Simulation of CANDU Bundle Cross-Sectional Averaged Actual Flow Quality and Void in One-Dimensional Two-Phase Flow Models

G. Hotte
(Hydro-Québec, 1155 Metcalfe, Bureau 880, Montréal, Québec, Canada H3B 2V6)

M. Soulard
(AECL, 2251 Speakman Drive, Mississauga, Ontario, Canada L5K 1B2)

L. Leung
(AECL, Chalk River Laboratories, Chalk River, Ontario, Canada K0J 1J0)

Paper presented at the Twentieth Nuclear Simulation Symposium of the Canadian Nuclear Society (September 7-9, 1997)

Abstract

This paper presents the theoretical and empirical background for the representation of CANDU bundle sub-channel void distribution effects in One-Dimensional Two-Phase flow. Due to the non-uniform velocity profile in the sub-channels and to the non-uniform fuel element power distribution in the bundle, the cross-sectional average flow quality is quite different than the thermodynamic quality in a bundle. This is clearly seen in CANDU fuel bundle full-scale tests which show transition to two-phase pressure drop well before the onset of bulk boiling based on thermodynamic quality. Models have therefore been proposed to represent the bundle cross-sectional averaged void-quality relationship in one dimensional two-phase flow. The focus of this paper is the application of the Leung sub-cooled boiling model in steady state and transient simulations as implemented in NUCIRC and SOPHT-G2. The Leung model predicts the onset of significant void in a fuel bundle string and computes the bundle actual flow quality using the Saha-Zuber model developed for uniformly heated tubes. The paper shows the importance of representing actual quality and void for predictions of two-phase pressure drop, CHF and void reactivity feedback.

Introduction

The homogeneous two phase flow model assumes that the steam-water mixture is at equilibrium with the phase properties determined at saturation by the mass fraction of the phases flowing at equal velocities and equal temperatures. However, boiling first occurs in the subcooled liquid where the phase temperatures and velocities are not equal. Separate flow, drift flux or two-fluid models are required to correctly represent the steam mixture properties and flow. This is further complicated in one-dimensional two-phase flow modeling of nuclear fuel bundles and fuel assemblies by the non-uniform subchannel velocity and subchannel enthalpies profiles, which result in net vapour generation at higher steam-water mixture subcooling than that seen in tubes.

Analyses of CANDU full-scale fuel bundle pressure drop data show that transition to two-phase pressure drop occurs well before the thermodynamic quality at onset the onset of significant void in tubes [1,2]. Bundle specific models are therefore required for the simulation of cross-sectional averaged flow in one-dimensional separate flow, drift flux or two-fluid flow models. This paper presents the theoretical and empirical background for the representation of CANDU bundle sub-channel imbalances in a cross sectional averaged separate flow model based on a similar form of that proposed by Saha and Zuber for tubes. Numerical examples, based on the application of the Leung sub-cooled boiling model [2,3] in SOPHT-G2 steady state and transient simulations, illustrate the importance of the representation of flow quality in fuel bundle one-dimensional two-phase flow simulations.

Derivation of the Mixture Flow Quality

Before presenting the derivation of the expression for flow quality used in the steam-water mixture energy equation, it is first useful to recall the definitions of static quality, flowing quality and thermodynamic quality.

Static quality is defined as the ratio of the mass of vapour to the total mass in a control volume:

$$x_s = \frac{\rho_g A_g}{\rho_g A_g + \rho_l A_l}$$

Flowing quality is defined as the ratio of the mass flow rate of vapour to the total mass flow rate in a control volume:

$$x = \frac{\rho_g A_g v_g}{\rho_g A_g v_g + \rho_l A_l v_l}$$

Thermodynamic quality is the flowing quality of the steam-water mixture at thermodynamic equilibrium, that is at equal temperatures and velocities of the phases:

$$x_{th} = \frac{h - h_l^{sat}}{h_{fg}}$$

The void fraction is defined as the volume of vapour over the total volume, that is for cross-sectional averaged models as the flow area of the vapour phase over the total flow area:

$$\alpha = \frac{A_g}{A_g + A_l}$$

Equation of Conservation of Energy

The equation of conservation of energy for the steam-water flow mixture solved in SOPHT-G2 is given by

$$\frac{\partial}{\partial t}\left[(1-\alpha)\rho_l h_l + \alpha\rho_g h_g\right] - \frac{\partial}{\partial t}\left[(1-\alpha)p + \alpha p\right] + \frac{\partial}{\partial z}\left[(1-\alpha)\rho_l v_l h_l + \alpha\rho_g v_g h_g\right] = \frac{q^{'} P_h}{A}$$

Using the following relation between void and flowing quality

$$\alpha\rho_g v_g = \frac{A_g}{A_g + A_l}\rho_g v_g = \frac{\rho_g A_g v_g}{\rho_g A_g v_g + \rho_l A_l v_l}\,\frac{\rho_g A_g v_g + \rho_l A_l v_l}{A} = xG$$

the energy equation can be written as

$$\frac{\partial}{\partial t}\left[(1-\alpha)\rho_l u_l + \alpha\rho_g u_g\right] + \frac{\partial}{\partial z}\left\{\left[(1-x)h_l + xh_g\right]G\right\} = \frac{q^{'} P_h}{A}$$

with the internal energy defined as $u_{l,g} = h_{l,g} + p/\rho_{l,g}$

Flow Quality

An analytical expression for flow quality is obtained from the steady state energy equation. Taking the derivatives, at constant mass flux, the steady state energy equation is written as

$$(1-x)\frac{\partial h_l}{\partial z} - h_l\frac{\partial x}{\partial z} + x\frac{\partial h_g}{\partial z} + h_g\frac{\partial x}{\partial z} = \frac{q^{'} P_h}{GA}$$

Using $h_l = c_{pl}\left(T_{sat} - T_l\right) - h_l^{sat}$ and $h_g = h_{fg} + c_{pl}\left(T_{sat} - T_l\right) + h_l$ and assuming that, in the subcooled region, the change in saturate liquid and saturate enthalpy is small compared to the change sensible heat, the steady state energy equation becomes:

$$(1-x)c_{pl}\frac{d(\Delta T_l)}{dz} - h_l\frac{dx}{dz} + \left(h_{fg} + c_{pl}\Delta T_l + h_l\right)\frac{dx}{dz} = \frac{q^{'} P_h}{GA}$$

with $\Delta T_l = \left(T_{sat} - T_l\right)$. Solving this equation for the change in flow quality, recognizing that $(1-x) \approx 1$ in the subcooled boiling region provides the following relationship:

$$dx = \frac{1}{h_{fg} + c_{pl}\Delta T_l}\left[\frac{qP_h dz}{GA} - c_{pl}d(\Delta T_l)\right]$$

Integrating this equation from the axial OSV point at Z=0 at which $x = 0$ and $T = T_{osv}$, we obtain the following relation for flow quality:

$$x = \frac{\frac{qP_h Z}{GA} - c_{pl}\left(\Delta T_{osv} - \Delta T_l\right)}{h_{fg} + c_{pl}\Delta T_l} \qquad (1)$$

Using the following definition for liquid subcooling $\Delta T^* = \frac{\Delta T_l}{\Delta T_{osv}}$, this relation can be written as

$$x = \frac{C_1 Z - 1 + \Delta T^*}{B + \Delta T^*} \qquad (2)$$

with $C_1 = \frac{qP_h}{\Delta T_l G A c_{pl}} = \frac{h_0 P_h}{G A c_{pl}}$ (assuming $q_l = h_0 \left(T_w - T_l\right) \approx h_0 \Delta T_l$) and $B = \frac{h_{fg}}{c_{pl} \Delta T_{osv}}$

Thermodynamic Quality

The thermodynamic quality is given by

$$x_{th} = \frac{h - h_l^{sat}}{h_{fg}} = \frac{h_{osv} + qP_h Z / GA - h_l^{sat}}{h_{fg}} = \frac{h_{osv} - h_l^{sat}}{h_{fg}} + \frac{qP_h Z}{GAh_{fg}}$$

which can be written as

$$x_{th} = \frac{-c_{pl} \Delta T_{osv}}{h_{fg}} + \frac{qP_h Z}{GAh_{fg}} = \frac{c_{pl} \Delta T_{osv}}{h_{fg}} \left(\frac{qP_h Z}{GAc_{pl} \Delta T_{osv}} - 1 \right) \approx \frac{C_1 Z - 1}{B} \qquad (3)$$

At the OSV point, we have $x_{thosv} = -1/B$ and equation (3) can be written as

$$C_1 Z = 1 - \frac{x_{th}}{x_{thosv}} .$$

Expression for Flow Quality used in the Saha-Zuber Model

Using the thermodynamic quality given by equation (3) in equation (2) results in the following expression for flow quality

$$x = \frac{Bx_{th} + \Delta T^*}{B + \Delta T^*} = \frac{x_{th} - x_{thosv} \Delta T^*}{1 - x_{thosv} \Delta T^*} \qquad (4)$$

The expression for liquid subcooling is obtained by substituting the flow quality given by equation (1) in the energy conservation equation and solving for ΔT_l , which results in the following expression, recognizing that $h_{fg} + c_{pl} \Delta T_l \approx h_{fg}$ and $(1 - x) \approx 1$ in the subcooled boiling region:

$$-\frac{d(\Delta T_l)}{\Delta T_l} = \frac{h_0 P_h}{GAc_{pl}} dZ$$

Integrating from the axial OSV point at which $\Delta T_l = \Delta T_{osv}$, we obtain the following for the liquid subcooling

$$-\ln\left(\frac{\Delta T_l}{\Delta T_{osv}}\right) = \frac{h_0 P_h}{G A c_{pl}} Z,$$

The liquid subcooling can therefore be written as

$$\Delta T^* = \exp[-C_1 * Z] = \exp\left[\frac{x_{th}}{x_{thosv}} - 1\right]$$

Using this expression in (4), we obtain the expression used for flow quality in the Saha-Zuber model:

$$x = \frac{x_{th} - x_{thosv} \exp\left(\frac{x_{th}}{x_{thosv}} - 1\right)}{1 - x_{thosv} \exp\left(\frac{x_{th}}{x_{thosv}} - 1\right)}$$

Leung Correlation for the Thermodynamic Quality at OSV

Analyses of CANDU full-scale fuel bundle pressure drop data show that transition to two-phase pressure drop occurs well before the thermodynamic quality at the onset of significant void in tubes. Bundle specific correlation based on a similar form of the Saha-Zuber correlation [4] were derived and compared to the bundle full-scale tests [2,3]. A preliminary model, which proposed to use a corrected mass flux in a correlation for the point of net vapour generation derived from tube-flow data [3], was implemented in SOPHT-G2.

In this model, the thermodynamic quality at the point of net vapour generation or OSV point is expressed as

$$x_{thosv} = -34.08 \, \mathrm{Re}_l^{0.147} \left(\frac{q}{G_{eff} h_{fg}}\right)^{0.858} \left(\frac{\rho_g}{\rho_l}\right)^{0.362}$$

This correlation, derived with tube-flow data, uses a corrected mass flux to account for the effect of bundle eccentricity which result in a shift of the net vapour generation point towards lower qualities:

$$G_{eff} = G\sqrt{\frac{K D_{hy}}{D_{hy,efff}}}$$

in which K is an eccentric bundle correction factor.

Numerical Applications

Figure 1 shows the variation of void fraction as a function of thermodynamic quality based on measurements in tube experiments [5] along with predictions made with the Saha-Zuber correlation [4]. These data are typical of those seen in the Stern Laboratories 37-element CHF test program [6]. As illustrated, OSV occurs for subcooling as high as 15% to 20%. Also, void at onset of bulk boiling is significantly greater than that predicted for equilibrium models and the difference between non-equilibrium and equilibrium quality and void remains significant up to around 5% to 10% thermodynamic quality, above which flow quality converges to thermodynamic quality.

The impact of modeling flow quality on the flow and void prediction in cross-sectional averaged simulations of a fuel channel is illustrated in the following numerical examples:

- A steady state simulation of test no 1145 from Phase 1 of the Stern Laboratories 37-element CHF test program [6], performed at measured inlet flow and inlet temperature and measured outlet pressure
- A channel transient flow rundown simulation typical of Loss of Class 4 power in CANDU-6 reactors

Simulations compare the results obtained using thermodynamic quality to those obtained using the flow quality model described above. Void fraction is computed in both cases using the Armand-Massena correlation, given by:

$$\alpha = (0.833 + 0.167 * x)\left[1 + \frac{1-x}{x}\frac{\rho_g}{\rho_l}\right]^{-1}$$

in which either thermodynamic quality or flow quality is used, according to the case simulated. This was done to isolate the effect of representing flow quality even though it has been demonstrated that only the void fraction obtained based on flow quality should be determined using a void-quality relationship with slip [7].

Figure 2 compares the predicted pressure gradients along the fuel string to the pressure tap measurements for test no 1145. As shown, simulations done with the thermodynamic quality predicts that the transition from single to two phase flow occurs downstream from that seen in the measurements and consequently under predicts the measured total pressure drop. Simulations with the flow quality model agree much better with the measured total pressure drop and pressure drop profile.

Figures 3 and 4 illustrate the pressure drop and power transient used in the flow rundown simulation. Figure 5 shows the predicted channel flow rundown transient. Figure 6 shows the predicted void distribution along the fuel string at different times in the transient. As shown, even though the flow transients are quite similar, the flow quality model predicts a significantly larger void generation in the middle of the channel before reactor shutdown. The increased void generation seen by the flow quality model is, as expected, more important in the low quality region of the channel and is therefore more pronounced in the center of the channel where the neutron importance of the void generation is also greater. Predictions from models based on thermodynamic quality can therefore be expected to underestimate the void reactivity feedback in loss of flow or flow oscillation events.

Conclusion

The homogeneous two phase flow model can not predict boiling which occurs in the subcooled liquid where the phase temperatures and velocities are not equal. Separate flow, drift flux or two-fluid models are required to correctly represent the steam mixture properties and flow. This is further complicated in one-dimensional two-phase flow modeling of nuclear fuel bundles and fuel assemblies by the non-uniform subchannel velocity and subchannel enthalpies profiles, which result in net vapour generation at higher steam-water mixture subcooling than that seen in tubes. Bundle specific models are therefore required for the simulation of cross-sectional averaged flow in one-dimensional separate flow, drift flux or two-fluid flow models. This paper presented the theoretical and empirical background for the representation of CANDU bundle subchannel imbalances in a cross sectional averaged separate flow model. The expression for flow quality used in the Saha-Zuber model is derived from the steady state conservation of energy equation for the steam-water mixture and is applicable to steady and transient flow simulations. Application of the model should however be restricted to situations with fully developed flow in the range of experimental data used for the derivation of the correlation for thermodynamic quality at the point of net vapour generation, also known as the onset of significant void.

Numerical examples illustrate the importance of the representation of flow quality in fuel bundle one-dimensional two-phase flow simulations in order to correctly predict the two-phase pressure drop and void generation. This has been shown to be of primary importance for accurate prediction of critical heat flux, critical channel power and void feedback power transients [8,9,10].

References

[1] C.W. Snoek, "A Comparison of Predictions Methods for Pressure Drop in Multi-Element CANDU-Fuel Channels", CRNL-4017, AECL, 1986.

[2] L.K.H. Leung, K.F. Rudzinski, "Prediction of Onset of Significant Void in a String of 37-Element Bundles Inside a Reference Pressure Tube, COG-97-242, AECL, 1997 (Under Review).

[3] L.K.H. Leung, D.C. Groeneveld, "A method for Calculating the Axial Pressure Drop along a String of 37-Element Bundles", COG-95-490, AECL, 1995 (Under Review).

[4] P. Saha, N. Zuber, "Point of Net Vapour Generation and Vapour Void Fraction in Subcooled Boiling", Proc. of the 5th International Heat Transfer Conference, Tokyo, 1974.

[5] Bartolomei, G.G., Brantov, V.G., Molochnikov, Yu.S., Kharitonov, Yu.V., Solodkii, V.A., Batashova, G.N. and Mikhailov, V.N., "An Experimental Investigation of True Volumetric Vapour Content with Subcooled Boiling in Tubes", Thermal Engineering, Vol. 29, No. 3, pp. 132-135, 1982.

[6] R.A. Fortman, R.C. Hayes, G.I. Hadaller, "37-Element CHF Program - Phase 1 Test Results", COG-93-218, Stern Laboratories Inc., July 1994.

[7] P. Tye, A. Tesseydou, N. Troche, "A Review of Void Quality Relationships: Applicability to ASSERT", IGE-202, École Polytechnique de Montréal, November 1995.

[8] G. Hotte, T. Jouhanique, "An Investigation In to the Accuracy if CHF Modeling in One-Dimensional Two-Phase Flow Analyses", 4th Conf. On Simulation Methods in Nuclear Engineering, CNS/ANS, Montréal, June 2-3 1993.

[9] M. Soulard et al., "Investigation into the Modeling of the Effect of Pressure Tube Creep on CHF, Dryout Power and Pressure Drop", 16th Annual Conference of the Canadian Nuclear Society, Saskatoon, June 4-7, 1995.

[10] A. Baudouin et al., "Gentilly-2 Overpower Transient Initiated by a Loss of Electrical Power", 5th Conf. On Simulation Methods in Nuclear Engineering, CNS/ANS, Montréal, September 8-9, 1993.

Nomenclature

A	Cross Section
c_{pl}	Liquid Specific Heat
D_{hy}	Hydraulic Diameter
G	Mass Flux
h	Enthalpy
h_{fg}	Latent Heat
P_h	Wetted Perimeter
p	Pressure
q	Heat Flux
T	Temperature
u	Internal Energy
v	Velocity
x	Flow Quality
x_s	Static Quality
x_{th}	Thermodynamic Quality`
Z, z	Axial Position
ρ	Density
α	Void Fraction

<u>Subscript/Superscript</u>

g	Vapour Phase
l	Liquid Phase
sat	Saturation
osv	Onset of Significant Void

Figure 1

Void-Quality in a CANDU 37-Element Fuel Bundle String

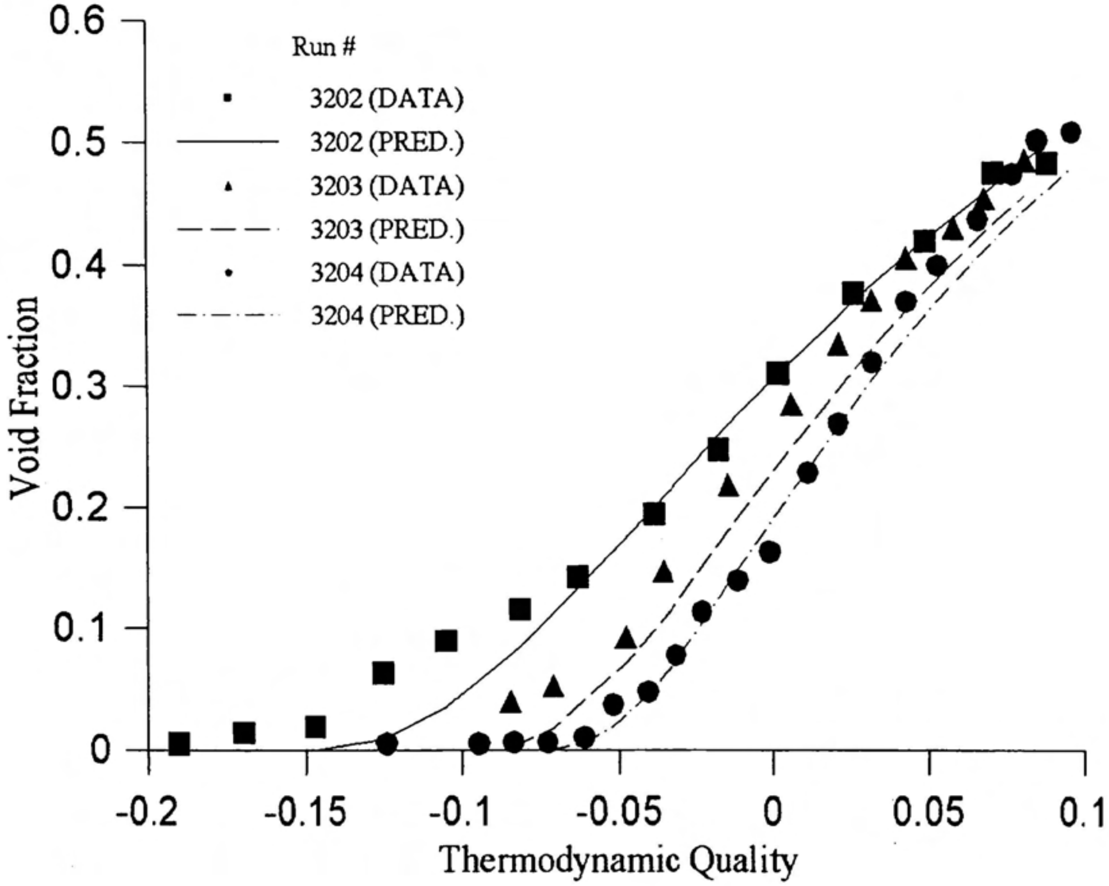

Figure 2
Pressure Gradient - Case 1145 Stern Lab. Full Scale Test

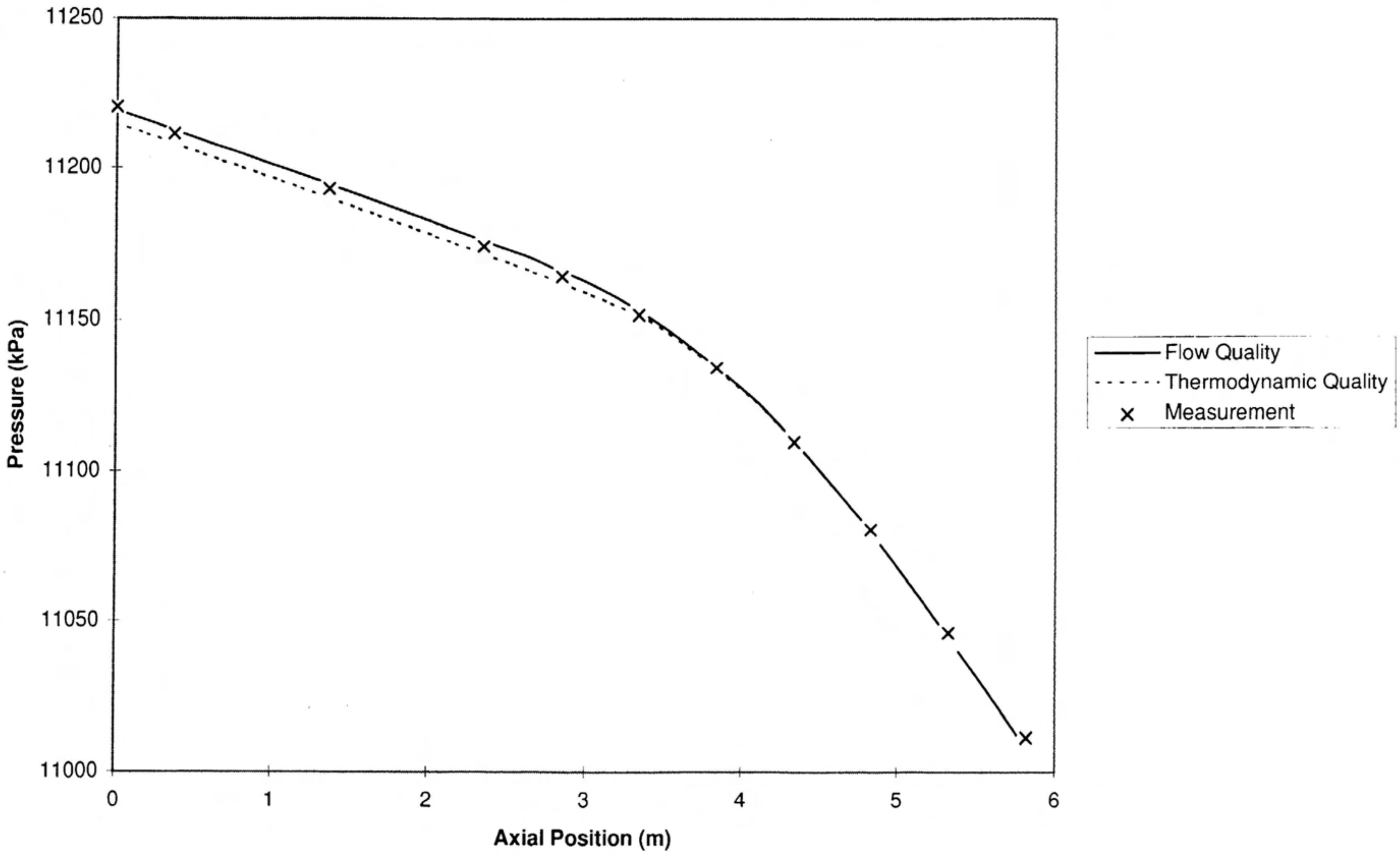

Figure 3
Flow Rundown Pressure Drop Transient

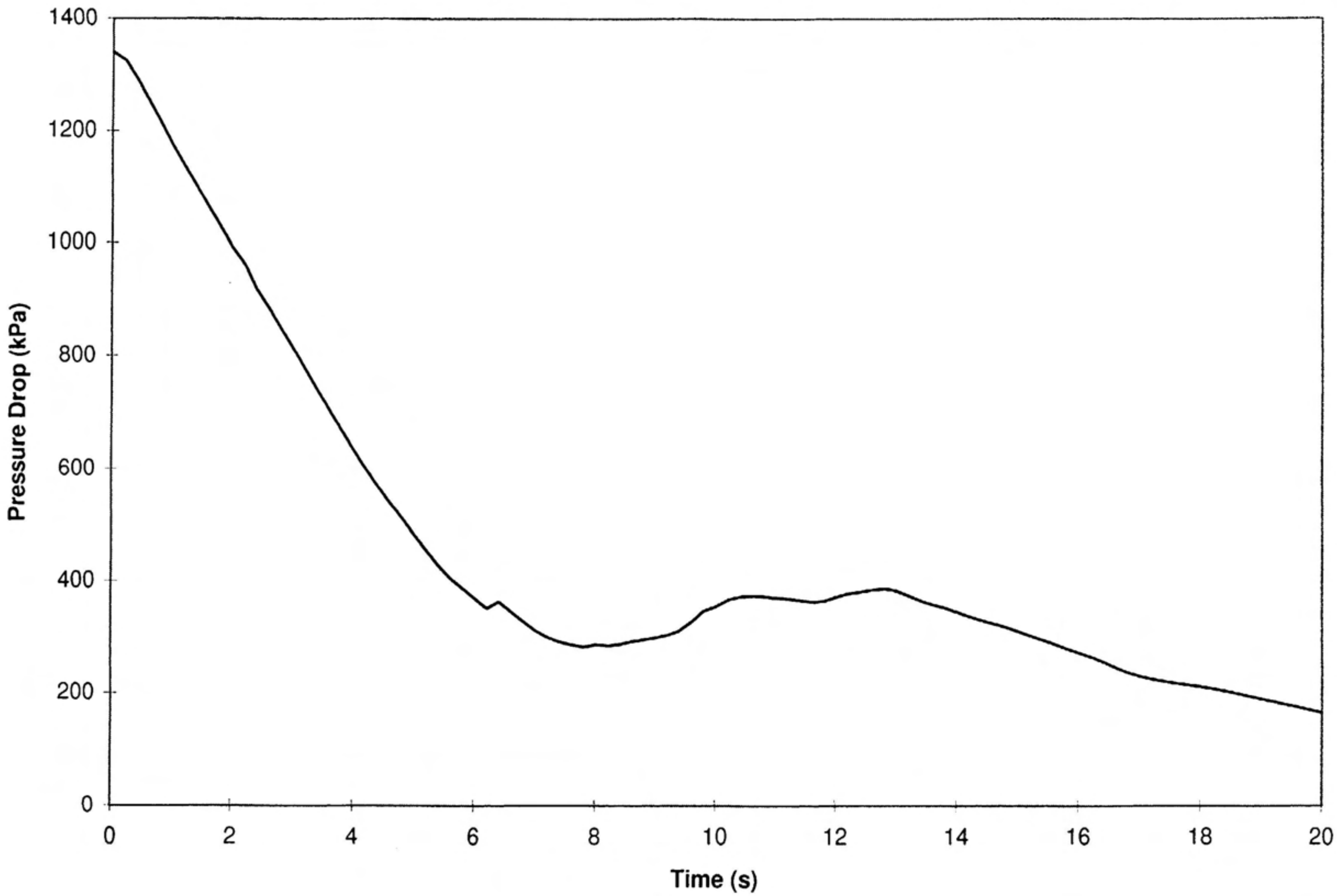

Figure 4
Flow Rundown Channel Power Transient

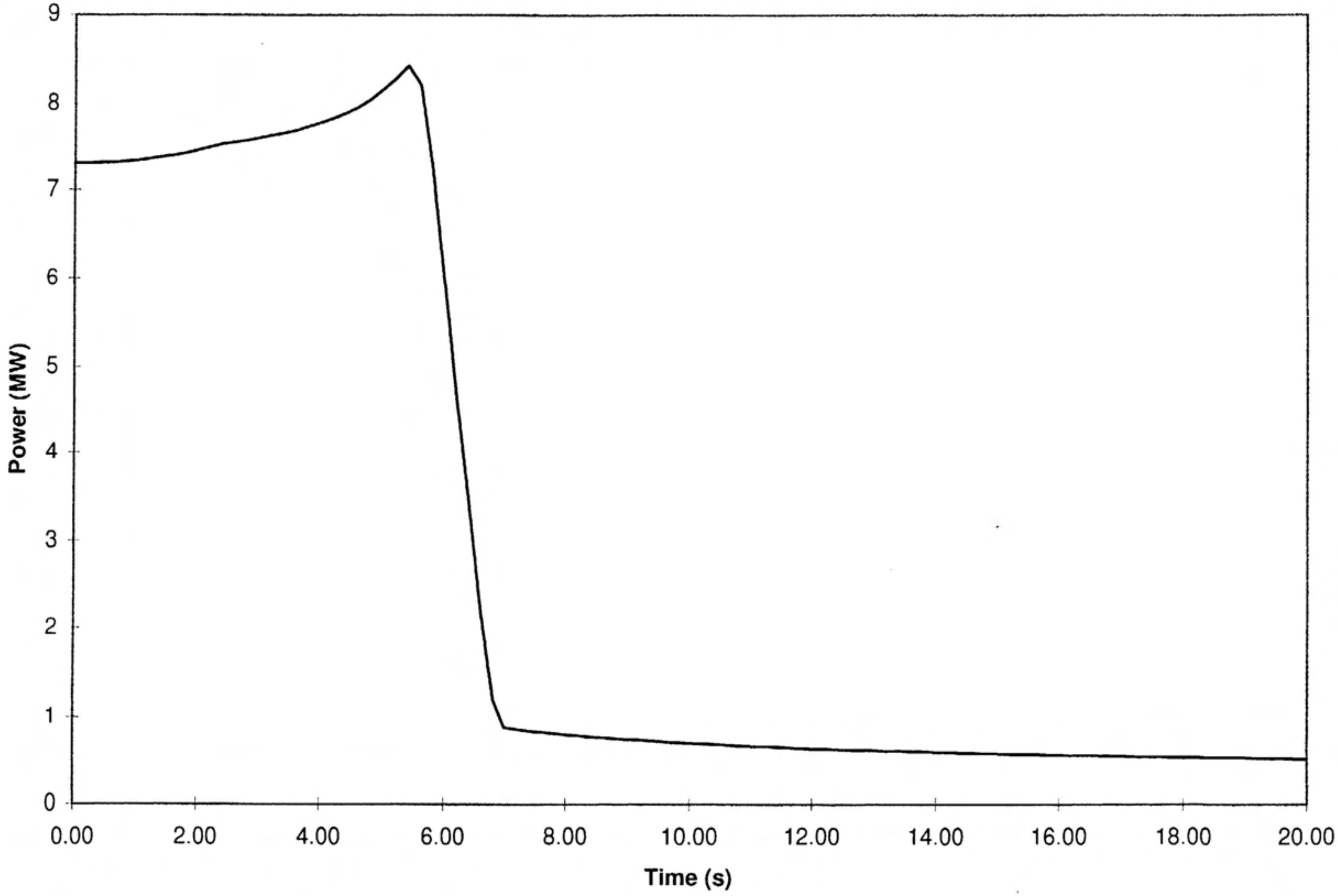

Figure 5

Predicted Channel Flow Rundown Transient

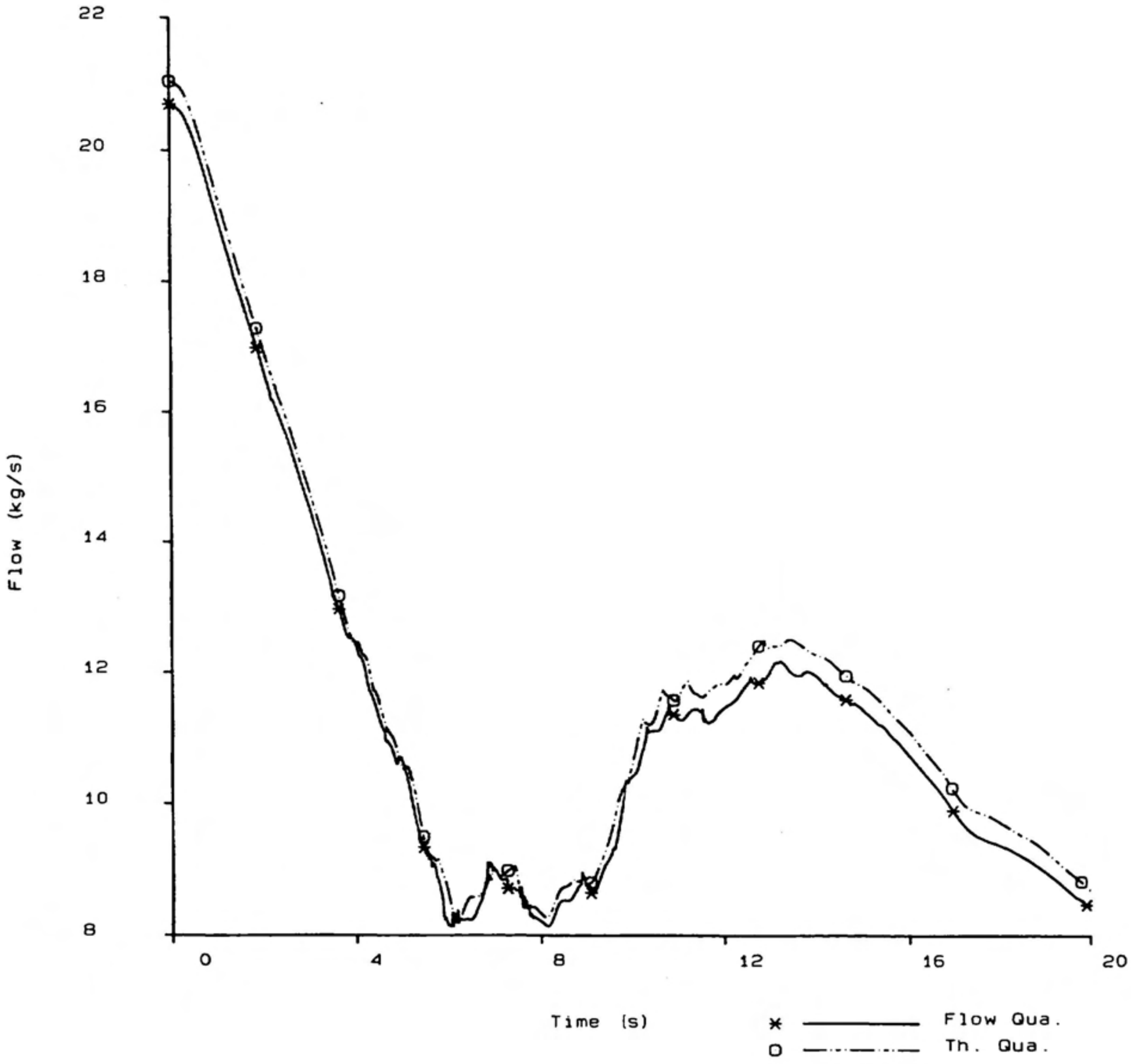

Figure 6
Typical Flow Rundown Axial Void Profiles