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# LOCO - A LINEARISED MODEL FOR ANALYSING THE ONSET OF COOLANT OSCILLATIONS AND FREQUENCY RESPONSE OF BOILING CHANNELS

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## ABSTRACT

Industrial plant such as heat exchangers, thermosiphon reboilers, and nuclear and conventional boilers are prone to coolant flow oscillations (or density wave oscillations) which may not be detected

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(Continued)

until some catastrophic failure (e.g. boiler tube burnout, corrosion or rupture) terminates normal operation.

In this report, a hydrodynamic model is formulated in which the one-dimensional, non-linear, partial differential equations for the conservation of mass, energy and momentum are perturbed with respect to time, linearised (that is, terms higher than first order are neglected), and Laplace-transformed into the s-domain for frequency response analysis. A computer program has been developed to integrate numerically the resulting non-linear ordinary differential equations by finite difference methods. A sample problem demonstrates how the computer code is used to analyse the frequency response and flow stability characteristics of a heated channel.

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L CODES; FLOW MODELS; TWO-PHASE FLOW; HYDRODYNAMICS; DIFFERENTIAL EQUATIONS; FINITE DIFFERENCE METHOD; FREQUENCY ANALYSIS

CONTENTS

## 1. INTRODUCTION

The performance and reliability of nuclear and conventional steam generators, process heat exchangers, thermosiphon reboilers and other two-phase heat transfer equipment are dependent on the steady flow of coolant through their component heated channels. Under certain operating conditions (coolant pressures, temperatures, flow rates, heat fluxes etc.), a variety of fundamental and higher mode coolant flow instabilities can occur which may cause:

a) failure of the channel structure or containment due to the high thermal stresses or corrosion induced by thermal cycling, dryout or burnout of the heat transfer surfaces;

b) fatigue failure of the channel structure or containment due to the excitation of mechanical resonances;

c) control problems in maintaining the desired operating conditions, particularly the steam conditions supplied to subsequent process equipment (e.g. steam turbine).

The following analysis formulates a linearised hydrodynamics model for calculating the frequency response of a 'boiling channel' and, in particular, for predicting the onset of static (flow excursions) and dynamic (flow or density wave oscillations) instabilities in the coolant flow. The analysis is prefaced by a review of the basic regions and two-phase flow regimes that are postulated to occur in the boiling channel, and the possible methods for modelling the coolant flow behaviour.

The model is based on a linearised solution of the cross-section averaged equations for the conservation of mass, energy and momentum of the two-phase (vapour/liquid) mixture. The equations are perturbed with respect to time, linearised (that is, higher than first-order terms are neglected), and Laplace-transformed into the s-domain for frequency response analysis. The resulting non-linear ordinary differential equations are spatially integrated by finite difference methods. Finite difference equations are derived for the steady state and dynamic analysis of the thermal non-equilibrium two-phase flow through the subcooled boiling region of the channel. Specification of certain parameters and variables reduces these equations to simpler forms for analysis of the single phase liquid and saturated boiling regions.

The channel is divided into a number of volume elements, and the continuity in flow conditions between successive elements is provided by coupling equations at the boundary (or interface). In a similar manner, the flow conditions between the single phase and two-phase regions are coupled by mass, energy and momentum conservation equations at the boiling boundary. The steady state and dynamic relationships between variables at the channel inlet and exit are calculated by piecewise integration along the channel. The channel may be operated in parallel with a number of other channels, in parallel with a large bypass, or in a closed loop in series with a pump. Stability criteria are derived by specification of appropriate boundary conditions for the parallel channel, channel/bypass and closed loop systems, and these enable the stability of the coolant flow through the boiling channel to be assessed.

A computer program (LOCO - a Linearised model for analysing the Onset of Coolant Oscillations in boiling channels) has been developed to perform the computations. The program data input specifies the channel geometry and operating conditions, and permits the calculation of the frequency response relationships between perturbations in channel inlet flow rate, temperature, pressure, average power (inputs) and the over pressure drop, exit void fraction (outputs). The inputs may be frequency independent ('white noise') for transfer function and stability calculations, or frequency dependent real or complex (experimental) data for frequency response calculations.

This analysis is part of a larger investigation which is described in more detail in the references by Romberg (1978) and Romberg and Rees (1980).

## 2. FLOW REGIONS AND REGIMES IN BOILING TWO-PHASE FLOW

During normal operation, the coolant enters the heated channel as subcooled liquid and discharges as a vapour/liquid mixture or superheated vapour from the channel exit. For modelling purposes the flow structure (vapour/liquid distribution) may be divided into five inter-connected hydrodynamic regions (Figure 1):

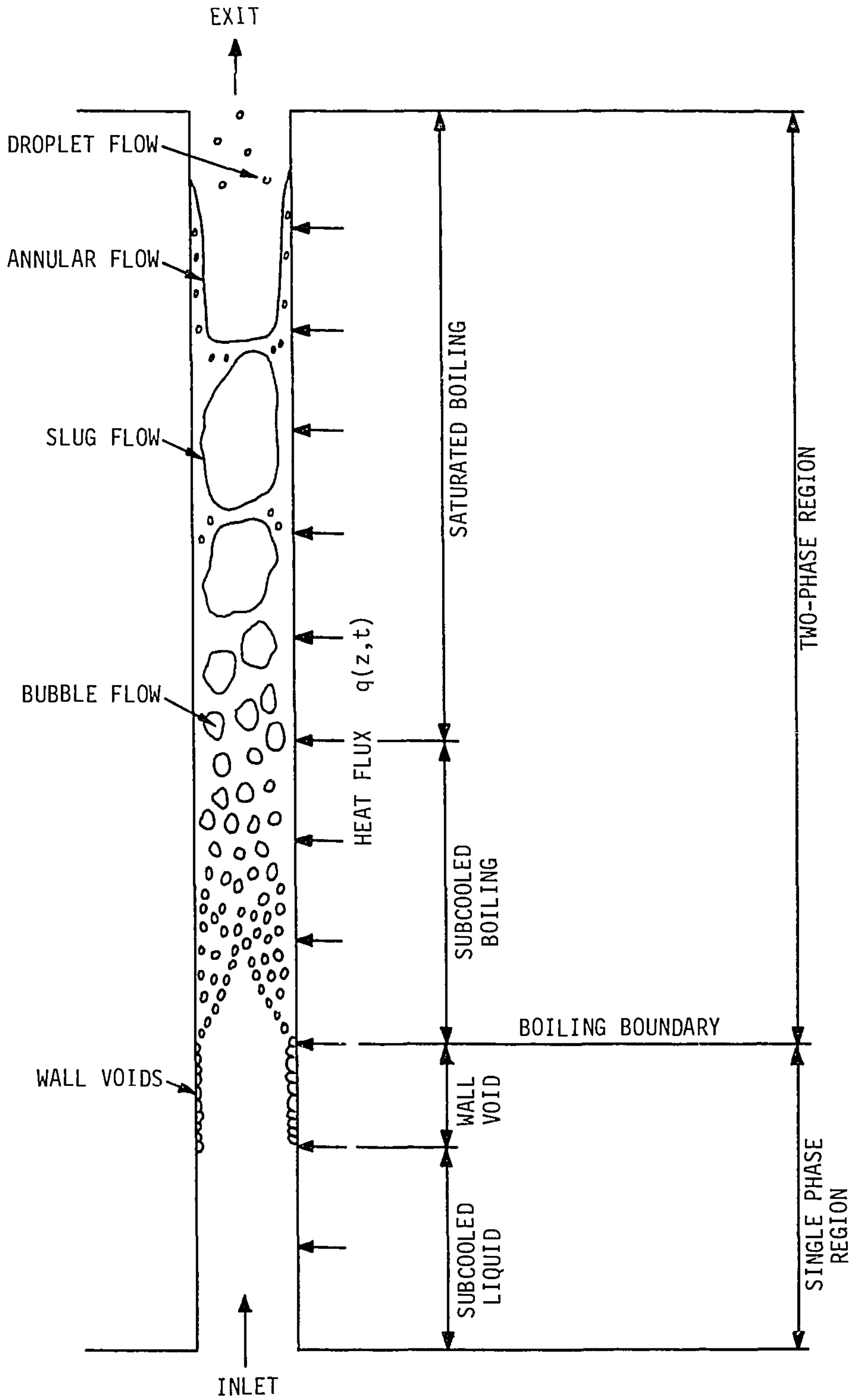


FIGURE 1 - SCHEMATIC DIAGRAM OF A BOILING CHANNEL SHOWING FLOW REGIONS AND TWO-PHASE REGIMES

1. single phase liquid region - no vapour bubbles, incompressible flow;

2. wall void region - the local wall temperature is greater than the local saturation temperature, vapour bubbles form and remain attached to the heated surface;

3. subcooled boiling region - the bulk (average) liquid temperature is less than the local saturation temperature, the vapour bubbles become detached from the wall due to thermal effects (low flow rates) or hydrodynamic drag effects (high flow rates);

4. saturated boiling region - the liquid temperature reaches saturation, violent boiling agitation at the heated surface;

5. superheated vapour region - no liquid phase, compressible vapour flow.

The liquid entering the channel has its temperature raised by heat transfer at the heat source/coolant interface. The rate of heat transfer depends on the cross-sectional velocity and temperature profiles. Since the bulk (cross-sectional average) liquid temperature is less than the saturation temperature, it is also called the subcooled liquid region. The local wall temperature is higher than the local liquid temperature, but not high enough to initiate nucleate boiling on the heated surface.

As a volume element of coolant moves further along the channel, the local conditions at the heated surface (heat fluxes, wall/coolant temperatures, surface asperities, etc.) are sufficient to initiate nucleate boiling, but the bubble diameters are small and are dominated by surface tension effects, so that they remain attached to the heated surface. These bubbles act as surface asperities to increase the frictional resistance to fluid motion, and improve the wall/coolant heat transfer by their agitation and action as turbulence promoters. This region is termed the wall void region. Further downstream the bubbles grow in size and eventually become detached from the heated surface by thermal agitation or hydrodynamic action. The axial position at which this occurs denotes the subcooled boiling boundary, the beginning of the subcooled boiling region.

In the subcooled boiling region, the bubbles travel downstream near the wall or move, by turbulent interaction, into the centre of the channel, where they collapse due to thermal non-equilibrium with the subcooled liquid phase. The mean lifetime of the bubbles in this region is statistically random, and their growth and collapse can cause pressure transients (acoustic oscillations) which vibrate the channel structure. In general, the mean lifetime of a bubble ensemble is dependent on their mean free path, boundary layer profiles, number of nucleation sites etc. These are nonmeasurable quantities, and the axial void (vapour fraction) distribution in this region must be evaluated by empirical correlations based on experimental data. These correlations are a function of the channel geometry and operating conditions (pressures, temperatures, flow rates, power inputs etc.).

Further downstream, turbulent mixing of the vapour and liquid phases ultimately raises the liquid temperature to saturation, and this is the commencement of the saturated boiling region. In contrast to the subcooled boiling region, the vapour and liquid phases in the saturated boiling region are in thermal equilibrium (neglecting the slight superheat of the vapour phase), and the bubbles grow in size and no longer collapse. The heat input in this region is entirely dissipated in producing more voids, whereas the heat input to the subcooled boiling region is dissipated in raising the liquid temperature and producing more voids.

The flow structure in the two-phase region is divided into flow regimes, principally bubble, slug, annular and droplet flow regimes (Tong 1965). Combinations of these basic regimes are possible. The vapour bubbles merge as they move downstream to form slugs of vapour. These slugs may also merge to form larger slugs, until the channel cross-section consists of a vapour core (with droplet entrainment), and liquid at the solid surface. This is termed annular flow. With further heating, the liquid phase at the wall disappears altogether, and is only present as droplets or mist in the vapour core. Ultimately the liquid phase disappears entirely, and only superheated vapour is left (superheat region). The superheat region is neglected in the present analysis, but may be approximately modelled with unit quality (vapour mass fraction) flow conditions.

## 3. ANALYSIS CONSIDERATIONS AND ALTERNATIVE METHODS

The previous description of the boiling channel flow structure gives some indication of the difficulties involved in the development of suitable models. Most analyses solve the partial differential equations for the conservation of mass, energy and momentum in the single phase and two-phase regions of the channel assuming one-dimensional turbulent flow. A detailed mathematical model of the two-phase flow structure requires six conservation equations (one for each phase), plus constitutive equations to define the fluid properties of the system, and mass, energy and momentum transfer relationships at the vapour/liquid boundaries (Bird et al. 1960, Govier and Aziz 1972, Boure et al. 1973, Boure 1975). However, since detailed transfer relationships (laws) are still not available, the use of six conservation equation models is not yet possible, and they are only useful in clarifying the assumptions of existing simplified models (Boure 1975). In recent years, there has been considerable emphasis on the development of mathematically consistent two-phase flow models, particularly for application to thermal non-equilibrium and non-linear flow conditions (limit cycle and acoustic oscillations, rapid depressurisation transients), in which the use of empirical steady state correlations to replace the vapour/liquid transfer laws is suspect.

The traditional methods for analysing the excursive and oscillatory flow stability of boiling channels are schematically summarised in Figure 2. The mass, energy and momentum conservation equations are averaged over the channel flow area, and are spatially integrated by analytical or piecewise methods using constitutive equations to define local values for the fluid properties, heat transfer, subcooled boiling, two-phase friction and slip ratio. The analytical methods are dependent on simplifying assumptions (e.g. invariant fluid properties, homogeneous flow, no slip between vapour and liquid phases, etc.) to enable integration of the conservation equations in the two-phase region of the channel. These assumptions, however, restrict the models to a limited range of applications. The piecewise methods are less restrictive, and are based on the subdivision of the channel into small volume elements and the replacement of the spatial derivatives by their first order finite difference equivalents.

The alternative dynamic models depicted in Figure 2 result from the different methods for integrating the time dependent terms. The most important models are the non-linear time domain (NLTD) and linear frequency domain (LFD) distributed models, in which the time derivative is eliminated respectively by direct numerical integration of the non-linear differential equations, or by small perturbation methods and Laplace transformation of the linear equations for transfer function analysis in the frequency domain. The relative merits of NLTD and LFD models may be assessed from the following observations (see reviews by Neal and Zivi 1965 and Grumbach 1969):

a) Discrepancies between theoretical and experimental flow instability thresholds are primarily caused by inadequate mathematical

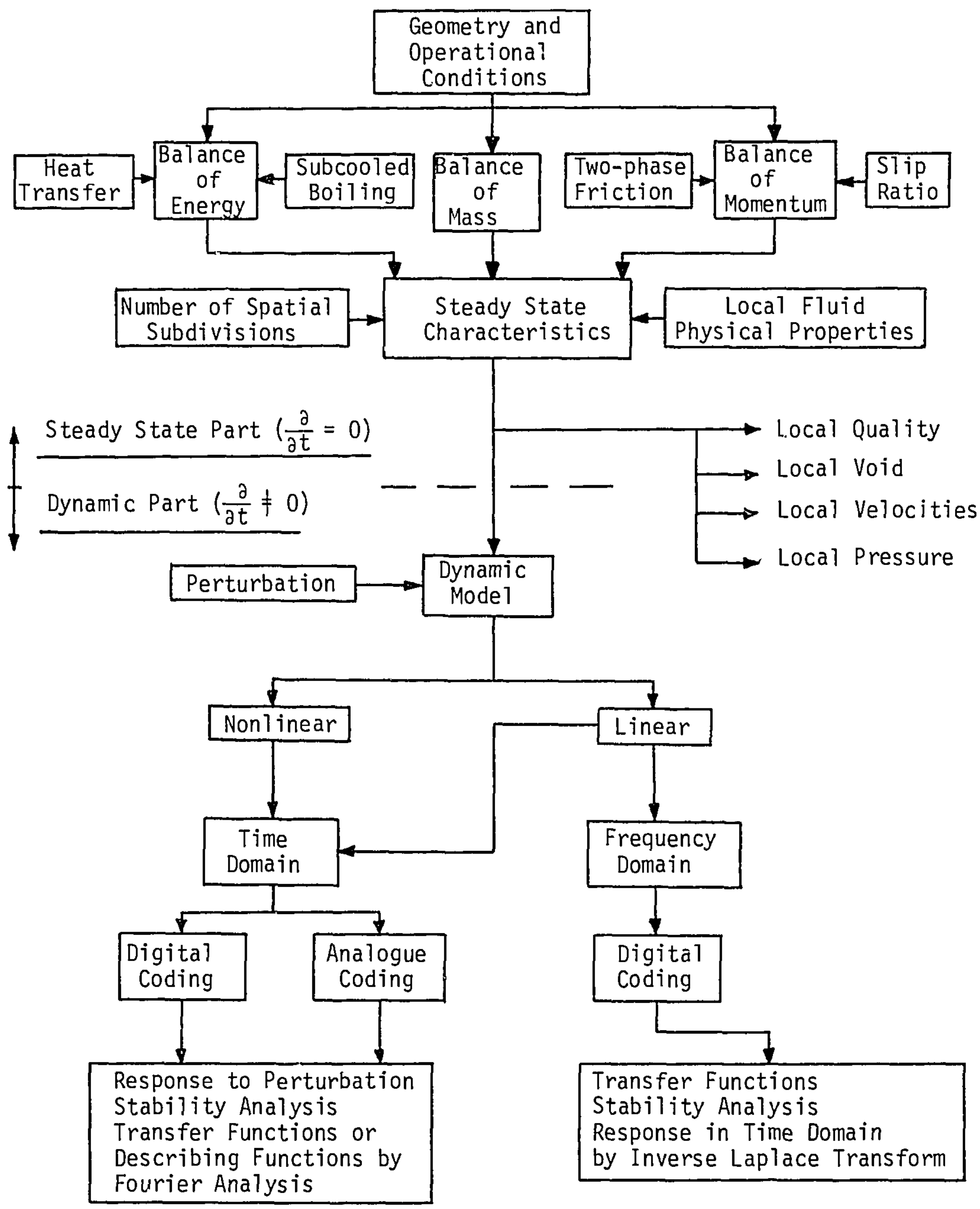


FIGURE 2 - POSSIBLE METHODS FOR BOILING CHANNEL CALCULATIONS

formulations, particularly numerical instabilities in the dynamic calculations. The NLTD models require small time steps to satisfy numerical stability constraints, and take between one and two orders of magnitude longer in computing time than LFD models (Spinks 1972).

b) Discrepancies between theoretical and experimental flow instability thresholds are reduced by matching the steady state characteristics (especially flow rate and/or pressure drop). In some models this can be achieved by adjustment of the coefficients in the empirical correlations.

c) Both models predict the local stability of the boiling channel, and NLTD models are also able to predict the amplitude and period of non-linear limit cycle oscillations beyond the instability threshold. However the empirical correlations are designed to model steady state conditions, and their validity for non-linear dynamic analysis is suspect. The LFD models assume the perturbed variables fluctuate about time invariant mean (steady state) values, and thus small perturbation of an arbitrary function or correlation f(x,y) is linearly related to the steady state by the first order partial differential equation

$$f^{*}(x,y) = \left(\frac{\partial f^{o}}{\partial x^{o}}\right) x^{*} + \left(\frac{\partial f^{o}}{\partial y^{o}}\right) y^{*}$$

where the superscripts (o) and (*) denote respectively the steady state and perturbed variables.

Neal and Zivi (1965) found that the LFD model by Jones (1961) proved to be the most accurate in predicting the flow instability thresholds of experimental data, and for this type of analysis the greater computational efficiency of LFD models is an important consideration. Some NLTD models, however, are able to assess the channel flow stability during start-up and shut-down operation of the plant, and are useful benchmark models for evaluation of non-linear lumped parameter control models.

## 4. CONSERVATION EQUATIONS AND MODEL ASSUMPTIONS

In the present analysis the mass, energy and momentum conservation equations for two-phase flow are solved assuming one-dimensional turbulent flow. The equations are perturbed, linearised and Laplace transformed for frequency domain analysis. The linearised differential equations are spatially integrated by finite difference methods. Constitutive equations define the local fluid properties, heat transfer, friction, subcooled boiling and slip correlations.

The two-phase conservation equations of mass, energy and momentum averaged over the channel flow area are respectively

Mass: $$\frac{\partial}{\partial z} \langle \rho_\ell (1-\alpha) U_\ell + \rho_g \alpha U_g \rangle + \frac{\partial}{\partial t} \langle \rho_\ell (1-\alpha) + \rho_g \alpha \rangle = 0 \qquad (1)$$

Energy: $$\frac{\partial}{\partial z} \langle \rho_\ell (1-\alpha) U_\ell h_\ell + \rho_g \alpha U_g h_g \rangle + \frac{\partial}{\partial t} \langle \rho_\ell (1-\alpha) h_\ell + \rho_g \alpha h_g - \alpha p \rangle = \langle Q \rangle \qquad (2)$$

where $$\langle Q \rangle = -\frac{1}{A} \int_0^R \frac{1}{r} \frac{\partial}{\partial r} (r q_r) \cdot 2\pi r \, dr$$

$$= \frac{2\pi R}{A} q_w = \frac{P_H}{A} q_w \quad \text{(single tube)}$$

$$= \frac{1}{A} \sum_{j=1}^{N} P_{Hj} \, q_{wj} \quad \text{(fuel rod cluster)}$$

and kinetic energy, potential energy, viscous heating, and axial conduction effects are neglected;

Momentum: $$\frac{\partial}{\partial z} \langle \rho_\ell (1-\alpha) U_\ell^2 + \rho_g \alpha U_g^2 \rangle + \frac{\partial}{\partial t} \langle \rho_\ell (1-\alpha) U_\ell + \rho_g \alpha U_g \rangle + K_f \frac{\rho_\ell \langle U_\ell \rangle^2}{2} \phi^2 + \langle \rho_\ell (1-\alpha) + \rho_g \alpha \rangle g \cos\theta = -\frac{\partial}{\partial z} \langle p \rangle \qquad (3)$$

where the single phase friction factor ($K_f$) and the two-phase local friction multiplier ($\phi^2$) are defined in Appendix A.

In the above equations the brackets <-------> denote the cross-section averaging operation

$$\langle F\rangle \quad = \quad F(z,t) \quad = \quad \frac{1}{A}\int_A F(r,z,t)\, dA \tag{4}$$

The product terms in the brackets <-------> cannot be readily determined from experimental data, and are usually assumed to be approximated by the product of the cross-section averaged individual variables, for example,

$$\begin{aligned}\langle \rho_\ell\,(1-\alpha)U_\ell^2 + \rho_g \alpha U_g^2\rangle \quad &= \quad \langle G_\ell U_\ell + G_g U_g\rangle \\ &\approx \quad \langle G_\ell\rangle\langle U_\ell\rangle + \langle G_g\rangle\langle U_g\rangle\end{aligned}$$

where the liquid, vapour and mixture mass fluxes are respectively

$$\left.\begin{aligned}\langle G_\ell\rangle \quad &= \quad \langle \rho_\ell\,(1-\alpha)U_\ell\rangle \quad = \quad \langle (1-x)G\rangle \\ \langle G_g\rangle \quad &= \quad \langle \rho_g\,\alpha\, U_g\rangle \quad = \quad \langle xG\rangle \\ \langle G\rangle \quad &= \quad \langle \rho_\ell\,(1-\alpha)U_\ell + \rho_g \alpha U_g\rangle = \langle G_\ell\rangle + \langle G_g\rangle\end{aligned}\right\} \tag{5}$$

This approximation is reasonable for fully developed turbulent flow in which the radial profiles of the variables are relatively uniform in the central region of the channel.

The conservation equations (1) to (3) can thus be simplified to

<u>Mass</u>: $$\frac{\partial}{\partial z}\{G\} + \frac{\partial}{\partial t}\{\rho_\ell\,(1-\alpha) + \rho_g\alpha\} \quad = \quad 0 \tag{6}$$

<u>Energy</u>: $$\frac{\partial}{\partial z}\{G_\ell h_\ell + G_g h_g\} + \frac{\partial}{\partial t}\{\rho_\ell\,(1-\alpha)h_\ell + \rho_g\alpha h_g - \alpha p\} = Q \tag{7}$$

<u>Momentum</u>: $$\frac{\partial}{\partial z}\{G_\ell U_\ell + G_g U_g\} + \frac{\partial}{\partial t}\{G\} + \frac{K_f}{2}\,\frac{G^2\phi^2}{\rho_\ell} + \{\rho_\ell\,(1-\alpha) + \rho_g\alpha\}\, g \cos\theta \quad = \quad -\frac{\partial p}{\partial z} \tag{8}$$

in which the brackets <----> have been omitted, and the symbols denote cross-section averaged variables, as in the notation in equation (4).

The mixture conservation equations (6) to (8) are solved as follows:

1. the channel variables (pressures, mass fluxes, void fraction, etc.) are perturbed with respect to time, and the product terms linearised (terms higher than first order are neglected);

2. the perturbed variables are transformed into the frequency domain by Laplace transformation,

$$F(z,s) = \tilde{F}(z) = \int_0^{\infty} F^*(z,t)\, e^{-st}\, dt \qquad (9)$$

where $F(z,t) = F^o(z) + F^*(z,t)$, $s$ ($= \sigma + j\omega$) is the complex Laplace operator, and zero initial conditions are assumed;

3. the first order differential equations are integrated spatially over a small space node (axial length $\Delta z$ x channel cross-sectional area) using the forward difference equation

$$\int_0^{\Delta z} \frac{\partial \tilde{F}(z)}{\partial z}\, dz \approx \tilde{F}_{i+1} - \tilde{F}_i \qquad (10)$$

and the trapezoidal rule,

$$\int_0^{\Delta z} \tilde{F}(z)\, dz \approx \frac{\Delta z}{2} (\tilde{F}_{i+1} + \tilde{F}_i) \qquad (11)$$

4. the fluid properties and heat flux at the wall/coolant interface are assumed spatially invariant within the space node, and all fluid properties except the vapour density ($\rho_g$) are assumed time invariant.

## 5. FINITE DIFFERENCE EQUATIONS

In the following analysis the finite difference equations for thermal non-equilibrium two-phase (vapour/liquid) flow are derived. The equations apply to a single space node in the subcooled boiling region of the channel. By specifying appropriate values for certain variables, the same equations are applicable to the single phase liquid, wall void and saturated boiling regions of the channel. The analysis is based on a special form of the energy equation which is derived by manipulation of the mass and energy equations (6), (7) in conjunction with a subcooled boiling liquid enthalpy correlation. The mixture enthalpy is used as the fundamental variable rather than the vapour void fraction, which is usually obtained by solution of a void propagation equation (Zuber et al 1967, Zuber and Staub 1966, Zuber and Staub 1967, Hancox and Nicoll 1971). If the vapour void fraction is used as the fundamental variable then separate finite difference equations are required for the single phase and two-phase regions of the channel, rather than the single set of equations as derived in the present analysis.

5.1 Subcooled Boiling Region Energy Equation

The energy equation (7) may be rewritten as

$$\frac{\partial}{\partial z}\{Gh\} + \frac{\partial}{\partial t}\{\rho_\ell(1-\alpha)\, h_\ell + \rho_g\, \alpha\, h_g\} \quad = \quad Q + \alpha \frac{\partial p}{\partial t} \tag{12}$$

where the liquid and vapour mass fluxes are replaced by their respective equations from (5), and the mixture enthalpy is defined as

$$h \quad = \quad (1-x)h_\ell + x\, h_g \tag{13}$$

The mass equation (6) may be rewritten as

$$\frac{\partial}{\partial z}\{G\} - \frac{\partial}{\partial t}\{\Delta\rho\alpha\} \quad = \quad 0 \tag{14}$$

and substitution in the energy equation (12) yields

$$G\frac{\partial}{\partial z}\{h\} - \Delta\rho\alpha\frac{\partial}{\partial t}\{h\} + \frac{\partial}{\partial t}\{\rho_\ell h_\ell + (\rho_g h_g - \rho_\ell h_\ell + h\Delta\rho)\alpha\}$$

$$= \quad Q + \alpha\frac{\partial p}{\partial t} \tag{15}$$

The vapour void fraction is eliminated from the third term on the left side of (15) by noting that, from (13) and (C.16), Appendix C,

$$\rho_\ell h_\ell + (\rho_g h_g - \rho_\ell h_\ell + h\Delta\rho)\alpha \quad = \quad \rho_\ell\{(1-K_o)h_\ell + K_o h\}$$

and thus (15) becomes

$$G \frac{\partial}{\partial z} \{h\} + (K_o \rho_\ell - \Delta\rho\alpha) \frac{\partial}{\partial t} \{h\} + \rho_\ell \, (1-K_o) \frac{\partial}{\partial t} \{h_\ell\}$$

$$= \quad Q \; + \alpha \; \frac{\partial p}{\partial t} \qquad (16)$$

where the Bankoff factor $K_o$, (C.11) Appendix C, is assumed to be space and time invariant within the space node.

The liquid enthalpy in the subcooled boiling region is related to the mixture enthalpy by either an exponential or a hyperbolic tangent subcooled boiling correlation as follows (Zuber et al 1967, Kroeger and Zuber 1968):

Exponential correlation -

$$h_\ell^+ \quad = \quad \frac{h_\ell - h_o}{h_f - h_o} \quad = \quad 1 - \exp\,(-h^+) \qquad (17)$$

Hyperbolic tangent correlation -

$$h_\ell^+ \quad = \quad \tanh\,(h^+) \qquad (18)$$

where $$h^+ \quad = \quad \frac{h \; - h_o}{h_f - h_o}$$

in which $h_o$ is the liquid enthalpy at the subcooled boiling boundary. Equations (17) and (18) satisfy the boundary conditions

$h_\ell = h_o$ at the subcooled boiling boundary ($z = z_o$), and

$h_\ell = h_f$ at the saturated boiling boundary.

Hence, in equation (16), the liquid enthalpy is related to the mixture enthalpy by

$$\frac{\partial}{\partial t} \{h_\ell\} = \frac{\partial h_\ell^o}{\partial h^o} \; \frac{\partial}{\partial t} \{h\} = \frac{\partial h_\ell^+}{\partial h^+} \; \frac{\partial h}{\partial t} \; = \; F^+ \frac{\partial h}{\partial t} \qquad (19)$$

$$\left.\begin{array}{lll} \text{where} & F^+ = \exp\,(-h^+) & \text{(Exponential correlation)} \\ \text{and} & F^+ = 1 - \tanh^2\,(h^+) & \text{(Tanh correlation)} \end{array}\right\} \qquad (20)$$

Hence equation (16) simplifies to

$$G \frac{\partial h}{\partial z} + \{\rho_\ell \; (K_o + (1-K_o) \; F^+) - \Delta\rho\alpha\} \frac{\partial h}{\partial t} \;\; = \; Q + \alpha \frac{\partial p}{\partial t} \qquad (21)$$

5.2 Subcooled Boiling Region Steady State Equations

Mass flux: Setting the time derivative term in (6) or (14) to zero yields

$$\frac{d}{dz}\{G^o\} = 0 \quad (22)$$

which, on integration, gives

$$G_2^o = G_1^o = G^o \quad \text{(a constant)} \quad (23)$$

Enthalpy: The steady state form of (21) is

$$G^o \frac{d}{dz}\{h^o\} = Q^o \quad (24)$$

which, on integration, gives

$$h_2^o = h_1^o + \frac{Q^o \Delta z}{G^o} \quad (25)$$

The liquid enthalpy $h_\ell^o$ is calculated from the correlations in equations (17) or (18), and the other variables of interest are calculated as follows:

(13) → $$x_2^o = \frac{h_2^o - h_{\ell 2}^o}{h_g - h_{\ell 2}^o} \quad (26)$$

(C.16), Appendix C →

$$\alpha_2^o = \frac{K_o \rho_\ell x_2^o}{\rho_\ell + \Delta\rho \, x_2^o} \quad (27)$$

(5) →
$$\left.\begin{aligned} G_{\ell 2}^o &= (1-x_2^o)\, G_2^o \\ G_{g2}^o &= x_2^o \, G_2^o \\ U_{\ell 2}^o &= \frac{G_{\ell 2}^o}{\rho_\ell (1-\alpha_2^o)} \\ U_{g2}^o &= \frac{G_{g2}^o}{\rho_g^o \, \alpha_2^o} \end{aligned}\right\} \quad (28)$$

Pressure drop: From equation (8)

$$\frac{d}{dz}\left(G_\ell^o U_\ell^o + G_g^o U_g^o\right) + \frac{K_f^o}{2}\,\frac{G^{o2}\,\phi^{o2}}{\rho_\ell} + \left(\rho_\ell\,(1-\alpha^o) + \rho_g^o\,\alpha^o\right) g \cos\theta = -\frac{dp^o}{dz} \qquad (29)$$

and integration gives

$$\Delta p_2^o = p_1^o - p_2^o = \Delta p_{2m}^o + \Delta p_{2f}^o + \Delta p_{2g}^o \qquad (30)$$

where the momentum, friction and gravitational pressure drop components are respectively

$$\left.\begin{aligned}
\Delta p_{2m}^o &= G_{\ell 2}^o\,U_{\ell 2}^o - G_{g2}^o\,U_{g2}^o \\
\Delta p_{2f}^o &= \frac{K_f^o}{2}\,\frac{G_2^{o2}}{\rho_\ell}\int_1^2 \phi^{o^2}\,dz = \Delta p_{1f}^o\,\frac{(\phi_1^{o^2} + \phi_2^{o^2})}{2} \\
\Delta p_{2g}^o &= g\cos\theta\int_1^2 (\rho_\ell - \Delta\rho\alpha^o)\,dz \\
&= \Delta z\,\left\{\rho_\ell - \Delta\rho\,\frac{(\alpha_1^o + \alpha_2^o)}{2}\right\} g\,\cos\theta
\end{aligned}\right\} \qquad (31)$$

5.3 Subcooled Boiling Region Dynamic Equations

Perturbation, linearisation and Laplace transformation of equation (14) yields

$$\frac{d}{dz}\,\{\tilde{G}\} = s\,\{\Delta\rho\tilde{\alpha} - \alpha^o\,\rho_g'\,\tilde{p}\} \qquad (32)$$

The perturbed void fraction $\tilde{\alpha}$ is replaced by the perturbed mixture enthalpy $\tilde{h}$. From (C.18), Appendix C, the perturbed void fraction is

$$\tilde{\alpha} = \frac{1}{X}\,\{\tilde{x} - x^o\,(1-x^o)\,\frac{\rho_g'}{\rho_g^o}\,\tilde{p}\} \qquad (33)$$

and, from equations (14) and (19), the perturbed flow quality in terms of the mixture enthalpy is

$$\tilde{x} = \frac{\left[1 - (1-x^o)\ F^+\right] \tilde{h}}{(h_g - h_\ell^o)} = \frac{\Gamma^o \tilde{h}}{Q^o} \tag{34}$$

where $\Gamma^o$ is a vapour source term, and is given by

$$\Gamma^o = \frac{Q^o}{h_g - h_\ell^o} \left[ 1 - (1-x^o)\ F^+ \right] \tag{35}$$

Hence equation (32) becomes

$$\frac{d}{dz} \left[\tilde{G}\right] = sa\tilde{h} - sb\tilde{p} \tag{36}$$

$$\text{where} \qquad a = \frac{\Delta\rho\ \Gamma^o}{X\ Q^o} = \frac{\Delta\rho}{X(h_g - h_\ell^o)} \left[1 - (1-x^o)F^+\right]$$

$$\text{and} \qquad b = \rho_g' \left[\alpha^o + \frac{\Delta\rho\ x^o(1-x^o)}{X\ \rho_g}\right] \tag{37}$$

Integration of (36) gives

$$\tilde{G}_2 = \tilde{G}_1 + \frac{s\Delta z}{2} \ \{a_1\tilde{h}_1 + a_2\tilde{h}_2 - (b_1+b_2)\ \tilde{p}_1\} \tag{38}$$

Similarly, perturbation, linearisation and Laplace transformation of the energy equation (21) yields

$$G^o \frac{d}{dz} \ \{\tilde{h}\} + cs\tilde{h} = Q^o \left\{ \frac{\tilde{Q}}{Q^o} - \frac{\tilde{G}}{G^o} \right\} + s\alpha^o\tilde{p} \tag{39}$$

which has been simplified using (24), and where

$$c = \rho_\ell \ \{K_o + (1-K_o)\ F^+\} - \Delta\rho\alpha^o \tag{40}$$

From (B.19), Appendix B, and noting that $\tilde{h}_\ell = F^+\tilde{h}$,

$$\frac{\tilde{Q}}{Q^o} = \frac{\tilde{q}_w}{q_w^o} = (1 + \tau_H s)^{-1} \left[\frac{\tilde{Q}_s}{Q_s^o} + b_t\ \tau_H s\ \frac{\tilde{G}}{G_o} - F^+\ \tau_H s\ \frac{\tilde{h}}{\Delta h_w^o}\right] \tag{41}$$

$$\text{where} \qquad \Delta h_w^o = C_{p\ell}\ \Delta T_w^o = C_{p\ell}\ (T_w^o - T_\ell^o)$$

Substitution of (41) in (39) and integrating gives, in conjunction with (38)

$$\tilde{h}_2 = \frac{\left(1-sT_1(s)\right)\tilde{h}_1 + \left(\frac{\Delta h^o}{1+\tau_H s}\right)\frac{\tilde{Q}_s}{Q_s^o} - P(s)\,\frac{\tilde{G}_1}{G^o} + s\bar{T}_p(s)\,\tilde{p}_1}{\{1 + sT_2\,(s)\}} \tag{42}$$

$$\left.\begin{aligned}
\text{where}\quad P(s) &= \Delta h^o \left[\frac{1 + (1-b_t)\,\tau_H s}{1 + \tau_H s}\right] \\
T(s) &= \frac{\Delta z}{2G^o}\left[c + \frac{Q^o F^+ \tau_H}{\Delta h_w^o\,(1+\tau_H s)} + \frac{a\,P(s)}{2}\right] \\
T_p(s) &= \frac{\Delta z}{2G^o}\left[(\alpha_1^o+\alpha_2^o) + \frac{(b_1+b_2)}{2}\,P(s)\right]
\end{aligned}\right\} \tag{43}$$

The perturbed flow quality, void fraction, mass fluxes and velocities are given respectively by:

$$\left.\begin{aligned}
(13) \quad \rightarrow \quad \tilde{x}_2 &= \frac{\{1 - (1-x_2^o)\,F_2^+\}\,\tilde{h}_2}{(h_g - h_{\ell 2}^o)} \\
(\text{C.18}),\ \text{Appendix C} \quad \rightarrow & \\
\tilde{\alpha}_2 &= \frac{1}{X_2}\left[\tilde{x}_2 - x_2^o\,(1-x_2^o)\,\frac{\rho_g'}{\rho_g^o}\,\tilde{p}_1\right] \\
(5) \quad \rightarrow \quad \tilde{G}_{g2} &= x_2^o\,\tilde{G}_2 + G^o\tilde{x}_2 \\
\tilde{G}_{\ell 2} &= \tilde{G}_2 - \tilde{G}_{g2} \\
\tilde{U}_{g2} &= U_{g2}^o\left[\frac{\tilde{G}_{g2}}{G_{g2}^o} - \frac{\tilde{\alpha}_2}{\alpha_2^o} - \frac{\rho_g'}{\rho_g^o}\,\tilde{p}_1\right] \\
\tilde{U}_{\ell 2} &= U_{\ell 2}^o\left[\frac{\tilde{G}_{\ell 2}}{G_{\ell 2}^o} + \frac{\tilde{\alpha}_2}{(1-\alpha_2^o)}\right]
\end{aligned}\right\} \tag{44}$$

where $\tilde{G}_2$ is calculated from (38).

Perturbation, linearisation and Laplace transformation of the momentum equation (8) gives the nodal pressure drop as

$$\Delta\tilde{p}_2 = \Delta\tilde{p}_{2m} + \Delta\tilde{p}_{2f} + \Delta\tilde{p}_{2g} \qquad (45)$$

where the perturbed momentum, friction and gravitational pressure drop components are respectively

<u>Momentum</u>: $$\Delta\tilde{p}_{2m} = \int_1^2 d\left[U_\ell^o\tilde{G}_\ell + G_\ell^o\tilde{U}_\ell + U_g^o\tilde{G}_g + G_g^o\tilde{U}_g\right] + s\int_o^{\Delta z}\tilde{G}\,dz$$

or $$\Delta\tilde{p}_{2m} = \Delta\left[U_\ell^o\tilde{G}_\ell + G_\ell^o\tilde{U}_\ell + U_g^o\tilde{G}_g + G_g^o\tilde{U}_g\right] + \frac{s\Delta z}{2}(\tilde{G}_1+\tilde{G}_2)$$

<u>Friction</u>: $$\Delta\tilde{p}_{2f} = \frac{K_f^o {G^o}^2}{2\rho_\ell}\int_o^{\Delta z}\left[\left(\frac{\tilde{K}_f}{K_f^o} + \frac{2\tilde{G}}{G^o}\right){\phi^o}^2 + \tilde{\phi}^2\right]dz$$

or $$\Delta\tilde{p}_{2f} = \frac{\Delta p_{1f}^o}{2}\left[(2-B_f)\frac{({\phi_1^o}^2\tilde{G}_1 + {\phi_2^o}^2\tilde{G}_2)}{G^o} + (\tilde{\phi}_1^2 + \tilde{\phi}_2^2)\right] \qquad (46)$$

<u>Gravitation</u>:

$$\Delta\tilde{p}_{2g} = \int_o^{\Delta z}\left[\Delta\rho\tilde{\alpha} - \alpha^o\rho_g'\tilde{p}\right] g\,\mathrm{Cos}\,\theta.\,dz$$

or $$\Delta\tilde{p}_{2g} = \frac{1}{2}\left[\Delta\rho\,(\tilde{\alpha}_1+\tilde{\alpha}_2) - (\alpha_1^o+\alpha_2^o)\,\rho_g'\,\tilde{p}_1\right]\Delta z\, g\cos\theta.$$

The perturbed two-phase friction multiplier ($\phi^2$) in equation (46) is calculated from equation (A.13), Appendix A.

5.4 <u>Single Phase Region Equations</u>

Since the single phase liquid region has no vapour, the variables relating to the vapour phase are zero, that is, for the steady state and dynamics

$$\alpha = 0, \quad x = 0$$
$$\text{and} \quad G_g = 0, \quad U_g = 0 \tag{47}$$

The coefficients $F^+$ and $K_o$ in the subcooled boiling region energy equation (21) assume the values

$$F^+ = 1$$
$$\text{and} \quad K_o = 1 \tag{48}$$

With these modifications the subcooled boiling region equations automatically reduce to simpler single phase region equations.

The single phase region equations are also used to model the wall void region. The vapour bubbles attached to the wall act as surface asperities, and are hydrodynamically represented by increasing the relative roughness ratio ($\varepsilon$) in the single phase friction factor equation (A.3), Appendix A. This method, proposed by Staub (1968), results in an increased single phase friction pressure drop component. The equations to calculate the incipience of the wall void region and the relative roughness factors based on vapour bubble height (Romberg 1972) are not considered in the present model.

5.5 Saturated Boiling Region Equations

The temperature of the subcooled liquid ultimately reaches the local saturation temperature, and the fluid properties of the liquid phase are defined by their local saturation values. Of particular importance is the subcooled liquid enthalpy, which becomes

$$h_\ell^o = h_f$$
$$\tilde{h}_\ell = \tilde{h}_f = 0 \tag{49}$$

so that, from equations (17), (18) and (20),

$$F^+ = 0 \tag{50}$$

Equations (49) and (50) assume that the saturated liquid enthalpy $h_f$ is time invariant (Jones 1963), that is, the subcooled liquid enthalpy perturbations propagating through the single phase and subcooled boiling regions are completely attenuated in the saturated boiling region. Hence, perturbations in the mixture enthalpy, equation (13), are solely due to perturbations in the flow quality (x). The subcooled boiling region energy equation (21) and finite difference equations automatically apply to the saturated boiling region with these constraints.

## 6. SECTION BOUNDARY EQUATIONS

The spatial integration of the conservation equations (6) - (8) is performed by dividing a heated channel of arbitrary geometry into a number of sections of constant flow area. These sections are further subdivided into smaller nodes and subnodes to satisfy numerical stability requirements when the finite difference equations derived previously are applied. The boundary between any two sections may represent a localised discontinuity in area and/or obstruction (bend, orifice plate, valve etc.) in the coolant flow path. Boundary coupling equations are required to model the flow conditions due to the obstruction or restriction, and these are obtained by solution of the macroscopic conservation equations (Bird et al 1960, Govier and Aziz 1972). Of particular importance is the two-phase restriction pressure drop, for which a number of models have been developed (Tong 1965, Janssen 1966, Husain and Weisman 1975, Weisman et al 1976).

In the following analysis the macroscopic equations for the conservation of mass and energy are solved for the general case of a section boundary with an abrupt change in cross-sectional area.

### 6.1 Section Boundary Conservation Equations

The boundary interface may represent an abrupt expansion or contraction (Figure 3).

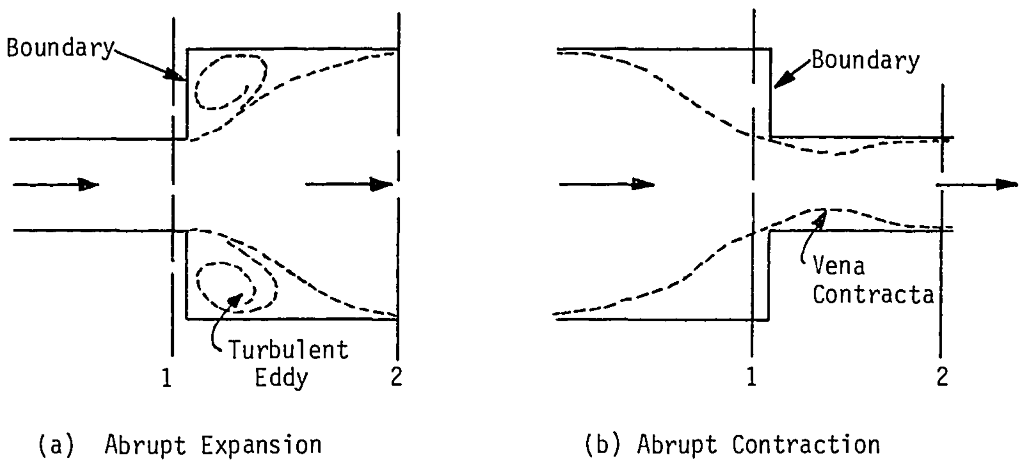


FIGURE 3 - SECTION BOUNDARY WITH AREA CHANGES

The macroscopic mass balance for the small control volume between stations (1) and (2) is, neglecting mass accumulation (Bird et al 1960),

$$\frac{dM}{dt} = W_1 - W_2 = \Delta W = 0 \tag{51}$$

where

$$\left.\begin{aligned} W &= W_\ell + W_g = AG \\ W_\ell &= A_\ell \rho_\ell U_\ell = A(1-\alpha)\rho_\ell U_\ell = AG_\ell = A(1-x)G \\ W_g &= A_g \rho_g U_g = A\alpha\, \rho_g\, U_g = AG_g = AxG \end{aligned}\right\} \tag{52}$$

The convected energy at stations (1) and (2) is, neglecting potential energy,

$$\left.\begin{aligned} E &= W_\ell h_\ell + \tfrac{1}{2} W_\ell U_\ell^2 + W_g h_g + \tfrac{1}{2} W_g U_g^2 \\ &= W \{u + pv_m + e\} \end{aligned}\right\} \tag{53}$$

where

$$\left.\begin{aligned} h &= u + pv_m \\ u &= (1-x)u_\ell + xu_g \\ v_m &= \frac{1}{\rho_m} = v_\ell\,(1-x) + v_g x \\ \rho_m &= \frac{\rho_\ell\,\rho_g}{\rho_g + \Delta\rho\ x} = \frac{1}{v_m} \\ e &= \frac{1}{2}\{\,(1-x)\,U_\ell^2 + x\,U_g^2\,\} \end{aligned}\right\} \qquad (54)$$

The macroscopic energy balance for the small control volume is, neglecting energy accumulation,

$$\frac{dE}{dt} = E_1 - E_2 = \Delta E = 0 \qquad (55)$$

6.2 Steady State Equations

From (51) and (55) the steady state mass and energy equations are respectively

$$W_2^o = W_1^o \qquad (56)$$

$$u_1^o + p_1^o\,v_{m1}^o + e_1^o = u_2^o + p_2^o\,v_{m2}^o + e_2^o \qquad (57)$$

For no phase change ("flashing") across the boundary, the flow quality and mixture specific volume are respectively

$$\left.\begin{aligned} x_2^o &= x_1^o \\ v_{m2}^o &= v_{m1}^o = v_m^o \end{aligned}\right\} \qquad (58)$$

From (52) and (56), the downstream mass flux is

$$G_2^o = \frac{A_1}{A_2}\,G_1^o \qquad (59)$$

and from (27) the void fraction is

$$\alpha_2^o = \frac{K_{o2}\ \rho_\ell\ x_1^o}{\rho_\ell + \Delta\rho\ x_1^o} \tag{60}$$

The other variables (liquid and vapour mass fluxes and velocities) are calculated from equations (28).

From (57) the inlet restriction pressure drop is

$$\Delta p_R^o = (p_1^o - p_2^o) = \rho_m^o \{(e_2^o - e_1^o) + (u_2^o - u_1^o)\} \tag{61}$$

The change in internal energy is due to the irreversible friction loss, and is given by

$$\Delta p_L^o = \rho_m^o\ (u_2^o - u_1^o) = K_R^o\ \frac{G_2^{o^2}\ \phi_R^{o^2}}{2\rho_\ell} \tag{62}$$

where the two-phase friction multiplier is (Beattie 1973)

$$\phi_R^2 = 1 + 1.284\ \{ \frac{\rho_\ell}{\rho_g} - 1 \}\ \ x \tag{63}$$

and $K_R$ is the single phase loss factor for the abrupt expansion or contraction (Bird et al 1960).

The momentum pressure drop component is

$$\begin{aligned} \Delta p_I^o &= \rho_m^o\ (e_2^o - e_1^o) \\ &= \frac{\rho_m^o}{2}\ \{\ (1-x_1^o)(U_{\ell 2}^{o^2} - U_{\ell 1}^{o^2}) + x_1^o\ (U_{g2}^{o^2} - U_{g1}^{o^2})\ \} \end{aligned} \tag{64}$$

and hence equation (61) becomes

$$\Delta p_R^o = \Delta p_I^o + \Delta p_L^o \tag{65}$$

Note that for $A_2 > A_1$ (expansion) there is a deceleration of the coolant flow ($\Delta p_I^o < 0$), and if $|\Delta p_I^o| > |\Delta p_L^o|$ there will be an overall pressure rise ($p_2^o > p_1^o$, $\Delta p_R^o$ is negative). For no area change ($A_2 = A_1$), $\Delta p_I^o$ is zero so that $\Delta p_R^o = \Delta p_L^o$ (e.g. bends, valves, etc.).

6.3 Dynamic Equations

Perturbation, linearisation and Laplace transformation of the mass and energy equations (51) and (53) gives

$$\tilde{W}_2 = \tilde{W}_1 \tag{66}$$

and $$\tilde{u}_1 + v^o_{m1}\tilde{p}_1 + p^o_1\tilde{v}_{m1} + \tilde{e}_1 = \tilde{u}_2 + v^o_{m2}\tilde{p}_2 + p^o_2\tilde{v}_{m2} + \tilde{e}_2 \tag{67}$$

For no flashing, the perturbed values of the flow quality and mixture specific volume are respectively

$$\tilde{x}_2 = \tilde{x}_1$$

and $$\tilde{v}_{m2} = \tilde{v}_{m1} = \tilde{v}_m \tag{68}$$

where, from equation (54),

$$\tilde{v}_m = \left(\frac{\partial v^o_m}{\partial x^o}\right)\tilde{x} + \left(\frac{\partial v^o_m}{\partial \rho^o_g}\right)\tilde{\rho}_g$$

$$= \left(\frac{\Delta\rho}{\rho_\ell \rho^o_g}\right)\tilde{x}_1 - \left(\frac{x^o_1}{\rho^o_g} \quad \frac{\rho'_g}{\rho^o_g}\right)\tilde{p}_1 \tag{69}$$

The perturbed inlet restriction pressure drop is, from equation (67),

$$\Delta\tilde{p}_R = (\tilde{p}_1 - \tilde{p}_2) = \rho^o_m \{(\tilde{u}_2 - \tilde{u}_1) - \Delta p^o_R\, \tilde{v}_m + (\tilde{e}_2 - \tilde{e}_1)\} \tag{70}$$

Now, from equation (62), the loss component of the restriction pressure drop is

$$\Delta p_L = \rho_m (u_2 - u_1) = K_R \frac{G^2_2 \ \phi^2_R}{2\rho_\ell} \tag{71}$$

so that

$$\Delta\tilde{p}_L = \rho_m^o (\tilde{u}_2 - \tilde{u}_1) - \rho_m^o \Delta p_L^o \tilde{v}_m$$

$$= \Delta p_L^o \left[ 2 \frac{\tilde{G}_2}{G_2^o} + \frac{\tilde{\phi}_R^2}{\phi_R^{o2}} \right] \quad (72)$$

where, from equations (54) and (63) respectively,

$$\tilde{\rho}_m = - \rho_m^{o^2} \tilde{v}_m$$

$$(73)$$

and $$\tilde{\phi}_R^2 = (\phi_R^{o^2} - 1) \left[ \frac{\tilde{x}_1}{x_1^o} - \left( \frac{\rho_\ell}{\Delta\rho} \quad \frac{\rho_g'}{\rho_g^o} \right) \tilde{p}_1 \right]$$

Similarly, from equation (64), the inertia component of the restriction pressure drop is

$$\Delta p_I = \rho_m (e_2 - e_1) \quad (74)$$

so that,

$$\Delta\tilde{p}_I = \rho_m^o (\tilde{e}_2 - \tilde{e}_1) - \rho_m^o \Delta p_I^o \tilde{v}_m \quad (75)$$

where, from equation (54),

$$\tilde{e}_i = \frac{1}{2} \{U_{gi}^{o^2} - U_{\ell i}^{o^2}\} \tilde{x}_1 + (1-x_1^o) U_{\ell i}^o \tilde{U}_{\ell i} + x_1^o U_{gi}^o \tilde{U}_{gi} \qquad i=1,2$$

Substitution of equations (72) and (75) in (70) gives

$$\Delta\tilde{p}_R = \Delta\tilde{p}_I + \Delta\tilde{p}_L \quad (76)$$

The perturbed mass flux at station (2), Figure 3, is, from equations (52) and (66),

$$\tilde{G}_2 = \frac{A_1}{A_2} \tilde{G}_1 \quad (77)$$

The perturbed values of the other variables are calculated from equations (44).

These steady state and dynamic equations apply to both the subcooled and saturated boiling regions. The assumption of no flashing across the restriction is more inaccurate for

a) the subcooled boiling region, in which the temperature difference between the subcooled liquid and saturated (or superheated) vapour phases is greater, and

b) large restriction pressure drops ($\Delta p_R$), particularly those resulting in choked flow conditions. The equations automatically reduce to simpler forms for single phase flow ($\alpha$=0, x=0) and constant flow area ($A_2$=$A_1$).

## 7. SUBCOOLED AND SATURATED BOILING BOUNDARIES

The integration of the conservation equations (6) - (8) also requires coupling equations for the interface (boiling boundary) between the single phase and two-phase regions. The interface may denote either a subcooled or saturated boiling boundary depending on whether or not a subcooled boiling region is included in the model. The boundary between the subcooled and saturated boiling regions does not require special coupling equations, since the subcooled boiling region finite difference equations asymptote to the correct limits as defined by equations (49) and (50). The following analysis derives equations for the subcooled boiling boundary, and it is shown how these equations may be modified to model the saturated boiling boundary.

The subcooled boiling boundary (point of net vapour generation) is mathematically denoted by the position where the wall voids become detached from the heated surface. In practice, however, the statistical variations at the heated surface (heat fluxes, surface cavities, etc.) preclude a precise definition of the subcooled boiling position, and thus it is predicted from empirical correlations based on experimental data. Kroeger and Zuber (1968) show that the ability to predict the void fraction in the subcooled boiling region depends on the accurate prediction of the boiling boundary position.

### 7.1 Subcooled Boiling Boundary Correlation

A number of methods have been developed to predict the subcooled boiling boundary position. These include

1. mathematical analyses which attempt to predict the local thermal-hydraulic conditions which cause bubble detachment (Bowring 1962, Levy 1967, Staub 1968), and

2. empirical correlations based on a postulated heat transfer coefficient (Ahmad 1970, Hancox and Nicoll 1971).

The mathematical models are too complicated and difficult for transient studies, and both methods, although agreeing with experimental data for high mass flow rates, give unsatisfactory results at low mass flow rates (Saha and Zuber 1974). Saha and Zuber (1974) postulate that at low mass flow rates the point of net vapour generation is dependent only on the local thermal conditions, and that condensation as the bubbles move away from the heated surface is governed by a diffusion process. They regard this as the 'thermally controlled region' in which the local Nusselt number is the dominant dimensionless parameter. At high mass flow rates the bubbles are detached by viscous shear effects, and they regard this as a 'hydrodynamically controlled' region in which, using Reynolds analogy (Knudsen and Katz 1958), the Stanton number becomes the dominant dimensionless parameter. The Nusselt and Stanton numbers are related by the Peclet number:

$$Nu = Pe \times St \tag{78}$$

where $$Nu = \frac{h_t D_e}{k_\ell}, \quad Pe = \frac{G D_e C_{p\ell}}{k_\ell}, \quad St = \frac{h_t}{G C_{p\ell}} \tag{79}$$

Saha and Zuber plotted the Peclet number versus the Stanton number for a range of experimental data, and obtained (Figure 4) a straight line of slope minus one for Peclet numbers less than 70,000 (thermally controlled region), which implies a constant value for the local Nusselt number. For Peclet numbers greater than 70,000 (hydrodynamically controlled region) the data has a constant Stanton number.

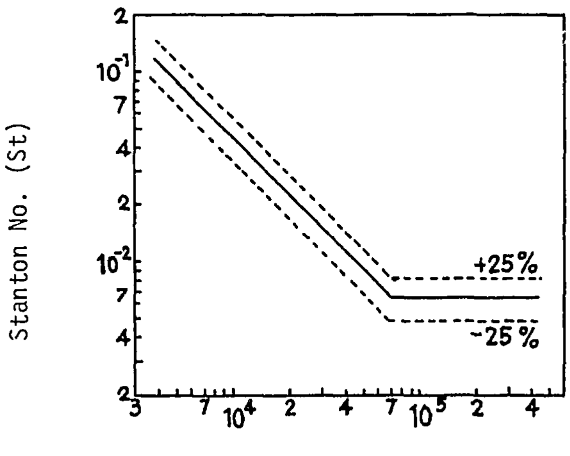


FIGURE 4 - PECLET NUMBER VERSUS STANTON NUMBER AT THE POINT OF NET VAPOUR GENERATION

Their correlation is given by

$$\left.\begin{aligned} Nu &= \frac{h_{to}\, D_e}{k_\ell} = 455, \quad Pe < 70{,}000 \\ St &= \frac{h_{to}}{G\, C_{p\ell}} = 0.0065, \quad Pe > 70{,}000 \end{aligned}\right. \qquad (80)$$

Hence the heat transfer coefficient at the onset of subcooled boiling is

$$\left.\begin{aligned} h_{to} &= \frac{455\ k_\ell}{D_e} \qquad Pe \leqslant 70{,}000 \\ h_{to} &= 0.0065\ G\ C_{p\ell} \qquad Pe > 70{,}000 \end{aligned}\right\} \qquad (81)$$

Their correlation is modified in the present analysis by replacing the equivalent hydraulic diameter ($D_e$) by the equivalent heated diameter ($D_h$), as suggested by Forgan and Whittle (1967) and Kreyger and Essler (1970). This improves the correlation of data by Evangelisti (1969) for annuli, which previously fell outside the ± 25% tolerance band in Figure 4.

The liquid enthalpy for the onset of subcooled boiling is given by

$$h_o = h_f - \frac{C_{p\ell}\, q_{wo}}{h_{to}} \tag{82}$$

and the boiling boundary occurs when

$$h_\ell^o\,(z_o) = h_o \tag{83}$$

### 7.2 Subcooled Boiling Boundary Conservation Equations

The coupling of the steady state and perturbed variables between the single phase and two-phase regions is provided by the equations for the conservation of mass, energy and momentum at the boiling boundary interface (Jones 1963). Some analytical models (Davies and Potter 1967, Spinks 1972) express the perturbed variables in the two-phase region in terms of the movement in the boiling boundary position (perturbed boiling boundary). This method is impractical for finite difference models, since movement of the perturbed boiling boundary across a fixed space node boundary introduces numerical instabilities in the calculation of the perturbed variables in the two-phase region.

The mass, energy and momentum conservation equations at the boiling boundary interface are respectively:

Mass: $$\left[G_\ell\right]' = \left[G_\ell + G_g\right]'' = \left[G\right]'' \tag{84}$$

Energy: $$\left[G_\ell h_\ell\right]' = \left[G_\ell h_\ell + G_g h_g\right]'' = \left[Gh\right]'' \tag{85}$$

Momentum: $$\left[G_\ell U_\ell\right]' = \left[G_\ell U_\ell + G_g U_g\right]'' \tag{86}$$

The superscripts (') and (") refer respectively to conditions upstream and downstream of the boiling boundary interface.

Neglecting the voids attached to the wall, the steady state free-stream void fraction and flow quality are zero at the boiling boundary, that is

$$[\alpha^o]'' = 0, \qquad [x^o]'' = 0 \tag{87}$$

so that $\quad [h_\ell^o]'' = [h^o]'' = [h_\ell^o]' = h_o$

and, $\quad [F^+]'' = 1 \qquad (88)$

Hence it follows that

$$\left.\begin{aligned} (5) &\rightarrow [G_g^o]'' = 0 \ , \\ (84) &\rightarrow [G_\ell^o]'' = [G_\ell^o]' = [G^o]' \\ (86) &\rightarrow [U_\ell^o]'' = [U_\ell^o]' \\ \text{and, implicitly, } & [U_g^o]'' = 0 \end{aligned}\right\} \tag{89}$$

The perturbed, linearised and transformed conservation equations are respectively, from equations (84) - (86):

<u>Mass</u>: $$[\tilde{G}_\ell]' = [\tilde{G}_\ell + \tilde{G}_g]'' = [\tilde{G}]'' \tag{90}$$

<u>Energy</u>: $$[G_\ell^o\tilde{h}_\ell + h_\ell^o\tilde{G}_\ell]' = [G_\ell^o\tilde{h}_\ell + h_\ell^o\tilde{G}_\ell + h_g\tilde{G}_g]'' = [G^o\tilde{h} + h^o\tilde{G}]'' \tag{91}$$

<u>Momentum</u>: $$[G_\ell^o\tilde{U}_\ell + U_\ell^o\tilde{G}_\ell]' = [G_\ell^o\tilde{U}_\ell + U_\ell^o\tilde{G}_\ell + G_g^o\tilde{U}_g + U_g^o\tilde{G}_g]'' \tag{92}$$

From (44) the perturbed flow quality at the boiling boundary is

$$[\tilde{x}]'' = \left[\frac{\{1 - (1-x^o)\ F^+\}\ \tilde{h}}{h_g - h_\ell^o}\right]'' = 0 \tag{93}$$

using equations (87) and (88), and hence it follows that

$$\left.\begin{array}{lllll} (44) \rightarrow & [\tilde{\alpha}]'' & = & 0 & \\ (5) \rightarrow & [\tilde{G}_g]'' & = & 0 & \\ (90) \rightarrow & [\tilde{G}_\ell]'' & = & [\tilde{G}_\ell]' & = [\tilde{G}]' \\ (91) \rightarrow & [\tilde{h}]'' & = & [\tilde{h}_\ell]'' & = [\tilde{h}_\ell]' \\ (92) \rightarrow & [\tilde{U}_\ell]'' & = & [\tilde{U}_\ell]' & \\ \text{and, implicitly,} & [\tilde{U}_g]'' & = & 0 & \end{array}\right\} \quad (94)$$

7.3 Saturated Boiling Boundary

In certain applications the subcooled boiling region may be neglected and the boiling channel hydrodynamics represented by a two region (single phase/saturated two-phase) model. The saturated boiling boundary denotes the position where the bulk liquid temperature reaches saturation. Hence (88) becomes

$$[h_\ell^o]'' = [h_\ell^o]' = h_f \quad (95)$$

The steady state equations (87) and (89) apply as previously for the subcooled boiling boundary, except that the subcooled liquid subscript ($\ell$) is replaced by the saturated liquid subscript (f). Since the saturated liquid enthalpy is time invariant, equations (49), (3.50),

$$[\tilde{h}_f]'' = 0 \quad \text{and} \quad [F^+]'' = 0 \quad (96)$$

at the saturated boiling boundary, and the perturbed flow quality, (93), becomes

$$[\tilde{x}]'' = \frac{[\tilde{h}]''}{h_g - h_f} = \frac{[\tilde{h}_\ell]'}{h_{fg}} \quad (97)$$

Hence,

$$\left.\begin{aligned}
(44) \rightarrow \quad [\tilde{\alpha}]'' &= [\tfrac{\tilde{X}}{X}]'' \\
(5) \rightarrow \quad [\tilde{G}_g]'' &= [G^o\, \tilde{x}]'' \\
(90) \rightarrow \quad [\tilde{G}_f]'' &= [\tilde{G} - \tilde{G}_g]'' \\
(92) \rightarrow \quad [\tilde{U}_f]'' &= \frac{[G^o_\ell \tilde{U}_\ell]' + [U^o_f \tilde{G}_g]''}{[G^o_\ell]'} \\
\text{since, implicitly,} \quad [\tilde{U}_g]' &= 0.
\end{aligned}\right\} \qquad (98)$$

A comparison of the above models shows that the essential difference between the subcooled and saturated boiling boundaries is the transfer of the perturbed energy flux across the boundary. The perturbed energy flux of the upstream liquid phase is transferred entirely to the downstream liquid phase at a subcooled boiling boundary, whereas it is transferred entirely to the downstream vapour phase at a saturated boiling boundary.

## 8. CHANNEL, BYPASS AND PUMP MODELS

A heated channel is usually one component of a larger system, and may be operated

a) in parallel with a large number of channels of similar geometry,

b) in parallel with a large bypass, or

c) in closed circuit with a pump.

The following analysis shows how the finite difference equations derived previously are used to model the total channel. Equations are derived for the bypass and pump to permit analysis of the complete system.

### 8.1 Single Channel Model

The stepwise integration of the conservation equations using the finite difference, spatial boundary and boiling boundary equations yields the local steady state and dynamic conditions along the channel. The steady state calculations are performed first to evaluate the coefficients in the dynamic equations and to obtain, in particular, the overall channel pressure drop, which may be written as

$$\Delta p^o = \Delta p_1^o + \Delta p_2^o \qquad (99)$$

where the single phase and two-phase steady state pressure drops are respectively

$$\left.\begin{aligned} \Delta p_1^o &= \sum_{j=1}^{NSAT-1} \Delta p_{1j}^o + \sum_{k=1}^{N1} \{ \Delta p_{1R}^o \}_k \\ \text{and} \quad \Delta p_2^o &= \sum_{j=NSAT}^{N} \Delta p_{2j}^o + \sum_{k=N1+1}^{NCH} \{ \Delta p_{2R}^o \}_k \end{aligned}\right\} \qquad (100)$$

The nodal pressure drops ($\Delta p_{1j}^o$, $\Delta p_{2j}^o$) have momentum, friction and gravitational components, equations (31). The channel is divided into NCH sections and N sub-nodes (see description of computer program, Section 10), and boiling is assumed to occur at the beginning of sub-node NSAT in section N1. Restriction pressure drops ($\Delta p_{1R}^o$, $\Delta p_{2R}^o$) are evaluated at the beginning of each section in the single phase and two-phase regions of the channel.

The subdivision of the sections into nodes and sub-nodes is particularly important near the boiling boundary, where small node sizes are required to accurately resolve the boundary position and to ensure that the steady state and dynamic calculations in the two-phase region of the channel are numerically stable. The steady state piecewise integration is similar to that used for the dynamic analysis, Figure 5, in which the perturbed variables are replaced by their equivalent steady state values. The top blocks represent the nodal mass and energy conservation equations, and the lower blocks represent the nodal

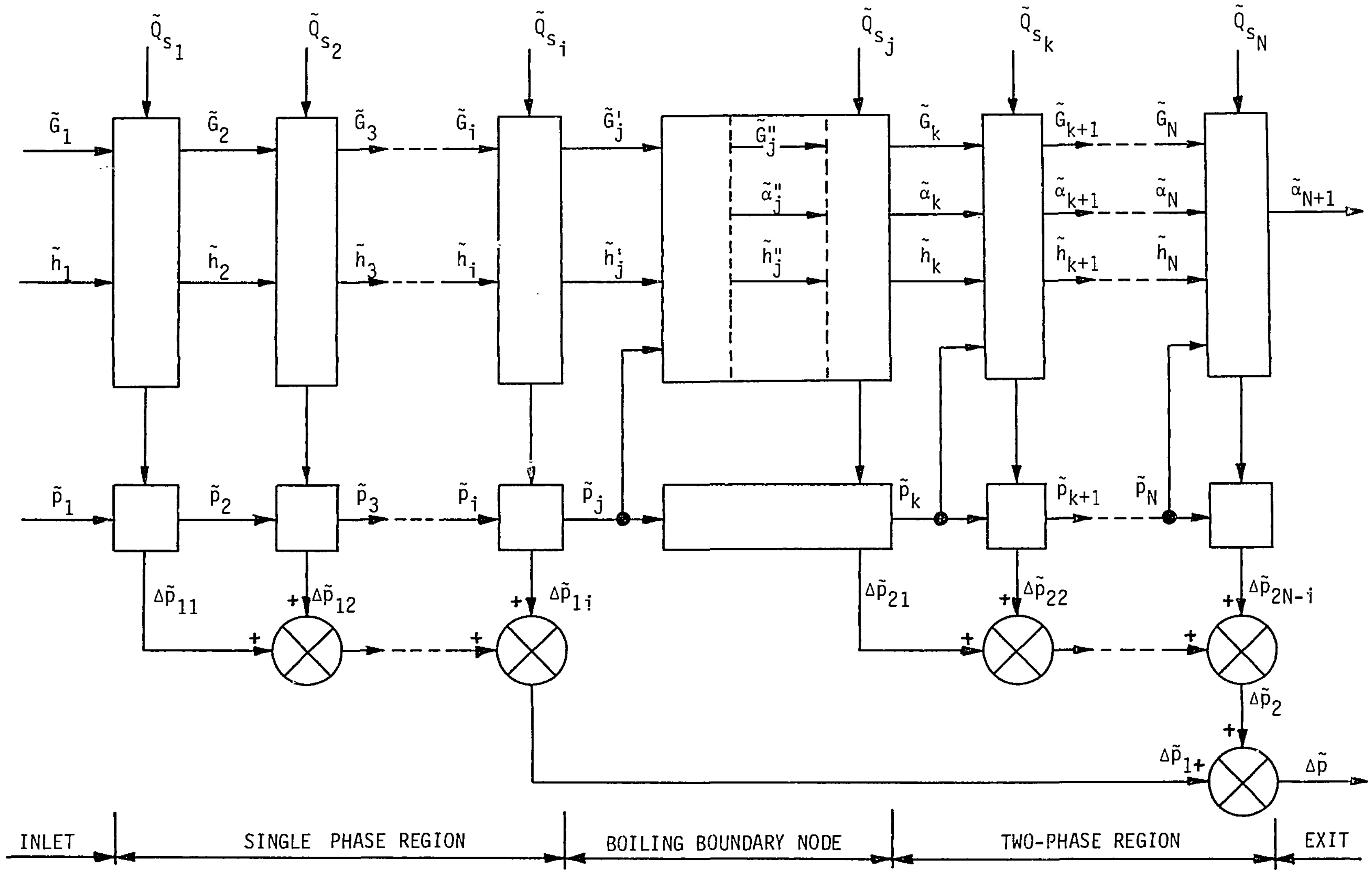


FIGURE 5 - SCHEMATIC DIAGRAM OF BOILING CHANNEL MODEL

momentum conservation equations. Only the transfer of principal variables between the blocks is shown.

In the dynamic analysis, the piecewise calculation of the local perturbed variables is performed for specified values of the complex Laplace operator. The mass flux ($\tilde{G}_1$), enthalpy ($\tilde{h}_1$) and pressure ($\tilde{p}_1$) perturbations at the channel inlet, and the nodal power density ($\tilde{Q}_s$) perturbations of the heat source are the system inputs, and the overall pressure drop perturbation ($\Delta\tilde{p}$) and the perturbed void fraction at the channel exit ($\tilde{\alpha}_{N+1}$) are the outputs. The perturbations at the channel inlet travel through the single phase region to the boiling boundary, where they are transmitted to the two-phase region. The perturbations of the vapour and liquid phases travel to the channel exit, where they interact with the external system.

The overall perturbed pressure drop is obtained by summation of the single phase and two-phase region pressure drops (Figure 5):

$$\Delta\tilde{p} = \Delta\tilde{p}_1 + \Delta\tilde{p}_2 \qquad (101)$$

where $\Delta\tilde{p}_1$ and $\Delta\tilde{p}_2$ are given by equation (100) with the steady state values replaced by their respective perturbed values. From Figure 5, $\Delta\tilde{p}$ (via $\Delta\tilde{p}_1$, $\Delta\tilde{p}_2$) is also linearly related to the inlet mass flux, pressure, enthalpy and average power density by the equation

$$\Delta\tilde{p} = \tilde{H}(\Delta p,G_1)\tilde{G}_1 + \tilde{H}(\Delta p,p_1)\tilde{p}_1 + \tilde{H}(\Delta p,h_1)\tilde{h}_1 + \tilde{H}(\Delta p,\langle Q_s\rangle)\langle\tilde{Q}_s\rangle \qquad (102)$$

where $\tilde{H}(\quad)$ is the frequency dependent transfer function relating the variables in the brackets.

The first term $\tilde{H}(\Delta p,G_1)$ in (102) is the channel 'hydraulic impedance' (Anderson 1970), and is the dominant term in the frequency range of interest (0.1 - 2 Hz). The second term $\tilde{H}(\Delta p,p_1)$ is due to the compressibility of the two-phase region, and is more influential at higher frequencies (above 2 Hz). The third term, $\tilde{H}(\Delta p, h_1)$, results from the transfer of the inlet enthalpy perturbation to the boiling boundary, where it produces a marginal change in the two-phase region perturbed pressure drop. The fourth term, $\tilde{H}(\Delta p, <Q_s>)$, is dependent on the heat source/coolant time constant $\tau_H$, and is usually insignificant at frequencies above 0.1 Hz. Although the latter three terms have a marginal effect on the overall pressure drop $\Delta\tilde{p}$ in most heat transfer systems, they are retained in the present model for general system analysis.

8.2 Bypass Model

A bypass is sometimes placed in parallel with a test channel to control its overall pressure drop (e.g. Collins and Gacesa 1969). The steady state pressure drop of the bypass is given by

$$\Delta p_B^o = \sum_{k=1}^{NB} \{ \Delta p_{Bf}^o + \Delta p_{Bg}^o + \Delta p_{BR}^o \}_k \qquad (103)$$

where NB is the number of bypass sections, and the friction, gravitation and restriction pressure drop components are calculated from equations (31) and (65) for single phase flow.

The perturbed pressure drop of the bypass is given by

$$\Delta\tilde{p}_B = \sum_{k=1}^{NB} \{ \Delta\tilde{p}_{Bm} + \Delta\tilde{p}_{Bf} + \Delta\tilde{p}_{BR} \}_k \qquad (104)$$

where the momentum, friction and restriction pressure drop components are calculated from equations (46) and (76) for single phase flow. The perturbed pressure drop is linearly related to the perturbed mass flux at the bypass inlet by

$$\Delta\tilde{p}_B = \tilde{H}(\Delta p_B, G_B)\, \tilde{G}_{B1} \qquad (105)$$

8.3 Pump Model

The pump operating in closed circuit with a test channel may have variable speed, throttle and/or bypass flow control. The net pump head as seen by the channel is assumed to be approximated by the quadratic equation

$$H_P \;=\; A_P + B_P\, Q_1 + C_P\, Q_1^2 \tag{106}$$

where $Q_1$ is the volumetric flow rate at the inlet to section 1 (pump discharge) of the channel, and is given by

$$Q_1 \;=\; \frac{A_1\, G_1}{\rho_{\ell 1}} \tag{107}$$

The pressure rise across the pump is given by

$$\begin{aligned} -\Delta p_P \;&=\; H_P\, \rho_{\ell 1}\, g \\ &=\; \{A_P + B_P\, Q_1 + C_P\, Q_1^2\}\, \rho_{\ell 1}\, g \;. \end{aligned} \tag{108}$$

Equation (108) gives the steady state pressure differential across the pump by insertion of the appropriate steady state values. Perturbation linearisation and Laplace transformation of (108) yields

$$\begin{aligned} -\Delta \tilde{p}_P \;&=\; \{B_P + 2C_P\, Q_1^o\}\;\; A_1\, g\, \tilde{G}_1 \\ &=\; \tilde{H}(\Delta p_P, G_1)\; \tilde{G}_1 \end{aligned} \tag{109}$$

where $\tilde{H}(\Delta p_P, G_1) \;=\; \{B_P + 2C_P\, Q_1^o\}\;\; A_1\, g$ (110)

9. BOUNDARY CONDITIONS AND STABILITY CRITERIA

The analysis of the flow stability in parallel channel, channel/bypass and closed loop systems is performed by consideration of the mass and momentum exchange between the sub-systems (channel, bypass, pump), together with appropriate boundary conditions based on assumptions regarding the overall system behaviour. In this section, the stability criteria for each type of system are derived.

9.1 Parallel Channel Stability

For N heated channels connected in parallel between common headers, the total inlet mass flow rate is

$$W_T = \sum_{n=1}^{N} W_n \tag{111}$$

and the overall pressure drop across all channels is

$$\Delta p = \Delta p_n , \qquad n = 1,N \tag{112}$$

The mass and momentum equations (111) and (112) apply to both the steady state and dynamic behaviour of the system. At the onset of self-sustained oscillations in the coolant flow through a particular channel (n), flow oscillations are induced in the adjacent stable channels as per (111), and this redistribution is assumed to result in no change in the system pressure differential (or net pump head $\Delta p$) and, consequently, the pressure drop across the nth channel ($\Delta p_n$). Thus, the (linear) 'instability threshold' boundary condition for the parallel channel system is

$$\Delta p(f_{oo}) = \Delta p_n (f_{oo}) = 0 \tag{113}$$

where $f_{oo}$ is the frequency of the self-sustained oscillations (subscript (oo) = fundamental mode, (01) = first harmonic, etc.).

Dividing equation (101) by the perturbed mass flux at the channel inlet and invoking (113) results in the parallel channel stability criterion

$$\tilde{H}_{oo}(\Delta p,G_1) = \tilde{H}_{oo}(\Delta p_1,G_1) + \tilde{H}_{oo}(\Delta p_2,G_1) > 0$$

that is, instability threshold occurs when

$$\tilde{R}_{oo}(\Delta p,G_1) = 0$$

and

$$\tilde{I}_{oo}(\Delta p,G_1) = 0 \tag{114}$$

where the single phase, two-phase and overall hydraulic impedance functions are respectively

$$\left.\begin{aligned} \Delta\tilde{p}_1 &= \tilde{H}(\Delta p_1,\ G_1)\ \tilde{G}_1 \\ \Delta\tilde{p}_2 &= \tilde{H}(\Delta p_2,\ G_1)\ \tilde{G}_1 \\ \Delta\tilde{p} &= \tilde{H}(\Delta p,\ G_1)\ G_1 \end{aligned}\right\} \qquad (115)$$

$\tilde{R}(\Delta p, G_1)$ and $\tilde{I}(\Delta p, G_1)$ are the real and imaginary components of $\tilde{H}(\Delta p, G_1)$, and the subscript (oo) denotes the frequency $f_{oo}$ in equation (113). Equation (114) neglects the influence of the other terms in equation (101), and is consistent with most hydrodynamic models (Jones 1961, Davies and Potter 1967, Takahashi and Shindo 1971, Spinks 1972, Yadigaroglu and Bergles 1972).

When $\tilde{H}(\Delta p, G_1)$ is plotted on an Argand diagram, the channel stability is defined by the locus in the clockwise direction as follows:

a) the channel is stable if the locus intersects the positive real axis, $\tilde{R}(\Delta p, G_1) > 0$, resulting in no encirclement of the origin;

b) the channel is at the instability threshold if the locus passes through the origin, $\tilde{R}(\Delta p, G_1) = 0$;

c) the channel is unstable if the locus intersects the negative real axis, $\tilde{R}(\Delta p, G_1) < 0$, resulting in an encirclement of the origin.

The locus of the hydraulic impedance function $\tilde{H}(\Delta p, G_1)$ also has the following important characteristics:

1) $\tilde{H}(\Delta p, G_1)$ has no poles, only zeros (see equation (46), Spinks 1972) and thus $\tilde{H}(\Delta p, G_1) \rightarrow j\infty$ as $f \rightarrow \infty$;

2) the number of encirclements of the origin is indicative of the number of unstable modes (fundamental and higher mode instabilities, Yadigaroglu and Bergles 1972);

3) the 'margin to instability' is given by the intercept of the positive real axis (= $\tilde{R}_c(\Delta p, G_1)$) at the crossover frequency $f_c$;

4) a negative zero frequency value of $\tilde{H}(\Delta p, G_1)$, that is $\tilde{R}_o(\Delta p, G_1) < 0$, indicates an unstable steady state (excursive or Ledinegg flow instability, see Section 9.4);

5) for a given frequency ($f_n$) the vector $\tilde{H}_k(\Delta p, G_1)$ is the resultant of the single phase and two-phase region vectors $\tilde{H}_k(\Delta p_1, G_1)$ and $\tilde{H}_k(\Delta p_2, G_1)$, which, in turn, are vector sums of their respective perturbed pressure drop components.

The latter point is illustrated by the simplified block diagram of the boiling channel model given in Figure 6, and is important in diagnosing the inherent mechanisms tending to drive the channel unstable. The single phase region impedance function $\tilde{H}(\Delta p_1, G_1)$ has orthogonal resistive (friction and restriction) and inductive (inertia) components in the positive real and imaginary directions respectively, and is mostly stabilising. The two-phase region impedance function $\tilde{H}(\Delta p_2, G_1)$ has vector components whose phase relationships are dependent on the vapour transit time through the two-phase region, and which have a destabilising influence on the channel hydrodynamics. The magnitudes and phase angles of dominant destabilising vector components (usually two-phase friction and restriction) can be evaluated by alteration of the channel dimensions, operating conditions, correlation coefficients, etc., and gives important information for design assessment studies. It can be seen from Figure 6 that the boundary condition (113) is satisfied when the perturbed two-phase pressure drop ($\Delta\tilde{p}_2$) lags the perturbed single phase pressure drop ($\Delta\tilde{p}_1$) by $180^o$.

The block diagram in Figure 6 can be readily manipulated into a closed loop feedback diagram to permit application of conventional control theory. For example, Davies and Potter (1967) manipulate their analytical equations to formulate a feedback model with the single phase region dynamics in the forward loop, and the two-phase region dynamics in the feedback loop. Channel stability is determined by

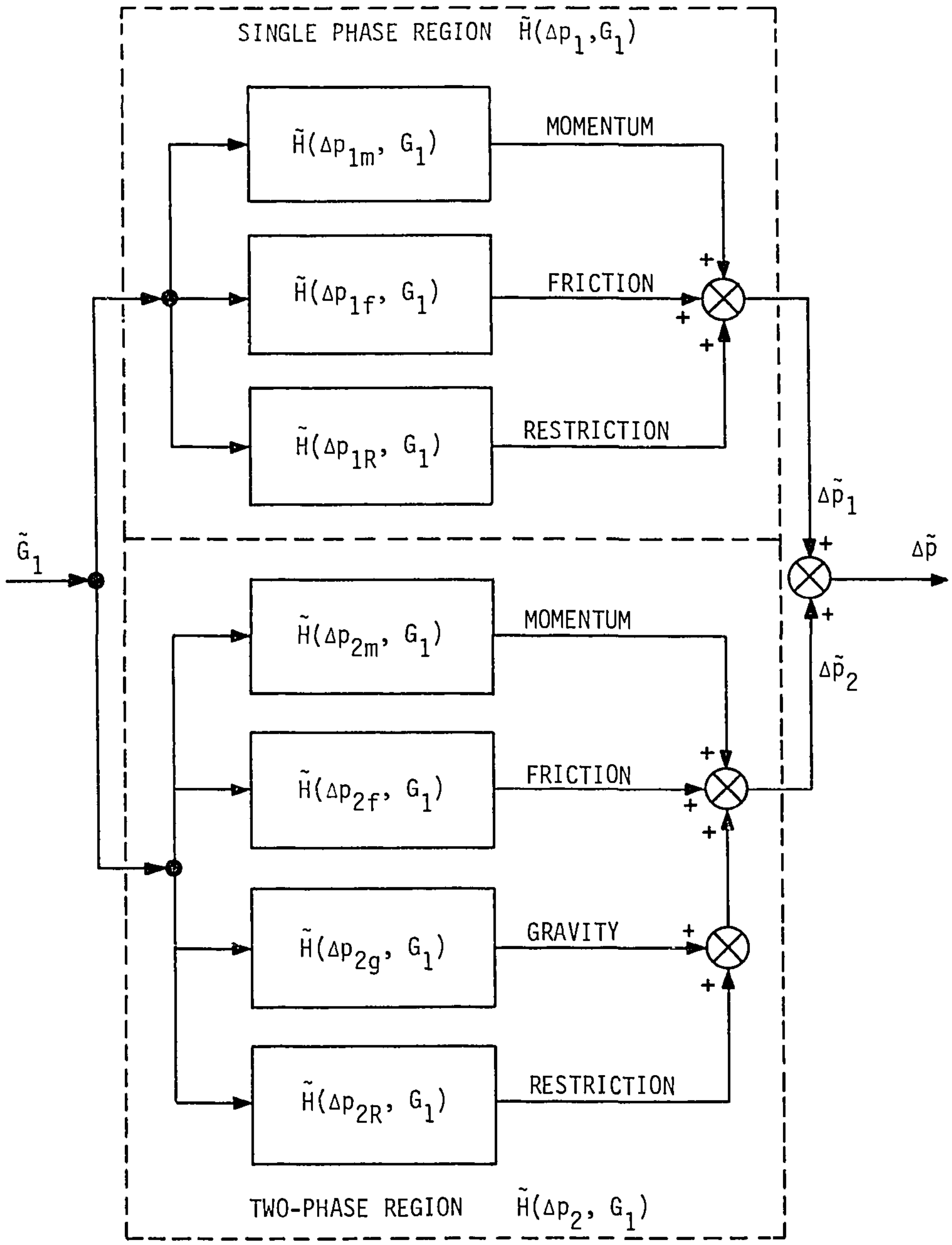


FIGURE 6 - SIMPLIFIED BLOCK DIAGRAM OF BOILING CHANNEL MODEL

applying the Nyquist stability criterion to the open loop transfer function

$$\frac{\Delta\tilde{p}_2}{\Delta\tilde{p}_1} = \tilde{H}(G_1,\Delta p_1)\ \tilde{H}(\Delta p_2,G_1) \geqslant (-1,0) \qquad (116)$$

using the same boundary condition (113) as the present model. Jones (1961) manipulated his hydrodynamic equations to obtain a feedback model with inlet pressure and mass flux perturbations as the input and output respectively, and the pressure perturbation at the boiling boundary ($\tilde{p}_0$) as the output of the feedback loop. Channel stability is determined by applying the Nyquist stability criterion to the open loop transfer function

$$\frac{\tilde{p}_0}{\Delta\tilde{p}_1} = \tilde{H}(G_1,\Delta p_1)\ \tilde{H}(p_0,G_1) \geqslant (-1,0) \qquad (117)$$

and results from the boundary condition that both the inlet and exit pressure perturbations are assumed to be zero, which is a particular solution of the boundary condition (113).

A major advantage of the present model is that the hydraulic impedance function $\tilde{H}(\Delta p,G_1)$ is defined in terms of measurable variables $(\tilde{G}_1,\Delta\tilde{p})$, and can be applied to system identification studies of experimental data from a test channel (e.g. Romberg and Rees 1975). By comparison, the feedback models (116) and (117) have the disadvantage that the perturbed variables $\Delta\tilde{p}_1$, $\Delta\tilde{p}_2$ and $\tilde{p}_0$ are non-measurable, since they are a function of an experimentally indeterminate boiling boundary position.

9.2 <u>Channel/Bypass Stability</u>

The bypass connected in parallel with a heated channel is designed to simulate the other (N-1) heated channels. For this configuration the mass equation (111) becomes

$$W_1 + W_B = W_T \qquad (118)$$

and the momentum equation (112) becomes

$$\Delta p = \Delta p_B \tag{119}$$

If it is assumed that hydrodynamic interaction is between the channel and bypass only, that is, perturbations in the external system are negligible, then the dynamic boundary conditions are

$$\tilde{W}_1 + \tilde{W}_B = 0$$

or $$A_1\tilde{G}_1 + A_{B1}\tilde{G}_{B1} = 0 \tag{120}$$

and $$\Delta p\ (f_{oo}) = \Delta p_B\ (f_{oo}) \tag{121}$$

From (105) and (120) the bypass pressure drop perturbation is

$$\Delta\tilde{p}_B = \tilde{H}(\Delta p_B, G_{B1})\ \tilde{G}_{B1} = -\tilde{H}(\Delta p_B, G_1)\ \tilde{G}_1 \tag{122}$$

Substitution of (115) and (122) in (121) results in the channel/bypass stability criterion

$$\tilde{H}_{oo}(\Delta p, G_1) + \tilde{H}_{oo}(\Delta p_B, G_1) \geqslant 0 \tag{123}$$

that is, for the channel/bypass system to be stable the locus of equation (123) on an Argand diagram must not encircle the origin. A block diagram representation of the channel/bypass system is given in Figure 7.

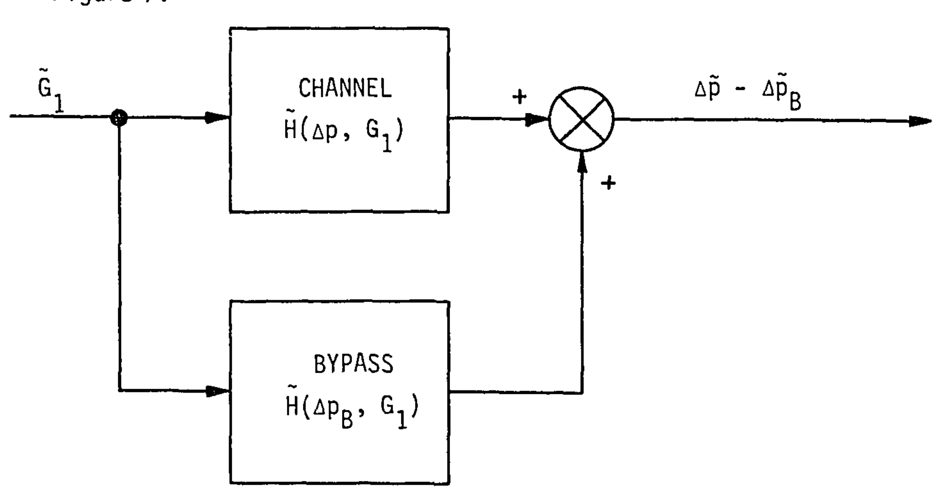


FIGURE 7 - BLOCK DIAGRAM OF CHANNEL/BYPASS SYSTEM

The bypass hydraulic impedance, $\tilde{H}(\Delta p_B, G_1)$, has single phase resistance and inertia components only, and has a stabilising effect on the channel flow. This was investigated experimentally by Collins and Gacesa (1969) and theoretically by Carver (1969), who showed that the threshold power (TP) for the onset of flow oscillations decreased asymptotically to the parallel channel ('infinite' bypass) threshold power when plotted as a function of the bypass ratio ($W_B/W$). Mathematically this means that, for large bypass ratio, in the frequency range of interest

$$\tilde{H}(\Delta p_B, G_1) \rightarrow 0 \tag{124}$$

and the channel/bypass stability criterion (123) converges to the parallel channel stability criterion (114).

9.3 Closed Loop Stability

For a closed loop system in which a channel is in series with a pump, summation of the pressure drops around the circuit results in the momentum boundary condition

$$\begin{aligned} \Delta p - \Delta p_P &= 0 \\ \text{or} \quad \Delta p(f_{oo}) - \Delta p_P(f_{oo}) &= 0 \end{aligned} \tag{125}$$

which is the same as the channel/bypass conditions (119) and (121) respectively. However, implicit in the boundary conditions (125) is the assumption that the channel exit and pump suction inlet conditions are separated by a large dispersive volume (e.g. steam drum), which decouples the input and output pressure perturbations in the frequency range of interest.

Substitution of equations (109) and (115) in (125) yields the "loop" stability criterion

$$\tilde{H}_{oo}(\Delta p, G_1) + \tilde{H}_{oo}(\Delta p_P, G_1) \geqslant 0 \tag{126}$$

From equation (110), the pump hydraulic impedance, $\tilde{H}(\Delta p_P, G_1)$, adds a single phase resistance to the channel hydraulic impedance, $\tilde{H}(\Delta p, G_1)$, and is stabilising. If the pump characteristic is fairly 'flat' ($B_P, C_P = 0$), or the system has 'natural circulation' flow due to a net gravitational head between inlet and outlet, the boundary condition (125) reduces to the parallel channel boundary condition (113).

9.4 Steady State Stability Criteria

The parallel channel, channel/bypass and closed loop boundary conditions (112), (119) and (125) must also be satisfied in the steady state,

i.e.
$$\Delta p^o = \Delta p_s^o \tag{127}$$

where $\Delta p_s^o$ is the net (supply) differential pressure imposed across the channel. Flow excursions (Ledinegg instabilities) occur when the channel pressure drop-flow characteristic has a negative slope region in which

$$\frac{\partial \Delta p^o}{\partial G_1^o} \leqslant \frac{\partial \Delta p_s^o}{\partial G_1^o} \tag{128}$$

Equation (128) can be replaced by the zero frequency transfer function equation

$$\tilde{H}_0(\Delta p, G_1) \leqslant \tilde{H}_0(\Delta p_s, G_1) \tag{129}$$

for the channel to be statically unstable, where

$$\left.\begin{aligned} \tilde{H}_0(\Delta p_s, G_1) &= 0 && \text{(parallel channel)} \\ &= -\tilde{H}_0(\Delta p_B, G_1) && \text{(bypass)} \\ &= -\tilde{H}_0(\Delta p_P, G_1) && \text{(pump)} \end{aligned}\right\} \tag{130}$$

As noted in Section 9.1, flow excursions occur when the resultant real vector of the zero frequency transfer functions in equations (129) and (130) is negative or zero.

## 10. DESCRIPTION OF COMPUTER PROGRAM (LOCO)

The finite difference equations derived in the previous sections have been incorporated in a digital computer program (LOCO - a Linearised model for analysing the Onset of Coolant Oscillations and frequency response of boiling channels), which performs the numerical calculations. This section describes the overall logic of the LOCO code. A complete listing of the code is given in Appendix D.

### 10.1 Program Data Input and Options

The hydraulic circuit between inlet and outlet headers is divided into an arbitrary number of sections (NCH $\leq$ 40), and may optionally consist of an inlet region (ND > 0), a channel (or fuelled) region (NC > 0) and a riser region (NR > 0). The total number of sections is

$$NCH = ND + NC + NR \leq 40 \qquad (131)$$

The geometry and operating data required for each section are specified by comment cards at the beginning of the program, and are listed in Appendix D. Each section has uniform flow area and power input or output. Total condensation of the two-phase flow is not permitted since no condensing boundary has been included in the present model. The two-phase slip correlation and friction multiplier coefficients are specified for each section, and may be varied between sections to account for changes in flow regime.

The program control parameters specify the various options available.

a) Bypass (NB) - the bypass is divided into NB sections; for no bypass NB = 0.

b) Flow rate (NDROP) - NDROP = 0: the channel pressure drop is calculated for a specified flow rate (W kg/s); NDROP = 1: the flow rate is calculated for a specified pressure drop (PDROP kPa).

c) Subcooled boiling (NOSUB) - the liquid enthalpy in the subcooled boiling region is modelled using an exponential correlation (NOSUB = 1) or a hyperbolic tangent correlation (NOSUB = 2), equations (17), (18) respectively; subcooled boiling is neglected if NOSUB = 0.

d) Hydrodynamics (NDYN) - the program may be used for steady state calculations only (NDYN = 0), or steady state and transient calculations (NDYN > 0); the perturbed inputs (inlet mass flux, pressure, enthalpy and average power density) may be frequency independent (white noise, NDYN = 1) for stability calculations, frequency dependent and real (NDYN = 2) for frequency response calculations, or frequency dependent and complex (NDYN = 3) for multivariate spectral calculations.

e) Perturbed pressure drop components - these give information on the mechanisms tending to drive the channel unstable, and are calculated for

i) specified frequencies (CFREQ(N), N=1, NCFREQ) when 0 < NCFREQ < 10;

ii) the initial frequency (FREQ) when the number of frequencies NF = 1;

iii) the 'crossover' frequency calculated by the program at which the polar plot of the perturbed pressure drop ($\Delta\tilde{p}$) crosses the real axis in moving from the negative to positive imaginary half plane.

The print options (NPRINT), plot options (NPLOT), and fluid property options (NCARDS) are input device options as specified by the comment cards listed in Appendix D.

10.2 Program Operation

The LOCO program calculates the steady state and transient variables (mass fluxes, void fraction, component pressure drops etc.) for each space node in the channel as shown in the overall flow chart given in Figure 8. The MAIN subprogram reads and writes the input

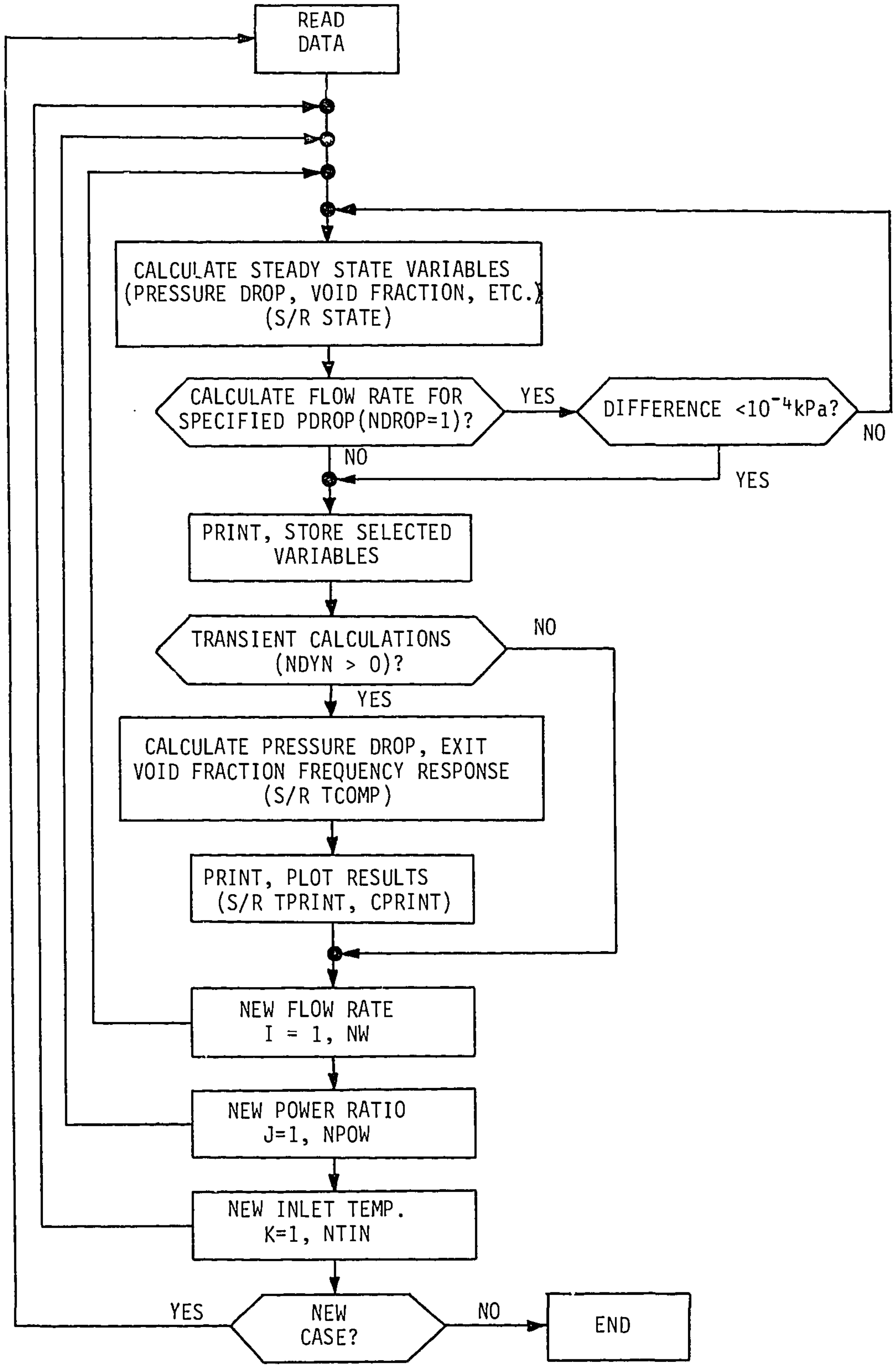


FIGURE 8 - 'LOCO' PROGRAM OVERALL FLOWCHART

data, converts the fluid properties to consistent units (subroutine TABLES), and transfers control to an executive subprogram (subroutine EXEC). This subroutine initialises the channel operating conditions (coolant inlet temperature, power input mass flow rate) and calls subroutine STATE for calculation of the channel steady state variables. These may be determined for a specified flow rate (NDROP = 0, W kg/s) or a specified pressure drop (NDROP = 1, PDROP kPa). In the latter case PDROP is specified as data input, or is calculated by the program if there is a bypass (NB > 0, subroutine BYPASS). The difference (PDIFF) between the calculated pressure drop (PTOT) and PDROP is tested for a change in sign, and if this occurs, a regula falsi iteration procedure is used to calculate the mass flow rate (W) for the next repetitive calculation. The iteration is terminated when |PDIFF| < $10^{-4}$ kPa. If no sign change in PDIFF has occurred, the mass flow rate is incremented or decremented (DW kg/s) and a new PTOT (and PDROP if NB > 0) is calculated. The program prints W, PTOT, PDROP and PDIFF for each calculation, and terminates after NW flow rate steps if no sign change in PDIFF has occurred (NDYN is set to zero). Selected steady state variables are printed (subroutine STATE) for each node (NPRINT = 0) or section (NPRINT > 0) for the specified or calculated mass flow rate.

The program then proceeds to the transient calculations (if NDYN > 0) and calls subroutine TFUNCN, which edits the perturbed inputs (subroutine DYNIN) read in as data and calculates the value of the Laplace operator (s) for each frequency (FREQ(J), J = 1, NF). Subroutine TCOMP is called at each frequency step to compute the channel pressure drop and exit void fraction frequency response. The channel pressure drop is modified by the perturbed pressure drop of the bypass (NB > 0) or pump. TFUNCN stores this information and tests whether the resultant perturbed pressure drop value has crossed the real axis of the polar plot. If so, the subprogram calculates the crossover frequency by a regula falsi iteration procedure, and the value is stored, together with the single phase and two-phase perturbed pressure drop components. After completing the frequency calculations (J = NF), the channel pressure drop and exit void fraction frequency response values are printed (subroutine TPRINT, 0 $\leqslant$ NPRINT $\leqslant$ 3) and plotted (subroutine NORGRA, 0 $\leqslant$ NPRINT $\leqslant$ 2). This is followed by a printout of the single phase and two-phase perturbed pressure drop components of the calculated crossover frequencies, and the component frequencies (CFREQ(N), N = 1, NCFREQ) read in as data.

A list of the LOCO code subprograms and their respective functions is given in Appendix E. Spatial integration and default procedures are described in more detail in the following sections.

### 10.3 Spatial Integration Procedures

The NCH channel sections (131) are further subdivided by the program to ensure that the finite difference integration is numerically stable. In this respect, the spatial resolution of the subcooled or saturated boiling boundaries is particularly important. The shift in the boiling boundary position for changes in an operating variable (flow rate, power input etc.) must be continuous (or as smooth as possible), otherwise the steady state and, more particularly, the transient variables exhibit numerical instabilities.

The subdivision of the channel sections is performed in subroutine STATE, and the number of nodes (NODE) and subnodes (NBOIL) in each section is stored (COMMON/STATIC/··) and transferred to subroutine TCOMP, where it is used in the transient calculations. The steps in the spatial integration procedure are as follows:

a) the sections in the single phase region are initially divided into 5 nodes (NODE = 5) and 1 subnode (NBOIL = 1);

b) for each section in the single phase region, the program performs a heat balance based on the fluid conditions at the section inlet;

c) if the section power input is 0.80 times the power required to boil the coolant, the number of section nodes (NODE) is calculated by

$$\text{NODE} = \text{DZ(K)/0.50} + 1 < 50 \qquad (132)$$

where DZ(K) is the Kth section length (cm);

d) for each node, another heat balance is performed, and if the nodal power input is 0.90 times the power required to boil the coolant, the node is subdivided into NBOIL subnodes, where

$$\text{NBOIL} = \text{DZ(K)/NODE/0.10} + 1 \qquad (133)$$

e) the boiling boundary is shifted to the beginning of the Ith subnode (labelled NSAT) where boiling occurs;

f) after the boiling boundary position has been calculated, the number of nodes and subnodes are respectively

$$\begin{aligned} \text{NODE} &= 5 \\ \text{and} \quad \text{NBOIL} &= \text{(NODES-I)/NODE/(NCH-K+1)} + 1 \end{aligned} \qquad (134)$$

where the maximum number of subnodes has been set at 600. (NODES <=600).

This procedure is designed to yield numerically stable results, but care must be exercised in deciding how the channel is sectioned, particularly in regions of high power input (channel region) or large pressure drop (valves, restrictions, etc.). The accuracy of the numerical calculation may be tested by increasing the number of sections in these regions and noting the change in numerical results for key variables (e.g. boiling boundary position, channel pressure drop, exit void fraction) in the steady state and transient calculations.

10.4 Abnormal Termination Procedures

Statements have been incorporated in subroutine STATE which will terminate program execution when

a) the static pressure at the exit of a subnode, P(I+1), is less than the minimum saturation pressure, PRESS(1), in the fluid property tables;

b) sufficient heat is removed from a section to cause condensation of the two-phase mixture.

The first case only applies when |NCARDS|>0. The subroutine prints the variables in the subnode where (a) applies, and returns control to subroutine EXEC, which proceeds to the next case or terminates execution.

In the second case the steady state calculation continues, but no transient calculations are performed (NDYN is set to zero). The present version of the LOCO code does not include a model for the condensation boundary.

## 11. SAMPLE TEST CASE

The transfer function of a test channel is calculated to demonstrate how the LOCO code may be used to assess its flow stability.

### 11.1 Test Channel

The test channel is connected between headers at the inlet and outlet, and consists of an inlet pipe with a venturi flowmeter, a heated section made of Pyrex glass tube with a concentric electric heater rod, and a glass riser section. The principal dimensions of the test channel are given in Appendix F. Details of the test channel instrumentation and hydrodynamic experimental results are given in the references by Romberg (1978) and Romberg and Rees (1980).

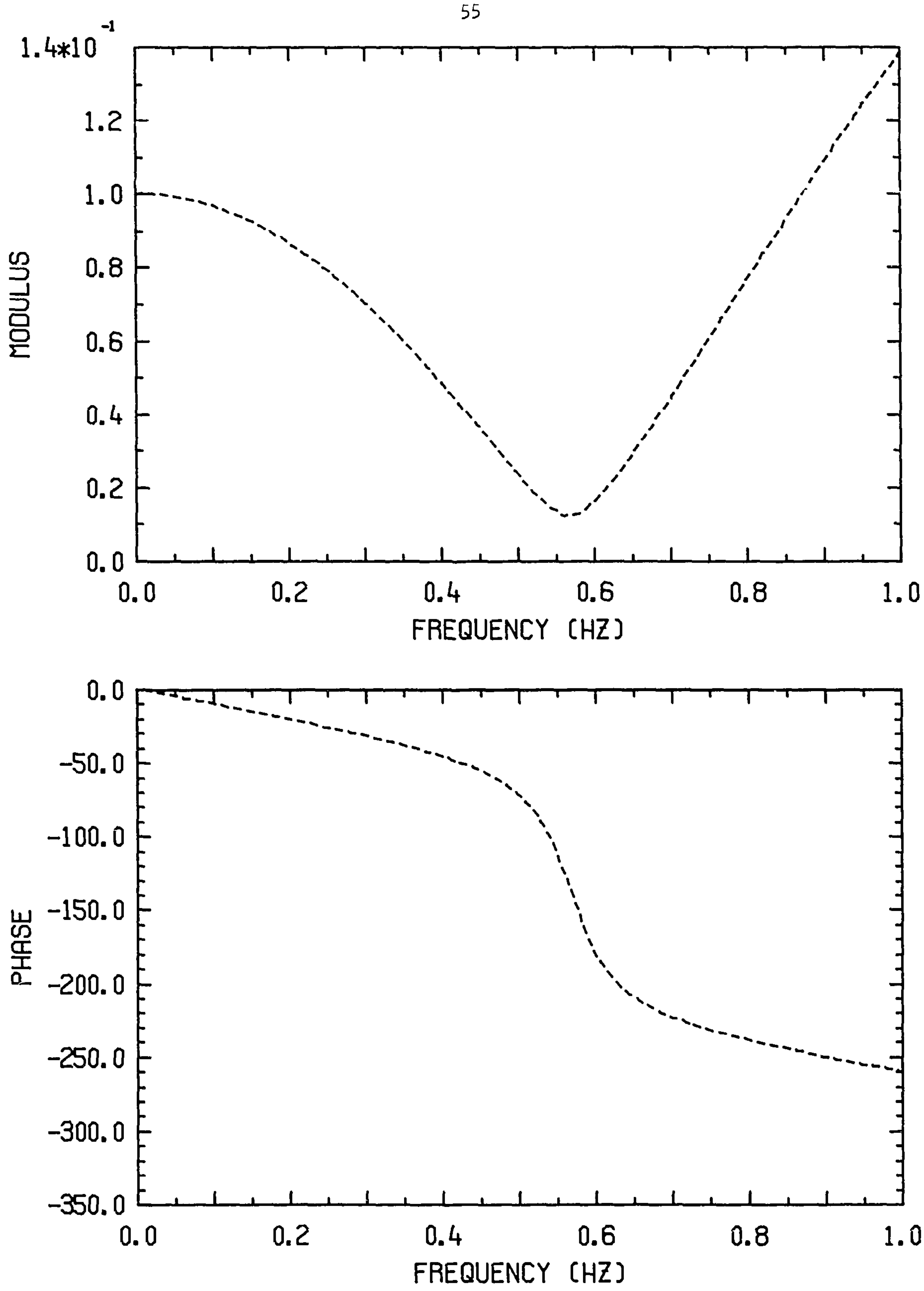


FIGURE 9 - FLOW - PRESSURE DROP TRANSFER FUNCTION

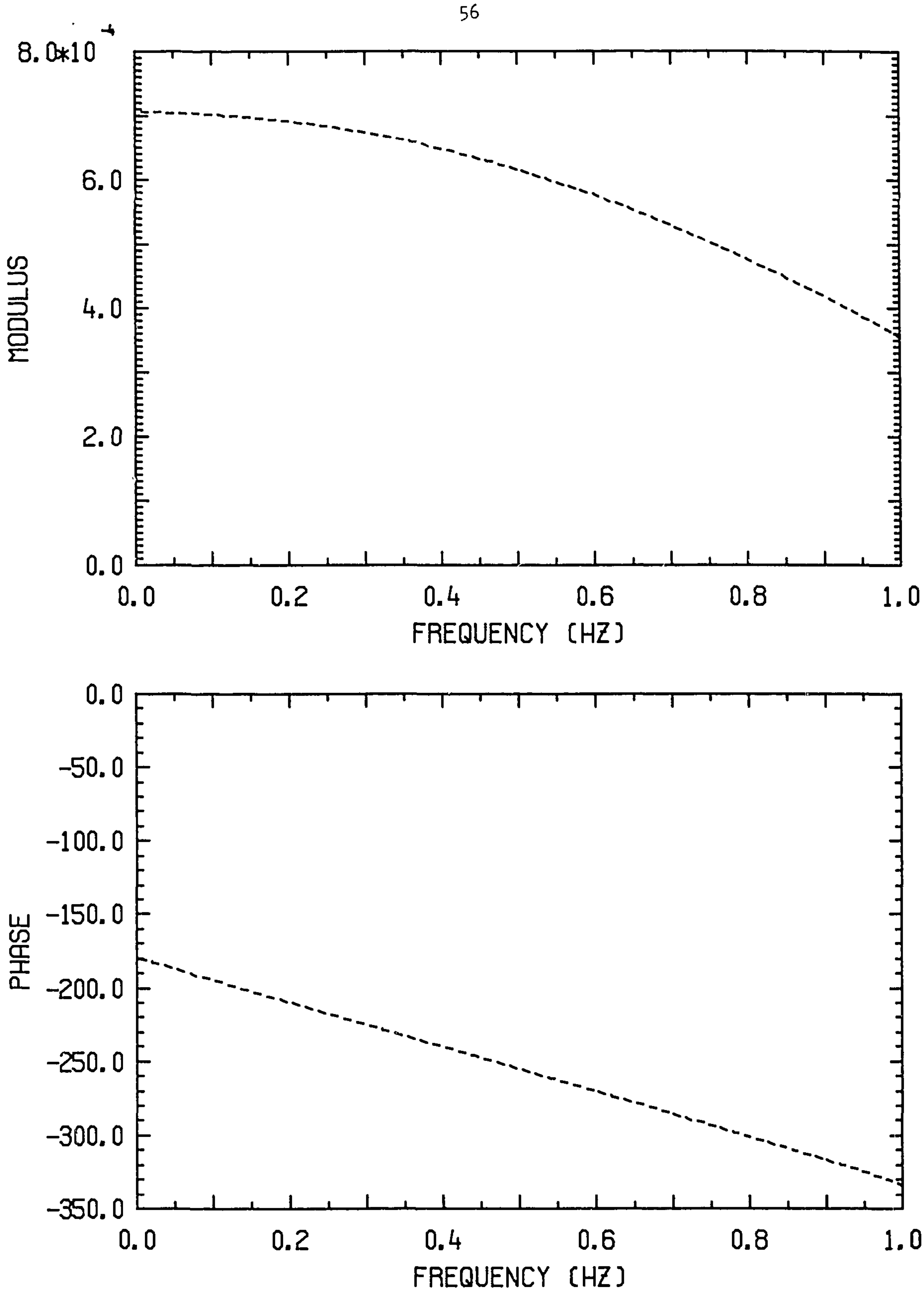


FIGURE 10 - FLOW - EXIT VOID FRACTION TRANSFER FUNCTION

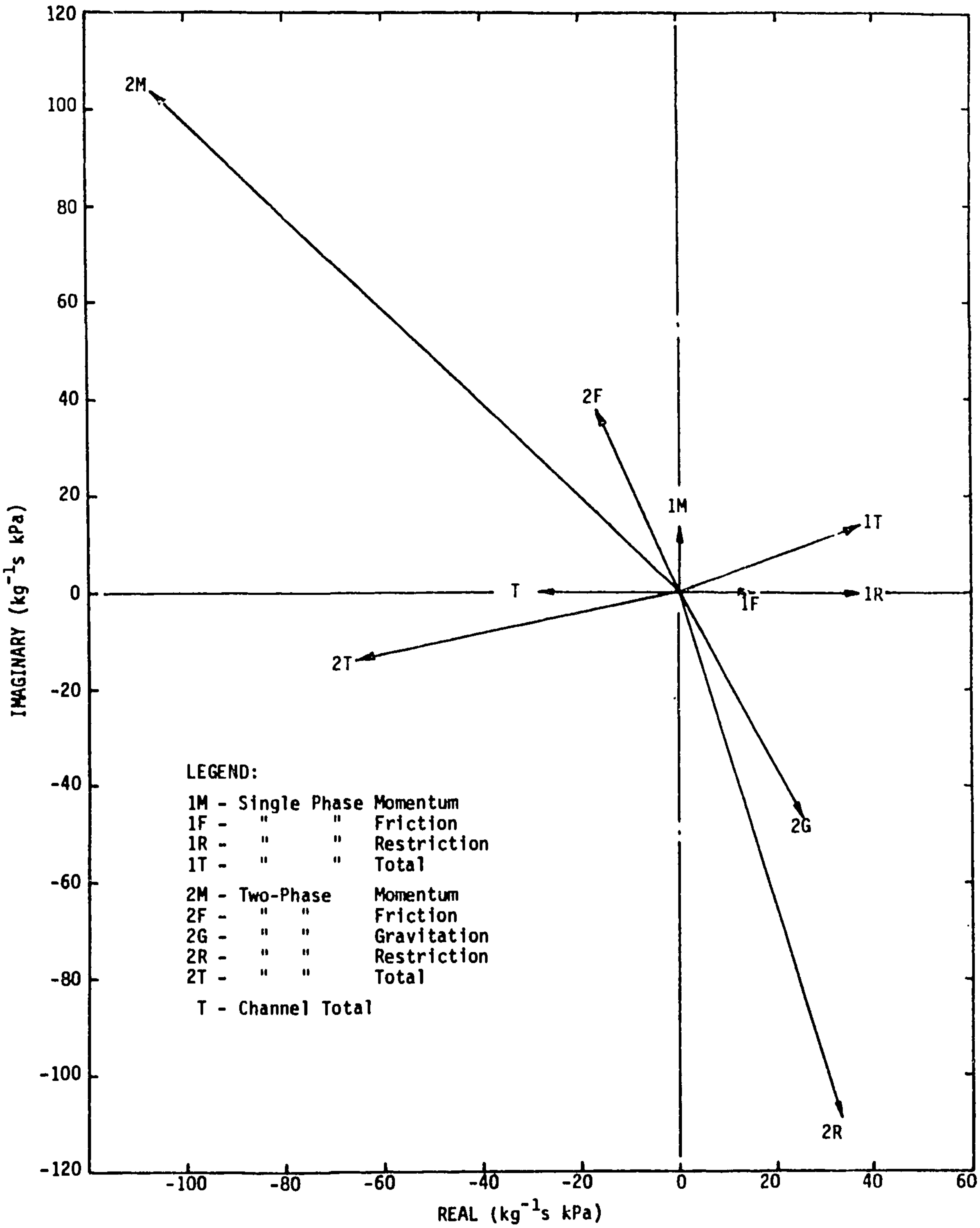


FIGURE 11 - VECTOR DIAGRAM OF TRANSFER FUNCTION COMPONENTS (1.84 kW)
(Crossover frequency = 0.595 Hz)

## 11.2 LOCO Results

A printout of the computer program input data is given in Appendix G. The inlet flow-pressure drop and inlet flow-exit void fraction transfer functions are plotted in Figures 9 and 10 respectively. The phase values of the inlet flow-pressure drop transfer function (hydraulic impedance) show that there is an encirclement of the origin, and thus, as discussed in Section 9.1, the channel is unstable. The code automatically prints the transfer function components ac which it crosses the real axis, and these are plotted in Figure 11. The resultant vector (T) is to the left of the origin, which confirms that the channel is operating beyond the flow stability threshold.

Frequency response results, and their comparison with spectral estimates computed from the hydrodynamic measurements, are presented in the source references.

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## NOMENCLATURE

| Symbol | Meaning | Units |
|---|---|---|
| $A$ | flow area or cross-sectional area | $m^2$ |
| $A_p$ | equation (152) | m |
| $a$ | equation (A.11) | - |
| $a$ | equation (37) | $kg^2\ J^{-1}\ m^{-3}$ |
| $a_t$ | equation (B.8) | $W\ m^{-2}\ {}^oC^{-1}$ |
| $B_f$ | equation (A.9a) | - |
| $B_p$ | equation (152) | $m^{-2}\ s$ |
| $b$ | equation (A.11) | - |
| $b$ | equation (37) | $m^{-2}\ s^{-2}$ |
| $b_t$ | equation (B.8) | - |
| $C_o$ | distribution parameter (C.6) | - |
| $C_p$ | equation (106) | $m^{-5}\ s^2$ |
| $C$ | specific heat | $J\ kg^{-1}\ {}^oC^{-1}$ |
| $c$ | equation (A.11) | - |
| $c$ | equation (40) | $kg\ m^{-3}$ |
| $D_e$ | equivalent hydraulic diameter (A.6) | m |
| $D_h$ | equivalent heated diameter = $4A/P_h$ | m |
| $E$ | total energy per unit time (53) | W |
| $E_{HC}$ | heat source/cladding thermal resistance (B.9) | - |
| $e$ | mixture specific kinetic energy (54) | $m^2\ s^{-2}$ |
| $\tilde{F},\tilde{F}(z)$ | arbitrary perturbed, transformed variable (13) | - |
| $F^+$ | subcooled boiling region correlation (20) | - |
| $f$ | single phase friction factor (A.2) | - |
| $G$ | mass flux | $kg\ m^{-2}\ s^{-1}$ |
| $g$ | gravitational acceleration | $m\ s^{-2}$ |
| $\tilde{H}(y,x)$ | transfer function between x (input), y (output) | - |
| $H_p$ | pump head (106) | m |

| Symbol | Meaning | Units |
|---|---|---|
| $h$ | specific enthalpy | $J\ kg^{-1}$ |
| $h_t$ | heat transfer coefficient (B.8) | $W\ m^{-2}\ {}^{o}C^{-1}$ |
| $h^+$ | dimensionless specific enthalpy (18) | - |
| $J$ | mixture volumetric flux (C.4) | $m\ s^{-1}$ |
| $K_f$ | single phase friction loss factor (A.5) | $m^{-1}$ |
| $K_o$ | Bankoff factor (C.11) | - |
| $K_R$ | single phase restriction loss factor | - |
| $k$ | thermal conductivity | $W\ m^{-1}\ {}^{o}C^{-1}$ |
| Nu | Nusselt number (79) | - |
| $P$ | surface perimeter | m |
| $\tilde{P}$ | transfer function (43) | $m^{-1}$ |
| Pe | Peclet number (79) | - |
| $p$ | static pressure | Pa |
| $Q$ | power density | $W\ m^{-3}$ |
| $q$ | heat flux | $W\ m^{-2}$ |
| Re | Reynolds number (A.7) | - |
| $r$ | radius vector | m |
| $S$ | Slip ratio | - |
| St | Stanton number (79) | - |
| $s$ | Laplace transform operator | $s^{-1}$ |
| $T$ | temperature | ${}^{o}C$ |
| $\tilde{T}$ | transfer function (43) | s |
| $\tilde{T}_p$ | transfer function (43) | $kg^{-1}\ m^3 s$ |
| $t$ | time | s |
| $U$ | velocity | $m\ s^{-1}$ |
| $\Delta U_g$ | vapour drift velocity (C.5) | $m\ s^{-1}$ |
| $u$ | specific internal energy | $J\ kg^{-1}$ |
| $V$ | weighted mean vapour drift velocity (C.12) | $m\ s^{-1}$ |
| $v$ | specific volume | $m^3\ kg^{-1}$ |

| Symbol | Meaning | Units |
|---|---|---|
| W | mass flow | kg $s^{-1}$ |
| X | equation (C.19) | - |
| x | flow quality | - |
| z | axial coordinate | m |

Greek Symbols

| | | |
|---|---|---|
| $\alpha$ | void fraction | - |
| $\Gamma$ | vapour source term (35) | kg $m^{-3}$ $s^{-1}$ |
| $\Delta$ | difference operator | - |
| $\varepsilon$ | relative roughness ratio | - |
| $\theta$ | angle of inclination to vertical | - |
| $\mu$ | dynamic viscosity | Pa s |
| $\rho$ | density | kg $m^{-3}$ |
| $\sigma$ | real component of Laplace operator | $s^{-1}$ |
| $\tau$ | shear stress | Pa |
| $\tau$ | time constant | s |
| $\omega$ | angular frequency | $s^{-1}$ |

Subscripts

| | |
|---|---|
| B | bypass |
| C | cladding |
| H | heat source |
| I | restriction inertia |
| L | restriction loss |
| P | pump |
| R | restriction total |
| T | total |
| f | saturated liquid; friction component |
| g | saturated vapour; gravitational component |
| h | heated dimension or variable |

| Symbol | Meaning | Units |
|---|---|---|
| $\ell$ | subcooled liquid | |
| m | mixture; momentum component | |
| p | pressure | |
| r | radial component | |
| s | source | |
| w | wall; wetted surface | |
| 0 | subcooled boiling boundary | |
| 1 | space node inlet; channel inlet; single phase | |
| 2 | space node outlet; two-phase | |

Superscripts

| | | |
|---|---|---|
| ~ | Laplace transformed variable; tensor | |
| o | steady state variable | |
| ' | upstream of boiling boundary | |
| " | downstream of boiling boundary | |

# APPENDIX A.

## SINGLE PHASE FRICTION FACTOR AND TWO-PHASE MULTIPLIER CORRELATIONS

### A1. Single Phase Friction Factor

Integration of the momentum conservation equation (3) over the flow area requires evaluation of the shear stress integral

$$\frac{1}{A}\int_A \frac{1}{r}\frac{\partial}{\partial r}(r\,\bar{\tau}_{rz})\,dA = \frac{1}{A}\int_0^R \frac{1}{r}\frac{\partial}{\partial r}(r\,\bar{\tau}_{rz})\,2\pi r dr$$

$$= \frac{2\pi R}{A}\tau_w = \frac{P_w}{A}\tau_w \quad \text{(round tubes)}$$

$$= \frac{1}{A}\sum_{j=1}^{N} P_{wj}\,\tau_{wj} \quad \text{(annuli, rod clusters)} \qquad \text{(A1)}$$

The wall shear stress ($\tau_w$) is related to the single phase friction factor (f) by

$$\tau_w = f\,\frac{\rho_\ell \langle U_\ell\rangle^2}{2} \qquad \text{(A2)}$$

where f is a function of the single phase Reynolds number (Re) and the relative roughness ratio ($\varepsilon$) of the channel walls, and is given by the Colebrook equation (Knudsen and Katz 1958)

$$\frac{1}{\sqrt{f}} = 4\log\left[\frac{Re\sqrt{f}}{\varepsilon\,Re\sqrt{f} + 4.67}\right] + 2.28 \qquad \text{(A3)}$$

From (A1) and (A2) the single phase pressure gradient is

$$\frac{\partial p_{1f}}{\partial z} = K_f\,\frac{\rho_\ell \langle U_\ell\rangle^2}{2} = K_f\,\frac{G^2}{2\rho_\ell} \qquad \text{(A4)}$$

in which the single phase friction loss factor is

$$K_f = \frac{P_w f}{A} = \frac{4f}{D_e} \qquad \text{(A5)}$$

where $D_e$ is the equivalent hydraulic diameter:

$$D_e = \frac{4 \text{ x flow area}}{\text{wetted perimeter}} = \frac{4A}{P_w} \qquad (A6)$$

A2. Transient Single Phase Friction Factor

From (A5) the perturbed and transformed friction loss factor is

$$\tilde{K}_f = \frac{4}{D_e} \tilde{f} = \frac{4}{D_e} \left( \frac{\partial f^o}{\partial Re^o} \right) \tilde{Re}$$

$$= \frac{4}{D_e} Re^o \left( \frac{\partial f^o}{\partial Re^o} \right) \frac{\tilde{G}}{G^o} \qquad (A7)$$

where $Re = \frac{G D_e}{\mu_\ell}$ and $G = \rho_\ell \langle U_\ell \rangle$

From (A3) $$\frac{\partial f^o}{\partial Re^o} = - \left[ \frac{2m}{m + B\ Re^o} \right] \frac{f^o}{Re^o} \qquad (A8)$$

where $$m = \frac{4 \times 4.67}{\ell n\ 10} = 8.11262 \qquad (A8a)$$

and $$B = \varepsilon + \frac{4.67}{Re^o \sqrt{f^o}} \qquad (A8b)$$

Substitution of (A8) in (A7) gives

$$\frac{\tilde{K}_f}{K_f^o} = - B_f \frac{\tilde{G}}{G^o} \qquad (A9)$$

where $$B_f = \frac{2m}{m + B\ Re^o} \qquad (A9a)$$

A3. Local Two-phase Friction Multiplier

The two-phase friction pressure gradient is expressed as a function of the single phase pressure gradient by

$$\frac{\partial p_{2f}}{\partial z} = \frac{\partial p_{1f}}{\partial z} \phi^2 \qquad (A10)$$

where $\phi^2$ is the local two-phase friction multiplier, and is given by the correlation (Beattie 1973)

$$\phi^2 = 1 + a\left[\left(\frac{\rho_\ell}{\rho_g} - 1\right) x\right]^b G^c \qquad \text{(A11)}$$

In the single phase region $\phi^2=1$, and for homogeneous two-phase flow $a=1$, $b=1$ and $c=0$.

A4. Transient Two-phase Friction Multiplier

From (A3.11) the perturbed two-phase friction multiplier is

$$\tilde{\phi}^2 = \left(\frac{\partial \phi^{o^2}}{\partial x^o}\right)\tilde{x} + \left(\frac{\partial \phi^{o^2}}{\partial G^o}\right)\tilde{G} + \left(\frac{\partial \phi^{o^2}}{\partial \rho_g^o}\right)\tilde{\rho}_g \qquad \text{(A12)}$$

that is,

$$\tilde{\phi}^2 = (\phi^{o^2} - 1)\left[b\left(\frac{\tilde{x}}{x^o} - \frac{\rho_\ell}{\Delta\rho}\frac{\rho_g'}{\rho_g^o}\tilde{p}\right) + c\,\frac{\tilde{G}}{G^o}\right] \qquad \text{(A13)}$$

# APPENDIX B

## HEAT SOURCE/COOLANT HEAT TRANSFER

### B1. Heat Source Cladding Equations

Neglecting axial conduction and the temperature dependence of the material properties, the heat source energy equation for an arbitrary space node is

$$\rho_H \, C_H \frac{\partial}{\partial t} \; [T_H(r,t)] \; + \frac{1}{r} \, \frac{\partial}{\partial r} \; [r \, q_r \, (r,t)] \; = Q_s \, (r,t) \qquad \text{(B1)}$$

The energy equation for the adjacent cladding is

$$\rho_c \, C_c \frac{\partial}{\partial t} \; [T_c(r,t)] \; + \frac{1}{r} \, \frac{\partial}{\partial r} \; [r \, q_r \, (r,t)] \; = 0 \qquad \text{(B2)}$$

Integration of (B1) and (B2) over their respective cross-sectional areas gives

$$\rho_H \, C_H \frac{d}{dt} \quad T_H \quad + \quad \frac{(P_H \, q_H)_o - (P_H \, q_H)_i}{A_H} \quad = \quad Q_s \qquad \text{(B3)}$$

and

$$\rho_c \, C_c \frac{d}{dt} \quad T_c \quad + \quad \frac{(P_c \, q_c)_o - (P_c \, q_c)_i}{A_c} \quad = \quad 0 \qquad \text{(B4)}$$

where, in general,

$$\left.\begin{aligned} T \quad &= \quad T(t) \quad = \quad \frac{1}{A} \int_A T(r,t) \; dA \\ Q_s \quad &= \quad Q_s(t) \quad = \quad \frac{1}{A} \int_A Q_s(r,t) \; dA \\ \text{and} \quad \frac{1}{A} \int_A \frac{1}{r} \frac{\partial}{\partial r} (r \, q_r) \; dA \quad &= \quad \frac{(P \, q)_o - (P \, q)_i}{A} \end{aligned}\right\} \qquad \text{(B5)}$$

in which the subscripts i,o refer to the inner and outer perimeters respectively. In the last equation of (B5) the radius and flux vectors are assumed to act in the same direction. If they act in opposite directions then the right hand side has a negative sign.

Equations (B3) and (B4) are solved for an annular channel in which the inner or outer wall is heated. The boundary conditions at the heat source/cladding interface and the cladding/coolant interface are respectively

$$\text{a)} \quad (q_H)_i = 0; \quad (q_H)_o = (q_c)_i = q_{HC} \tag{B6}$$

$$\text{and b)} \quad (q_c)_o = q_w; \quad q_w = h_t\,(T_w - T) \tag{B7}$$

where $h_t$, the local heat transfer coefficient, is a function of the local Reynolds number (Re) and Prandtl number (Pr), and is given by the correlation

$$h_t = a_t\,(Re)^{b_t}\,(Pr)^{c_t} \tag{B8}$$

If it is assumed that

$$T_c = E_{HC}\,T_H = T_w \tag{B9}$$

where $E_{HC}$ is a thermal resistance factor to account for temperature gradients across the heat source/cladding interface, then (B3) and (B4) become respectively

$$\frac{A_H \rho_H C_H}{E_{HC}} \frac{d}{dt}[T_w] + P_{HC}\,q_{HC} = A_H Q_s \tag{B10}$$

and

$$A_c \rho_c C_c \frac{d}{dt}[T_w] + P_c\,q_w - P_{HC}\,q_{HC} = 0 \tag{B11}$$

Adding (B10) and (B11) yields:

$$\left[\frac{\rho_H C_H}{E_{HC}} + \frac{A_c \rho_c C_c}{A_H}\right] \frac{d}{dt}[T_w] + \frac{P_c\,q_w}{A_H} = Q_s \tag{B12}$$

Perturbation, linearisation and Laplace transformation of (B12) gives the steady state and transient equations respectively as

$$\frac{P_c\,q_w^o}{A_H} = Q_s^o \tag{B13}$$

$$\left[ \frac{\rho_H C_H}{E_{HC}} + \frac{A_c \rho_c C_c}{A_H} \right] s\ \tilde{T}_w + \frac{P_c}{A_H}\ \tilde{q}_w = \tilde{Q}_s \qquad \text{(B14)}$$

The cladding/coolant boundary condition (B7) is used to eliminate the perturbed wall temperature $\tilde{T}_w$ from (B14). Perturbation and transformation of (B7) gives:

$$\tilde{q}_w = h_t^o (\tilde{T}_w - \tilde{T}) + \Delta T_w^o\ \tilde{h}_t \qquad \text{(B15)}$$

or

$$\tilde{T}_w = \frac{\tilde{q}_w}{h_t^o} - \Delta T_w^o \frac{\tilde{h}_t}{h_t^o} + \tilde{T}$$

Substitute (B15) into (B14):

$$\frac{\tilde{q}_w}{q_w^o} = \frac{1}{(1+\tau_H s)} \frac{\tilde{Q}_s}{Q_s^o} + \frac{\tau_H s}{(1+\tau_H s)} \frac{\tilde{h}_t}{h_t^o} - \frac{\tau_H s}{(1+\tau_H s)} \frac{\tilde{T}}{\Delta T_w^o} \qquad \text{(B16)}$$

where $\tau_H$ is the fundamental mode time constant, and is given by

$$\tau_H = \frac{A_H}{P_c h_t^o} \left[ \frac{\rho_H C_H}{E_{HC}} + \frac{A_c \rho_c C_c}{A_H} \right] \qquad \text{(B17)}$$

From (B8) the perturbed heat transfer coefficient is

$$\tilde{h}_t = \left\{ \frac{\partial h_t^o}{\partial Re^o} \quad \frac{\partial Re^o}{\partial G^o} \right\} \tilde{G} = b_t\ h_t^o\ \frac{\tilde{G}}{G^o} \qquad \text{(B18)}$$

and the perturbed liquid enthalpy is

$$\tilde{h}_\ell = \left( \frac{\partial h_\ell^o}{\partial T^o} \right) \tilde{T} = C_{P\ell}\ \tilde{T}$$

Hence (B16) becomes

$$\frac{\tilde{q}_w}{q_w^o} = \frac{1}{1+\tau_H s} \left[ \frac{\tilde{Q}_s}{Q_s^o} + b_t\ \tau_H\ s\ \frac{\tilde{G}}{G^o} - \frac{\tau_H s}{C_{P\ell} \Delta T_w^o}\ \tilde{h}_\ell \right] \qquad \text{(B19)}$$

This equation applies for the single phase and subcooled boiling regions of the channel. In the saturated boiling region

$$\tilde{h}_\ell = \tilde{h}_f = 0 \tag{B20}$$

Equation (B19) is applicable to other channel geometries by alteration of equation (B17) for the overall time constant $\tau_H$. An average 'thermal capacitance factor' (stored heat/unit surface area/unit temperature) is defined as

$$\langle\theta_T\rangle = \frac{\sum_n^N \left[\frac{A_H \rho_H C_H}{E_{HC}} + A_c \rho_c C_c\right]_n}{\sum_n^N [P_c]_n} \tag{B21}$$

where the cladding values apply to those between the heat source (or sources) and the coolant only. The heat transfer coefficient implicitly becomes

$$\langle h_t^o\rangle = h_t^o = \frac{1}{N} \sum_n^N [h_t^o]_n \tag{B22}$$

Hence the average fundamental mode time constant is

$$\langle\tau_H\rangle = \tau_H = \frac{\langle\theta_T\rangle}{\langle h_t^o\rangle} \tag{B23}$$

Note that heat source/coolant heat transfer is neglected if

$$\tau_H = 0 \tag{B24}$$

# APPENDIX C

## TWO-PHASE SLIP CORRELATION AND VOID/QUALITY RELATIONS

### C1. Two-phase Slip Correlation

The slip ratio, or holdup ratio (Govier and Aziz 1972), is defined as the ratio of the weighted cross-section averaged vapour and liquid velocities:

$$S = \frac{<\overline{U}_g>}{<\overline{U}_\ell>} \tag{C1}$$

The weighted cross-section averaged vapour and liquid velocities are defined as

$$\left.\begin{aligned} <\overline{U}_g> &= \frac{\int U_g \, dA_g}{\int dA_g} = \frac{\int \alpha U_g \, dA}{\int \alpha \, dA} = \frac{<\alpha U_g>}{<\alpha>} \\ <\overline{U}_\ell> &= \frac{\int U_\ell \, dA_\ell}{\int dA_\ell} = \frac{\int (1-\alpha) U_\ell \, dA}{\int (1-\alpha) \, dA} = \frac{<(1-\alpha)U_\ell>}{<1-\alpha>} \end{aligned}\right\} \tag{C2}$$

Hence (C1) becomes

$$S = \frac{<\alpha \; U_g>}{<\alpha>} \qquad \frac{<1-\alpha>}{<(1-\alpha)U_\ell>} \tag{C3}$$

Zuber and Findlay (1965) define the volumetric flux (mixture velocity) by

$$J = (1-\alpha) \; U_\ell + \alpha \; U_g \tag{C4}$$

a vapour drift velocity by

$$\Delta U_g = U_g - J \tag{C5}$$

and a distribution parameter by

$$C_o = \frac{<\alpha J>}{<\alpha><J>} \tag{C6}$$

From (C5) and (C6) it follows that

$$<\alpha U_g> \quad = \quad C_o \quad <\alpha><J> \quad + \quad <\alpha \Delta U_g> \qquad \text{(C7)}$$

and substitution in (C4) gives

$$<(1-\alpha)U_\ell> \quad = \quad <J> \; (1 - C_o<\alpha>) \; - \; <\alpha \Delta U_g> \qquad \text{(C8)}$$

Hence the Zuber and Findlay slip correlation is

$$S \quad = \quad \frac{<1-\alpha>}{\dfrac{1}{C_o + \dfrac{<\alpha \Delta U_g>}{<\alpha><J>}} - <\alpha>} \qquad \text{(C9)}$$

Alternatively,

$$S \quad = \quad \frac{<1 - \alpha>}{K_o - <\alpha>} \qquad \text{(C10)}$$

where $$K_o \quad = \quad \frac{<\alpha><J>}{<\alpha U_g>} \quad = \quad \frac{1}{C_o + \dfrac{V}{<J>}} \qquad \text{(C11)}$$

and $$V \quad = \quad \frac{<\alpha \Delta U_g>}{<\alpha>} \qquad \text{(C12)}$$

The factor ($K_o$) is commonly termed the Bankoff factor (Bankoff 1960), and (V) is termed the weighted mean (cross-section averaged) vapour drift velocity (Zuber and Findlay 1965). The distribution parameter ($C_o$) and the weighted mean drift velocity (V) are a function of the two-phase flow regime (bubble, slug, annular, droplet regime - Zuber et al. 1967). In the present analysis the factor ($K_o$) and the weighted mean drift velocity are assumed to vary in space, but invariant in time. This assumption is not unreasonable in view of the indeterminate nature of the void and velocity profiles.

C2. Void-Quality Relations

From equation (C5), the weighted mean vapour and liquid velocities are also given by

$$\langle \overline{U}_g \rangle = \frac{\langle x \rangle \langle G \rangle}{\langle \rho_g \rangle \langle \alpha \rangle}$$

$$\langle \overline{U}_\ell \rangle = \frac{\langle 1-x \rangle \langle G \rangle}{\langle \rho_\ell \rangle \langle 1-\alpha \rangle} \qquad \text{(C13)}$$

Substitution in (C1) gives

$$S = \frac{\langle 1-\alpha \rangle \langle x \rangle \langle \rho_\ell \rangle}{\langle \alpha \rangle \langle 1-x \rangle \langle \rho_g \rangle} \qquad \text{(C14)}$$

Equating (C10) and (C14) gives:

$$x = \frac{\alpha \, \rho_g}{K_o \, \rho_\ell - \Delta\rho\alpha} , \qquad \Delta\rho = \rho_\ell - \rho_g \qquad \text{(C15)}$$

or alternatively,

$$\alpha = \frac{K_o \, \rho_\ell \, x}{(\rho_g + \Delta\rho \, x)} \qquad \text{(C16)}$$

where cross-section averaged variables are assumed.

From (C16) the perturbed and Laplace transformed void fraction is

$$\tilde{\alpha} = \left(\frac{\partial \alpha^o}{\partial x^o}\right) \tilde{x} + \left(\frac{\partial \alpha^o}{\partial \rho_g^o}\right) \tilde{\rho}_g \qquad \text{(C17)}$$

or

$$\tilde{\alpha} = \frac{1}{X} \left[ \tilde{x} - x^o(1-x^c) \frac{\rho_g'}{\rho_g^o} \tilde{p} \right] \qquad \text{(C18)}$$

where

$$X = \frac{(\rho_g^o + \Delta\rho \, x^o)^2}{K_o \, \rho_\ell \, \rho_g^o} = K_o \left(\frac{\rho_\ell}{\rho_g^o}\right) \left(\frac{x^o}{\alpha^o}\right)^2 \qquad \text{(C19)}$$

and

$$\tilde{\rho}_g = \left(\frac{\partial \rho_g^o}{\partial p^o}\right) \tilde{p} = \rho_g' \, \tilde{p} \qquad \text{(C20)}$$

# APPENDIX D

## LISTING OF 'LOCO' COMPUTER PROGRAM

```
C ********************************************************************
C * LOCO - A LINEARISED MODEL FOR CALCULATING THE FREQUENCY RESPONSE   *
C *         AND ONSET OF COOLANT OSCILLATIONS IN BOILING CHANNELS.     *
C * AUTHOR : T. M. ROMBERG, AUSTRALIAN ATOMIC ENERGY COMMISSION.       *
C ********************************************************************
C
C***GENERAL NOTE : THE DATA CARDS ARE READ IN AS INDICATED BY THE FOLL-
C   OWING COMMENT CARDS. SUBSEQUENT CASES ARE READ IN AFTER THE FLUID
C   PROPERTIES CARDS, WHICH ARE READ IN AFTER THE FIRST CASE ONLY.
C
C ---------------------------------------------------------------------
C***TITLE CARD : FORMAT (20A4)
C ---------------------------------------------------------------------
C***CONTROL CARDS : FORMAT (16I5)
C ND     = NUMBER OF INLET PIPING SECTIONS )
C NC     = NUMBER OF CHANNEL SECTIONS      ) TOTAL = NCH = ND+NC+NR
C NR     = NUMBER OF RISER SECTIONS        )
C NB     = NUMBER OF BYPASS PIPING SECTIONS.
C NTIN   = NUMBER OF INLET TEMPERATURE INCREMENTS OR DECREMENTS.
C NPOW   = NUMBER OF CHANNEL POWER RATIO INCREMENTS OR DECREMENTS.
C NW     = NUMBER OF FLOW RATE INCREMENTS OR DECREMENTS.
C NF     = NUMBER OF FREQUENCY VALUES.
C NCFREQ = NUMBER OF FREQUENCIES FOR COMPONENT PRESS. DROP CALCULATIONS
C ---------------------------------------------------------------------
C NDROP  = Ø : NO ITERATION TO FIND FLOW RATE FOR GIVEN PRESSURE DROP
C NODES  =  MAXIMUM NUMBER OF SPACE NODES (<=6ØØ)
C        = 1 : ITERATION TO FIND FLOW RATE FOR GIVEN PRESSURE DROP
C NOSUB  = Ø : NO SUBCOOLED BOILING REGION
C        = 1 : SUBCOOLED BOILING REGION (EXPONENTIAL CORRELATION)
C        = 2 : SUBCOOLED BOILING REGION (HYPERBOLIC TANGENT CORRELATION)
C NDYN   = CONTROL PARAMETER FOR DYNAMIC CALCULATIONS
C        = Ø : NO DYNAMIC CALCULATIONS
C        = 1 : REAL INPUTS (FREQUENCY INDEPENDENT)
C        = 2 : REAL INPUTS (FREQUENCY DEPENDENT)
C        = 3 : COMPLEX INPUTS (FREQUENCY DEPENDENT)
C NPRINT = PRINTOUT CONTROL PARAMETER
C        = Ø : AXIAL NODAL VALUES+PRESSURE DROP AND EXIT VOID DYNAMICS
C        = 1 : AXIAL SECTION VALUES+PRESSURE DROP AND EXIT VOID DYNAMICS
C NPLOT  = PLOT OPTION
C        = Ø : NO PLOTS
C        = 1 : BODE PLOTS OF PRESSURE DROP AND EXIT VOID DYNAMICS
C NCARDS = NUMBER OF FLUID PROPERTY DATA CARDS.
C        = +VE : FLUID PROPERTIES ARE PRINTED (NOTE : NCARDS>3)
C        = -VE : FLUID PROPERTIES ARE NOT PRINTED (NOTE : NCARDS<-3)
C        =  Ø  : CONSTANT FLUID PROPERTIES.
C ---------------------------------------------------------------------
C NGDYN  = INPUT DEVICE OPTION FOR MASS FLUX FREQUENCY DATA
C NPDYN  = INPUT DEVICE OPTION FOR INLET PRESSURE FREQUENCY DATA
C NHDYN  = INPUT DEVICE OPTION FOR INLET ENTHALPY FREQUENCY DATA
C NQDYN  = INPUT DEVICE OPTION FOR HEAT SOURCE FREQUENCY DATA
C NSPEC  = INPUT DEVICE FOR PRESS DROP+EXIT VOID FREQUENCY DATA
C NPROP  = INPUT DEVICE OPTION FOR FLUID PROPERTIES DATA
C***NOTE : NXXXX - NO INPUT=Ø, CARDS=1, DATASET=N : NPROP=1 IF NCARDS=Ø
C ---------------------------------------------------------------------
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C***THE FOLLOWING CARDS HAVE FORMAT (8F10.3)
C TIN     = INLET TEMPERATURE TO SECTION 1..............................C
C DTIN    = +VE : INCREMENT IN INLET TEMPERATURE........................C
C         = -VE : DECREMENT IN INLET TEMPERATURE........................C
C -----------------------------------------------------------------------
C POWR    = CHANNEL REGION POWER RATIO (POW(N)=PKW(N)*POWR)
C DPOWR   = +VE : INCREMENT IN CHANNEL REGION POWER RATIO
C         = -VE : DECREMENT IN CHANNEL REGION POWER RATIO
C -----------------------------------------------------------------------
C W       = INITIAL MASS FLOW RATE...................................KG/S
C DW      = +VE : INCREMENT IN MASS FLOW RATE........................KG/S
C         = -VE : DECREMENT IN MASS FLOW RATE........................KG/S
C -----------------------------------------------------------------------
C PIN     = INLET PRESSURE TO SECTION 1...............................KPA
C PDROP   = PRESSURE DROP BETWEEN INLET AND OUTLET....................KPA
C         = 0.0 FOR NDROP = 0 OR NB > 0
C WTOT    = TOTAL MASS FLOW RATE THROUGH CHANNEL AND BYPASS..........KG/S
C AP,BP,  = COEFFICIENTS FOR PUMP HEAD-FLOW CHARACTERISTIC,
C CP      = (HEAD=AP+BP*Q+CP*Q*Q, HEAD=M, Q=LITRE/S)
C -----------------------------------------------------------------------
C ASB     = LOCAL NUSSELT NUMBER FOR ONSET OF SUBCOOLED BOILING
C           (PECLET NO<=70000 : ASB=455.0 NORMALLY)
C BSB     = LOCAL STANTON NUMBER FOR ONSET OF SUBCOOLED BOILING
C           (PECLET NO >70000 : BSB=0.0065 NORMALLY)
C           NOTE : ASB AND BSB ARE RELATED BY THE EQUATION ASB=70000*BSB
C AHT,    = COEFFICIENTS FOR THE SUBCOOLED AND SATURATED BOILING REGION
C BHT,    = HEAT TRANSFER CORRELATION : HT = AHT*RE**BHT*PRL**CHT,
C CHT     = WHERE RE = REYNOLDS NUMBER, PRL = LIQUID PRANDTL NUMBER
C -----------------------------------------------------------------------
C***FOLLOWING ELEVEN (11) CARDS ARE NOT REQUIRED IF NDYN=0.
C SIGMA   = REAL COMPONENT OF THE LAPLACE OPERATOR.....................HZ
C FREQ    = INITIAL FREQUENCY FOR DYNAMIC CALCULATIONS.................HZ

C DFREQ   = FREQUENCY INCREMENT FOR DYNAMIC CALCULATIONS...............HZ
C -----------------------------------------------------------------------
C CARD NOT REQUIRED IF NDYN = 0 OR NCFREQ = 0 : N=1,NCFREQ
C CFREQ(N)=FREQUENCIES FOR COMPONENT PRESSURE DROP CALCULATIONS.......HZ
C -----------------------------------------------------------------------
C GDFAC   = NORMALISING FACTOR FOR INLET MASS FLUX PERTURBATION.
C PDFAC   = NORMALISING FACTOR FOR INLET PRESSURE PERTURBATION.
C HDFAC   = NORMALISING FACTOR FOR INLET ENTHALPY PERTURBATION.
C QDFAC   = NORMALISING FACTOR FOR CHANNEL POWER DENSITY PERTURBATION.
C -----------------------------------------------------------------------
C***MODULUS (NDYN<3) OR REAL COMPONENT (NDYN=3).
C GDYN(N)   = SPECTRUM OF INLET MASS FLUX PERTURBATION........KG/(S*M**2)
C -----------------------------------------------------------------------
C***COMPLEX COMPONENT (REQUIRED ONLY IF NDYN=3).
C GCDYN(N) = SPECTRUM OF INLET MASS FLUX PERTURBATION........KG/(S*M**2)
C -----------------------------------------------------------------------
C***MODULUS (NDYN<3) OR REAL COMPONENT (NDYN=3).
C PDYN(N)   = SPECTRUM OF INLET PRESSURE PERTURBATION.................KPA
C -----------------------------------------------------------------------
C***COMPLEX COMPONENT (REQUIRED ONLY IF NDYN=3).
C PCDYN(N) = SPECTRUM OF INLET PRESSURE PERTURBATION.................KPA
C -----------------------------------------------------------------------
C***MODULUS (NDYN<3) OR REAL COMPONENT (NDYN=3).
C HDYN(N)   = SPECTRUM OF INLET ENTHALPY PERTURBATION...............KJ/KG
C -----------------------------------------------------------------------
C***COMPLEX COMPONENT (REQUIRED ONLY IF NDYN=3)
C HCDYN(N) = FREQUENCY SPECTRUM OF INLET ENTHALPY PERTURBATION.....KJ/KG
C -----------------------------------------------------------------------
```

```
C***MODULUS (NDYN<3) OR REAL COMPONENT (NDYN=3)
C QDYN(N)  = FREQUENCY SPECTRUM OF NORMALISED CHANNEL POWER PERT.....W/W
C ---------------------------------------------------------------------
C***COMPLEX COMPONENT (REQUIRED ONLY IF NDYN=3)
C QCDYN(N) = FREQUENCY SPECTRUM OF NORMALISED CHANNEL POWER PERT.....W/W
C ---------------------------------------------------------------------
C***SECTION SPECIFICATIONS (N=1,NCH) :
C DZ(N)    = LENGTH.....................................................CM
C A(N)     = FLOW AREA...............................................CM**2
C DE(N)    = EQUIVALENT HYDRAULIC DIAMETER..............................CM
C PH(N)    = HEATED PERIMETER...........................................CM
C ANG(N)   = ANGLE TO VERTICAL (UPFLOW=0.0 : DOWNFLOW=180.0)...........DEG

C RK(N)    = INLET RESTRICTION LOSS FACTOR
C E(N)     = SURFACE RELATIVE ROUGHNESS RATIO
C ---------------------------------------------------------------------
C PKW(N)   = POWER INPUT (+VE, ZERO OR -VE).............................KW
C TCAP(N)= THERMAL CAPACITANCE OF HEAT SOURCE AND CLADDING......KJ/(M*S)
C CO(N)    = DISTRIBUTION PARAMETER
C V(N)     = WEIGHTED MEAN VAPOUR DRIFT VELOCITY.......................M/S
C AA(N),   = LOCAL TWO-PHASE FRICTION MULTIPLIER COEFFICIENTS :
C BB(N),   = PHI = 1.0 + AA(N)*((RHOL/RHOG-1.0)*X)**BB(N))*G**CC(N), WHERE
C CC(N)    = RHOL,RHOG=LIQUID,VAPOUR DENSITIES:X=FLOW QUALITY:G=MASS FLUX
C ---------------------------------------------------------------------
C***BYPASS SECTION SPECIFICATIONS (NB>0 ONLY : N=1,NB)
C ZB(N)    = LENGTH.....................................................CM
C AB(N)    = FLOW AREA...............................................CM**2
C DB(N)    = EQUIVALENT HYDRAULIC DIAMETER..............................CM
C ANGB(N)= ANGLE OF INCLINATION TO VERTICAL.........................DEG
C RKB(N)   = INLET RESTRICTION FACTOR
C EB(N)    = SURFACE RELATIVE ROUGHNESS RATIO
C ---------------------------------------------------------------------
C TPLOT1 = PLOT TITLE CARD FOR PRESSURE DROP DYNAMICS (NPLOT.NE.0)
C TPLOT2 = PLOT TITLE CARD FOR EXIT VOID FRACTION DYNAMICS (NPLOT.NE.0)
C ---------------------------------------------------------------------
C***SATURATION FLUID PROPERTY DATA CARDS (NCARDS.NE.0 : N=1,NCARDS)
C***FORMAT (F5.1,F9.2,F8.2,F8.1,F10.6,F10.5,F6.1,F8.4,F8.3)
C TEMP(N)   = TEMPERATURE................................................C
C PRESS(N)  = PRESSURE.................................................KPA
C ENTHF(N)  = LIQUID ENTHALPY.........................................KJ/KG
C ENTHG(N)  = VAPOUR ENTHALPY.........................................KJ/KG
C SPVF(N)   = LIQUID SPECIFIC VOLUME..................................M**3/KG
C SPVG(N)   = VAPOUR SPECIFIC VOLUME..................................M**3/KG
C VISCDF(N)= LIQUID DYNAMIC VISCOSITY..........................MICRO PA*S
C CONDF(N)  = LIQUID THERMAL CONDUCTIVITY..........................W/(M*K)
C SPHF(N)   = LIQUID SPECIFIC HEAT...............................KJ/(KG*K)
C ---------------------------------------------------------------------
C***SATURATION FLUID PROPERTIES DATA CARD (NCARDS=0)
C***FORMAT (F5.1,F8.2,F8.1,F10.6,F10.5,F6.1,F8.4,F8.3)
C TSAT      = TEMPERATURE................................................C
C HF        = LIQUID ENTHALPY.........................................KJ/KG
C HG        = VAPOUR ENTHALPY.........................................KJ/KG
C VF        = LIQUID SPECIFIC VOLUME..................................M**3/KG
C VG        = VAPOUR SPECIFIC VOLUME..................................M**3/KG
C VISCF     = LIQUID DYNAMIC VISCOSITY..........................MICRO PA*S
C CONF      = LIQUID THERMAL CONDUCTIVITY..........................W/(M*K)
C CPF       = LIQUID SPECIFIC HEAT...............................KJ/(KG*K)

C ---------------------------------------------------------------------
```

```
C
      COMMON / CONT / ND,NC,NR,NTIN,NPOW,NW,NF,NDROP,NOSUB,NPRINT,NCH
      COMMON /OPTION/ NGDYN,NPDYN,NHDYN,NQDYN,NODES
      COMMON /DATA1 / TIN,DTIN,POWR,DPOWR,W,DW,
     .                PIN,PDROP,AP,BP,CP,ASB,BSB,AHT,BHT,CHT,
     .                TSAT,HF,HG,RHOF,RHOG,VISCF,CONF,CPF
      COMMON /DATA2 / DZ(40),A(40),DE(40),PH(40),ANG(40),RK(40),E(40),
     .                PKW(40),TCAP(40),CO(40),V(40),AA(40),BB(40),CC(40)
      COMMON /DATA3 / SIGMA,FREQ,DFREQ,FHZ(120),GDYN(120),HDYN(120),
     .                QDYN(120),PDYN(120),CFREQ(10),NDYN,NCFREQ
      COMMON /DATA4 / GDFAC,PDFAC,HDFAC,QDFAC,GCDYN(120),PCDYN(120),
     .                HCDYN(120),QCDYN(120)
      COMMON /BYPAS / ZB(20),AB(20),DB(20),ANGB(20),RKB(20),EB(20),
     .                CONL,CPL,DRHO,HFG,PRL,RHOL,VISCL,WTOT,NB
      COMMON /TABLE / TEMP(100),PRESS(100),ENTHF(100),ENTHFG(100),
     .                ENTHG(100),SPVF(100),SPVG(100),DENF(100),
     .                DENG(100),VISCDF(100),CONDF(100),SPHF(100),
     .                PRF(100),FAC1,FAC2,ADRG,BDRG,NCARDS
      COMMON /ERROR / CSPEC(80),CPHASE(80),ASPEC(80),APHASE(80),NERR
      COMMON /CPLOT / TPLT1(20),TPLT2(20),NPLOT
      DIMENSION   STC(40),SCO(40),SV(40),SAA(40),SBB(40),SCC(40)
      LOGICAL*4 TITLE(20)
C
      NCASE =0
      READ (1,210) (TITLE(I),I=1,20)
 1100 READ (1,100,END=1000) ND,NC,NR,NB,NTIN,NPOW,NW,NF,NCFREQ
      READ (1,100) NDROP,NODES,NOSUB,NDYN,NPRINT,NPLOT,NCARDS
      READ (1,100) NGDYN,NPDYN,NHDYN,NQDYN,NSPEC,NPROP
      READ (1,110) TIN,DTIN
      READ (1,110) POWR,DPOWR
      READ (1,110) W,DW
      READ (1,110) TCFAC,COFAC,VFAC,AAFAC,BBFAC,CCFAC
      READ (1,110) PIN,PDROP,WTOT,AP,BP,CP
      READ (1,110) ASB,BSB,AHT,BHT,CHT
      BSB=ASB/70000.0
      NERR=NDYN
      IF (NDYN.EQ.0) NSPEC=0
      NDYN=IABS(NDYN)
      IF (NCASE.GT.0) GO TO 30
      IF (NDYN) 15,15,10
   10 READ (1,110) SIGMA,FREQ,DFREQ
      IF (NCFREQ.GT.0) READ (1,110) (CFREQ(I),I=1,NCFREQ)
      READ (1,110) GDFAC,PDFAC,HDFAC,QDFAC
      NT=NF
      IF (NDYN.EQ.1) NT=1
      IF (NGDYN.EQ.0) GO TO 11
      IF (NDYN.EQ.1.AND.NGDYN.NE.1) NGDYN=1
      READ (NGDYN,110) (GDYN(I),I=1,NT)
      IF (NDYN.EQ.3) READ (NGDYN,110) (GCDYN(I),I=1,NT)
   11 IF (NPDYN.EQ.0) GO TO 12
      IF (NDYN.EQ.1.AND.NPDYN.NE.1) NPDYN=1
      READ (NPDYN,110) (PDYN(I),I=1,NT)
      IF (NDYN.EQ.3) READ (NPDYN,110) (PCDYN(I),I=1,NT)
   12 IF (NHDYN.EQ.0) GO TO 13
      IF (NDYN.EQ.1.AND.NHDYN.NE.1) NHDYN=1
      READ (NHDYN,110) (HDYN(I),I=1,NT)
      IF (NDYN.EQ.3) READ (NHDYN,110) (HCDYN(I),I=1,NT)
   13 IF (NQDYN.EQ.0) GO TO 14
      IF (NDYN.EQ.1.AND.NQDYN.NE.1) NQDYN=1
```

```
      :
      READ (NQDYN,110) (QDYN(I),I=1,NT)
      IF (NDYN.EQ.3) READ (NQDYN,110) (QCDYN(I),I=1,NT)
   14 IF (NSPEC.EQ.0) GO TO 15
      READ (NSPEC,110) (CSPEC(I),I=1,NF)
      READ (NSPEC,110) (CPHASE(I),I=1,NF)
      READ (NSPEC,110) (ASPEC(I),I=1,NF)
      READ (NSPEC,110) (APHASE(I),I=1,NF)
   15 NCH=ND+NC+NR
      DO 16 I=1,NCH
   16 READ (1,110) DZ(I),A(I),DE(I),PH(I),ANG(I),RK(I),E(I)
      DO 20 I=1,NCH
   20 READ (1,110) PKW(I),TCAP(I),CO(I),V(I),AA(I),BB(I),CC(I)
      IF (NB) 30,30,22
   22 DO 24 I=1,NB
   24 READ (1,110) ZB(I),AB(I),DB(I),ANGB(I),RKB(I),EB(I)
   30 WRITE (3,140) (TITLE(I),I=1,20)
      WRITE (3,142)
      WRITE (3,150) ND,NC,NR,NB,NTIN,NPOW,NW,NF,NCFREQ
      WRITE (3,144)
      WRITE (3,150) NDROP,NODES,NOSUB,NERR,NPRINT,NPLOT,NCARDS
      WRITE (3,146)

      WRITE (3,150) NGDYN,NPDYN,NHDYN,NQDYN,NSPEC,NPROP
      WRITE (3,152)
      WRITE (3,160) TIN,DTIN
      WRITE (3,154)
      WRITE (3,160) POWR,DPOWR
      WRITE (3,156)
      WRITE (3,160) W,DW
      WRITE (3,157)
      WRITE (3,160) TCFAC,COFAC,VFAC,AAFAC,BBFAC,CCFAC
      WRITE (3,158)
      WRITE (3,160) PIN,PDROP,WTOT,AP,BP,CP
      WRITE (3,159)
      WRITE (3,160) ASB,BSB,AHT,BHT,CHT
      IF (NCASE.GT.0) GO TO 42
      IF (NDYN) 40,40,31
   31 WRITE (3,162)
      WRITE (3,160) SIGMA,FREQ,DFREQ
      IF (NCFREQ) 33,33,32
   32 WRITE (3,163)
      WRITE (3,160) (CFREQ(I),I=1,NCFREQ)
   33 WRITE (3,190)
      WRITE (3,160) GDFAC,PDFAC,HDFAC,QDFAC
      IF (NGDYN.EQ.0) GO TO 34
      WRITE (3,192)
      IF (NDYN.EQ.3) WRITE (3,200)
      WRITE (3,160) (GDYN(I),I=1,NT)
      IF (NDYN.NE.3) GO TO 34
      WRITE (3,202)
      WRITE (3,160) (GCDYN(I),I=1,NT)
   34 IF (NPDYN.EQ.0) GO TO 35
      WRITE (3,194)
      IF (NDYN.EQ.3) WRITE (3,200)
      WRITE (3,160) (PDYN(I),I=1,NT)
      IF (NDYN.NE.3) GO TO 35
      WRITE (3,202)
      WRITE (3,160) (PCDYN(I),I=1,NT)
```

```
35 IF (NHDYN.EQ.Ø) GO TO 36
   WRITE (3,196)
   IF (NDYN.EQ.3) WRITE (3,200)
   WRITE (3,160) (HDYN(I),I=1,NT)
   IF (NDYN.NE.3) GO TO 36
   WRITE (3,202)
   WRITE (3,160) (HCDYN(I),I=1,NT)
36 IF (NQDYN.EQ.Ø) GO TO 37

   WRITE (3,198)
   IF (NDYN.EQ.3) WRITE (3,200)
   WRITE (3,160) (QDYN(I),I=1,NT)
   IF (NDYN.NE.3) GO TO 37
   WRITE (3,202)
   WRITE (3,160) (QCDYN(I),I=1,NT)
37 IF (NSPEC.EQ.Ø) GO TO 4Ø
   WRITE (3,220)
   WRITE (3,160) (CSPEC(I),I=1,NF)
   WRITE (3,160) (CPHASE(I),I=1,NF)
   WRITE (3,222)
   WRITE (3,160) (ASPEC(I),I=1,NF)
   WRITE (3,226)
   WRITE (3,160) (APHASE(I),I=1,NF)
4Ø WRITE (3,164)
   DO 42 I=1,NCH
   IF (ND.GT.Ø.AND.I.EQ.1) WRITE (3,170)
   IF (NC.GT.Ø.AND.I.EQ.(ND+1)) WRITE (3,172)
   IF (NR.GT.Ø.AND.I.EQ.(ND+NC+1)) WRITE (3,174)
42 WRITE (3,168) DZ(I),A(I),DE(I),PH(I),ANG(I),RK(I),E(I),I
   ND1=ND+1
   DO 43 I=ND1,NCH
   IF (NCASE.EQ.Ø) STC(I)=TCAP(I)
   TCAP(I)=STC(I)*TCFAC
   IF (NCASE.EQ.Ø) SCO(I)=CO(I)
   CO(I)=SCO(I)*COFAC
   IF (NCASE.EQ.Ø) SV(I)=V(I)
   V(I)=SV(I)*VFAC
   IF (NCASE.EQ.Ø) SAA(I)=AA(I)
   AA(I)=SAA(I)*AAFAC
   IF (NCASE.EQ.Ø) SBB(I)=BB(I)
   BB(I)=SBB(I)*BBFAC
   IF (NCASE.EQ.Ø) SCC(I)=CC(I)
43 CC(I)=SCC(I)*CCFAC
   WRITE (3,166)
   DO 44 I=1,NCH
   IF (ND.GT.Ø.AND.I.EQ.1) WRITE (3,170)
   IF (NC.GT.Ø.AND.I.EQ.(ND+1)) WRITE (3,172)
   IF (NR.GT.Ø.AND.I.EQ.(ND+NC+1)) WRITE (3,174)
44 WRITE (3,168) PKW(I),TCAP(I),CO(I),V(I),AA(I),BB(I),CC(I),I
   IF (NB) 5Ø,5Ø,46
46 WRITE (3,176)
   WRITE (3,178)
   NDROP=1
   DO 48 I=1,NB
48 WRITE (3,160) ZB(I),AB(I),DB(I),ANGB(I),RKB(I),EB(I),I
5Ø FAC1=1.ØØØØØØE+Ø3
   FAC2=1.ØØØØØØE-Ø6
   NPRINT=IABS(NPRINT)
```

```
      IF (NDYN.EQ.0) GO TO 53
      IF (NPLOT) 51,53,51
   51 READ(1,210)(TPLT1(I),I=1,20)
      READ(1,210)(TPLT2(I),I=1,20)
      WRITE (3,215) (TPLT1(I),I=1,20)
      WRITE (3,215) (TPLT2(I),I=1,20)
   53 IF (NCASE.GT.0) NCARDS=IABS(NCARDS)
      IF (NCASE) 54,54,60
   54 NCARD=IABS(NCARDS)
      IF (NPROP.EQ.0) NPROP=1
      READ (NPROP,120) (TEMP(N),PRESS(N),ENTHF(N),ENTHG(N),SPVF(N),
     .                 SPVG(N),VISCDF(N),CONDF(N),SPHF(N),N=1,NCARD)
      IF (NCARDS.LT.0) GO TO 56
      WRITE (3,180)
      WRITE (3,182)
      WRITE(3,184) (TEMP(N),PRESS(N),ENTHF(N),ENTHG(N),SPVF(N),
     .                 SPVG(N),VISCDF(N),CONDF(N),SPHF(N),N=1,NCARDS)
   56 CALL TABLES
      GO TO 60
   58 READ (1,130) TSAT,HF,HG,VF,VG,VISCF,CONF,CPF
      RHOF=1.0/VF
      RHOG=1.0/VG
      WRITE (3,185)
      WRITE (3,186)
      WRITE (3,188) TSAT,HF,HG,VF,VG,VISCF,CONF,CPF
   60 CALL EXEC (NCASE)
      NCASE=1
      GO TO 1100
  100 FORMAT (16I5)
  110 FORMAT (8F10.3)
  120 FORMAT (F5.1,F9.2,F8.2,F8.1,F10.6,F10.5,F6.1,F8.4,F8.3)
  130 FORMAT (F5.1,F8.2,F8.1,F10.6,F10.5,F6.1,F8.4,F8.3)
  140 FORMAT ('1',' LOCO INPUT DATA : ',20A4,/2X,15('*'))
  142 FORMAT ('0',6X,'ND',6X,'NC',6X,'NR',6X,'NB',5X,'NTIN',4X,
     .        'NPOW',5X,'NW',6X,'NF',4X,'NCFREQ')
  144 FORMAT ('0',5X,'NDROP',2X,'NODES',4X,'NOSUB',3X,'NDYN',3X,
     .             'NPRINT',3X,'NPLOT',2X,'NCARDS')
  146 FORMAT ('0',5X,'NGDYN',3X,'NPDYN',3X,'NHDYN',3X,'NQDYN',3X,
     .        'NSPEC',3X,'NPROP')
  150 FORMAT (1X,16I8)
  152 FORMAT ('0',1X,'TIN',7X,'DTIN')
  154 FORMAT ('0',1X,'POWR',6X,'DPOWR')
  156 FORMAT ('0',1X,'W',9X,'DW')
  157 FORMAT ('0 TCFAC',5X,'COFAC',5X,'VFAC',6X,'AAFAC',5X,
     .        'BBFAC',5X,'CCFAC')
  158 FORMAT ('0',1X,'PIN',7X,'PDROP',5X,'WTOT',6X,'AP',8X,'BP',8X,'CP')
  159 FORMAT ('0 ASB',7X,'BSB',7X,'AHT',7X,'BHT',7X,'CHT')
  160 FORMAT (1X,1P8E10.3)
  162 FORMAT ('0',1X,'SIGMA',5X,'FREQ',6X,'DFREQ')
  163 FORMAT ('0',1X,'CFREQ')
  164 FORMAT ('0',1X,'DZ(N)',5X,'A(N)',6X,'DE(N)',5X,'PH(N)',5X,
     .        'ANG(N)',4X,'RK(N)',5X,'E(N)')
  166 FORMAT ('0',1X,'PKW(N)',4X,'TCAP(N)',3X,'CO(N)',5X,'V(N)',6X,
     .        'AA(N)',5X,'BB(N)',5X,'CC(N)')
  168 FORMAT (1X,1P7E10.3,I6)
  170 FORMAT ('  INLET PIPING REGION')
  172 FORMAT ('  CHANNEL REGION')
  174 FORMAT ('  RISER REGION')
```

```
  176 FORMAT ('0 BYPASS PIPING')
  178 FORMAT ('  ZB(N)',5X,'AB(N)',5X,'DB(N)',5X,'ANGB(N)',3X,'RKB(N)',
     .        4X,'EB(N)')
  180 FORMAT ('1',28X,'FLUID PROPERTIES')
  182 FORMAT ('0',1X,'TEMP',4X,'PRESS',3X,'ENTHF',3X,'ENTHG',4X,'SPVF',
     .        7X,'SPVG',2X,'VISCF',3X,'CONDF',4X,'SPHF')
  184 FORMAT (1X,F5.1,F9.2,F8.2,F8.1,F10.6,F10.5,F6.1,F8.4,F8.3)
  185 FORMAT ('0',24X,'FLUID PROPERTIES')
  186 FORMAT ('0',1X,'TEMP',3X,'ENTHF',3X,'ENTHG',4X,'SPVF',7X,'SPVG',
     .        2X,'VISCF',3X,'CONDF',4X,'SPHF')
  188 FORMAT (1X,F5.1,F8.2,F8.1,F10.6,F10.5,F6.1,F8.4,F8.3)
  190 FORMAT ('0 GDFAC',5X,'PDFAC',5X,'HDFAC',5X,'QDFAC')
  192 FORMAT ('0 GDYN(N)')
  194 FORMAT ('0 PDYN(N)')
  196 FORMAT ('0 HDYN(N)')
  198 FORMAT ('0 QDYN(N)')
  200 FORMAT ('  REAL COMPONENT')
  202 FORMAT ('  IMAGINARY COMPONENT')
  210 FORMAT (20A4)
  215 FORMAT (1X,20A4)
  220 FORMAT ('0 CSPEC(N)')
  222 FORMAT ('0 ASPEC(N)')
  224 FORMAT ('0 CPHASE(N)')
  226 FORMAT ('0 APHASE(N)')
 1000 STOP
      END
      SUBROUTINE EXEC (NCASE)
      COMMON / CONT / ND,NC,NR,NTIN,NPOW,NW,NF,NDROP,NOSUB,NPRINT,NCH
      COMMON /DATA1 / TIN,DTIN,POWR,DPOWR,W,DW,
     .                PIN,PDROP,AP,BP,CP,ASB,BSB,AHT,BHT,CHT,
     .                TSAT,HF,HG,RHOF,RHOG,VISCF,CONF,CPF
      COMMON /DATA2 / DZ(40),A(40),DE(40),PH(40),ANG(40),RK(40),E(40),
     .                PKW(40),TCAP(40),CO(40),V(40),AA(40),BB(40),CC(40)
      COMMON /DATA3 / SIGMA,FRFQ,DFREQ,FHZ(120),GDYN(120),HDYN(120),
     .                QDYN(120),PDYN(120),CFREQ(10),NDYN,NCFREQ
      COMMON /EXSTAT/ DPT,FAC,FAC3,GC,PI,PUMP,PY,NIT,NODE
      COMMON /BYPAS / ZB(20),AB(20),DB(20),ANGB(20),RKB(20),EB(20),
     .                CONL,CPL,DRHO,HFG,PRL,RHOL,VISCL,WTOT,NB
      COMMON /TABLE / TEMP(100),PRESS(100),ENTHF(100),ENTHFG(100),
     .                ENTHG(100),SPVF(100),SPVG(100),DENF(100),
     .                DENG(100),VISCDF(100),CONDF(100),SPHF(100),
     .                PRF(100),FAC1,FAC2,ADRG,BDRG,NCARDS
      FAC=1.0000E-02
      FAC3=FAC1
      NDYNS=NDYN
      IF (NCASE.GT.0) GO TO 15
      IF (NCARDS) 10,10,15
   10 RHOL=RHOF
      DRHO=RHOF-RHOG
      HF=HF*FAC1
      HG=HG*FAC1
      HFG=HG-HF
      CPF=CPF*FAC1
      CPL=CPF
      VISCF=VISCF*FAC2
      VISCL=VISCF
      CONL=CONF
      PRL=CPF*VISCF/CONF
      HSUB=CPF*(TSAT-TIN)/FAC1
```

```
   15 GC=9.807
      WI=W
      POWRI=POWR
      DO 90 K=1,NTIN
      POWR=POWRI
      DO 80 J=1,NPOW
      IT1=0
      IT2=0
      NIT=0
      W=WI
      IF (NDROP.EQ.1) WRITE (3,120)
      DO 70 I=1,NW
   20 IF (NCARDS) 25,25,22
   22 RHOL=TDF(TIN)
      VISCL=TVISCD(TIN)
      TSAT=SAT(TEMP,PRESS,PIN,NCARDS)
      HSUB=(THF(TSAT)-THF(TIN))/FAC1
   25 PY=3.141592/180.0
   30 IF (NB.GT.0) GO TO 35
      QT=W/RHOL*FAC1
      DPUMP=-RHOL*(AP+BP*QT+CP*QT*QT)*GC/FAC1
      PUMP=-(BP+2.0*CP*QT)*A(1)/FAC1
      GO TO 40
   35 DPUMP=0.0
      PUMP=0.0
      PDROP=0.0
      CALL BYPASS(0)
   40 IF (NDROP.EQ.0) WRITE (3,100) TIN,HSUB,POWR,W
      IF (NIT.EQ.1) WRITE (3,110) TIN,HSUB,POWR,W
      NDYN=NDYNS
      CALL STATE
      IF (NIT) 45,45,75
   45 PTOT=DPT+DPUMP
      PDIFF=PTOT-PDROP
      IF (NDROP) 65,65,50
C
C     CALCULATION OF FLOW RATE FOR SPECIFIED PRESSURE DROP.
   50 WRITE (3,130) W,PTOT,PDROP,PDIFF
      IF (PDIFF) 52,62,54
   52 W1=W
      PDIFF1=PDIFF
      IT1=1
      GO TO 56
   54 W2=W
      PDIFF2=PDIFF
      IT2=1
   56 IF (IT1) 70,70,58
   58 IF (IT2) 70,70,60
   60 W=(PDIFF2*W1-PDIFF1*W2)/(PDIFF2-PDIFF1)
      CHECK=ABS(PDIFF)
      IF (PDROP.NE.0.0) CHECK=ABS(PDIFF/PDROP)
      IF (CHECK.LE.0.0050) GO TO 62
      GO TO 20
   62 NIT=1
      GO TO 20
   65 IF (NDYN.GT.0) CALL TFUNCN
   70 W=W+DW
      GO TO 80
```

```
    6 HL1=H1
      HIN=H1
      ALFA(1)=0.0
      CKO(1)=1.0
      X(1)=0.0
      PHI(1)=1.0
      UL1=W/AC/RHOL
      UG1=0.0
      GM1=W*W/AC/AC
      TAU1=0.0
      TAU2=0.0

      Z=0.0
      ZBB=0.0
      IF (NDYN.EQ.0) DFREQ=0
      IF (NC.GT.1) GO TO 8
      NOSUB=0
      NPRINT=0
    8 NBB=0
      NCD=0
      NSB=0
      NSUB=0
      NSAT=0
      NCON=0
      I=0
      IF (NPRINT) 10,10,15
   10 IF (NDROP.EQ.0.OR.NIT.EQ.1) WRITE (3,200)
      GO TO 20
   15 IF (NDROP.EQ.0.OR.NIT.EQ.1) WRITE (3,205)
   20 DO 190 K=1,NCH
      IF (NDROP.GT.0.AND.NIT.EQ.0) GO TO 22
      IF (ND.GT.0.AND.K.EQ.1) WRITE (3,210)
      IF (NC.GT.0.AND.K.EQ.(ND+1)) WRITE (3,220)
      IF (NR.GT.0.AND.K.EQ.(ND+NC+1)) WRITE (3,230)
      IF (NC.EQ.1) GO TO 22
      IF (NPRINT.EQ.0) WRITE (3,235) K
   22 AR=A(1)/A(K)
      A1=AC
      PKWK=PKW(K)
      IF (K.GT.ND.AND.K.LE.(ND+NC)) PKWK=POWR*PKW(K)
      ZK=DZ(K)*FAC
      NWARN=0
      IF (NDROP.EQ.1.AND.NIT.EQ.0) NWARN=1
      AC=A(K)*FAC*FAC
      DC=DE(K)*FAC
      PC=PH(K)*FAC
      THETA=COS((ANG(K)*PY))
      DHE=4.0*AC/PC
      FLK=PKWK*FAC1/DZ(K)/PH(K)
      FLX=FLK/FAC/FAC
      G=W/AC
      G2=G*G
      DRGDK(K)=0.0
      IF (NC.GT.1) GO TO 23
      NODE=1
      NBOIL=1
      IF (K.GT.ND.AND.K.LE.(ND+NC)) NODE=2
      CHECK=PKWK*FAC1/W/(HBB-HIN)
      IF (CHECK.LE.1) NODE=1
```

```
      GO TO 26
   23 IF (NSAT.GT.Ø.AND.NSAT.LT.I) GO TO 25
      HBB=HF
      IF (NOSUB.EQ.Ø) GO TO 24
      PEC=G*DC*CPL/CONL
      HTT=ASB*CONL/DC
      IF (PEC.GT.7.ØØE+Ø4) HTT=BSB*G*CPL
      HSB=HF-CPL*FLX/HTT
      HBB=HSB
   24 NODE=ABS(1Ø.Ø*PKWK*FAC1/W/(HBB-H1))+2
   25 NCHECK=(NODES-I)/(NCH-K+1)+1
      IF (NSAT.GT.Ø) NODE=2.Ø*DFREQ*ZK/UG1+1
      IF (NODE.GT.NCHECK) NODE=NCHECK
   26 MODE(K)=NODE
      DO 18Ø J=1,NODE
      IF (NC.EQ.1) GO TO 3Ø
      IF (NSAT.GT.Ø.AND.NSAT.LT.I) GO TO 28
      HBB=HF
      IF (NOSUB.GT.Ø) HBB=HSB
      NBOIL=ABS(1Ø.Ø*PKWK*FAC1/W/(HBB-H1))/NODE+2
      LBOIL=(NODES-I)/NODE/(NCH-K+1)+1
      IF (NBOIL.GT.LBOIL) NBOIL=LBOIL
      IF ((NODE*NBOIL).GT.1ØØ) NBOIL=1ØØ/NODE
      IF (K.LE.ND) NBOIL=5
      JBOIL=2.Ø*DFREQ*ZK/NODE/UL1+1
      GO TO 3Ø
   28 NBOIL=(NODES-I)/NODE/(NCH-K+1)+1
      JBOIL=2.Ø*DFREQ*ZK/NODE/UG1+1
   3Ø ZC=ZK/NODE/NBOIL
      IF (NWARN.EQ.1) GO TO 31
      IF (JBOIL.LT.NBOIL) GO TO 31
      NWARN=1
      NDIV=JBOIL/NBOIL+1
      WRITE (3,295) K,NDIV
   31 AS=PC*ZC
      DH=PKWK*FAC1/W/NODE/NBOIL
      IF (NC.GT.1) GO TO 38
      IF (K.LE.ND.OR.K.GT.(ND+NC)) GO TO 38
      DH=PKWK*FAC1/W
      DHB=HBB-HIN
      IF (DH-DHB) 32,32,34
   32 ZC=ZK
      GO TO 36
   34 DH=DHB
      IF (J.EQ.2) DH=PKWK*FAC1/W-DHB
      ZC=DH*W*ZK/PKWK/FAC1
   36 ZCL(J)=ZC
      AS=PC*ZC
   38 MBOIL(K,J)=NBOIL
      DO 18Ø L=1,NBOIL
      I=I+1
      H2=H1+DH
      HA=(H1+DH/2.Ø)/FAC1
      IF (NCARDS) 45,45,4Ø
   4Ø TSAT=SAT(TEMP,PRESS,P1,NCARDS)
      HF=THF(TSAT)
      HG=THG(TSAT)
      HFG=THFG(TSAT)
```

```
      CPL=TSH(TL1)
      RHOL=TDF(TL1)
      RHOG=TDG(TSAT)
      DRHO=RHOL-RHOG
      VISCL=TVISCD(TL1)
      CONL=TCOND(TL1)
      PRL=TPRN(TL1)
   45 RE=G*DC/VISCL
      DRGDP(I)=0.0
      IF (NC.GT.1) GO TO 55
      IF (I.LE.(ND+1)) GO TO 70
      IF (J.EQ.2) GO TO 125
      IF (NBB.EQ.1) GO TO 130
      GO TO 70
   50 NCD=1
      IF (NCON.EQ.0) NCON=I
      X(I+1)=0.0
      WRITE (3,270) ZBB
      NDYN=0
   55 IF (NCD) 60,60,70
   60 IF (NBB) 65,65,130
   65 IF (NSB) 70,70,82
C
C     SINGLE PHASE REGION
   70 DHL=DH
      HL2=H2
      TL2=TL1+DH/CPL
      TLA=(TL1+TL2)/2.0
      HT(I)=0.023*CONL/DHE*RE**0.80*PRL**0.40
      HTB(I)=0.80
      PEC=RE*PRL
      HTT=ASB*CONL/DC
      IF (PEC.GT.7.00E+04) HTT=BSB*G*CPL
      HSB=HF-CPL*FLX/HTT
      ALFA(I+1)=0.0
      ALFM=0.0
      X(I+1)=0.0
      CKO(I+1)=1.0
      XM=0.0
      DX=0.0
      UL2=G/RHOL
      UG2=0.0
      GL2=G
      GG2=0.0
      GM2=G2/RHOL
      PHI(I+1)=1.0
      PHIA=1.0
      RHOA=RHOL
      IF (J.GT.1.OR.L.GT.1) GO TO 72
      ALFK(K)=0.0
      CKK(K)=1.0
      PHIK(K)=1.0
      E1=UL1*UL1/2.0
      UL1=G/RHOL
      GM1=G2/RHOL
   72 IF (NC.EQ.1) GO TO 78
      IF (NOSUB) 74,74,76
   74 IF (H2-HF) 78,78,125
```

```
   76 IF (H2-HSB) 78,78,80
   78 TAU1=TAU1+ZC/UL1
      GO TO 150
C
C     SUBCOOLED BOILING REGION
   80 NSB=1
      FHP(I)=1.0
      NSAT=I
      NSUB=I
   82 IF (HF-HSB) 128,128,84
   84 IF (H2-HSB) 50,50,88
   88 IF (NOSUB-1) 90,90,94
   90 FHP(I+1)=1.0/EXP((H2-HSB)/(HF-HSB))
      HL2=HF-(HF-HSB)*FHP(I+1)
      GO TO 96
   94 FHP(I+1)=TANH((H2-HSB)/(HF-HSB))
      HL2=HSB+(HF-HSB)*FHP(I+1)
      FHP(I+1)=1.0-FHP(I+1)*FHP(I+1)
   96 IF (HL2-HF) 100,128,128
  100 X(I+1)=(H2-HL2)/(HG-HL2)
      IF (X(I+1)) 102,102,110
  102 IF (I-NSAT) 104,104,106
  104 NSB=0
      NSAT=0
      GO TO 150
  106 X(I+1)=X(I)
  110 DX=X(I+1)-X(I)
      DHL=HL2-HL1
      HLA=(HL1+HL2)/2.0
      TL2=TL1+DHL/CPL
      TLA=(TL1+TL2)/2.0
      IF (I-NSAT) 120,120,145
  120 IF (NDROP.EQ.0.OR.NIT.EQ.1) WRITE (3,250) ZBB,PEC
      GO TO 145
  125 FHP(I)=0.0
  128 NBB=1
      NSAT=I
      IF (NDROP.EQ.0.OR.NIT.EQ.1) WRITE (3,260) ZBB
C
C     BULK BOILING REGION
  130 HL2=HF
      TL2=TSAT-0.010
      TLA=TL2
      FHP(I+1)=0.0
      X(I+1)=(H2-HF)/HFG
      IF (X(I+1).GE.1.0) X(I+1)=0.999999
      IF (X(I+1)) 50,50,140
  140 DX=X(I+1)-X(I)
  145 GL2=(1.0-X(I+1))*G
      GG2=X(I+1)*G
      UJ=GL2/RHOL+GG2/RHOG
      CKO(I+1)=1.0/(CO(K)+V(K)/UJ)
      DUM=RHOG+DRHO*X(I+1)
      ALFA(I+1)=CKO(I+1)*RHOL*X(I+1)/DUM
      IF (ALFA(I+1).GE.1.0) ALFA(I+1)=0.999999
      ALFM=(ALFA(I)+ALFA(I+1))/2.0
      UL2=GL2/(1.0-ALFA(I+1))/RHOL
      UG2=GG2/ALFA(I+1)/RHOG
```

```
      GM2=GL2*UL2+GG2*UG2
      PHI(I+1)=1.0+AA(K)*((RHOL/RHOG-1.0)*X(I+1))**BB(K)*G**CC(K)
      PHIA=(PHI(I)+PHI(I+1))/2.0
      IF (J.GT.1.OR.L.GT.1) GO TO 148
      E1=((1.0-X(I))*UL1*UL1+X(I)*UG1*UG1)/2.0
      GL1=(1.0-X(I))*G
      GG1=X(I)*G
      UJ=GL1/RHOL+GG1/RHOG
      CKK(K)=1.0/(CO(K)+V(K)/UJ)
      DUM=RHOG+DRHO*X(I)
      ALFK(K)=CKK(K)*RHOL*X(I)/DUM
      IF (ALFK(K).GE.1.0) ALFK(K)=0.999999
      UL1=GL1/(1.0-ALFK(K))/RHOL
      IF (I.EQ.NSUB.OR.I.EQ.NSAT) GO TO 146
      UG1=GG1/ALFK(K)/RHOG
      PHIK(K)=1.0+AA(K)*((RHOL/RHOG-1.0)*X(I))**BB(K)*G**CC(K)
      GM1=GL1*UL1+GG1*UG1
      GO TO 147
  146 UG1=0.0
      PHIK(K)=1.0
      GM1=GL1*UL1
  147 ALFM=(ALFK(K)+ALFA(I+1))/2.0
      PHIA=(PHIK(K)+PHI(I+1))/2.0
  148 XM=(X(I)+X(I+1))/2.0
      RHOA=RHOL-DRHO*ALFM
      TAU2=TAU2+2.0*ZC/(UG1+UG2)
      HTL=0.023*((1.0-XM)*RE)**0.80*PRL**0.40*CONL/DHE
      HTG=AHT*(XM*RE)**BHT*PRL**CHT*CONL/DHE
      HT(I)=HTL+HTG
      HTB(I)=(0.80*HTL+BHT*HTG)/HT(I)
C
C     SINGLE PHASE AND TWO PHASE PRESSURE DROPS
  150 DPG=RHOA*ZC*GC*THETA/FAC1
      DPM=(GM2-GM1)/FAC1
      FK=FRIC(RE,E(K))
      BF(I)=16.22542/(8.11262+RE*E(K)+4.67/SQRT(FK))
      DP1F(I)=4.0*FK*ZC/DC*G2/RHOL/2.0
      DPF=DP1F(I)*PHIA/FAC1
      DPK=0.0
      IF (J.GT.1.OR.L.GT.1) GO TO 151
      E2=((1.0-X(I))*UL1*UL1+X(I)*UG1*UG1)/2.0
      IF (A1.EQ.AC) E2=E1
      PHIR(K)=1.0+1.285*X(I)*(RHOL/RHOG-1.0)
      DPR(K)=RK(K)*G2*PHIR(K)/RHOL/2.0
      DPI(K)=RHOL*RHOG*(E2-E1)/(RHOG+DRHO*X(I))
      DPK=(DPI(K)+DPR(K))/FAC1
      DPRT=DPRT+DPK
  151 DP=DPM+DPF+DPG+DPK

      DPGT=DPGT+DPG
      DPMT=DPMT+DPM
      DPFT=DPFT+DPF
      DPT=DPT+DP
      P2=P1-DP
      PA=(P1+P2)/2.0
      IF (FLX) 154,152,154
  152 HTW(I)=0.0
      GO TO 156
  154 HTW(I)=HT(I)/FLX/CPL
```

```
156 HW(I)=HL1
    HS(I)=HG
    RHOW(I)=RHOL
    RHOS(I)=RHOG
    IF (NCARDS.EQ.Ø) GO TO 162
    IF ((P2-PRESS(1)).GT.Ø.Ø) GO TO 158
    NDYN=Ø
    WRITE (3,24Ø) I,G,FLK,TLA,HA,ALFM,XM,PA,DPMT,DPFT,DPGT,DPRT,DPT
    RETURN
158 IF (NSAT.EQ.Ø.OR.I.LE.NSAT) GO TO 162
    IF (J.GT.1.OR.L.GT.1) GO TO 16Ø
    DRGDK(K)=ADRG*(P1-DPK)**BDRG/FAC1
16Ø DRGDP(I)=ADRG*P1**BDRG/FAC1
162 H1=H2
    HL1=HL2
    TL1=TL2
    GM1=GM2
    GL1=GL2
    GG1=GG2
    UL1=UL2
    UG1=UG2
    P1=P2
    NTOT=I
    IF (K.GT.ND) ZBB=ZBB+ZC/FAC
    Z=Z+ZC/FAC
    IF (NDROP.GT.Ø.AND.NIT.EQ.Ø) GO TO 18Ø
    IF (NPRINT) 18Ø,175,18Ø
175 WRITE (3,24Ø) I,G,FLK,TLA,HA,ALFM,XM,PA,DPMT,DPFT,DPGT,DPRT,DPT
18Ø CONTINUE
    IF (NDROP.GT.Ø.AND.NIT.EQ.Ø) GO TO 19Ø
    IF (NPRINT) 19Ø,19Ø,188
188 WRITE (3,24Ø) K,G,FLK,TLA,HA,ALFM,XM,PA,DPMT,DPFT,DPGT,DPRT,DPT
19Ø CONTINUE
    IF (NDROP.GT.Ø.AND.NIT.EQ.Ø) GO TO 3ØØ

    WRITE (3,28Ø) TAU1,TAU2
    WRITE (3,29Ø) NTOT,NSUB,NSAT
    IF (NOSUB.NE.Ø) NSAT=NSUB
2ØØ FORMAT (1X,' NODE',4X,'MASS',6X,'HEAT',6X,'FLUID',5X,'ENTH-',
   .        4X,'VOID',6X,'FLOW',6X,'STATIC',5X,'MOM',8X,'FRIC',7X,
   .        'GRAV',7X,'REST',7X,'TOTAL'/3X,'NO',5X,'FLUX',6X,'FLUX',
   .        6X,'TEMP',6X,'ALPY',5X,'FRAC',6X,'QUAL',6X,'PRESS',
   .        5(6X,'PDROP'))
2Ø5 FORMAT (1X,' SECT',4X,'MASS',6X,'HEAT',6X,'FLUID',5X,'ENTH-',
   .        4X,'VOID',6X,'FLOW',6X,'STATIC',5X,'MOM',8X,'FRIC',7X,
   .        'GRAV',7X,'REST',7X,'TOTAL'/3X,'NO',5X,'FLUX',6X,'FLUX',
   .        6X,'TEMP',6X,'ALPY',5X,'FRAC',6X,'QUAL',6X,'PRESS',
   .        5(6X,'PDROP'))
21Ø FORMAT (1X,'INLET PIPING REGION')
22Ø FORMAT (1X,'CHANNEL REGION')
23Ø FORMAT (1X,'RISER REGION')
235 FORMAT (1X,'SECTION NUMBER =',I2)
24Ø FORMAT (1X,I4,4F1Ø.2,2F1Ø.4,F1Ø.2,5F11.4)
25Ø FORMAT ('Ø SUBCOOLED BOILING BOUNDARY POSITION =',1PE11.4,
   .        ' CM FROM CHANNEL REGION INLET : PECLET NO =',1PE12.4)
26Ø FORMAT ('Ø SATURATED BOILING BOUNDARY POSITION =',1PE11.4,
   .        ' CM FROM CHANNEL REGION INLET'/)
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270 FORMAT ('0 CONDENSING BOUNDARY POSITION =',F8.3,' CM FROM ',
   .        'CHANNEL REGION INLET : NO CONDENSATION IS ALLOWED IN ',
   .        'DYNAMIC CALCULATIONS'/)
280 FORMAT ('0 SINGLE PHASE REGION TRANSIT TIME =',1PE12.4,' SEC'/
   .         1X,' TWO PHASE REGION TRANSIT TIME =',E12.4,' SEC')
290 FORMAT ('0 TOTAL NUMBER OF CHANNEL NODES =',I3,
   .        ' : SUBCOOLED NODES =',I3,' : SATURATED NODES =',I3)
295 FORMAT ('0 *** WARNING - SECTION',I3,' NUMERICALLY UNSTABLE : ',
   .        'SUBDIVIDE LENGTH BY',I3/)
300 RETURN
    END
    SUBROUTINE BYPASS (NBDYN)
    COMMON /DATA1 / TIN,DTIN,POWR,DPOWR,W,DW,
   .                PIN,PDROP,AP,BP,CP,ASB,BSB,AHT,BHT,CHT,
   .                TSAT,HF,HG,RHOF,RHOG,VISCF,CONF,CPF
    COMMON /DATA2 / DZ(40),A(40),DE(40),PH(40),ANG(40),RK(40),E(40),
   .                PKW(40),TCAP(40),CO(40),V(40),AA(40),BB(40),CC(40)
    COMMON /EXSTAT/ DPT,FAC,FAC3,GC,PI,PUMP,PY,NIT,NODE
    COMMON /BYPAS / ZB(20),AB(20),DB(20),ANGB(20),RKB(20),EB(20),

   .                CONL,CPL,DRHO,HFG,PRL,RHOL,VISCL,WTOT,NB
    COMMON /FUNCNC/ ALFA2,DELP1M,DELP1F,DELP1R,DELP1T,DELP2M,DELP2F,
   .                DELP2G,DELP2R,DELP2T,DELPT,H,S,GD,HD,QSJ,PDIN
    COMMON /BYPASD/ DELPTB
    DIMENSION      BFR(20),DPFB(20),DPRB(20),GB(20)
    COMPLEX*16    ALFA2,DELP1M,DELP1F,DELP1R,DELP1T,DELP2M,DELP2F,
   .                DELP2G,DELP2R,DELP2T,DELPT,H,S,GD,HD,QSJ,PDIN
    COMPLEX*16      DELPTB,GBD
C
    IF (NBDYN) 5,5,15
  5 WB=WTOT-W
    BA1=AB(1)*FAC*FAC
    DO 10 M=1,NB
    BZ=ZB(M)*FAC
    BA=AB(M)*FAC*FAC
    BDH=DB(M)*FAC
    THETB=COS((ANGB(M)*PY))
    BRK=RKB(M)
    BE=EB(M)
    GB(M)=WB/BA
    DPGB=RHOL*BZ*GC*THETB/FAC3
    REL=GB(M)*BDH/VISCL
    FKB=4.0*FRIC(REL,BE)*BZ/BDH
    BFR(M)=16.22542/(8.11262+REL*BE+4.67/SQRT(FKB))
    DPFB(M)=FKB*GB(M)*GB(M)/RHOL/2.0/FAC3
    RB=BA/BA1
    DPRB(M)=GB(M)*GB(M)*(1.0-RB*RB+BRK)/RHOL/2.0/FAC3
    BA1=BA
 10 PDROP=PDROP+DPGB+DPFB(M)+DPRB(M)
    RETURN
 15 A1=AB(1)
    GBD=CMPLX(1.0,0.0)*A(1)/A1
    DELPTB=0.0
    DO 40 I=1,NB
    GBD=GBD*A1/AB(I)
    DELPTB=DELPTB+(DPFB(I)*(2.0-BFB(I))+DPRB(I)+S*GB(I)*ZB(I)*
               FAC)*GBD/GB(I)/FAC3
```

```
40 A1=AB(I)
   RETURN
   END

   SUBROUTINE TFUNCN
   COMMON / CONT / ND,NC,NR,NTIN,NPOW,NW,NF,NDROP,NOSUB,NPRINT,NCH
   COMMON /DATA1 / TIN,DTIN,POWR,DPOWR,W,DW,
  .                PIN,PDROP,AP,BP,CP,ASB,BSB,AHT,BHT,CHT,
  .                TSAT,HF,HG,RHOF,RHOG,VISCF,CONF,CPF
   COMMON /DATA3 / SIGMA,FREQ,DFREQ,FHZ(120),GDYN(120),HDYN(120),
  .                QDYN(120),PDYN(120),CFREQ(10),NDYN,NCFREQ
   COMMON /DATA4 / GDFAC,PDFAC,HDFAC,QDFAC,GCDYN(120),PCDYN(120),
  .                HCDYN(120),QCDYN(120)
   COMMON /EXSTAT/ DPT,FAC,FAC3,GC,PI,PUMP,PY,NIT,NODE
   COMMON /BYPAS / ZB(20),AB(20),DB(20),ANGB(20),RKB(20),EB(20),
  .                CONL,CPL,DRHO,HFG,PRL,RHOL,VISCL,WTOT,NB
   COMMON /BYPASD/ DELPTB
   COMMON /FUNCNC/ ALFA2,DELP1M,DELP1F,DELP1R,DELP1T,DELP2M,DELP2F,
  .                DELP2G,DELP2R,DELP2T,DELPT,H,S,GD,HD,QSJ,PDIN
   COMMON /FUNIN / DGD,DHD,DPD,DQD,GOLD,HOLD,POLD,QOLD
   COMMON /PRINT / AA(60),AT(60),GA(60),GADB(60),GT(60),GTDB(60),
  .                QA(60),QT(60),RA(60),RT(60)
   DIMENSION       CDP1M(5),CDP1F(5),CDP1R(5),CDP1T(5),CDP2M(5),
  .                CDP2F(5),CDP2G(5),CDP2R(5),CDP2T(5),CDPT(5),OM(5)
   COMPLEX*16   ALFA2,DELP1M,DELP1F,DELP1R,DELP1T,DELP2M,DELP2F,
  .                DELP2G,DELP2R,DELP2T,DELPT,H,S,GD,HD,QSJ,PDIN
   COMPLEX*16      DGD,DHD,DPD,DQD,GOLD,HOLD,POLD,QOLD
   COMPLEX*16      DELPTB,PUMPD
   COMPLEX*16      CDP1M,CDP1F,CDP1R,CDP1T,CDP2M,CDP2F,CDP2G,CDP2R,
  .                CDP2T,CDPT
   PY=6.28319
   DOMEG=0.1000*PY*DFREQ
   NA=0
   NM=0
   NT=0
   PUMPD=PUMP
   IF (NB.EQ.0) DELPTB=0.0
   SREAL=SIGMA*PY
   DO 100 J=1,NF
   FHZ(J)=FREQ+(J-1)*DFREQ
   OMEGA=PY*FHZ(J)
   S=CMPLX(SREAL,OMEGA)
   CALL DYNIN (J)
   CALL TCOMP
   DELPT=DELPT/FAC3
   IF (NB.GT.0) CALL BYPASS (1)
   DELPT=DELPT+(DELPTB+PUMPD)*GD
   GT(J)=CDABS(DELPT)
   GTDB(J)=20.0*ALOG10(GT(J))
   RT(J)=DREAL(DELPT)
   QT(J)=DAIMAG(DELPT)
   IF (J-1) 30,30,35
30 IF (RT(J).LT.0.0) NT=1
   GO TO 60
35 IF (QT(J-1).LT.0.0.AND.(QT(J-1)*QT(J)).LT.0.0) GO TO 40
   GO TO 60
40 OMEGA1=PY*FHZ(J-1)
   QT1=QT(J-1)
   OMEGA2=OMEGA
```

```
      QT2=QT(J)
      IT=1
   42 OMEGM=(QT2*OMEGA1-QT1*OMEGA2)/(QT2-QT1)
      S=CMPLX(SREAL,OMEGM)
      IF (NDYN.EQ.1) GO TO 44
      DOM=(OMEGM/PY-FHZ(J-1))/DFREQ
      GD=GOLD+DGD*DOM
      PDIN=POLD+DPD*DOM
      HD=HOLD+DHD*DOM
      QSJ=QOLD+DQD*DOM
   44 CALL TCOMP
      DELPT=DELPT/FAC3
      IF (NB.GT.Ø) CALL BYPASS(1)
      DELPT=DELPT+(DELPTB+PUMPD)*GD
      ORD=DAIMAG(DELPT)
      IF (ABS(ORD)-Ø.ØØ1Ø) 55,46,46
   46 IT=IT+1
      IF (IT.GT.2) GO TO 55
      IF (ORD) 48,55,5Ø
   48 OMEGA1=OMEGM
      QT1=ORD
      GO TO 42
   5Ø OMEGA2=OMEGM
      QT2=ORD
      GO TO 42
   55 NM=NM+1
      DPMIN=DREAL(DELPT)
      IF (DPMIN.LT.Ø.Ø) NT=NT+1
      OM(NM)=OMEGM
      CDP1M(NM)=DELP1M
      CDP1F(NM)=DELP1F
      CDP1R(NM)=DELP1R
      CDP1T(NM)=DELP1T
      CDP2M(NM)=DELP2M
      CDP2F(NM)=DELP2F
      CDP2G(NM)=DELP2G
      CDP2R(NM)=DELP2R
      CDP2T(NM)=DELP2T
      CDPT(NM)=DELPT
      IF (IT.GT.2Ø) WRITE (3,21Ø) NM
   6Ø AT(J)=ATAN2(QT(J),RT(J))*57.2958-NT*36Ø.Ø
      GA(J)=CDABS(ALFA2)
      GADB(J)=2Ø.Ø*ALOG1Ø(GA(J))
      RA(J)=DREAL(ALFA2)
      QA(J)=DAIMAG(ALFA2)
      IF (J-1) 9Ø,9Ø,65
   65 IF (RA(J).LT.Ø.Ø.AND.(QA(J-1)*QA(J)).LT.Ø.Ø) GO TO 7Ø
      GO TO 9Ø
   7Ø OMEGA1=PY*FHZ(J-1)
      QA1=QA(J-1)
      OMEGA2=OMEGA
      QA2=QA(J)
      IT=1
   72 OMEGM=(QA2*OMEGA1-QA1*OMEGA2)/(QA2-QA1)
      S=CMPLX(SREAL,OMEGM)
      IF (NDYN.EQ.1) GO TO 74
      DOM=(OMEGM/PY-FHZ(J-1))/DFREQ
      GD=GOLD+DGD*DOM
```

```
      PDIN=POLD+DPD*DOM
      HD=HOLD+DHD*DOM
      QSJ=QOLD+DQD*DOM
   74 CALL TCOMP
      ORD=DAIMAG(ALFA2)
      IF (ABS(ORD)-1.0E-8) 82,82,76
   76 IT=IT+1
      IF (IT.GT.2) GO TO 82
      IF (ORD) 78,82,80
   78 OMEGA1=OMEGM
      QA1=ORD
      GO TO 72
   80 OMEGA2=OMEGM
      QA2=ORD
      GO TO 72
   82 AMIN=DREAL(ALFA2)
      IF (AMIN.LT.0.0) NA=NA+1
   90 IF (J.EQ.1.AND.RA(J).LT.0.0) NA=1
      AA(J)=ATAN2(QA(J),RA(J))*57.2958-NA*360.0
  100 CONTINUE
      CALL TPRINT
      IF (NF.EQ.1) CALL CPRINT
      IF (NM) 140,140,110
  110 DO 130 J=1,NM
      WRITE (3,200)
      S=CMPLX(SREAL,OM(J))
      DELP1M=CDP1M(J)
      DELP1F=CDP1F(J)
      DELP1R=CDP1R(J)
      DELP1T=CDP1T(J)
      DELP2M=CDP2M(J)
      DELP2F=CDP2F(J)
      DELP2G=CDP2G(J)
      DELP2R=CDP2R(J)
      DELP2T=CDP2T(J)
      DELPT=CDPT(J)
      CALL CPRINT
  130 CONTINUE
  140 IF (NCFREQ) 170,170,150
  150 DO 160 J=1,NCFREQ
      WRITE (3,220)
      OMC=CFREQ(J)*PY
      S=CMPLX(SREAL,OMC)
      JC=CFREQ(J)/DFREQ+1
      CALL DYNIN (JC)
      CALL TCOMP
      DELPT=DELPT/FAC3
      IF (NB.GT.0) CALL BYPASS (1)
      DELPT=DELPT+(DELPTB+PUMPD)*GD
      CALL CPRINT
  160 CONTINUE
  170 CONTINUE
  200 FORMAT (1H1,/////41X,'MINIMUM PURELY REAL PRESSURE DROP',
     .        ' COMPONENTS'/41X,44('-'))
  210 FORMAT ('0TOO MANY ITERATIONS FOR CONVERGENCE : NM =',I2)
  220 FORMAT (1H1,/////38X,'PRESSURE DROP COMPONENTS FOR SPECIFED',

     .        ' FREQUENCY'/38X,48('-'))
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```
300 RETURN
    END
    SUBROUTINE DYNIN (J)
    COMMON /OPTION/ NGDYN,NPDYN,NHDYN,NQDYN,NODES
    COMMON /DATA3 / SIGMA,FREQ,DFREQ,FHZ(120),GDYN(120),HDYN(120),
   .                QDYN(120),PDYN(120),CFREQ(10),NDYN,NCFREQ
    COMMON /DATA4 / GDFAC,PDFAC,HDFAC,QDFAC,GCDYN(120),PCDYN(120),
   .                HCDYN(120),QCDYN(120)
    COMMON /EXSTAT/ DPT,FAC,FAC3,GC,PI,PUMP,PY,NIT,NODE
    COMMON /FUNCNC/ ALFA2,DELP1M,DELP1F,DELP1R,DELP1T,DELP2M,DELP2F,
   .                DELP2G,DELP2R,DELP2T,DELPT,H,S,GD,HD,QSJ,PDIN
    COMMON /FUNIN / DGD,DHD,DPD,DQD,GOLD,HOLD,POLD,QOLD
    COMPLEX*16   ALFA2,DELP1M,DELP1F,DELP1R,DELP1T,DELP2M,DELP2F,
   .                DELP2G,DELP2R,DELP2T,DELPT,H,S,GD,HD,QSJ,PDIN
    COMPLEX*16      DGD,DHD,DPD,DQD,GOLD,HOLD,POLD,QOLD
    GD=0.0
    PDIN=0.0
    HD=0.0
    QSJ=0.0
    IF (NDYN-2) 10,20,30
 10 IF (NGDYN.EQ.1) GD=CMPLX(GDYN(1),0.0)*GDFAC
    IF (NPDYN.EQ.1) PDIN=CMPLX(PDYN(1),0.0)*PDFAC*FAC3
    IF (NHDYN.EQ.1) HD=CMPLX(HDYN(1),0.0)*HDFAC*FAC3
    IF (NQDYN.EQ.1) QSJ=CMPLX(QDYN(1),0.0)*QDFAC
    RETURN
 20 GCDYN(J)=0.0
    PCDYN(J)=0.0
    HCDYN(J)=0.0
    QCDYN(J)=0.0
 30 GOLD=GD
    POLD=PDIN
    HOLD=HD
    QOLD=QSJ
    IF (NGDYN.GT.0) GD=CMPLX(GDYN(J),GCDYN(J))*GDFAC
    IF (NPDYN.GT.0) PDIN=CMPLX(PDYN(J),PCDYN(J))*PDFAC*FAC3
    IF (NHDYN.GT.0) HD=CMPLX(HDYN(J),HCDYN(J))*HDFAC*FAC3
    IF (NQDYN.GT.0) QSJ=CMPLX(QDYN(J),QCDYN(J))*QDFAC
    DGD=-GOLD
    DPD=-POLD
    DHD=-HOLD
    DQD=-QOLD
    IF (CDABS(GD).GT.1.0E-30) DGD=GD-GOLD
    IF (CDABS(PDIN).GT.1.0E-30) DPD=PDIN-POLD
    IF (CDABS(HD).GT.1.0E-30) DHD=HD-HOLD
    IF (CDABS(QSJ).GT.1.0E-30) DQD=QSJ-QOLD
    RETURN
    END
    SUBROUTINE TCOMP
    COMMON / CONT / ND,NC,NR,NTIN,NPOW,NW,NF,NDROP,NOSUB,NPRINT,NCH
    COMMON /DATA1 / TIN,DTIN,POWR,DPOWR,W,DW,
   .                PIN,PDROP,AP,BP,CP,ASB,BSB,AHT,BHT,CHT,
   .                TSAT,HF,HG,RHOF,RHOG,VISCF,CONF,CPF
    COMMON /DATA2 / DZ(40),A(40),DE(40),PH(40),ANG(40),RK(40),E(40),
   .                PKW(40),TCAP(40),CO(40),V(40),AA(40),BB(40),CC(40)
    COMMON /DATA3 / SIGMA,FREQ,DFREQ,FHZ(120),GDYN(120),HDYN(120),
   .                QDYN(120),PDYN(120),CFREQ(10),NDYN,NCFREQ
    COMMON /EXSTAT/ DPT,FAC,FAC3,GC,PI,PUMP,PY,NIT,NODE
    COMMON /STATIC/ ALFA(601),BF(600),CKO(601),DP1F(600),DRGDP(600),
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     .                    HS(600),HT(600),HTW(600),HW(600),PHI(601),
     .                    FHP(601),RHOS(600),RHOW(600),HTB(600),ZCL(2),
     .                    X(601),ALFK(40),CKK(40),DPI(40),DPR(40),DRGDK(40),
     .                    PHIK(40),PHIR(40),NSUB,NSAT,NCON,NTOT,MODE(40),
     .                    MBOIL(40,50)
     .COMMON /FUNCNC/ ALFA2,DELP1M,DELP1F,DELP1R,DELP1T,DELP2M,DELP2F,
     .                    DELP2G,DELP2R,DELP2T,DELPT,H,S,GD,HD,QSJ,PDIN
      COMPLEX*16    ALFA2,DELP1M,DELP1F,DELP1R,DELP1T,DELP2M,DELP2F,
     .                    DELP2G,DELP2R,DELP2T,DELPT,H,S,GD,HD,QSJ,PDIN
      COMPLEX*16    ALFA1,E1,E2,GD1,GD2,GF1,GF2,GG1,GG2,GM1,GM2,H1,H2,
     .                    PD1,PHI1,PHI2,PHIR1,PS,PT,PTEX,UF1,UF2,UG1,UG2,
     .                    X1,X2,QSD,TAU1,TAU2,TAUP,TAUS,TSUB
      COMPLEX*16 ALFA4
C
C     CALCULATION OF TRANSFER FUNCTION COMPONENTS FOR A SPECIFIED FREQUE
C
      NPD=1
      PI=3.14159/180.0
      EHC=1.0
      A1=A(1)
      ULI=W/RHOW(1)/A1/FAC/FAC
      GD1=GD
      H=HD
      PD1=PDIN
      ALFA1=0.0
      ALFA2=0.0
      X1=0.0
      GG1=0.0
      UG1=0.0
      PHI1=0.0
      PHIR1=0.0
      E1=ULI*GD1
      DELP1M=0.0
      DELP1F=0.0
      DELP1R=0.0
      DELP2M=0.0
      DELP2F=0.0
      DELP2G=0.0
      DELP2R=0.0
      I=0
      DO 200 K=1,NCH
      NODE=MODE(K)
      GD1=GD1*A1/A(K)
      THETA=COS(PI*ANG(K))
      TAUF=TCAP(K)*FAC3/PH(K)/FAC
      PKWK=PKW(K)*FAC3
      IF (K.GT.ND.AND.K.LE.(ND+NC)) PKWK=POWR*PKWK
      AC=A(K)*FAC*FAC
      G=W/AC
      Q=PKWK/AC/DZ(K)/FAC
      DO 160 J=1,NODE
      NBOIL=MBOIL(K,J)
      ZC=DZ(K)*FAC/NODE/NBOIL
      IF (NC.GT.1) GO TO 10
      IF (K.LE.ND.OR.K.GT.(ND+NC)) GO TO 10
      ZC=ZCL(J)
   10 DO 150 L=1,NBOIL
```

```
      I=I+1
      TAUH=TAUF/HT(I)
      PS=1.0/(1.0+TAUH*S)
      QSD=0.0
      IF (NPD.EQ.0) PD1=0.0
      IF (K.GT.ND.AND.K.LE.(ND+NC)) QSD=POWR*QSJ
      IF (NSAT.GT.0.AND.I.GE.NSAT) GO TO 100
C
C     SINGLE PHASE REGION

      IF (CDABS(S)) 20,20,15
   15 PT=S/G*(RHOW(I)+Q*HTW(I)*TAUH*PS)
      PTEX=CDEXP((-PT*ZC))
      H=H*PTEX+Q/G*(PS*QSD-(0.20*TAUH*S+1.0)*PS*GD1/G)*(1.0-PTEX)/PT
      GO TO 25
   20 H=H+Q*ZC*(QSD-GD1/G)/G
   25 DELP1M=S*ZC*GD1+DELP1M
      DELP1F=DP1F(I)*(2.0-BF(I))*GD1/G+DELP1F
      ULI=G/RHOW(I)
      IF (J.GT.1.OR.L.GT.1) GO TO 30
      E2=ULI*GD1
      IF (A(K).EQ.A1) E2=E1
      DELP1R=E2-E1+2.0*DPR(K)*GD1/G+DELP1R
   30 E1=ULI*GD1
      DELP1T=DELP1M+DELP1F+DELP1R
      DELPT=DELP1T
      GO TO 150
C
C***SUBCOOLED AND SATURATED BOILING REGIONS.
  100 RHOD=RHOW(I)-RHOS(I)
      HWS=HS(I)-HW(I)
      FHPI=FHP(I)
      FHPO=FHP(I+1)
      XI=X(I)
      XO=X(I+1)
      DX=XO-XI
      ALFAI=ALFA(I)
      GGI=XI*G
      GLI=(1.0-XI)*G
      PHII=PHI(I)
      CKI=CKO(I)
      DRGDPI=DRGDP(I)
      IF (J.GT.1.OR.L.GT.1) GO TO 105
      ALFAI=ALFK(K)
      PHII=PHIK(K)
      CKI=CKK(K)
      DRGDPI=DRGDK(K)
      XE1=XI*(1.0-XI)*DRGDPI/RHOS(I)
  105 UGI=0.0
      ULI=GLI/(1.0-ALFAI)/RHOW(I)
      ALFAO=ALFA(I+1)

      ALFM=(ALFAI+ALFAO)/2.0
      GGO=XO*G
      GLO=(1.0-XO)*G
      UGO=GGO/ALFAO/RHOS(I)
      ULO=GLO/(1.0-ALFAO)/RHOW(I)
      PHIO=PHI(I+1)
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      XXD=RHOW(I)*DRGDPI/RHOD/RHOS(I)
      XXI=(RHOS(I)+RHOD*XI)**2.0/CKI/RHOW(I)/RHOS(I)
      XXO=(RHOS(I)+RHOD*XO)**2.0/CKO(I+1)/RHOW(I)/RHOS(I)
      XXP=2.0*ALFM*DRGDPI
      XXR=XO*(1.0-XO)*DRGDPI/RHOS(I)
      XNI=RHOW(I)*(CKI+(1.0-CKI)*FHPI)-RHOD*ALFAI
      XNO=RHOW(I)*(CKO(I+1)+(1.0-CKO(I+1))*FHPO)-RHOD*ALFAO
      XAI=RHOD*(1.0-(1.0-XI)*FHPI)/XXI/HWS
      XAO=RHOD*(1.0-(1.0-XO)*FHPO)/XXO/HWS
      XBI=DRGDPI*(ALFAI-XI*(1.0-XI)*RHOD/XXI/RHOS(I))
      XBO=DRGDPI*(ALFAO-XO*(1.0-XO)*RHOD/XXO/RHOS(I))
C
C***BOILING BOUNDARY EQUATIONS.
      IF (I.GT.NSAT) GO TO 110
      H1=H
      X1=(1.0-FHPI)*H1/HWS
      ALFA1=X1/XXI
      GG1=G*X1
      GF1=GD1-GG1
      UF1=GF1/RHOW(I)+ULI*ALFA1
      UG1=0.0
      GM1=2.0*ULI*GD1
      GO TO 120
  110 UGI=GGI/ALFAI/RHOS(I)
      IF (J.GT.1.OR.L.GT.1) GO TO 120
      GG1=XI*GD1+G*X1
      GF1=GD1-GG1
      ALFA1=(X1-XE1*PD1)/XXI
      UG1=UGI*(GG1/GGI-ALFA1/ALFAI-DRGDPI*PD1/RHOS(I))
      UF1=ULI*(GF1/GLI+ALFA1/(1.0-ALFAI))
      GM1=ULI*GF1+GLI*UF1+UGI*GG1+GGI*UG1
      PHI1=(PHII-1.0)*(BB(K)*(X1/XI-XXD*PD1)+CC(K)*GD1/G)
      PHIR1=(PHIR(K)-1.0)*(X1/XI-XXD*PD1)
  120 TAUS=ZC*Q*(1.0+(1.0-HTR(I))*TAUH*S)*PS/G
      TSUB=Q*TAUH*PS*HTW(I)
      TAU1=ZC*(XNI+FHPI*TSUB+XAI*TAUS/2.0)/2.0/G
      TAU2=ZC*(XNO+FHPO*TSUB+XAO*TAUS/2.0)/2.0/G
      TAUP=ZC*(ALFM+(XBI+XBO)*TAUS/4.0)/G
      H2=((1.0-S*TAU1)*H1+Q*ZC*PS/G*QSD-TAUS*GD1/G+S*TAUP*PD1)/
     .   (1.0+S*TAU2)
      X2=(1.0-(1.0-XO)*FHPO)*H2/HWS
      ALFA2=(X2-XXR*PD1)/XXO
      IF(K.EQ.(NCH-1))ALFA4=ALFA2
      GD2=GD1+S*ZC*(RHOD*(ALFA1+ALFA2)-XXP*PD1)/2.0
      GG2=G*X2+XO*GD2
      GF2=GD2-GG2
      UG2=UGO*(GG2/GGO-ALFA2/ALFAO-DRGDPI*PD1/RHOS(I))
      UF2=ULO*(GF2/GLO+ALFA2/(1.0-ALFAO))
      GM2=ULO*GF2+GLO*UF2+UGO*GG2+GGO*UG2
      PHI2=(PHIO-1.0)*(BB(K)*(X2/XO-XXD*PD1)+CC(K)*GD2/G)
      DELP2M=GM2-GM1+S*ZC*(GD1+GD2)/2.0+DELP2M
      DELP2F=DP1F(I)*((2.0-BF(I))*(PHIO*GD2+PHII*GD1)/G
     .       +PHI1+PHI2)/2.0+DELP2F
      DELP2G=-(RHOD*(ALFA1+ALFA2)-XXP*PD1)*ZC*GC*THETA/2.0+DELP2G
      IF (J.GT.1.OR.L.GT.1) GO TO 125
      E2=(UGI*UGI-ULI*ULI)*X1/2.0+(1.0-XI)*ULI*UF1+XI*UGI*UG1
      IF (A(K).EQ.A1) E2=E1
      RHOM=RHOD/(RHOS(I)+RHOD*XI)
```

```
      RHO=RHOM*RHOW(I)*RHOS(I)/RHOD
      XEK=XE1/(1.0-XI)*RHOW(I)/RHOD
      DELP2R=RHO*(E2-E1)-RHOM*DPI(K)*(X1-XEK*PD1)+
     .      DPR(K)*(2.0*GD1/G+PHIR1/PHIR(K))+DELP2R
  125 DELP2T=DELP2M+DELP2F+DELP2G+DELP2R
      DELPT=DELP1T+DELP2T
      E1=(UGO*UGO-ULO*ULO)*X2/2.0+(1.0-XO)*ULO*UF2+XO*UGO*UG2
      ALFA1=ALFA2
      GD1=GD2
      GG1=GG2
      GF1=GF2
      GM1=GM2
      H1=H2
      UF1=UF2
      UG1=UG2
      PHI1=PHI2
      X1=X2
  150 PD1=PDIN-DELPT
  160 CONTINUE
  200 A1=A(K)
      ALFA2=ALFA4
      RETURN
      END
      SUBROUTINE TPRINT
      COMMON / CONT / ND,NC,NR,NTIN,NPOW,NW,NF,NDROP,NOSUB,NPRINT,NCH
      COMMON /DATA1 / TIN,DTIN,POWR,DPOWR,W,DW,
     .                PIN,PDROP,AP,BP,CP,ASB,BSB,AHT,BHT,CHT,
     .                TSAT,HF,HG,RHOF,RHOG,VISCF,CONF,CPF
      COMMON /DATA3 / SIGMA,FREQ,DFREQ,FHZ(120),GDYN(120),HDYN(120),
     .                QDYN(120),PDYN(120),CFREQ(10),NDYN,NCFREQ
      COMMON /PRINT / AA(60),AT(60),GA(60),GADB(60),GT(60),GTDB(60),
     .                QA(60),QT(60),RA(60),RT(60)
      COMMON /CPLOT / TPLT1(20),TPLT2(20),NPLOT
      COMMON /ERROR / CSPEC(80),CPHASE(80),ASPEC(80),APHASE(80),NERR
      REAL  XX(2),YY(2)
   15 WRITE (3,200)
      DO 20 J=1,NF
   20 WRITE (3,210) FHZ(J),RT(J),QT(J),GT(J),GTDB(J),AT(J),RA(J),QA(J),
     .              GA(J),GADB(J),AA(J)
      IF (NERR.GE.0) GO TO 30
      SUM=0.0
      SUMA=0.0
      WRITE (3,300)
      DO 25 J=1,NF
      ERR=CSPEC(J)-GT(J)
      ERR=ERR*ERR
      SUM=SUM+ERR
      ERRA=ASPEC(J)-GA(J)
      ERRA=ERRA*ERRA
      SUMA=SUMA+ERRA
   25 WRITE (3,290) FHZ(J),CSPEC(J),GT(J),ERR,ASPEC(J),GA(J),ERRA
      SUM=SUM/NF
      SUMA=SUMA/NF
      WRITE (3,310) SUM,SUMA
   30 IF (NF.EQ.1) GO TO 100
      NLOG=1
      IF (NPLOT) 35,100,35
```

```
 35 XX(1)=Ø.Ø
    XX(2)=CSPEC(1)
    YY(1)=CPHASE(1)
    YY(2)=YY(1)
    CALL PLIM (NF,CSPEC,CPHASE,XX,YY)
    GO TO 37
 36 XX(1)=Ø.Ø
    XX(2)=GT(1)
    YY(1)=AA(1)
    YY(2)=YY(1)
 37 CALL PLIM (NF,GT,AA,XX,YY)
    CALL TPLOT (FHZ,GT,CSPEC,AT,CPHASE,XX,YY,NF,NPLOT)
    CALL XYPEXT (Ø.,-1.Ø,TPLT1,8Ø,2,Ø)
    XX(1)=Ø.Ø
    IF (NPLOT.GT.Ø) GO TO 44
    XX(2)=ASPEC(1)
    YY(1)=APHASE(1)
    YY(2)=YY(1)
    CALL PLIM (NF,ASPEC,APHASE,XX,YY)
    GO TO 46
 44 XX(2)=GA(1)
    YY(1)=AA(1)
    YY(2)=YY(1)
 46 CALL PLIM (NF,GA,AA,XX,YY)
    CALL TPLOT (FHZ,GA,ASPEC,AA,APHASE,XX,YY,NF,NPLOT)
    CALL XYPEXT (Ø.,-1.Ø,TPLT2,8Ø,2,Ø)
    CALL XYEND
2ØØ FORMAT ('1',23X,'TOTAL PRESSURE DROP PERTURBATION',31X,'EXIT ',
   .        'VOID FRACTION PERTURBATION'/24X,32('-'),31X,31('-')/3X,
   .        'FREQ',5X,'REAL',8X,'IMAG',8X,'GAIN',8X,'GAIN DB',5X,
   .        'PHASE',1ØX,'REAL',8X,'IMAG',8X,'GAIN',8X,'GAIN DB',5X,
   .        'PHASE')
21Ø FORMAT (1X,F6.4,1P5E12.3,2X,'*',5E12.3)
29Ø FORMAT (1X,F6.4,1P3E12.3,2X,'*',3E12.3)
3ØØ FORMAT ('1 ERROR ANALYSIS IN CROSS-SPEC DENSITY MODULUS'/
   .         3X,'FREQ',5X,'EXPT',8X,'THEORY',6X,'SQ ERR',
   .         9X,'EXPT',8X,'THEORY',6X,'SQ ERR'/)
31Ø FORMAT ('Ø',1ØX,'MEAN SQUARE ERROR =',1PE12.4,8X,'MEAN SQUARE ',
   .         'ERROR =',E12.4)
1ØØ RETURN
    END
    SUBROUTINE PLIM (NF,YA,YB,X,Y)
    DIMENSION YA(NF),YB(NF),X(2),Y(2)
    DO 1Ø J=2,NF
    IF (YA(J).GT.X(2)) X(2)=YA(J)
    IF (YB(J).LT.Y(1)) Y(1)=YB(J)
    IF (YB(J).GT.Y(2)) Y(2)=YB(J)
 1Ø CONTINUE
    RETURN
    END
    SUBROUTINE TPLOT (X,YAA,YAB,YBA,YBB,XX,YY,NF,NPLOT)
    DIMENSION X(NF),YAA(NF),YAB(NF),YBA(NF),YBB(NF),XX(2),YY(2)
    COMMON /XYCOM$ / IDUM(3),HOR(2),VER(2)
    REAL*4  ZERO(2)/2*Ø.Ø/
    DO 2Ø I=1,2
    IF (I.EQ.2) GO TO 1Ø
    CALL XYSKEW (1,1.Ø,6.Ø)
```

```
      CALL XYPAPE (-6.,-4.,X(1),X(NF),XX(1),XX(2))
      CALL XYNAMY ('MODULUS',7)
      CALL XYNAMX ('FREQUENCY (HZ)',14)
      CALL XYSETL (2)
      CALL XYLINE (X,YAA,NF)
      IF (NPLOT.GT.0) GO TO 20
      CALL XYSETL (1)
      CALL XYLINE (X,YAB,NF)
      GO TO 20
   10 CALL XYSKEW (-1,0.,-5,0)
      CALL XYPAPE (-6.,-4.,X(1),X(NF),YY(1),YY(2))
      CALL XYNAMY ('PHASE',5)
      CALL XYNAMX ('FREQUENCY (HZ)',14)
      IF (VER(1)*VER(2).GT.0.0) GO TO 15
      CALL XYSETL (1)
      CALL XYLINE (HOR,ZERO,2)
   15 CALL XYSETL (2)
      CALL XYLINE (X,YBA,NF)
      IF (NPLOT.GT.0) GO TO 20
      CALL XYSETL (1)
      CALL XYLINE (X,YBB,NF)
   20 CONTINUE
      RETURN
      END
      SUBROUTINE CPRINT
      COMMON /EXSTAT/ DPT,FAC,FAC3,GC,PI,PUMP,PY,NIT,NODE
      COMMON /FUNCNC/ ALFA2,DELP1M,DELP1F,DELP1R,DELP1T,DELP2M,DELP2F,
     .                DELP2G,DELP2R,DELP2T,DELPT,H,S,GD,HD,QSJ,PDIN
      COMPLEX*16    ALFA2,DELP1M,DELP1F,DELP1R,DELP1T,DELP2M,DELP2F,
     .                DELP2G,DELP2R,DELP2T,DELPT,H,S,GD,HD,QSJ,PDIN,COMP
      WRITE (3,100)
      PY=6.28319
      PI=57.2958
      SREAL=DREAL(S)/PY
      SIMAG=DAIMAG(S)/PY
      WRITE (3,120) SREAL,SIMAG
      WRITE (3,110)
      DO 20 J=1,10
      IF (J.EQ.1)  COMP=DELP1M/FAC3
      IF (J.EQ.2)  COMP=DELP1F/FAC3
      IF (J.EQ.3)  COMP=DELP1R/FAC3
      IF (J.EQ.4)  COMP=DELP1T/FAC3
      IF (J.EQ.5)  COMP=DELP2M/FAC3
      IF (J.EQ.6)  COMP=DELP2F/FAC3
      IF (J.EQ.7)  COMP=DELP2G/FAC3
      IF (J.EQ.8)  COMP=DELP2R/FAC3
      IF (J.EQ.9)  COMP=DELP2T/FAC3
      IF (J.EQ.10) COMP=DELPT
      CREAL=DREAL(COMP)
      CIMAG=DAIMAG(COMP)
      CGAIN=CDABS(COMP)
      IF (J.GT.1) GO TO 5
      IF (CDABS(S)) 10,10,5
    5 CDB=0.0
      IF (CGAIN.GT.0.0) CDB=20.0*ALOG10(CGAIN)
      CPHASE=0.0
      IF (CREAL.EQ.0.0.AND.CIMAG.GT.0.0) CPHASE=90.0
      IF (CREAL.EQ.0.0.AND.CIMAG.LT.0.0) CPHASE=-90.0
```

```
      IF (CREAL.NE.0.0) CPHASE=ATAN2(CIMAG,CREAL)*PI
      GO TO 15
   10 CDB=0.0
      CPHASE=0.0
      IF (CREAL.EQ.0.0.AND.CIMAG.GT.0.0) CPHASE=90.0
      IF (CREAL.EQ.0.0.AND.CIMAG.LT.0.0) CPHASE=-90.0
   15 IF (J.EQ.1)  WRITE (3,130) CREAL,CIMAG,CGAIN,CDB,CPHASE
      IF (J.EQ.2)  WRITE (3,140) CREAL,CIMAG,CGAIN,CDB,CPHASE
      IF (J.EQ.3)  WRITE (3,150) CREAL,CIMAG,CGAIN,CDB,CPHASE
      IF (J.EQ.4)  WRITE (3,160) CREAL,CIMAG,CGAIN,CDB,CPHASE
      IF (J.EQ.5)  WRITE (3,170) CREAL,CIMAG,CGAIN,CDB,CPHASE
      IF (J.EQ.6)  WRITE (3,180) CREAL,CIMAG,CGAIN,CDB,CPHASE
      IF (J.EQ.7)  WRITE (3,190) CREAL,CIMAG,CGAIN,CDB,CPHASE
      IF (J.EQ.8)  WRITE (3,200) CREAL,CIMAG,CGAIN,CDB,CPHASE

      IF (J.EQ.9)  WRITE (3,210) CREAL,CIMAG,CGAIN,CDB,CPHASE
      IF (J.EQ.10) WRITE (3,220) CREAL,CIMAG,CGAIN,CDB,CPHASE
   20 WRITE (3,110)
  100 FORMAT (//41X,'REAL',13X,'IMAGINARY',13X,'GAIN',14X,'GAIN DB',
     .           15X,'PHASE'/41X,4('-'),13X,9('-'),13X,4('-'),14X,7('-'),
     .           15X,5('-'))
  110 FORMAT(1X,125('-'))
  120 FORMAT (/' LAPLACE OPERATOR (HZ)',14X,1PE12.4,8X,E12.4)
  130 FORMAT (' 1-PHASE MOMENTUM',19X,4(1PE12.4,8X),0PF9.2)
  140 FORMAT (' 1-PHASE FRICTION',19X,4(1PE12.4,8X),0PF9.2)
  150 FORMAT (' 1-PHASE RESTRICTION',16X,4(1PE12.4,8X),0PF9.2)
  160 FORMAT (' 1-PHASE TOTAL',22X,4(1PE12.4,8X),0PF9.2)
  170 FORMAT (' 2-PHASE MOMENTUM',19X,4(1PE12.4,8X),0PF9.2)
  180 FORMAT (' 2-PHASE FRICTION',19X,4(1PE12.4,8X),0PF9.2)
  190 FORMAT (' 2-PHASE GRAVITY',20X,4(1PE12.4,8X),0PF9.2)
  200 FORMAT (' 2-PHASE RESTRICTION',16X,4(1PE12.4,8X),0PF9.2)
  210 FORMAT (' 2-PHASE TOTAL',22X,4(1PE12.4,8X),0PF9.2)
  220 FORMAT (' CHANNEL TOTAL',22X,4(1PE12.4,8X),0PF9.2)
      RETURN
      END
      FUNCTION FRIC (REW,E)
      RE=ABS(REW)
      FRICL=16.0/RE
      FF=0.00080
      DO 30 N=1,50
      F=1.0/(4.0*ALOG10(RE*FF/(4.67+E*RE*FF))+2.28)
      IF (ABS(1.0-FF*FF/(F*F)).LE.0.0010) GO TO 50
      FF=ABS(F)
   30 CONTINUE
      FRIC=F*F
      WRITE (3,40) RE,E,FRIC
   40 FORMAT (1X,'FRICTION FACTOR ITERATION DID NOT CONVERGE : RE =',
     .E12.4,'    E =',E12.4,'    F =',E12.4)
   50 FRIC=F*F
      IF (FRIC.LT.FRICL) FRIC=FRICL
      RETURN
      END
      SUBROUTINE TABLES
      COMMON /TABLE / TEMP(100),PRESS(100),ENTHF(100),ENTHFG(100),
     .                ENTHG(100),SPVF(100),SPVG(100),DENF(100),

     .                DENG(100),VISCDF(100),CONDF(100),SPHF(100),
     .                PRF(100),FAC1,FAC2,ADRG,BDRG,NCARDS
```

```
      NCARD=NCARDS
      NCARDS=IABS(NCARDS)
      SP=0.0
      SPP=0.0
      SVG=0.0
      SVP=0.0
      SVV=0.0
      DO 10 I=1,NCARDS
      ENTHF(I)=ENTHF(I)*FAC1
      ENTHG(I)=ENTHG(I)*FAC1
      ENTHFG(I)=ENTHG(I)-ENTHF(I)
      DENF(I)=1.0/SPVF(I)
      DENG(I)=1.0/SPVG(I)
      VISCDF(I)=VISCDF(I)*FAC2
      SPHF(I)=SPHF(I)*FAC1
      PRF(I)=SPHF(I)*VISCDF(I)/CONDF(I)
      PLOG=ALOG(PRESS(I))
      VGLOG=ALOG(SPVG(I))
      SP=SP+PLOG
      SPP=SPP+PLOG*PLOG
      SVG=SVG+VGLOG
      SVP=SVP+PLOG*VGLOG
   10 SVV=SVV+VGLOG*VGLOG
      A=SVP-SP*SVG/NCARDS
      B=SPP-SP*SP/NCARDS
      C=SVV-SVG*SVG/NCARDS
      BDRG=A/B
      ADRG=EXP((SVG-BDRG*SP)/NCARDS)
      ADRG=-BDRG/ADRG
      BDRG=-(1.0+BDRG)
      CORR=ABS(A)/SQRT(ABS(B*C))
      IF (NCARD.GT.0) WRITE (3,100) ADRG,BDRG,CORR
  100 FORMAT ('0POWER LAW FIT FOR DRHOG/DP = ADRG*PRESS(I)**BDRG :'/
     .         1X,'COEFFICIENTS ADRG =',1PE14.6,' : BDRG =',E14.6,
     .         ' : CORRELATION COEFFICIENT =',E14.6)
      RETURN
      END
      FUNCTION P(T)
      COMMON /TABLE / TEMP(100),PRESS(100),ENTHF(100),ENTHFG(100),
     .                ENTHG(100),SPVF(100),SPVG(100),DENF(100),
     .                DENG(100),VISCDF(100),CONDF(100),SPHF(100),
     .                PRF(100),FAC1,FAC2,ADRG,BDRG,NCARDS
      CALL POLATE (TEMP,PRESS,T,FUNT,NCARDS)
      P=FUNT
      RETURN
      ENTRY THF(T)
      CALL POLATE (TEMP,ENTHF,T,FUNT,NCARDS)
      THF=FUNT
      RETURN
      ENTRY THFG(T)
      CALL POLATE (TEMP,ENTHFG,T,FUNT,NCARDS)
      THFG=FUNT
      RETURN
      ENTRY THG(T)
      CALL POLATE (TEMP,ENTHG,T,FUNT,NCARDS)
      THG=FUNT
      RETURN
      ENTRY TVF(T)
```

```
      CALL POLATE (TEMP,SPVF,T,FUNT,NCARDS)
      TVF=FUNT
      RETURN
      ENTRY TVG(T)
      CALL POLATE (TEMP,SPVG,T,FUNT,NCARDS)
      TVG=FUNT
      RETURN
      ENTRY TDF(T)
      CALL POLATE (TEMP,DENF,T,FUNT,NCARDS)
      TDF=FUNT
      RETURN
      ENTRY TDG(T)
      CALL POLATE (TEMP,DENG,T,FUNT,NCARDS)
      TDG=FUNT
      RETURN
      ENTRY TVISCD(T)
      CALL POLATE (TEMP,VISCDF,T,FUNT,NCARDS)
      TVISCD=FUNT
      RETURN
      ENTRY TCOND(T)
      CALL POLATE (TEMP,CONDF,T,FUNT,NCARDS)
      TCOND=FUNT
      RETURN
      ENTRY TSH(T)
      CALL POLATE (TEMP,SPHF,T,FUNT,NCARDS)
      TSH=FUNT
      RETURN
      ENTRY TPRN(T)
      CALL POLATE (TEMP,PRF,T,FUNT,NCARDS)
      TPRN=FUNT
      RETURN
      END
      FUNCTION SAT(Y,X,P,NCARDS)
      DIMENSION Y(NCARDS),X(NCARDS)
      DO 10 J=1,NCARDS
      IF (P.LE.X(1)) GO TO 15
      IF (P.LT.X(J)) GO TO 20
   10 CONTINUE
   15 WRITE (3,100) J,X(J),X(NCARDS),P
  100 FORMAT (1X,I5,5X,'FUNCTION SAT - PRESSURE OUTSIDE DATA RANGE :',
     .        ' MINIMUM =',1PE10.3,' MAXIMUM =',E10.3,' PRESSURE =',
     .        E10.3)
      SAT=Y(1)
      RETURN
   20 GRAD=(Y(J)-Y(J-1))/(X(J)-X(J-1))
      SAT =Y(J-1)+GRAD*(P-X(J-1))
      RETURN
      END
      SUBROUTINE POLATE (X,Y,T,FUNT,NCARDS)
      DIMENSION X(NCARDS),Y(NCARDS)
      DO 10 J=1,NCARDS
      IF (T.LT.X(1)) GO TO 15
      IF (T.LT.X(J)) GO TO 20
   10 CONTINUE
   15 WRITE (3,100) J,X(J),X(NCARDS),T
  100 FORMAT(1X,I5,5X,'POLATE - TEMPERATURE OUTSIDE DATA RANGE: MINI',
     .       'MUM =',1PE10.3,' MAXIMUM =',E10.3,' TEMPERATURE =',E10.3)
```

```
      FUNT=Y(J)
      RETURN
   20 GRAD=(Y(J)-Y(J-1))/(X(J)-X(J-1))
      FUNT=Y(J-1)+GRAD*(T-X(J-1))
      RETURN
      END
```

# APPENDIX E
## 'LOCO' CODE SUBPROGRAM FUNCTIONS

| SUBPROGRAM | FUNCTION |
|---|---|
| MAIN | Reads, writes input data; calls subroutines TABLES (\|NCARDS\|>0), EXEC. |
| EXEC | Control subroutine; calls subroutines BYPASS (NB>0), STATE, TFUNCN (NDYN>0); calculates flow rate for specified pressure drop (NDROP = 1). |
| STATE | Calculates steady state variables (mass fluxes, velocities, void fraction, pressure drops, etc.) in each space node between channel inlet and outlet. |
| BYPASS | Calculates the steady state and dynamic pressure drop in the bypass (NB sections). |
| TFUNCN | Control subroutine for dynamic calculations; calls subroutines DYNIN, TCOMP, BYPASS (NB>0), TPRINT, CPRINT; calculates crossover frequency when perturbed pressure drop crosses real axis of polar plot. |
| DYNIN | Edits the dynamic inputs read in as data. |
| TCOMP | Calculates the single phase and two-phase region perturbed pressure drop components and the perturbed void fraction (channel exit) for a specified value of the Laplace operator (s). |
| TPRINT | Prints the total pressure drop and channel exit void fraction frequency response functions; calls NORGRA (NPRINT ⩽ 2). |
| CPRINT | Prints the single phase and two-phase region perturbed pressure drop components for a specified value of the Laplace operator (s). |

| SUBPROGRAM | FUNCTION |
|---|---|
| TPLOT | Plots the total pressure drop and channel exit void fraction frequency response functions (magnitude, phase and polar plots). |
| FRIC | Calculates single phase friction factor (STATE, BYPASS). |
| TABLES | Calculates the complete fluid properties data from the input data (\|NCARDS\|>0). |
| SAT | Calculates local saturation temperature from the local static pressure. |
| POLATE | Linear interpolation subroutine for fluid property calculations. |

APPENDIX F

SAMPLE TEST CHANNEL DIMENSIONS

| REGION | LENGTH (cm) | DIAMETER (cm) | FLOW AREA ($cm^2$) | HYDRAULIC DIAMETER (cm) | |
|---|---|---|---|---|---|
| Inlet* | 52.7 | 2.58 ID | 5.238 | 2.58 | Horizontal pipe with venturi flowmeter 45 dia. from inlet. |
| | 17.8 | 0.953 ID<br>1.352 OD | 0.722 | 0.399 | Vertical annulus with T-junction at inlet. |
| Channel* | 91.5 | 0.953 ID<br>1.352 OD | 0.722 | 0.399 | Vertical annulus with heated inner wall, glass outer wall. |
| Riser | 91.5 | 2.54 ID | 5.067 | 2.54 | Vertical glass tube. |

* Test region for input-output measurements = inlet + channel regions

# APPENDIX G

## COMPUTER PROGRAM INPUT DATA FOR SAMPLE TEST CASE

```
     ND        NC        NR        NB       NTIN      NPOW       NW        NF     NCFREQ
      2        13         0         0         1         1         1        51        0
    NDROP    NODES     NOSUB      NDYN     NPRINT     NPLOT    NCARDS
      0       600         2         1         1        -1       -21
    NGDYN    NPDYN     NHDYN      NQDYN     NSPEC     NPROP
      1         0         0         0         0         1
TIN         DTIN
4.138E+01 2.000E+00
POWR        DPOWR
1.835E+00 0.0
W           DW
8.830E-02 2.000E-02
TCFAC       COFAC       VFAC        AAFAC       BBFAC       CCFAC
0.0         9.835E-01 0.0         7.557E-01 1.000E+00 0.0
PIN         PDROP       WTOT        AP          BP          CP
1.628E+02 3.863E+01 2.100E+00 0.0         0.0         0.0
ASB         BSB         AHT         BHT         CHT
1.930E+02 2.757E-03 1.640E-01 0.0         1.000E+00
SIGMA       FREQ        DFREQ
0.0         0.0         2.000E-02
GDFAC       PDFAC       HDFAC       QDFAC
1.000E+00 1.000E+00 1.000E+00 1.000E+00
GDYN(N)
1.000E+00
DZ(N)       A(N)        DE(N)       PH(N)       ANG(N)      RK(N)       E(N)
INLET PIPING REGION
5.270E+01 5.238E+00 2.581E+00 8.108E+00 9.000E+01 0.0         0.0           1
1.780E+01 7.222E-01 3.991E-01 2.992E+00 0.0         1.000E+00 0.0           2
CHANNEL REGION
9.150E+00 7.222E-01 3.991E-01 2.992E+00 0.0         0.0         0.0           3
9.150E+00 7.222E-01 3.991E-01 2.992E+00 0.0         0.0         0.0           4
9.150E+00 7.222E-01 3.991E-01 2.992E+00 0.0         0.0         0.0           5
9.150E+00 7.222E-01 3.991E-01 2.992E+00 0.0         0.0         0.0           6
9.150E+00 7.222E-01 3.991E-01 2.992E+00 0.0         0.0         0.0           7
9.150E+00 7.222E-01 3.991E-01 2.992E+00 0.0         0.0         0.0           8
9.150E+00 7.222E-01 3.991E-01 2.992E+00 0.0         0.0         0.0           9
9.150E+00 7.222E-01 3.991E-01 2.992E+00 0.0         0.0         0.0          10
9.150E+00 7.222E-01 3.991E-01 2.992E+00 0.0         0.0         0.0          11
9.150E+00 7.222E-01 3.991E-01 2.992E+00 0.0         0.0         0.0          12
9.150E+00 7.222E-01 3.991E-01 2.992E+00 0.0         0.0         0.0          13
9.150E+00 7.222E-01 3.991E-01 2.992E+00 0.0         0.0         0.0          14
5.080E+00 4.355E+00 1.588E+00 2.992E+00 0.0         2.369E+01 0.0          15
PKW(N)      TCAP(N)     CO(N)       V(N)        AA(N)       BB(N)       CC(N)
INLET PIPING REGION
0.0         0.0         1.000E+00 0.0         1.000E+00 1.000E+00 0.0           1
0.0         0.0         1.000E+00 0.0         1.000E+00 1.000E+00 0.0           2
CHANNEL REGION
1.000E-01 0.0         9.835E-01 0.0         7.557E-01 1.000E+00 0.0           3
1.000E-01 0.0         9.835E-01 0.0         7.557E-01 1.000E+00 0.0           4
1.000E-01 0.0         9.835E-01 0.0         7.557E-01 1.000E+00 0.0           5
1.000E-01 0.0         9.835E-01 0.0         7.557E-01 1.000E+00 0.0           6
1.000E-01 0.0         9.835E-01 0.0         7.557E-01 1.000E+00 0.0           7
1.000E-01 0.0         9.835E-01 0.0         7.557E-01 1.000E+00 0.0           8
1.000E-01 0.0         9.835E-01 0.0         7.557E-01 1.000E+00 0.0           9
1.000E-01 0.0         9.835E-01 0.0         7.557E-01 1.000E+00 0.0          10
1.000E-01 0.0         9.835E-01 0.0         7.557E-01 1.000E+00 0.0          11
1.000E-01 0.0         9.835E-01 0.0         7.557E-01 1.000E+00 0.0          12
0.0         0.0         9.835E-01 0.0         7.557E-01 1.000E+00 0.0          13
0.0         0.0         9.835E-01 0.0         7.557E-01 1.000E+00 0.0          14
0.0         0.0         9.835E-01 0.0         7.557E-01 1.000E+00 0.0          15
FLOW - PRESSURE DROP TRANSFER FUNCTION
FLOW - EXIT VOID FRACTION TRANSFER FUNCTION
```