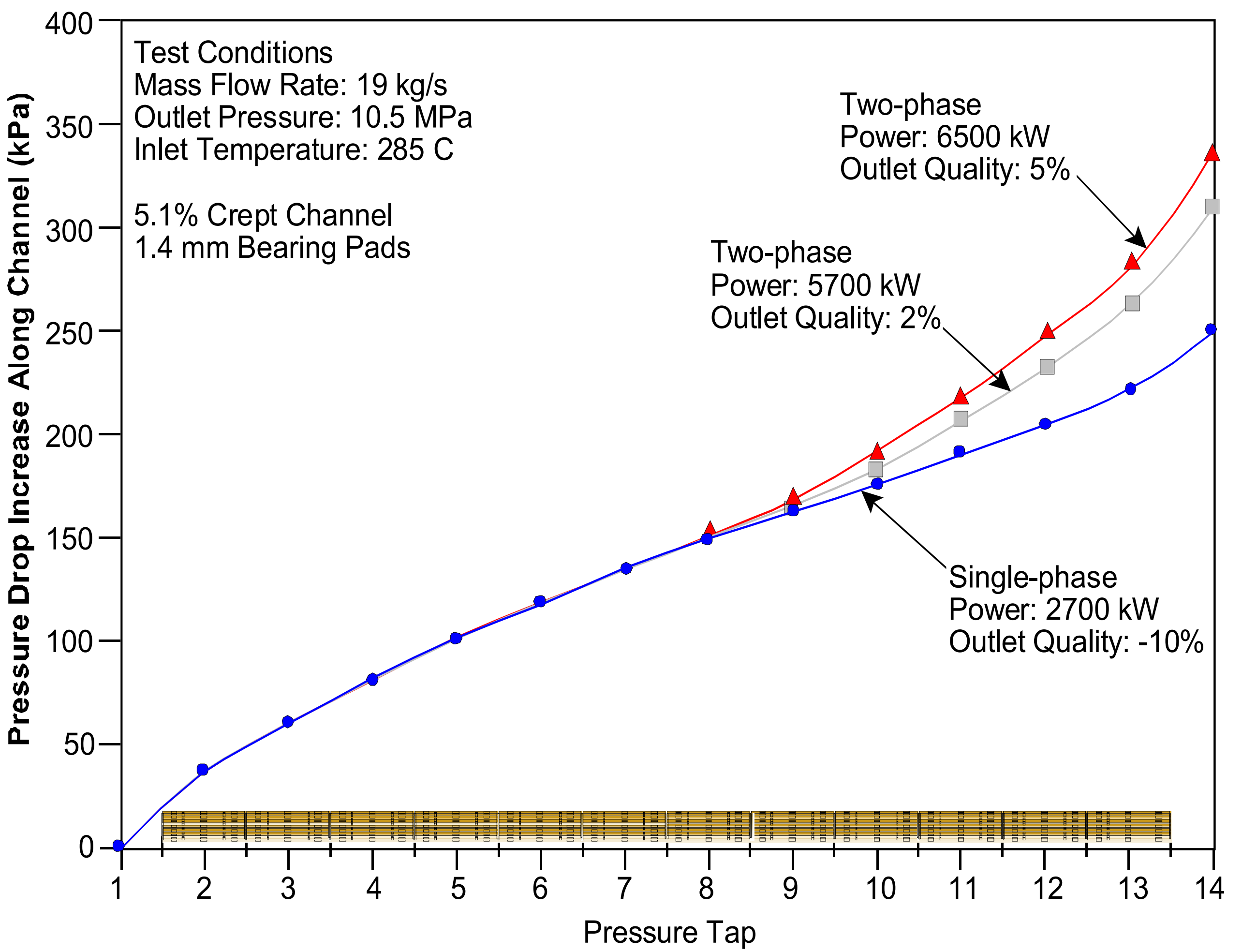


Onset of Significant Void



Dimmick et al., Proc. 6th Int. Conf. on CANDU Fuel, Niagara Falls, Canada, September 26-30, 1999

Pressure Gradient Along Flow Channel



Dimmick et al., Proc. 6th Int. Conf. on CANDU Fuel, Niagara Falls, Canada, September 26-30, 1999

Summary

- Pressure drop is one of the main thermal-hydraulics parameters in flow re-circulation systems
- Pressure drop depends on flow conditions, flow regimes, and surface heating
- Four main components in the overall pressure drop: friction, acceleration, gravity, and form
- Two-phase pressure drops due to friction and local disturbances are expressed in terms of two-phase multipliers
- A large number of correlations are available for two-phase multiplier; uncertainty remains high due to large scatter among data

Questions?