EFFECTS OF PARALLEL CHANNEL INTERACTIONS ON TWO-PHASE FLOW SPLIT IN NUCLEAR REACTORS

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ABSTRACT

Tests were performed to examine the mutual effects of parallel channel on the pattern of flows into or out of a pair of vertical channels, which have a common upper and a common lower plena, when two-phase flow mixtures are introduced through the plena. The tests would aid the development of a realistic transient computer model for tracking the distribution of two-phase flows into the multiple parallel channels of a Nuclear Reactor, during Loss of Coolant Accidents (LOCA), and were performed at the General Electric Nuclear Energy Division Laboratory, California.

The test channels consisted of two 5.22m long *25.4mm o.d. *23.6mm i.d. stainless steel tubes, with unequal orificing at the bottom, and equal orificing at the top. Provisions were made for electrical resistance heating of 3.5m of each tube, and for visual observation of flows into the tubes. Test fluids were steam and saturated water, and system pressures varied from near atmospheric to a little *over* 1.7 bar. The method of introducing the flows was varied so as to simulate different flow phenomena which might occur during a loss of coolant accident.

Steady flow configurations with both channels in co-current up upflow, or one channel in co-current upflow and the other in downward liquid flow, or one channel in co-current upflow and the other in counter-current flow, were obtained. Flow configurations showed a hysteresis and were history dependent. They depended also on the relative channel orifice restrictions, the state of two-phase mixture in each channel at the start of flow, the manner of initiation of the flows, and on the heat addition rates to the channels.

NOMENCLATURE

K - Orifice friction loss coefficient
LRC - Higher power and less restricted channel
MRC- Lower power and more restricted channel
QCV - Quick Closing Valves
2ϕ - Two-phase flow
1ϕ - Single phase flow
α - Void fraction
X - Flow quality
UP - Upper Plenum
LP - Lower Plenum
W - Flow rate kg/hr
Q- Power KW
P - Pressure bar
ΔP - Pressure drop or pressure difference bar
Cnt/C; Co/C - Counter-current; Co-current flows
ρ - Density kg/m^3
BWR - Boiling Water Reactors
PWR - Pressurized Water Reactors
A - Area m^2

Subscripts

1 Higher power and less restricted channel
2 Lower power and more restricted channel
gt Total vapour supply to system
ft Total liquid supply to system
lp Lower plenum
ch Channel
t Total
g,f Vapuur, liquid phases respectively

INTRODUCTION

The need to determine the distribution of coolant flows into the various channels of a Nuclear reactor during the depressurization and reflood transients that follow a Loss of Coolant Accident, has been acutely realized by both the reactor manufacturers and the nuclear regulatory agencies. It is expected that this would be a necessary design package for the approval of the construction of future Nuclear Reactors. As at the start of' the test programmes reported in this paper, no operational computer design code yet existed for an accurate prediction of channel flows during the above transients. Test programmes were therefore mounted to determine phase-split relationships applicable at the channel-plenum boundaries, which would aid in the development of the design code [this phase is reported in reference *[1];* and to determine the mutual effects of the parallel channels on the flow regimes at entry to the channels. The latter is the subject of this paper. The flow split relationships determined in phase one of the tests, would, due to experimental design limitations, be steady state relationships. However parallel channel interactions may determine the type of flow configurations that will exist during the transients, and hence predispose the sequence of logic of the computer model which will calculate the flows.

The design of the tests was biased towards Boiling Water Reactor (BWR) transients. However, Pressurized Water Reactors (PWR) can undergo flashing and two phase flows during severe depressurization transients. The results of the tests may therefore be applicable to PWR.

THE EXPERIMENT

The Test Loop

The test loop is as shown in figure 1. Steam was supplied from an Electro-Magic (Model 3100) generator, through the steam side of the lower plenum flow distributor, into the water/steam mixing region of the lower plenum. An inverted cup at the top of the upper plenum removed some of the entrained liquid before the steam was exhausted into the atmosphere. The water loop was a quasi-closed circuit, complete with a makeup water tank, regenerative heat exchanger, and a $33\frac{1}{2}$ KW preheated. The water could be valve into the lower or upper plenum, depending on the test being performed. A weir arrangement and an overflow drain line were provided in the upper plenum.

The 5.22m long *25.4mm o.d. *23.6mm i.d. test tubes were made of stainless steel. The two tubes had single hole bottom inlet orifices of sizes 9.5mm and 6.4mm, respectively. The less restricted tube simulated the higher power central bundle group of a nuclear power reactor, while the more restricted tube simulated the lower power peripheral bundle group. The bottom orifice (K/A^2) ratio was about 5. The top orifice plates of the tubes were identical, with 4 * 7.6mm holes. Each test tube had a 1.22m long visual section, made of Pyrex tube of the same internal diameter as the tube, below the heated section and between the quick closing valves. Other important test system dimensions are shown in figure 2. A visual port was also machined into the lower plenum. Power to the less restricted tube could be varied from 0.4 KW to 150.5 KW. and that to the other rube could be varied from 0 - 58 KW. The flow distributor designs, illustrates in figures 3 and 4 were used. The first had 33* 6.4mm water tubes and a steam chamber external to the tubes. Steam and water therefore flowed uniformly into the mixing region. To prevent liquid backflow from the mixing region to the steam chamber, the areas of the flow holes for the steam could be altered by a sliding plate controlled by a micrometer screw gauge. The second distributor design was a simple tube with holes for steam inlet drilled along its top. Runs 2000 to 2014 were done with the second design.

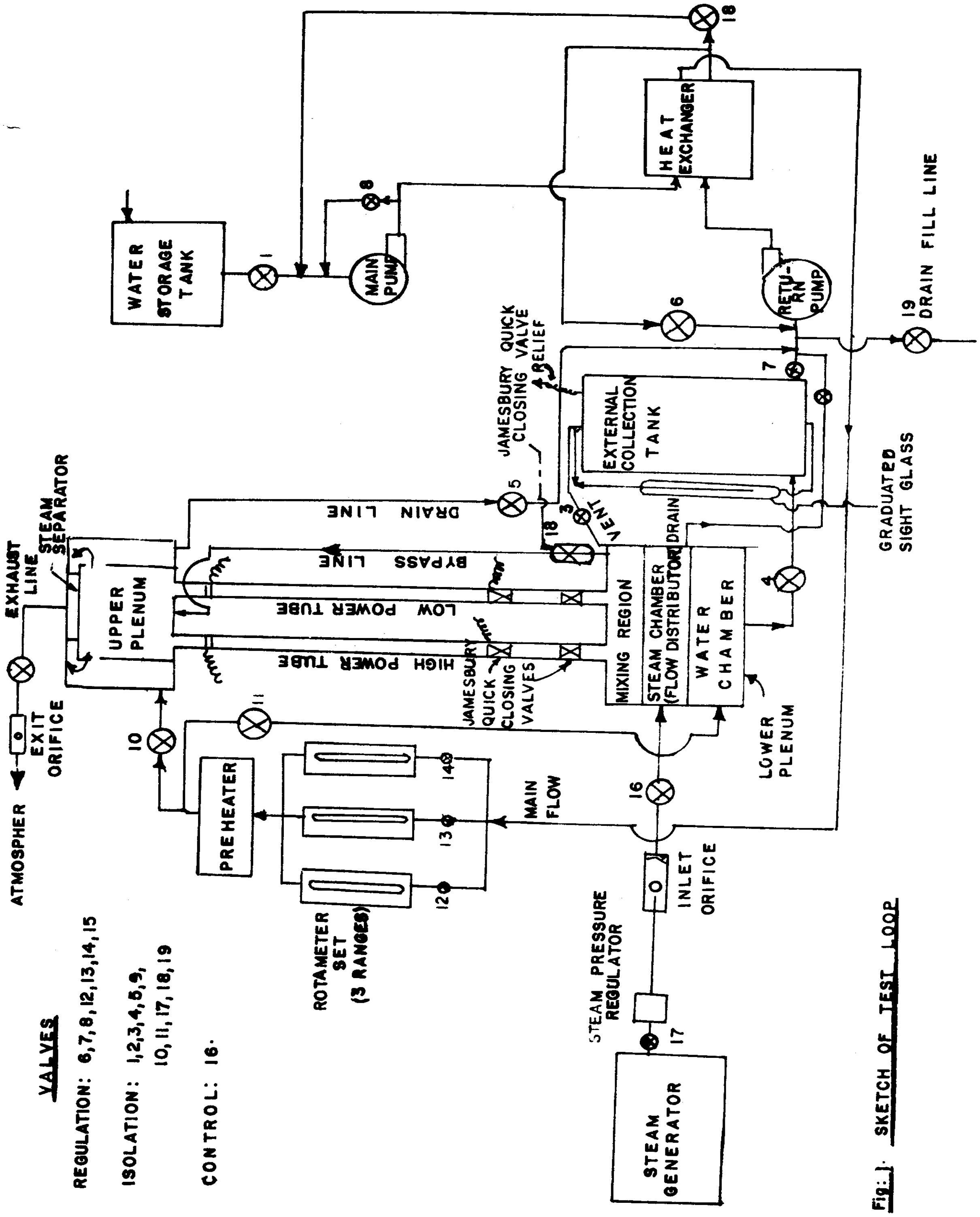
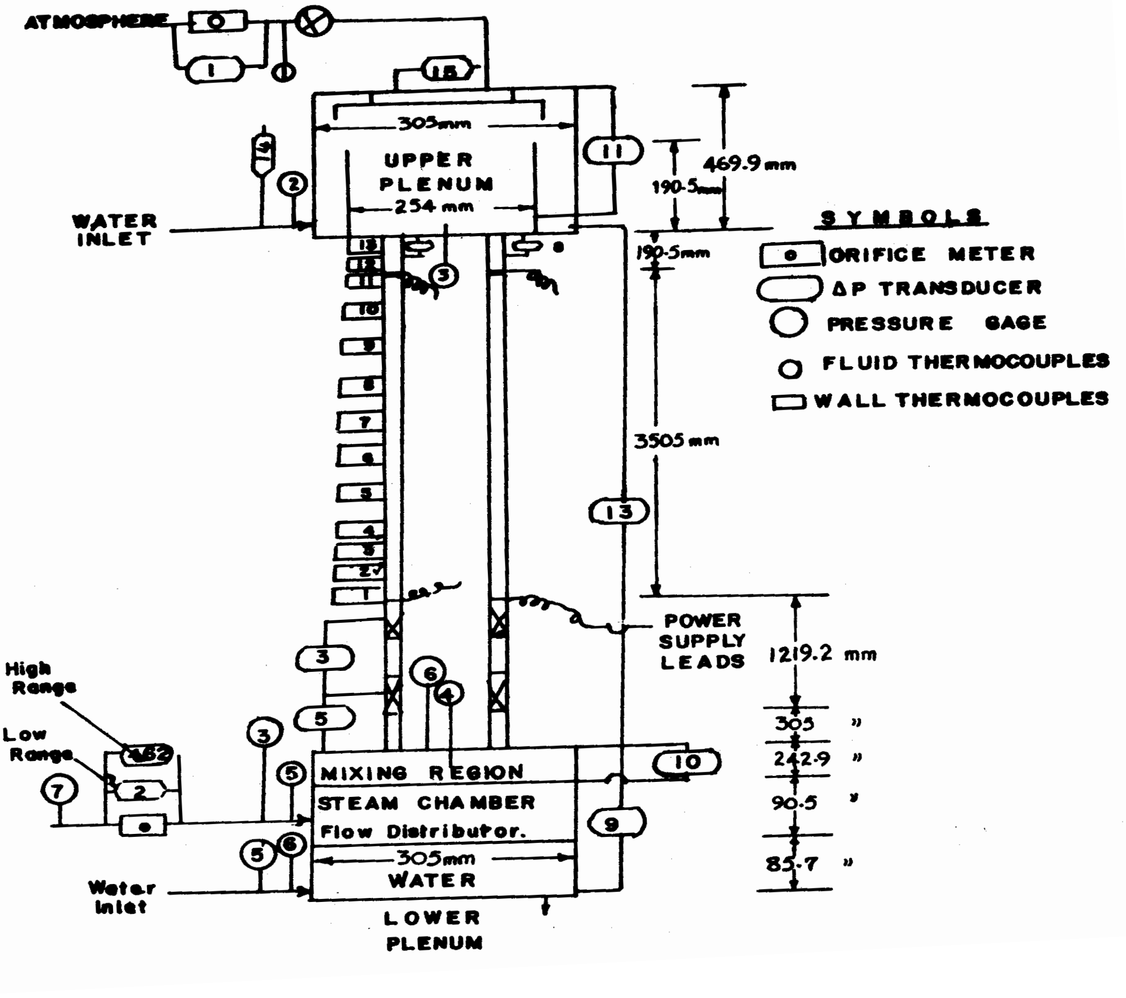


Fig. 1. SKETCH OF TEST LOOP

Fig: 2. Test Section Instrumentation



The mixing region was a 51mm wide section, above the steam distributor, running diametrically across the cylindrical lower plenum, of diameter *305mm.* With these arrangements, uniform flow distribution in the lower plenum was assured.

Instrumentation

The test loop was instrumented as shown in figure 2. Rotameters and orifice meters were used for water and steam flow measurements, respectively. Power was measured using Watt transducers with outputs in V, and appropriate conversion factors. Low power in the less restricted tube was measured with a 0-15KW table wattmeter. Valedyne pressure and differential pressure transducers, BLH differential pressure transducers, and thermocouples were used for differential pressure and temperature measurements. In particular an 0-1.27m (0-50") and a 0-2.54m (0-100") BLH transducers were connected to the upper and lower plena, respectively, to track fluid level changes in the plena.

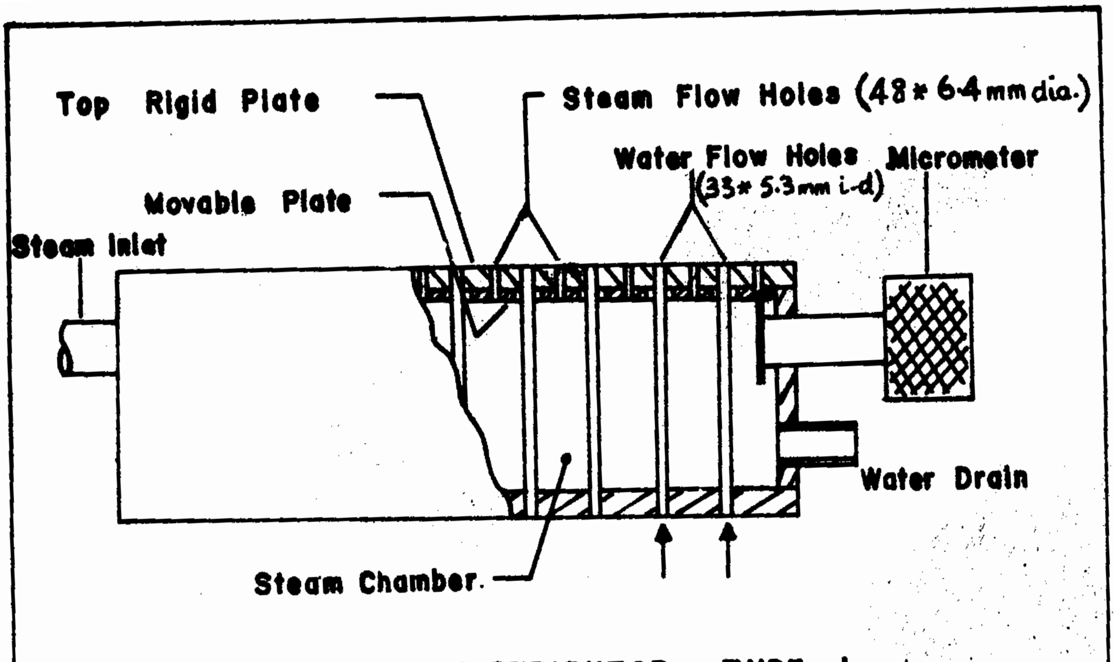


Fig. 3 FLOW DISTRIBUTOR TYPE 1

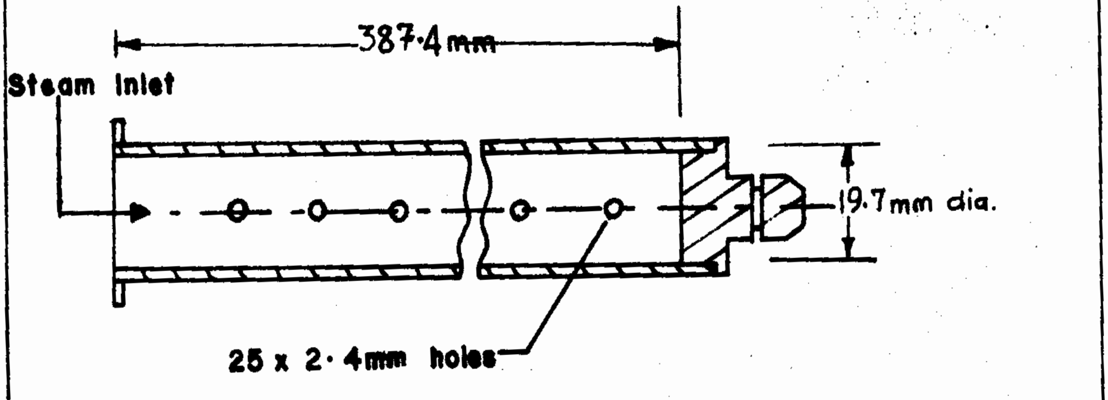


Fig. 4 FLOW DISTRIBUTOR TYPE 2

All the instruments were caliberated on site before use.

The instrument outputs, in Volts, were connected to a multichannel Hewlett Packard Model 2017D data acquisition system (the DYMEC). All the 62 data signals of the Dymec were also printed on paper tape within a cycle time of 11.594 seconds. Some transducer outputs, such as the plena fluid level indicators, were connected to Sanborn Chart Recorders for visual display. Further test loop and instrumentation details may be found in reference [2]

Experimental Procedure and Test Matrices

The system was first filled with water. The pressure and differential pressure transducers were bled of any air or vapour locks, and the Dymec/Recorder displays zeroed. The water was circulated through the system and brought to saturation using steam, test section power and the preheater. Steam was always introduced into the lower plenum, with water being valved to the upper or lower plenum as required. The method of flow admission was varied to simulate different transient flow phenomena, (see table 1). The steam and water total flow rates, and test section power, were set using the appropriate meters, transducers and their relevant conversion factors. For the steady state runs, the 62-channel DYMEC data were recorded on tape over a number of cycles, and then averaged for data reduction. Observations were also made on the flow modes passing through the transparent pyrex tube.

For the hysteresis tests, not total liquid flow and test section power were zero, and steam was introduced into the lower plenum. The steam flow rate was increased in steps up to maximum of 45.9 kg/hr, and then decreased in steps. At each step, the channel flow configuration and test section plenum to the plenum pressure drops were observed and recorded.

DATA REDUCTION

The total liquid and vapour flow rates, together with correlations relating void fraction to the phase flows, were used in determining the - separate liquid and vapour flows through each tube. Thus

$W_{gt} = (w_g)_1 + (w_g)_2$ (1)

$W_{ft} = (w_f)_1 + (w_f)_2$ (2)

$\alpha_1 = \alpha[(w_g)_1, (w_f)_1, P_1]$ (3)

$\alpha_2 = \alpha[(w_g)_2, (w_f)_2, P_2$ (4)

For co-current flows, equation 5 below, developed from calibration tests conducted for that specific purpose, (see reference [2]), was used. $\alpha = 1/\{1+2.649 \left[\left(\frac{1-X}{X}\right) \frac{\rho g}{\rho f}\right]^{0.732}\}$ (5)

For a channel in chugging counter-current flow, the Dix correlation, reference [3], developed primarily for co-current flow, was found to predict the counter-current calibration data taken during the tests, and was used. Due to throttling at the bottom orifices, heat losses, and kinetic and potential energy changes, the flow quality and void fractions at channel bottom orifices would be different from those within the Pyrex tubes where the void fractions were measured. The measured voids were assumed to be the average voids at the midplane of the Pyrex tube. Appropriate energy, .momentum and continuity equations were applied between channel entry and Pyrex tube midplane so as to determine the actual flows into or out of the channel bottom orifices. The details of the calculations are given in reference [2].

RESULTS AND ANALYSIS

Table 1 shows the test matrices and results. From the results of runs 19 to 41, and 2010 to 2014, it is evident that gradual introduction of vapour into the lower plenum led to a referential diversion of all the vapour into the less restricted channel. For same tests, however, the lower plenum was initially pressurized by introducing vapour into it while the quick closing valves (QcV) were shut. The pressure below the QCV's then rose above the gravity pressure head of the liquid above the valves. Upon suddenly opening the valves, vapour was admitted into both channels. The less restricted channel (LRC) was in co-current upflow while the more restricted channel (MRC) was in chugging counter-current flow. (The sudden admission of vapour into the channels simulated the rapid flashing phase in the transient flow following a Loss of Coolant Accident). It was found, however, that sudden admission of vapour did not guarantee the stability of the flow regim described above. The total vapour flow rate must be above a certain threshold value in order to maintain it, otherwise the configuration would collapse and revert to co-current upflow in the less restricted channel and single phase liquid downflow in the more restricted channel. These results were obtained with and without heat addition, and with zero or net liquid downflow in the system. The results are seen even more clearly in the hysteresis tests.

In the hysteresis tests, as W_{gt} was increased from zero, all the vapour went into the LRC with the MRC in downward liquid flow. The flow regime in the visible section of the less restricted channel went from bubbly to slug anular flow. At about 40.4 kg/hr total steam flow rate, vapour bubbles began to appear in the more restricted channel, and without further alteration to the steam flow setting, the MRC went into two-phase flow at an increasing pace. When steady state was finally established, the LRC was in co-current upflow, with the MRC in Chugging counter-current flow. W_{gt} settled to 40.8 kg/hr. The pressure drop across the test section at the $start of the above flow transition was equal to the single phase

Table 1. TEST MATRIX AND RESULTS

TESTS A: [$W_{ft} = 0$; $Q = 0$; $W_{gt} > 0$]

Run No.	POWER (KW)		W_{gt} kg/hr	W_{ft} kg/hr	TEST PROCEDURE	Flow mode in pyrex tube, and measured		Flows into channels at LP/channel boundary kg/hr				Fluid levels in Plena	
	LRC	MRC				LRC	MRC	Vapour		Liquid		UP	LP
								LRC	MRC	LRC	MRC		
19	0	0	18.0	0	System full of saturated water. Gradually increase W_{gt} to 18.9kg/hr. Take data at steady state. Close QCV's and measure α.	2ϕ Co-current upflow. α=0.821	1ϕ Liquid down flow α= 0.0	19.9	0	114.3	-114.3	½ full	full
20	0	0	21.1	0	LP pressure > 1.7bar. Open QCV's.(Sudden admission of vapour). Take data at steady state. Shut QCV's and measure α.	2ϕ Co-current upflow. α=0.962	2ϕ chugging Counter-current flow α=0.678	19.4	1.7	37.7	-37.7	full	full
21	0	0	18.8	0.0	LP pressure > 1.7bar. Open QCV's.(Sudden admission of vapour). Readjust W_{gt} to same value as for Run 19 Take data at steady state. Shut QCV's and measure α	2ϕCo/C upflow on opening QCV's W_{gt} = 22.7. 2ϕCo/C upflow after flow adjustment α=0.84	2ϕCnt/C on opening QCV's 1ϕ liquid downflow after flow adjustment α=0.0	18.8	0	857.3	-857.3	½ full	full

22	0	0	21.0	0.0	Re-establish condition of Run 21. Then increase W_{gt} to that of Run 20 Take data at steady state. Shut QCV's and measure α.	2ϕ Co/C upflow α=0.846	1ϕ liquid downflow α=0.0	21.0	0.0	860.3	-860.3		
23	0	0	22.9	0.0	LP pressure > 1.7bar. Open QCV's (sudden admission of vapour). Take data at steady state. Shut QCV's and measure α.	2ϕ Co/C upflow α=0.962	2ϕ chugging Cnt/C flow α=0.773	19.9	3.0	74.2	-74.2	full	
38	0	0	20.6	0.0	Gradually increase W_{gt} to test value. Take data at steady state. Shut QCV's and measure α. (Repeatability test for Run 22)	2ϕ Co/C upflow α=0.843	1ϕ liquid downflow α=0.0	20.6	0.0	891.2	-891.2	full	
39	0	0	20.7	0.0	LP pressure > 1.7 bar. Open QCV's (sudden admission of vapour). Reset W_{gt} as for Run 38. Take data at SS. Close QCV's and measure α. (Repeatability test for Run 20).	2ϕCo/C upflow α=0.956	2ϕ chugging Cnt/C flow α=0.780	17.8	2.9	99.3	-99.3	$\frac{2}{3}$ full	

TESTS B: $[W_{ft} = 0; Q > 0; W_{gt} > 0]$

1.88	1.0	20.4	0.0	Open QCV's (sudden admission of vapour). Vent vapour from LP to re-establish flow configuration of Run 38. Reset vapour flow rate and add power to tubes. Take data at SS. Close QCV's and measure α.	2ϕ Co/C upflow $\alpha=0.837$	1ϕ liquid downflow $\alpha=0.0$	20.4	0.0	835.7	-835.7	full	full
5.42	2.98	7.5	0.0	Gradually set required vapour flow rate. Add power and take data at SS. Shut QCV's and measure α.	2ϕ Co/C upflow $\alpha=0.426$	1ϕ liquid downflow $\alpha=0.0$	7.5	0.0	3603	-3603	full	full
1.84	0.98	21.7	0.0	Same as for Run 39 but with power	2ϕCo/C upflow $\alpha=0.934$	2ϕ Cnt/C chugging flow $\alpha=0.777$	18.5	3.2	66.4	-66.4	$\frac{3}{4}$ full	full

TESTS C. Hysteresis Tests

0	0	0.0 to 45.0	0.0	Hysteresis Tests. Increase W_{gt} in steps to maximum value and then decrease in steps. Record flow configuration changes and test section ΔP.	SEE SECTION ON RESULTS AND ANALYSIS

TESTS D: [$W_{ft} < 0$; $W_{gt} > 0$; $Q = 0$]

2010	0	0	15.2	-264	Set net liquid downflow and net vapour upflow. Observe and take data at SS.	2ϕ Co/C upflow α=0.767	1ϕ liquid downflow α=0.0	15.2	0.0	1586	-1850	Full Approx.
2013	0	0	15.2	-421	"	2ϕ Co/C upflow α=0.813	1ϕ liquid downflow α=0.0	15.2	0.0	757	-1175	Full
2014	0	0	15.2	-107	"	2ϕCo/C upflow α=0.770	1ϕ liquid downflow α=0.0	15.2	0.0	1480	-1587	Full

TESTS E: [$W_{ft} > 0$; $W_{gt} > 0$; $Q \geq 0$ (Co-current Upflow)]

3000	3.61	2.03	54.5	1081		2ϕ Co/C α=0.655	2ϕ Co/C α=0.655	4.20	0.30	979.8	101.2	Full
3010	3.68	2.03	4.9	168.7	Set both liquid and vapour in upflow mode at required flow rates	α=0.810	α=0.848	3.65	1.25	139	29.7	"
3013	0.0	0.0	4.9	108.4		α=0.131	α=0.832	1.76	3.14	12.6	95.8	"
3014	0.0	0.0	4.6	433.5		α=0.735	α=0.875	4.53	0.07	432.6	0.9	"
3035	20.4	11.05	22.5	440.4		α=0.724	α=0.918	1.10	21.4	136.6	303.8	"
3038	20.25	11.05	46	441.8		α=0.929	α=0.875	44.31	1.69	393.4	48.4	"

+ The above list is representative. Reference may be made to [2] for further details.

liquid pressure head across the test section, (ie. 0.51 bar). Figure 5 is a plot of the test section pressure drop during the flow regime transition. Increasing W_{gt} to 45.8 kg/hr after the transition led to counter-current flow limitation at the bottom orifice of the MRC, and single-phase vapour flow in the LRC. On decreasing W_{gt}, the flow regime in the MRC did not revert to single phase liquid downflow at a W_{gt} of 40.4 kg/hr, - the value at which the channel went from single phase liquid downflow to chugging counter current flow while W_{gt} was being increased. Instead, chugging counter-current flow in the MRC and co-current upflow in the LRC were maintained until W_{gt} was lowered to 22.7 kg/hr. At this piont, slugs of vapour began to bridge the more restricted tube, and counter-current slug-anular flow was set up. Without further alteration to the steam flow setting, two phase flow in the MRC finally broke down to single phase liquid downflow, with co-current upflow being maintained in the less restricted tube. When steady state was established, W_{gt} settled down at 20.9 kg/hr. Figure 6 shows the test section pressure drop history during the flow transition.

The flow behaviour observed above are linked with the necessity to maintain equal pressure drop across both channels, between the plena. When vapour was gradually introduced into the initially stagnant or downward liquid flow system, differences in channel orificing diverted the vapour into the less restricted channel. Since plenum to plenum pressure drop (ΔP) must be the same across both channels, liquid must flow down the more restricted channel and up the LRC so as to satisfy momentum and continuity equations. As more steam was introduced and flowed into the LRC, its pressure drop would first decrease due to increasing voids, and then increase due to an increase in the two-phase friction loss multiplier. The liquid downflow in the MRC would first increase and then decrease so as to maintain equal Δp with the LRC at all times. With this flow configuration, the maximum Δp across the test section would be the single phase gravity head which would occur when the flow rate in the MRC become zero. When this occurs, any further increase in the vapour flow rate through the LRC will tend to increase its Δp without a corresponding tendency to increase the Δp across the MRC. The hitherto prevailing flow configuration would therefore become unstable and must change. Vapour would have to be admitted into the MRC. Following this change, any further increase in w_{gt} would produce identical trends in Δp for both channels, and the resulting flow configuration would remain stable. Similar explanations apply to flow regime changes with W_{gt} decreasing.

For the net co-current flow tests,(Runs 3000 to 3038), with saturated liquid and vapour addition into the lower plenum, both channels were in co-current upflow within the range of flows tested. Net co-current upflow would occur during the flashing phase of a depressurization transient. However, it is conceivable that at low total vapour upflow rates, not all channels of a nuclear power reactor would be in co-current upflow.

The above observations on flow configurations indicate that the same net forcing flows will not necessarily produce the same conditions of flow in the channels Account must be taken of how the forcing flows were established, thus making the flow configurations history dependent. It would appear that for $W_{gt} <$ 20.9 kg/hr and $W_{ft} \leq 0$, two-phase co-current up flow in the LRC and single-phase liquid downflow in the MRC would be the stable flow configuration, irrespective of how the flows were established. For $20.9 < W_{gt} < 40.8$ kg/hr, two-phase co-current upflow in the LRC and single-phase liquid downflow in the MRC, or two-phase co-current upflow in the LRC and chugging counter-current flow in the MRC would be stable, depending on how the flows were established and on the preceding flow history. For higher steam flow rates, the flow conditions at channel bottom entries will tend towards complete counter-current Flow Limitation at the bottom orifices of both channels, with the less restricted channel in single phase vapour

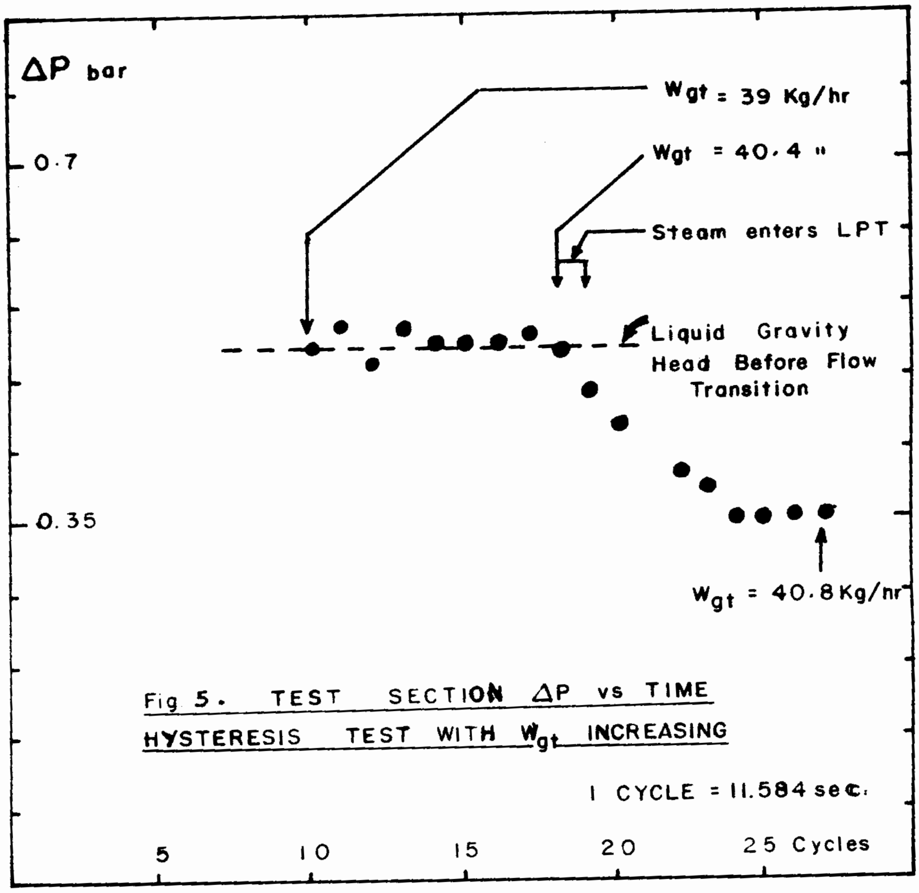


Fig 5. TEST SECTION ΔP vs TIME HYSTERESIS TEST WITH W_{gt} INCREASING

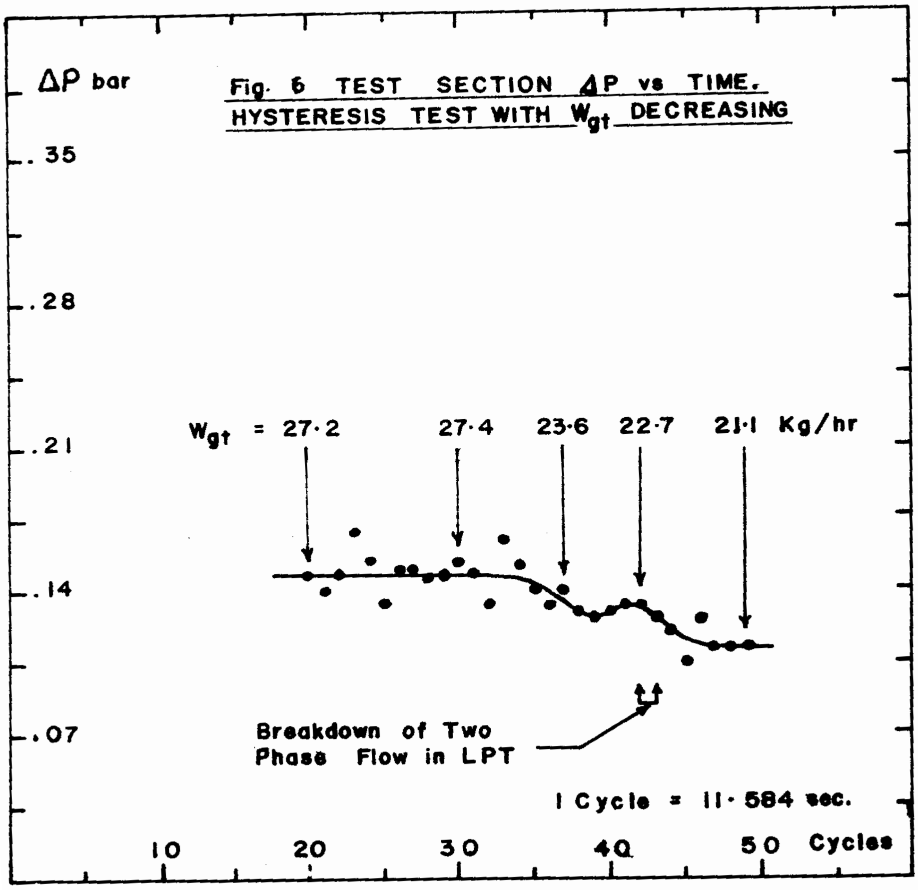


Fig. 6 TEST SECTION ΔP vs TIME. HYSTERESIS TEST WITH W_{gt} DECREASING

upflow. The threshold values at which flow configuration changes occur would vary from system to system, but such transitions and hysteresis are to be expected. The implications of the above observations have been factored into a parallel channel flow split model reported in reference *[4]*. The following conclusions can therefore be made:

CONCLUSIONS

1. Observations of the variations of channel flow configurations imply that in the modelling of a transient two phase flow split code for parallel channels, the establishment of phase split relationships at channel/plenum boundaries are not enough to effectively track the phase splits through the transients.
2. Even when channel inlets (or exits) are submerged in a two-phase mixture, one or more of the channels may still be in single phase liquid downflow.
3. The history of the transient must be followed in order to establish each channel's inlet flow mode, and hence the applicable flow split equation, at the particular time in question.
4. Once a stable flow configuration is established, the system will tend to maintain that configuration so long as the pressure drop, energy and continuity equations can be satisfied.

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