TWO PHASE FLOW SPLIT MODEL FOR PARALLEL CHANNELS

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ABSTRACT

A model has been developed for the determination of two phase flow distributions between multiple parallel channels which communicate between a common upper and a common lower plenum. It utilizes the requirement of equal plenum to plenum pressure drops through the channels, continuity equations at the lower plenum channel intake boundaries, together with phase-split relationships at the channel inlets, to set up a series of nonlinear simultaneous equations. The equations are solved using the Broyden'smethod [4], a modification of the Newton's method.

The model and code are capable of handling single and two phase flows, steady states and transients, up to ten parallel flow paths, simple and complicated geometries, including the boilers of fossil steam generators and nuclear power plants. A test calculation has been made with a simplified three-channel system subjected to a two-phase flow transient, and the results have been very encouraging.

NOTATION

ΔP	Pressure Drop N/m^2
W	Flow rate kg/s
J	Volumetric Flux m/s
J*	Dimensionless Volumetric Flux $J/\rho/gD\Delta\rho$
ρ	Density kg/m^3
$\Delta\rho$	Density Difference $(\rho_f - \rho_g)$ kg/m^3
D	Tube Diameter m
g	$9.8 m/s^2$
Vgj	Drift Velocity m/s
Co	Distribution Parameter
X	Flow Quality
α	Void Fraction
$Z_{2\phi}$	Two phase Level m
e_z	Small depth of liquid or two phase fluid m
e_g	small vapour flow rate kg/s
e_f	small liquid flow rate kg/s
e_n	small flow rate kg/s
e*	Small Dimensionless Volumetric Flux
ϕ	Wall Heat Addition Rate Watts
N	Number of Channels with Lower Plenum entry and Upper plenum exit
M	Number of Cross-flow paths
K	Number of Lower plenum partitions (i.e. LP Channel intake elevations)
Co/C	Co-current flow
Cnt/C	Counter –current flow
LP	Lower Plenum
UP	Upper Plenum
BWR	Boiling Water Reactor
HPCS	High Pressure Core Spray
LPCS	Low Pressure Core Spray
LPCI	Low Pressure Coolant Injection
LOCA	Loss of Coolant Accident
ECCS	Emergency Core Coolant Systems
CCFL	Counter Current Flow Limitation

Subscripts:

g	Vapour
f	Liquid

k LP partition elevation index
J j^{th} channel at K^{th} partition elevation
n Channel index

m Crossflow index
new Current time step
Old Previous time step

Superscripts:

t Total phase flow into a LP partition from the node below partition
l Identifies quantity at entry to LP node above partition
T Top of Channel
τ Transposed Matrix
xf Crossflow
i Channel Lower Plenum inlet
evap Evaporation

1. INTRODUCTION

In two phase fluid flow through parallel dissimilar channels, all of which communicate between a common upper and a common lower plenum, the known quantities are usually the total forcing flows, the local pressure at one or both plena, the thermal boundary conditions on the channel surfaces, and the hydrodynamic characteristics of the plena and channels. It will in many cases, as with the Boiling Water Reactor (BWR), be necessary to determine the actual split of the total phase flows into each of the channels.

1.1 BWR PARALLEL FLOW PATHS

Fig.1 is a sketch of the BWR showing the upper and lower plena, and the parallel flow paths. For purposes of modeling flows through the reactor, the fuel bundle region is grouped into a bypass region, (containing the control rods), a low power bundle, an average power bundle, and a high power or central bundle. The jet pumps are split into a broken loop jet pump group and an intact jet pump group, to permit the simulation of loss of coolant accidents (LOCA) due to a rupture of the recirculation pump suction piping. The guide tubes are simulated by a single flow region.

There are various leakages and cross-flow paths between the bypass and lower plenum, and bundle and bypass regions. A single flow path represents each of these. Ten parallel flow paths can thus be identified by going from the LP through either jet pump, the core, bypass and cross-flow paths, to the UP, or the steam dome.

1.2 PHASE FLOW BEHAVIOUR OF BWR DURING A LOCA TRANSIENT [1]

The normal steady state flow directions are as shown in Fig. 1 with single phase liquid from the lower plenum splitting into the various flow paths. In the event of a LOCA, due, for example, to the break of the recirculation pump suction, liquid in the angular region blows down through the break, and the reactor starts to depressurise. This eventually results in flash vaporization of the liquid, and a two phase flowing mixture replacing the single phase liquid in the LP (see references [1] and [5] for descriptions of a typical LOCA transient of a BWR).

Before the unset of flashing some of the channels would be accepting liquid upflow from the LP while others would be delivering liquid into the LP (liquid downflow). By the time the transient subsides, each of the channel lower plenum entries would have experinced changes in the phase of the flow passing through it, and in the direction of flow of the liquid phase.

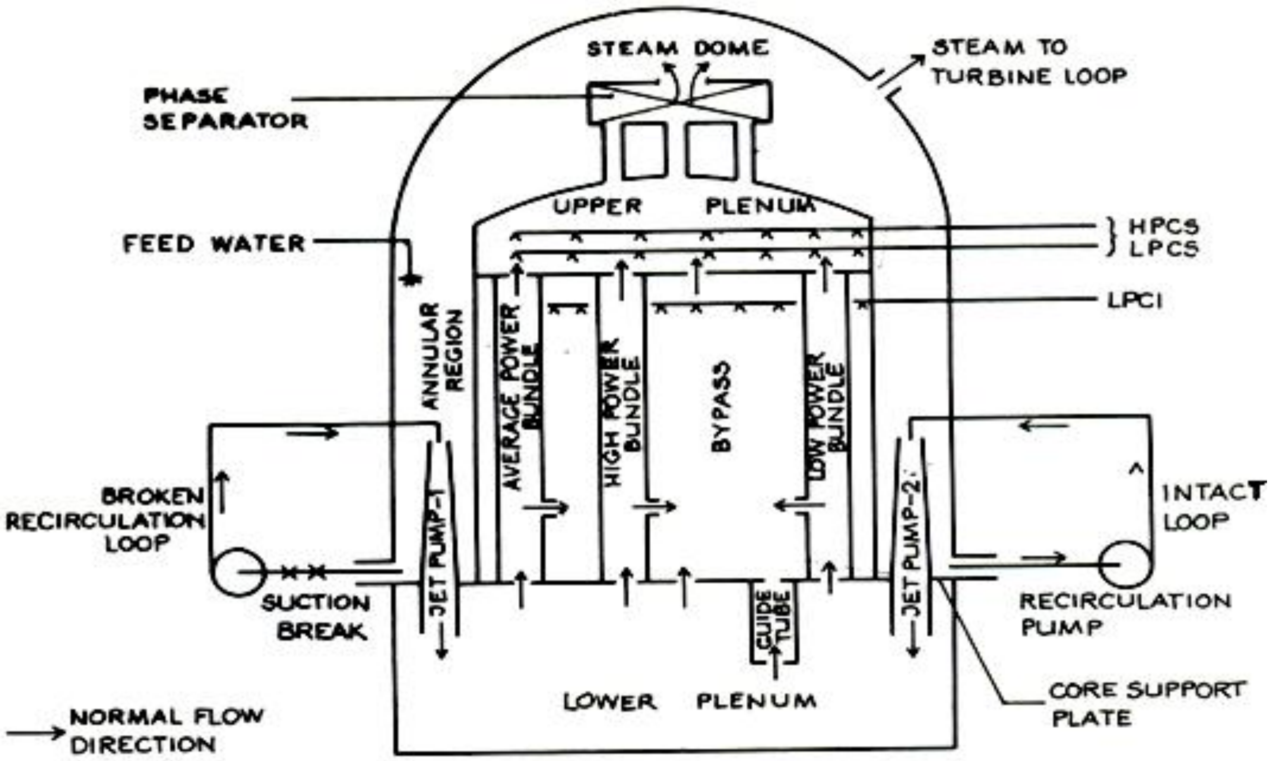

Fig. 1: BWR Parallel Flow Paths

A typical core flow transient 1S shown in Fig.2.

To prevent the fuel rods from over- heating and the fuel zircaloy cladding from melting, ECCS equipment (HPCS, LPCS and LPCI) are automatically switched on at different triggering conditions. The

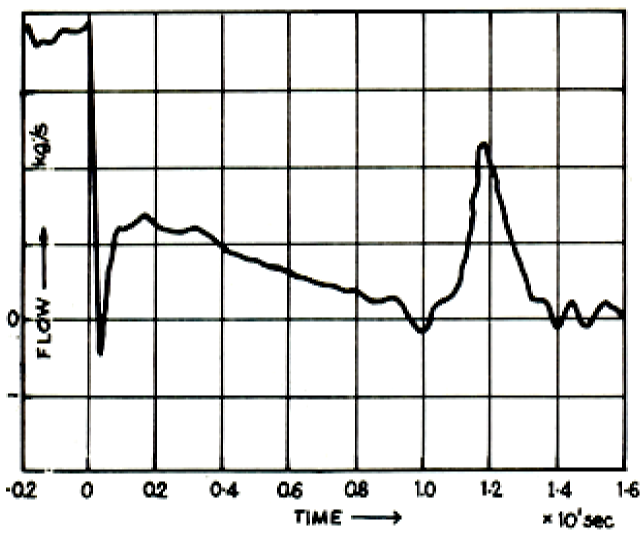

Fig. 2: Typical Core Flow Transient

cold liquid from these equipment affect CCFL at the top and bottom orifice plates of the channels, and also lead to a redistribution of flows into the channels.

Throughout the transient and flow mode changes, the phase flow rates into the channels must be reliably known so that the channel heat transfer coefficients and fuel rod temperatures may be calculated.

2. THE FLOW SPLIT MODEL

Fig. 3 is a simplified sketch of set of N parallel channels, between an upper and a lower plenum, only Co/C flows are shown. The external driving flows are W_{go} and W_{fo}; specified at the bottom of the Lp. It is assumed at the system pressure, the heat addition rates inside the channels, and hence the vaporization rate ϕ_n , are also specified. Thus given the inlet flow rates at the bottom or top entry to each channel, the exit flows at the other

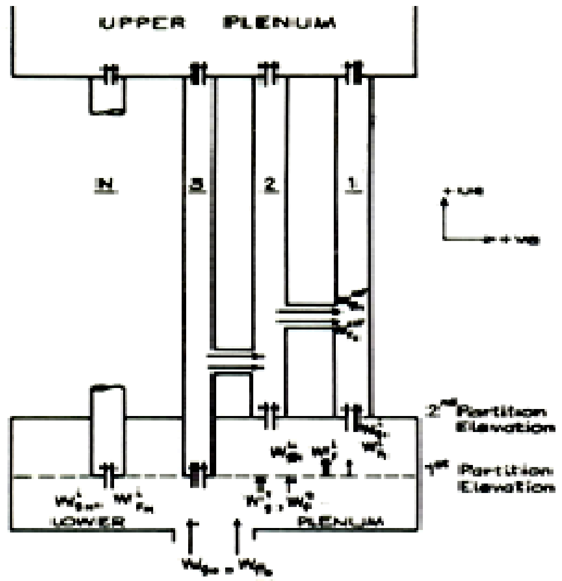

Fig. 3: Parallel Channel Flow Splits

entry are known from the energy and continuity equations in each channel. Similarly the flows into a partition elevation in the lower plenum, from the lower side, are known from solutions of the continuity and energy equations in the axial node below this partition.

2.1 LIST OF UNKNOWNS AND EQUATIONS

The unknowns then become:

Bottom inlet flow rates to the channels

$W_{gn}^{i}, W_{fn}^{i}; n = 1$, N (2N unknowns).

Lower plenum flows above a partition elevation

W_{gk}^{1}, W_{fk}^{1} ; k=1, k-1(2(k-1) unknowns)

Cross flows between channels

W_{gm}^{xf}, W_{fm}^{xf} ; m =1, M (2M Unknowns)

Total number of unknowns = 2(N +K + M - 1)

The relevant equations are:

Continuity equations for liquid and vapour at the lower plenum partition elevations:

$$W_{gk}^{t} - \left(\sum_{J(k,1)}^{J(k,r)} W_{g,k}^{i}\right) - W_{gk}^{1} = 0 \ldots k = 1, k \qquad (1)$$

$$W_{fk}^{t} - \left(\sum_{J(k,1)}^{J(k,r)} W_{g,J}^{i}\right) - W_{fk}^{1} = 0 \ldots k = 1, k \qquad (2)$$

Where J(k, j) = the index of the jth channel at the partition elevation k

r = number of channel whose inlets are at the partition elevation k

There are thus a total of 2K such continuity equations.

Axial Momentum or Pressure Drop Equations Across Channels:

If the dynamic pressure heads in the lower plenum and at the channel top exit elevation are negligible compared to the static heads, then any axial cross section in the lower or upper plenum becomes a constant pressure plane. The pressure drops from the bottom of LP, through each parallel path, to the UP will be equal. Then for the channel paths:

$$\Delta P\left(W_{g1}^{i}, W_{f1}^{i}, \phi_1\right) = \Delta P\left(W_{gn}^{i}, W_{fn}^{i}, \phi_n\right),\ n = 2, N \qquad (3)$$

and for the cross – flow paths:

$$\Delta P\left(W_{g1}^{i}, W_{f1}^{i}, \phi_1\right) = \Delta P\left(W_{gm}^{xf}, W_{fm}^{xf}, \phi_m^{xf}\right),\ \mathrm{m} = 1,\ \mathrm{M} \qquad (4)$$

Total number of equations from (1), (2), (3) and (4) = (2K + M + N - 1) It is obvious then that (N + M - 1) additional equations are needed so that a unique solution of the problem may be found.

Phase Split Equation

One way of obtaining the additional information is to define (N+M-l) phase relationships between the liquid and vapour flows at the channel inlets and at the crossflows. If~ as in Fig.3, the LP and the inlets to all the channels are in co-current upflow, the channel inlet quality may be assumed equal to the local quality in the LP at the relevant partition elevation, and equal to the average quality in the LP at that elevation - (uniform flow distribution) i.e.

$$X_{J(k,j)}^{i} = X_{k}^{t} \qquad (5)$$

Parallel channel test results reported in reference [2J, and shown in Fig.4 have verified the applicability of equation (5).

However, equation (5) is not valid throughout the transient since any channel inlet flow mode can change. The model described below gives specifications for determining when a channel's inlet flow mode should change, what mode it should change to, and what phase split equation is applicable in the new flow mode.

In this way, phase split relationships are defined for (N-l) channels and for M cross-flows at each time step. These, together with equations (1) to (4) give the sufficient number of equations to solve for all the unknowns.

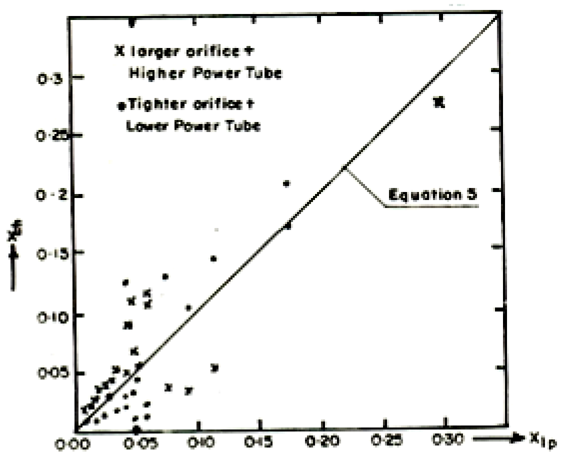

Fig. 4: Channel vs LP Qualities [2]

Another modelling approach is to combine equations (1) to (4) with a rigorous solution of the three dimensional flows in the LP. The transfer coefficients needed for this approach are not known to a reasonable degree of accuracy. The error in the results will not justify the rigour.

2.2 SOME MODELING ASSUMPTIONS

(a) Based on the results of reference *[2]*, it was assumed that once a flow configuration was established, it would be maintained as long as the pressure drop and other equations could be satisfied.

(b) A channel inlet is always provided at the top of the lower plenum. If such a channel physically does not exist, its inlet area is defined to be very small and the local loss coefficient is made very large.

(c) The code is envisaged to use the subroutine *HYDRA*, reference *[3]* for the solution of the conservation equations and calculation of pressure drops within· the channels. HYDRA does not permit downward vapour flow, and the MODEL accordingly does not.

(d) Crossflow is always Co/C, but may be positive or negative. The quality is the homogeneous quality of the donor cell in the donor channel.

(e) Because of the shape of jet pumps, their bottom inlets are not floodable.

2.3 PHASE SPLIT EQUAIONS

The channel bottom inlet flow modes and the corresponding phase split equations are given below. Each equation is identified by an equation number and the sign of flow of the liquid phase (±1) (see Table 1 for the equations).

2.4 FLOW MODEL AND COMPUTATION LOGIC

2.4.1 GENERAL

The inputs required by the flow split model are:

(i) The geometrical description of the parallel channel system, including the pressure loss coefficients;

(ii) The initial two phase levels in the channels and plena;

(iii) The initial flow modes in the lower plenum and at the bottom entries to the channels. However, the actual flow rates, i.e. the flow splits, into the channels do not have to be known accurately;

(iv) A guess of the initial flows into the channel which must be consistent with the specified initial flow modes;

(v) The transient forcing conditions. The model permits the external

<u>TABLE 1</u>

TABLE 1

Flow Mode	Phase Split Equation	Egn. No	Sign of liquid Flow
Single Phase Liquid Upflow Single Phase Liquid Downflow	$W_{gn}^{i} = 0$	 1	+1 -1
Single Phase vapour upflow	$W_{fn}^{i} = 0$	2	+1
Two phase co-current upflow, with LP in co-current upflow at intake elevation (equation 5)	$W_{gn}^{i} - X_{k}^{t}\left(W_{gn}^{i} + W_{fn}^{i}\right) = 0$	3	+1
Two-Phase Counter-current Flow Flooded	$\left(J_{gn}^{*i}\right)^{\frac{1}{2}} + \left\|J_{fn}^{*i}\right\|^{\frac{1}{2}} - \sqrt{3.2} = 0$	4	-1
Two Phase counter-current flow Draining	$W_{fn}^{i} + Max\left[\left(W_{fn}^{T} - W_{fn}^{evap}\right), 0\right] = 0$	6	-1
Two Phase co-current upflow with LP in counter-current flow at intake elevation	$J_{gn}^{i} - (\alpha_{k}^{t})\left[Co_{n}\left(J_{gn}^{i} + J_{fn}^{i}\right) + V_{gjn}\right] = 0$	7	+1

Specification of some of the channel inlet flows for part or all of the transient.

With the initial flow modes, the calculation logic does the fallowing:

(i) Selects the initial phase split equations from the list of table 1, which are then used to complete the equation set required to solve for the unknowns at that point in time.

(ii) The forcing conditions are stepped forward in time, and from this new time step onwards, the model begins to generate the appropriate channel inlet flow modes. It first assumes that the inlet flow configuration for the previous time step is maintained at the current time step. The same phase split equations are thus used for calculations at the current time step. The numerical computation logic iterates on the given equations for a specified maximum number of iterations, Imax. If convergence is obtained, the solution is accepted and the transient proceeds to the next time step. If convergence is not obtained in Imax interactions, the channel inlet flow mode is changed.

2.4.2 LOGIC FOR CHANNEL MODE CHANGES

The approach adopted is that changes of mode are to be undertaken if Old Modes do not give a converged solution. In the even that this is the case, channels with exposed inlets are treated differently from channels with submerged inlets.

EXPOSED CHANNEL INLETS

For exposed channel inlets, the flow mode is either one of the following:

i. single phase vavour upflow …

Table 1, equation (2)

ii. flooded counter-current flow…

Table 1, equation (4)

iii. Single phase liquid downflow…

Table 1, equation (1)

iv. Upper plenum draining through channel bottom inlet

Table 1, equation (6)

To ascertain if an exposed channel inlet should be in any of the above modes, it is sufficient to test if there is a two phase level inside the channel and above its inlet; or if liquid is draining from the upper plenum, through the channel, and out through the channel bottom without completely evaporating; and then to compare the last converged values of liquid and Vapor flows, for the channel, with the flooding correlation.

Therefore, for channel n:

If $Z_{2\phi,n} < e_z$

Then there is no two-phase mixture level in the channel. Flow through the channel bottom entry will be either single phase vapour, or of the UP draining type. The mode equation becomes:

$$W_{fn}^{i} = -Max\left[\left(W_{fn}^{T} - W_{fn}^{evap}\right), 0\right] \qquad (6)$$

If $Z_{2\phi,n} \geq e_z$, then a level exists in the channel, and

a. If channel is a jet pump, or if $\sqrt{3.2} - \left|J_{gn}^{*i}\right|^{\frac{1}{2}} \leq e^{*}$ or $\left|J_{fn}^{*i}\right|^{\frac{1}{2}} \leq e^{*}$,

Then $W_{gn}^{i} = 0$ (7)

b. If $\sqrt{3.2} - \left(J_{gn}^{*i}\right)^{\frac{1}{2}} \leq e^{*}$ or $\left|J_{fn}^{*i}\right|^{\frac{1}{2}} \leq e^{*}$,

Then $W_{fn}^{i} = 0$ (8)

c. If neither (a) nor (b) is true

$$\left(J_{gn}^{*i}\right)^{\frac{1}{2}} + \left(-J_{fn}^{*i}\right)^{\frac{1}{2}} = \sqrt{3.2} \qquad (9)$$

SUBMERGED CHANNELS

For submerged channels, the *new* inlet flow mode could be in one of the following states:

i. Zero liquid flow ... Table 1, equation (2)
ii. Single phase liquid upflow ... Table 1, equation (1)
iii. Single phase liquid downflow ... Table 1, equation (1)
iv. Two phase Co/C up flow .. Table 1, equation (3) or (7)
v. Two phase Cnt/C flow ... Not Allowed

The actual new mode for each channel is determined by examining the condition ·of flows in the lower plenum at the relevant intake elevation, and the manner in which the flow into or out of that channel has been changing over the previous time steps. For the channels, since $W_g^1 > 0$ by restriction, a change in mode can be tracked by following the variation in sign of the liquid flow rate. For the cross-flows, the total flow rate should be used. If then a channel's inlet liquid flow rate, or a cross-flow's total flow rate, has been positive and decreasing, and the extrapolated flow rate for the end of the current time step indicates that it should be negative, then this is a good indication that the inlet flow mode has a likelihood of changing during the current time step. A similar argument applies to channels with previously negative inlet flows. Channel and cross-flows satisfying the above condition are grouped into a mode-change class.

The above mode change logic is applicable provided that sudden changes in the condition of flow in the lower plenum do not necessitate mandatory mode changes, irrespective of the history of flows at the inlet. Such sudden changes are listed as classes 1 and 2 below. However, not all channels must change mode whenever sudden changes in LP conditions occur. The channels whose inlet modes must change belong to a higher mode change classification than the previously identified ones. The
summary of the classifications are given below.

CLASSIFICATION OF SUBMERGED CHANNELS FOR MODE CHANGE

Class 1: Channel LP inlet was previously uncovered, but now is suddenly submerged i.e.

$(Z_{2\phi,1p})_{old} \leq (Z_{ch,n})_{inlet}$ and
$(Z_{2\phi,1p})_{new} > (Z_{ch,n})_{inlet}$

Class 2: Channel originally in single phase liquid upflow and previously submerged in single phase liquid is suddenly exposed to two phase flow in LP at inlet elevation i.e.

$\left(W_{gk}^{t}\right)_{old} \leq e_g$ and $\left(W_{gk}^{t}\right)_{new} > e_g$

and $\left(W_{fn}^{i}\right)_{old} > e_f$ or

Channel originally in two phase co-current upflow and previously submerged in two phase flow is suddenly exposed to single phase flow in Lp at inlet elevation i.e $\left(W_{fn}^{i}\right)_{old} > e_f$ and $\leq e_g$

and $(w_{fn}^{i*} \quad w_{gn}^{i})old > 0$

Class 3: Channel liquid or cross-flow direction is about to change

$\left(W_{fn}^{i}\right)_{old} * \left(\mathrm{W}_{\mathrm{fn}}^{\mathrm{i}}\right)_{\mathrm{new}} \leq 0$ and $\frac{\delta W_{fn}^{i}}{\delta t} \neq 0$

Or $\left(W_{m}^{xf}\right)_{old} * \left(\mathrm{W}_{\mathrm{m}}^{\mathrm{xf}}\right)_{\mathrm{new}} \leq 0$ and $\frac{\delta W_{m}^{xf}}{\delta t} \neq 0$

where $\left(W_{fn}^{i}\right)_{new} = \left(\mathrm{W}_{\mathrm{fn}}^{\mathrm{i}}\right)_{\mathrm{old}} + \frac{\delta W_{fn}^{i}}{\delta t}\Delta t$

(=0 if $\left(\mathrm{W}_{\mathrm{fn}}^{\mathrm{i}}\right)_{\mathrm{new}} \leq e_n$)

(and similarly for cross-flow).

ORDERING OF CHANNELS ACCORDING TO LIKELINESS FOR MODE CHANGE

Channel modes are changed in the order of 1 to 3. Within each class, there may be more than one channel. All class 1 channels, and all class 2 channels have equal likelihood for mode change within their respective classes. They are therefore changed simultaneously. For class 3 channels, the representative time to mode change, t_n^*, given by $t_n^* = -\left(W_{fn}^{i}\right)/\frac{\delta W_{fn}^{i}}{\delta t}$ (similarly for cross flows) is calculated, and the channels are then ordered in increasing magnitude of t_n^*. The overall order then becomes,

i. All class 1 channels
ii. All class 2 channels
iii. $(t_n^*)_{\min}$...R Clas 3 channels

When mode change is desired, only one of the above R actions is taken according to the given order. Convergence is attempted. If satisfactory, the computation proceeds to the next time step. If not the mode of the next channel in the order is changed, and so on. The logic for the selection of the new mode, similar to that for the submerged channels is given in reference [1].

3 NUMERICAL TECHNIQUE

At any given time step, therefore, the appropriate (N+M-l) phase equations, together with equations 1, 2, 3 and 4 will form a set of 2(N+K+M-l) non-linear simultaneous equations with which to determine the unknown flows.

A modified form of the Newton's numerical technique, as developed by Broyden [4], was chosen for the numerical solutions.

The governing non-linear simultaneous equations can be written in the form

$f_q = (x_1, x_2, \text{---}\ x_r, \text{---}x_R) = 0$ (10)

for q = 1, R

where R = 2(N+K+M-1)

or $f(\bar{X}) = 0$ (11)

where $\bar{X}$= the column vector of the independent variables X_r

f = the column vector of the functions f_q

Supposing the column vector $\bar{x}$ is the i[th] approximation to the solution of equation (11) at the i[th] iteration, then the (i+1)[th] approximation $\bar{x}_{i+1}$s given by

$\bar{X}_{i+1} = \bar{X}_i - A_i^{-1} f_i$ (12)

where A_i is the Jacobian matrix $[\delta f_q/\delta x_r]$

Since f is not analytic, A_i will have to be determined numerically. By the Newton's method, this requires R(R+l) computations of f_q at each iteration. The Broyden's method is a shorter approach.

3.1 BROYDEN'S METHOD

A rough approximation to the Jacobian matrix A is initially guessed as B. Then from (12)

$\bar{X}_{i+1} \simeq \bar{X}_i - B_i^{-1} f_i$ (13)

A multiplier t_i is defined such that equation (13) is an equality, thus

$\bar{X}_{i+1} \simeq \bar{X}_i + t_i p_i$ (14)

where $p_i = -B_i^{-1} f_i$ (15)

The method then gives a better prediction of the matrix B, to be used for the next iteration, as

$B_{i+1} = B_i + \frac{(Y_i + s_i f_i)}{s_i p_i p_i} p_i^t$ (16)

where $Y_i = f_{i+1} - f(t_i - s_i)$ (17)

s_i = A perturbation around t_i

In equations (16) and (17), fi and B. are known from the previous iteration. Thus only R computations of f_{i+1} and R computation of $f(t_i - s_i)$ i.e. total of 2R functional evaluations are needed to compute B_{i+1}. This is a significant improvement over the R(R + 1) evaluations required for the straight Newton's method.

Having calculated B_{i+1} and f_{i+1}, P_{i+1} is obtained from equation (15). The predicted solution from this iteration is then given by

$$\bar{X}_{i+2} = \bar{X}_{i+1} + t_{i+1}p_{i+1} \qquad (18)$$

The multiplier t_i was chosen as

$t_i = 2^{-(i-1)}$, and the step

$S_i = t_i$ for the first iteration.

$S_i = -t_i$ for subsequent iterations.

4 TEST CALCULATION

The above model and numerical technique were programmed in Fortran. The resulting Flow Split Code (FSC) was run with a test problem as described in Fig.5. The input flows W_{fo} and W_{go} were constant at 1.105 kg/s and 0.264 kg/s respectively. A transient was simulated by making the height of liquid above channel 2, a function of time. The local pressure loss coefficients are given in the table below.

TABLE 2: LOCAL LOSS COEFFICIENT FOR TEST PROBLEM

Channel	Top Orifice	Bottom Orifice
1	1.5	2.29
2	1.0	0.5
3	1.5	2.56
Cross-Flow	1.5	

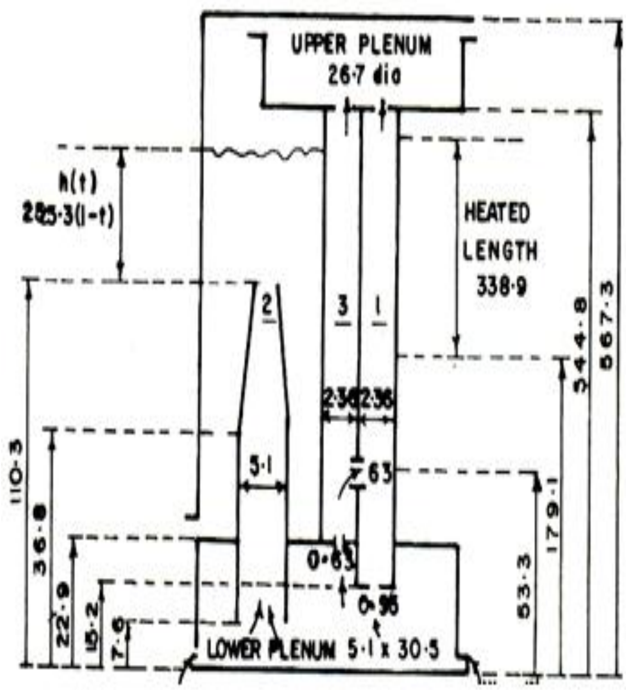

Fig. 5: Sketch of test problem

Figs.6 and 7 are plots of the results. The transient was designed to last for one second, with solutions being determined at 0.001 sec intervals. The solutions usually converged rapidly within 1 to 5 iterations. Exceptions were at 0.543 second when the crossflow showed a flow reversal and at 0.544 second, the next time step after that. Total number of iterations before convergence was obtained for these times was 77 and 18 respectively. At 0.546 second, it was down to 1 iteration.

Of particular significance is the fact that the model was capable of tracking flow mode changes, as it did

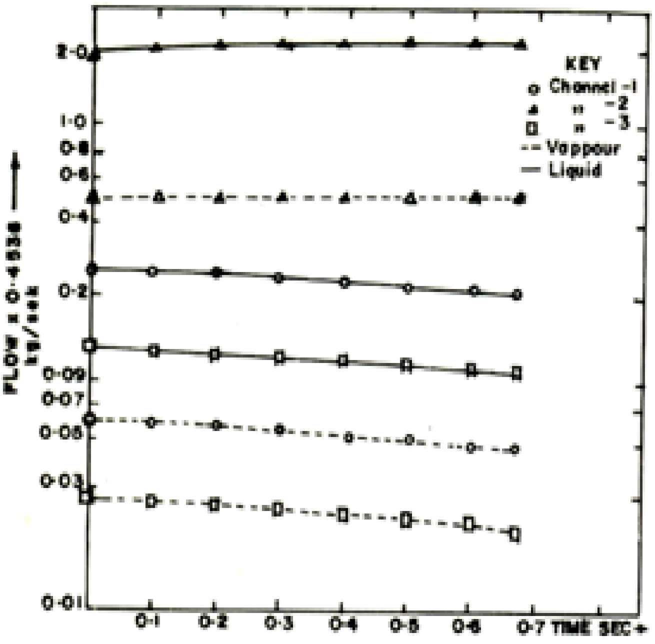

Fig. 6: Test problem results. Channel flow vs time.

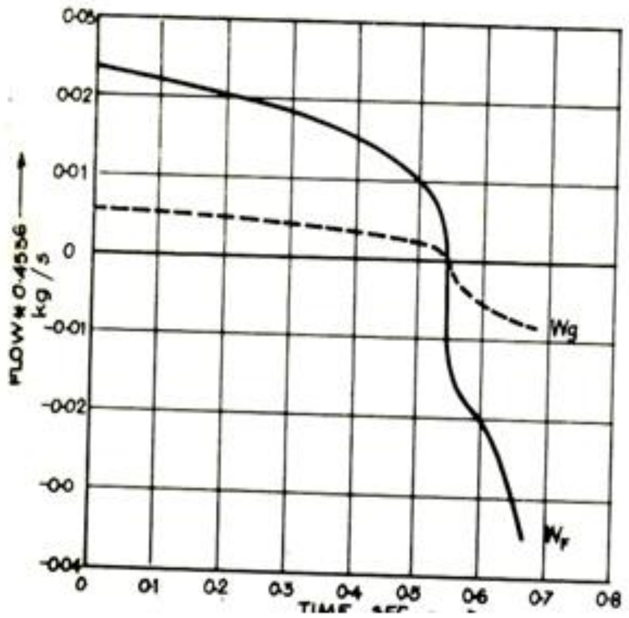

Fig. 7: Test problem results. X-flow vs Time.

for the cross – flow reversal. This sort of phenomenon usually presented the most difficult problem models and methods of this kind.

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