THE PREDICTION OF MULTIPLE HEATED CHANNEL FLOW PATTERNS FROM SINGLE CHANNEL PRESSURE DROP DATA

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Report No. 70318-57
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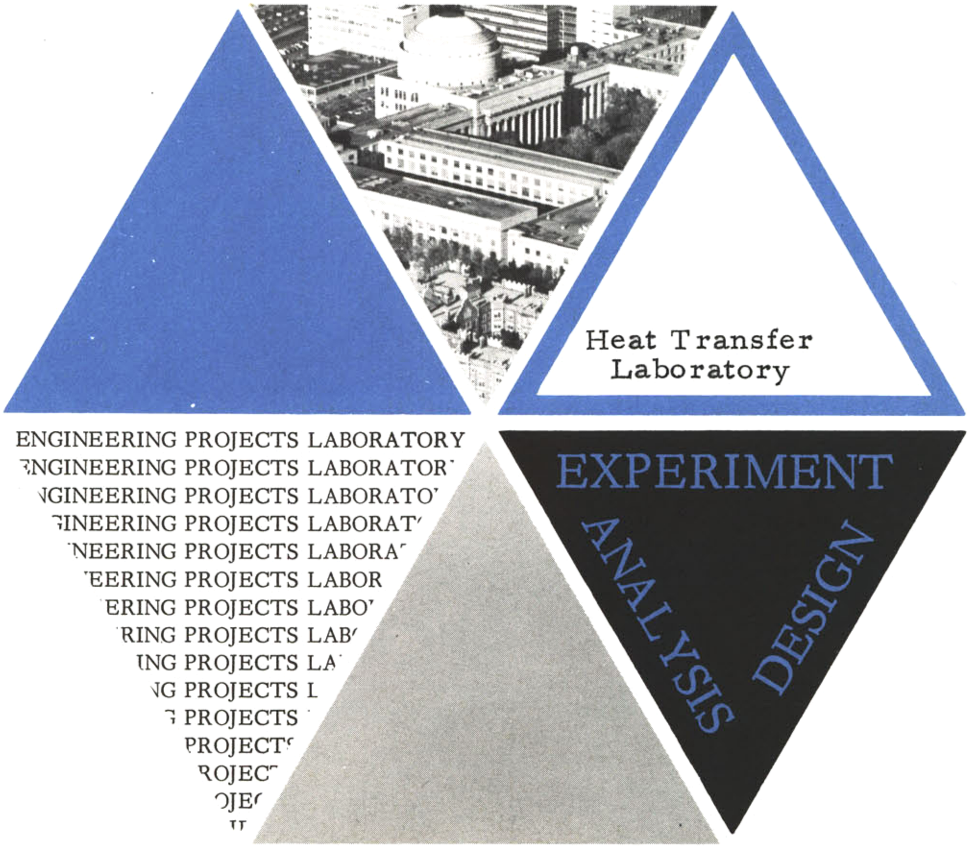

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Heat Transfer
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ABSTRACT

Pressure drop and burnout data taken on a single tube apparatus using Freon at one atmosphere has been used to predict the flow patterns, burnout and points at which flow reverses in a five tube array. All the behavior which might have been expected from the single tube experiments was found in the five tube apparatus but quantitative predictions of the details were not possible because of uncertain bubble nucleation and substantial departures from thermal equilibrium.

Application of the techniques suggested in this report is outlined for two reactor problems. One application concerns determining when the flow reverses in a channel of the core of a reactor in which a loss of pumping power accident has occurred. The other application concerns determining when a natural circulation loop will be set up during the quenching in a reactor which has already lost its coolant.

The Prediction of Multiple Heated Channel Flow Patterns from Single Channel Pressure Drop Data

Introduction

There are several occasions which can arise in the operation of a nuclear reactor during which it is desirable to know the flow configuration in the core. (The flow configuration in this context refers to the direction of flow in the channels.) These occasions are as follows.

1) A loss of pumping power accident. In the course of the flow run down, will some of the channels reverse their flow direction and form a natural circulation loop with other channels in the reactor? If they do, the liklihood of having a burnout occur is very much reduced.

2) A loss of coolant accident. After the emergency spray cooling system is turned on, will one reactor channel flow down and recirculate the emergency cooling water? If the flow in one or more channels reverses and a natural circulation loop is formed, the flow in the remaining up flow channels will be increased.

The experiments and analysis reported here are addressed to the general problem which is common to both of the above applications. How does one determine what the flow configuration is in an array of parallel heated channels?

This problem is considered in a general way in reference (4) but specific recommendations are not made for determining when the flow will reverse. In reference (1) the results of a series of single tube pressure drop versus flow rate experiments were reported. In comparing the results of these experiments to the calculations, it was found that the effects of non-equilibrium were very important and that the pressure drops were only poorly predicted from existing analytical expressions. The possibility still exists, however, of using single tube <u>experimental</u> results to predict multiple tube performances. This is one of the possibilities we are to explore here.

We shall begin by presenting the single tube pressure drop results obtained largely from reference (1). The multiple tube experiments on pressure drop and flow configuration will then be presented. Finally, the single tube predictions and multiple tube results will be compared and discussed in the light of the hwo general problems to which this work is addressed.

II Single Tube Results

The experimental set up and the details of the running procedure are given completely in reference (1). The primary experimental results from reference (1) are given on Fig. II-1. The tube used in all these experiments was .419" ID, glass 32 inches long with the center 23.4 inches heated by alternating current. The fluid in all cases is Freon 113 and the top plenum was always at or close to atmospheric pressure. Some extrapolations have been made on Fig. II-1 so the usefulness of the results is improved and the region in which uncertain nucleation was observed cross-hatched.

A gap in the original data on Fig. II-1 appears where the heat flux is less than 1000 Btu/hr ft^2. The apparatus used to get this data was reconstructed in order to fill in this gap. It was run at inlet velocities varying from 0 to +1 ft/sec and at heat fluxes between 500 and 1000 Btu/hr ft^2. For this entire range of conditions the bubble nucleation was found to be uncertain and the pressure drop to vary widely. The pressure drop ranged from .38 to 1 ft of Freon/ft. with an irregular period and occasional violent geysers. Nothing that could be called a steady minimum in the pressure drop curve was found to exist. Therefore it is not possible to draw a meaningful pressure drop versus flow rate curve for heat fluxes less than 1000 Btu/hr ft^2. This fact has an important bearing on the meaningfulness of these results.

A single tube can be run at any flow rate, no matter what the shape of the pressure drop versus flow rate curve is. In a multiple tube array, however, it is necessary that the slope of the pressure drop versus flow rate curve be positive in order that that flow rate be obtainable. The reason for this is developed for this specific case in reference (1). A more general explanation is given in reference (2), along with a complete analytical study of flow stability in heated tubes. Being this is the case, the negative sloped region shown on Fig. II-1 for downward velocities around .5 ft/sec is not accessable while the positive sloping region with up flow and large down flow velocities is.

Burnout is a quantity of considerable interest in these problems. Figure II-2 shows the burnout region observed in the single tube experiments. In every case, the burnouts reported in reference (1) consisted in the drying out of an annular film running down the wall. This is true even though the net liquid flow for those conditions was up. From time to time, plugs of liquid were carried up to the tube and it was these plugs which gave the net up liquid flow. This kind of burnout is peculiar to and characteristic of the very low flows which occur in these experiments.

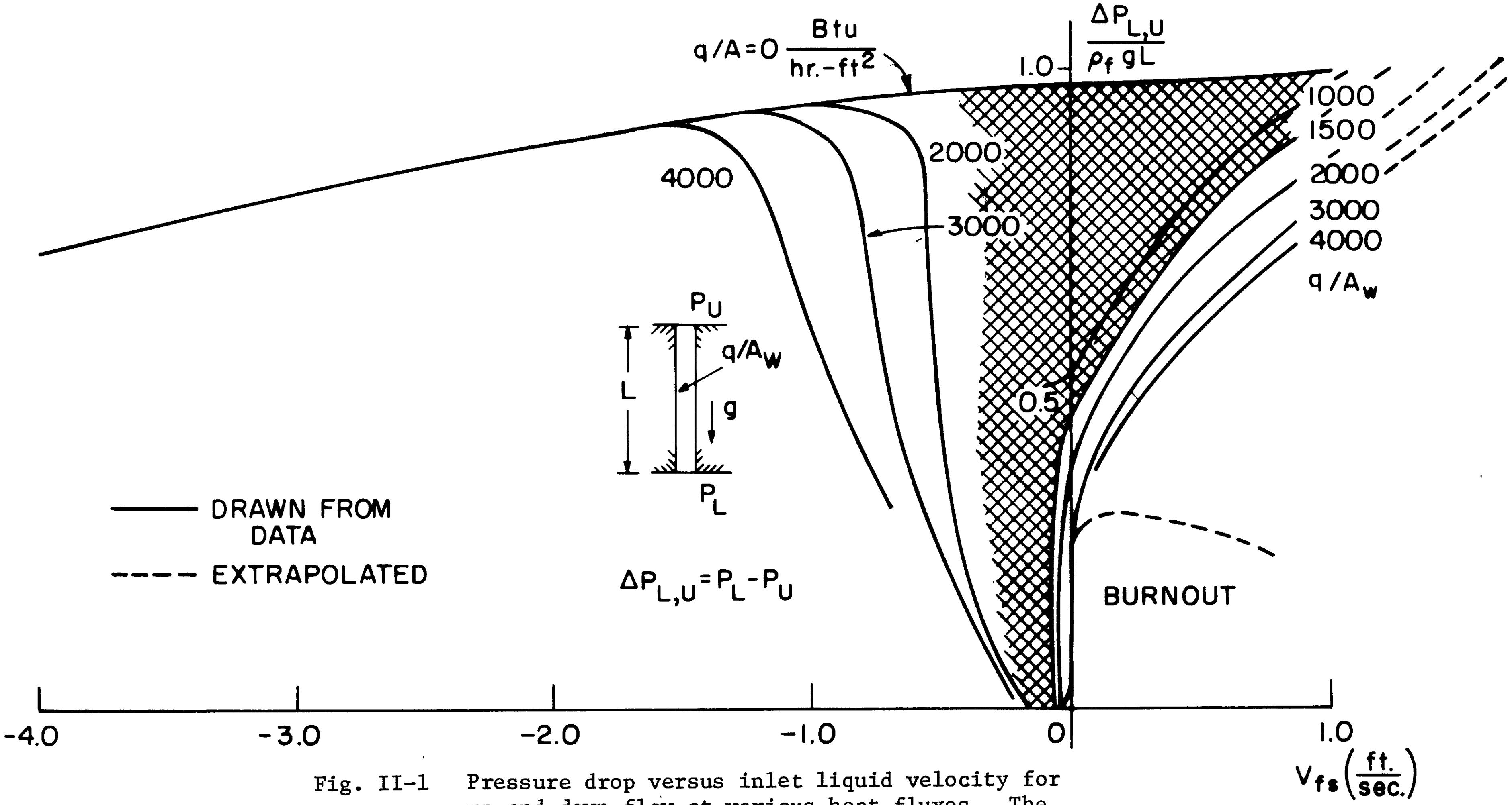

Fig. II-1 Pressure drop versus inlet liquid velocity for up and down flow at various heat fluxes. The cross hatched region is where bubble nucleation is uncertain and the pressure drop fluctuates wildly. Reference 1

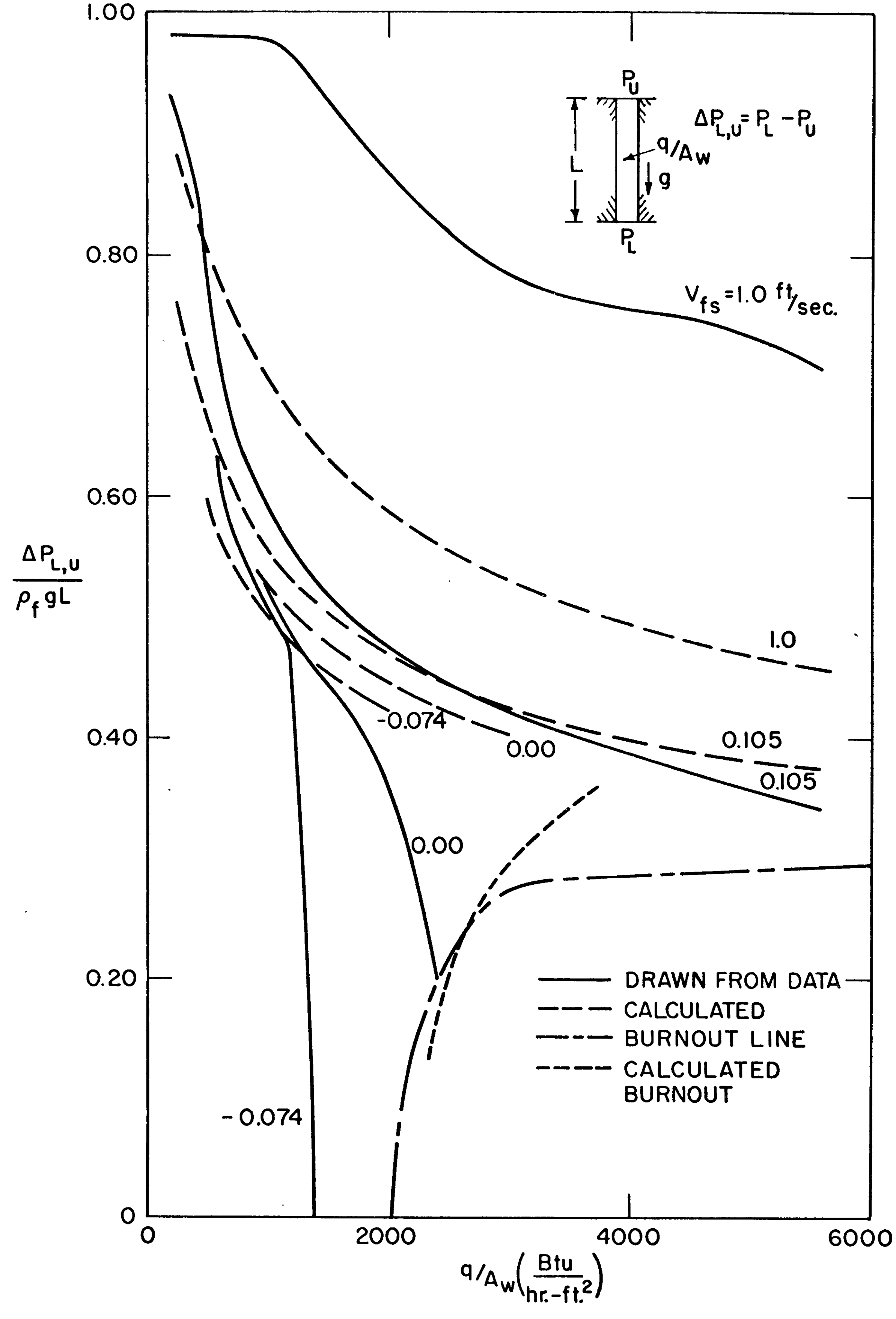

Fig. II-2 The same data of Fig. II-1 re-plotted differently to show the region of low flow more clearly. The burnout region is what is of interest here. Reference 1

III Predicting the Multiple Tube Performance from Single Tube Experiments

At any steady operating state for the multiple tube apparatus, two general conditions are known which had to be satisfied by the tubes. For the flows through the tubes

$$w_1 + w_2 + w_3 + \dots = 0 \qquad (1)$$

That is the net flow into the bottom plenum was equal to zero. The second condition is that the pressure drop for all the tubes has to be equal. That is

$$\Delta P_1 = \Delta P_2 = \Delta P_3 = \text{etc.} \qquad (2)$$

Both these equations are always true for all the reported 5 tube experiments. Now what predictions can be made from the single tube results?

Pressure Drop - The value of the pressure drop is not known but from equation (1), the flow configuration, and the single tube pressure drop experimental results, it is possible to determine the pressure drop for the whole array. To do this, turn to Fig. II-1 and go through the following graphical procedure.

1) Choose a pressure drop.

2) Draw a horizontal line for that pressure drop.

3) Depending on whether the flow is up or down in the tube and a knowledge of the heat flux in the tube, determine the intercept between the appropriate heat flux curve (for either up or down flow) and the horizontal pressure drop line. (Solutions occuring on negative sloping pressure drop versus flow rate curves are not possible in a multiple tube array.) The horizontal axis gives the flow rate in that tube.

4) Sum the flow rates. If the sum is zero, the right pressure drop has been assumed. If it is not, try another one. In any case, only

the intersections occuring on the positive sloping portions of the pressure drop versus flow rate curves should be chosen.

In order to determine what this pressure drop is, it is necessary to know the flow configuration, that is which tubes are flowing up and which are flowing down.

Flow Configuration - The flow configuration one observes depends entirely on history. At the start of these experiments it was thought that some notion such as "most stable configuration" might be useful. This was not found to be the case. Any possible configuration was found to be attainable by suitable manipulation of the histroy of the array. It was not found that the system spontaneously tended to any particular "most stable configuration". In other words, the natural disturbances occuring in the array were not sufficient to cause a spontaneous change of flow configuration as long as the external variables,such as heat flux,were not altered.

One must therefore know what the starting conditions are. Given these, can we predict at which heat flux a given tube might reverse the flow in that tube? The answer is yes. The procedure is as follows.

Let us assume the heat flux in four of the tubes is fixed, and and let us vary the heat flux in the fifth. If the fifth tube is flowing up, the flow in it will reverse when the heat flux is reduced to such a low value that the bubble nucleation becomes uncertain in it. For these experiments, this occurred when the heat flux dropped below about 1000 Btu/hr ft^2. In other words, flow reversal occurred when cross hatched region of Fig. II-1 was entered.

What happens is occasionally the tube becomes completely devoid of vapor bubbles. As the pressure drop for the array is less than 1 ft.

of Freon per ft., the flow must start down in the tube devoid of vapor. Once it starts down, it continues down.

How does one predict when the flow will reverse and start up in a tube which is originally flowing down? As the heat flux in such a tube is increased, the maximum on the pressure drop versus flow rate curve of Fig. II-1 moves down and to the left. For all practical purposes, the pressure drop for the array is determined by the four tubes in which the heat flux is not changed. When the pressure drop for the tube whose flux is being altered rises above that imposed by the other four tubes, the flow in that tube reverses.

In a more formal way, one can view the flow reversal heat flux for a given flow configuration as follows. It is just that heat flux for which no steady state solution is possible for that tube with that flow direction. The predicted and measured flow pressure drops and flow reversal points are compared in Section IV.

Impossible Configurations - If too many tubes are flowing down, the pressure drop it takes to get the liquid out of the lower plenum is more than that which gravity can provide. This is an impossible configuration. For the five tube apparatus, four tubes flowing down and one tube flowing up was found to be impossible. This can be seen by trying to simultaneously satisfy equation (1) and equation (2), using the data of Fig. II-1.

Burnout - The basic tool used to make burnout predictions is shown on Fig. II-2. This figure shows the relationship between the burnout heat flux, the pressure drop and the velocity into the tube. Burnout prediction consists of locating the pressure drop and heat flux appropriate to that tube under the existing operating conditions and seeing if these conditions place one in the burnout region of Fig. II-2. If they do not, no burnout is to be expected. Comparison of predicted and measured burnouts is also made in Section IV.

IV Multiple Tube Experiments and Comparison with the Predictions

Multiple tube experiments were conducted in the apparatus illustrated in Fig. IV-1. It consists of five electrically conducting glass tubes connecting two plenums each maintained at approximately saturation temperature. The top plenum was open to atmospheric pressure. The heat flux in each tube was independently controlled and measured. The details of the apparatus and the dimensions of the tubes are given on Fig. IV-1.

A variety of experiments have been run on this apparatus which show how good our single tube measurements are for predicting multiple tube performance. Let us simply list these experiments.

(1) The comparison can be made of the observed and calculated (from single tube experiments) pressure differences between the two plenums for a given flow pattern of up and down tubes and a given heat flux distribution on the tubes.

(2) The location and magnitude of the burnouts can be determined and measured.

(3) A comparison can be made of the possible modes of circulation with those actually observed. That is, it can be shown, using the methods of Section III, that for this apparatus at high heat flux, 3U and 2D (3U and 2D means 3 flowing up and 2 flowing down), or 4U and 1D, or 5U and OD are possible but not 1U and 4D or 2U and 3D. We can try to achieve the "impossible" patterns and see if, if fact, we can. We can also see if all the possible flow patterns can be achieved.

(4) A comparison can be made of the observed and calculated heat fluxes for flow reversal for one tube in the five.

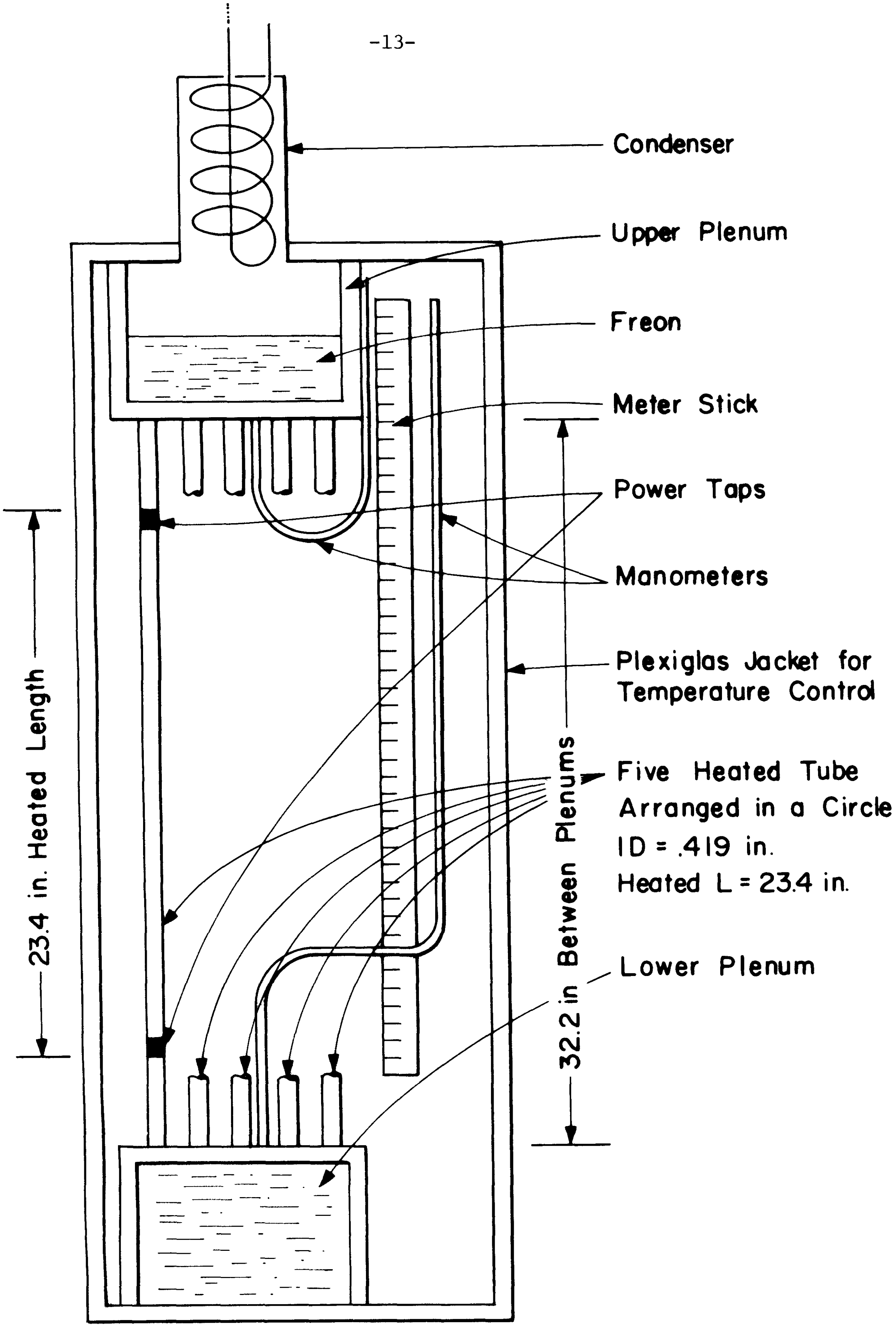

Fig. IV-1 The five tube apparatus used in these experiments. The tubes were arranged in a circle unlike this drawing, in which they are spread out for clarity.

All these comparisons will be made here.

Pressure Drop Predictions - In order to calculate the pressure difference between the upper and lower plenums, it is necessary to have single tube pressure difference versus flow rate data and know which tubes are going up and down. Let us assume the pressure drop curves of Fig. II-1 are appropriate and that the flow configuration is known.

A number of such measurements were made and a selected sample showing the extreme conditions is shown below in Table IV-1. A scatter plot is shown on Fig. IV-2. All pressure drop calculations are made using the methods outlined in Section III.

The comparison of the actual multiple tube pressure drops and those calculated using pressure drop versus flow rate information obtained from single tube experiments shows the calculated pressure drops are reasonably good. Close examination of the pressure drop predictions will indicate that they are not good enough for one to predict how many tubes are flowing up or down in a five tube apparatus, however. The change in overall pressure drop in going from one tube flowing down to two tubes flowing down is so small that very accurate pressure drop predictions are needed for one to infer what the state of the five tube system is. For a system with a much larger number of tubes, it is clear that the change in system pressure drop resulting from one tube changing direction is too small to detect. One, therefore, cannot infer very well the state of the system then from the overall pressure drop across it.

Burnout - The most striking aspect of the single tube burnout measurements reported in reference (1) is the fact that the burnouts did not

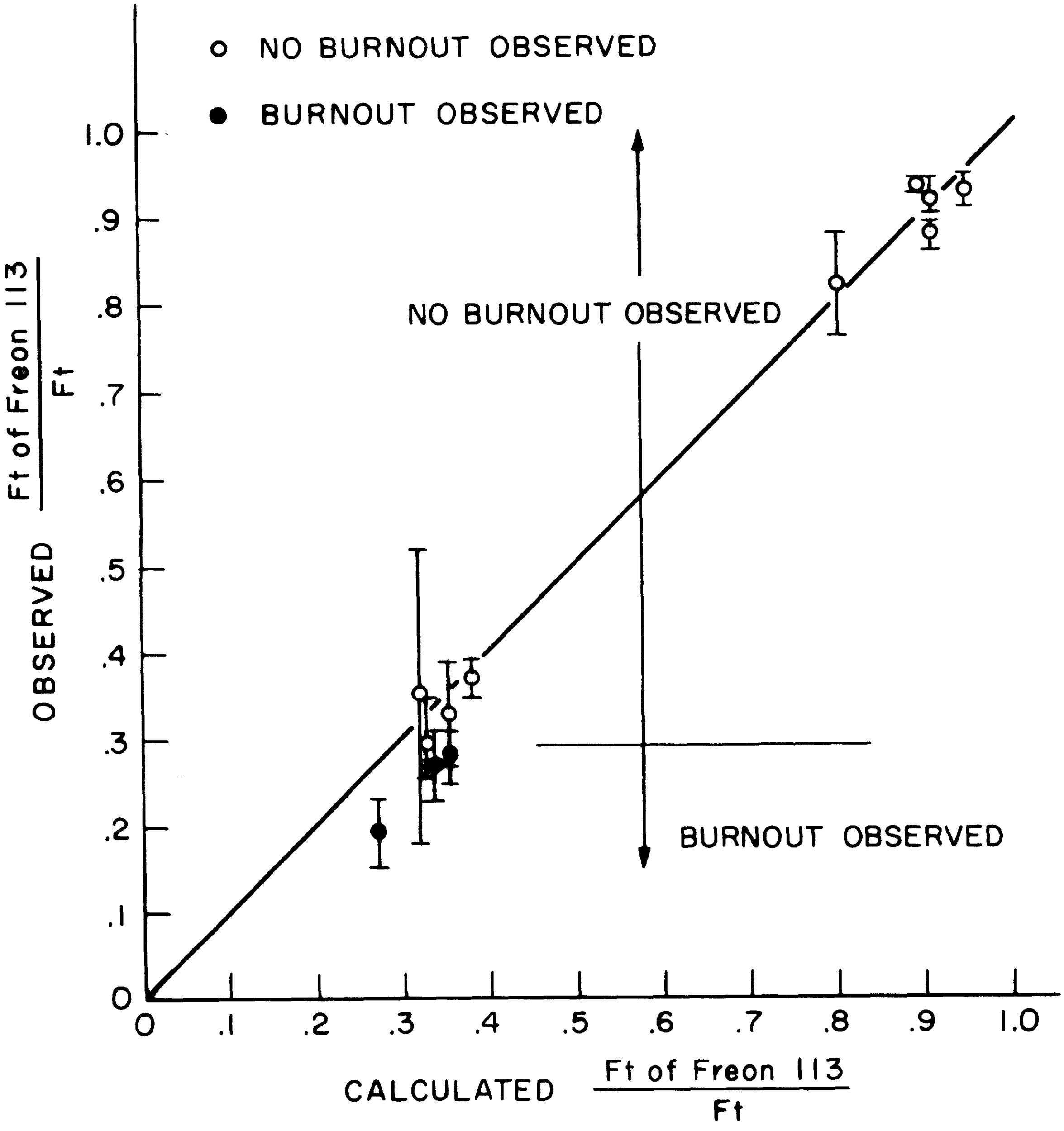

Fig. IV-2 Scatter plot of the measured five tube pressure drops and the computed pressure drops for five tubes based on the single tube results of Fig. II-1.

Table IV-1

A Comparison of Measured and Predicted Pressure Drops for Various Conditions

		Tube 1	Tube 2	Tube 3	Tube 4	Tube 5	$\frac{\Delta P}{\rho g L}$ meas range	$\frac{\Delta P}{\rho g L}$ calc	Burnout Visible	Burnout Predicted	Possible Flow Configuration
(1)	Up or Down q/A (Btu/hr ft^2)	U 3000	D 3000	D 3000	U 3000	U 3000	.92 .91 - .94	.91	No	No	Yes
(2)	Up or Down q/A	D 2000	D 2000	U 2000	U 2000	U 2000	.93 .92 - .94	.95* (minimum)	No	No	Yes*
(3)	Up or Down q/A	U 2000	U 2000	U 2000	U 2000	U 2000	.35 .52 - .18	.32	No	No	Yes
(4)	Up or Down q/A	U 3000	U 3000	U 3000	U 3000	U 3000	.19 .15 - .23	.27	Yes	Yes	Yes
(5)	Up or Down q/A	U 2200	U 2200	U 2200	U 2200	U 2200	.33 .27 - .39	.35	No	No	Yes
(6)	Up or Down q/A	U 2200	U 2200	U 2200	U 2200	U 2200	.28 .25 - .31	.35	Yes**	Yes	Yes
(7)	Up or Down q/A	U 2500	U 2500	U 2500	U 2500	U 2500	.29 .23 - .35	.33	No	No	Yes
(8)	Up or Down q/A	U 2500	U 2500	U 2500	U 2500	U 2500	.27 .23 - .31	.33	Yes**	Yes	Yes
(9)	Up or Down q/A	U 2000	U 2400	U 2800	U 3200	U 3600	.37 .35 - .39	.38	No	No	Yes

**This set of data is taken with the top plenum partly empty.

* With the curves of Fig. II-1 it is not possible to predict this flow pattern. The ΔP would have to be greater than .95, which is not possible at this pressure difference.

Table IV-1 Continued

		Tube 1	Tube 2	Tube 3	Tube 4	Tube 5	$\frac{\Delta P}{\rho gL}$ meas range	$\frac{\Delta P}{\rho gL}$ calc	Burnout Visible	Burnout Predicted	Possible Flow Configuration
(10)	Up or Down q/A (Btu/hr ft^2)	U 1600	U 2200	U 2800	D 3400	D 4000	.88	.92	No	No	Yes
(11)	Up or Down q/A	U 1600	U 2200	U 2800	U 3400	U 4000	.33 .29 - .37	.27	No	No	Yes
(12)	Up or Down q/A	D 400	U 1300	U 2200	U 3100	U 4000	.82 .76 - .88	.80	No	No	Yes
(13)	Up or Down q/A	U 3000	D 3000	U 3000	D 3000	U 3000	.93	.90	No	No	Yes

ever occur if

1) the heat flux was below 2000 Btu/hr ft^2 for this apparatus or

2) the pressure difference between the upper or lower plenum was greater than .29 ft. of Freon per ft.

The multiple tube apparatus was run at a variety of heat fluxes and flow configurations. Several burnout conditions and a number of non-burnout conditions were investigated. It can be seen on Fig. III-2 and in Table IV-1 that both the conditions given as one were satisfied where burnout was concerned. That is the burnout only occurred when the heat flux was greater than 2000 Btu/hr ft^2 and the pressure difference was less than .29 ft. of Freon/ft. The multiple tube burnouts can therefore be predicted quite well from the single tube experiments.

Flow Patterns, Up and Down - In Section III it is shown that certain flow patterns are possible and other ones are not. For all the tubes receiving a heat flux of 3000 Btu/hr ft^2 for instance the following patterns are possible.

1) 5U, 0D

2) 4U, 1D

3) 3U, 2D

All these flow patterns were observed. The conditions for two of them are tabulated in Table IV-1, runs (1), (4), and (13). In fact, any combination of up and down flow which could be predicted as a stable condition was accessable in the laboratory. In general one got in these experiments what one set in the experiments.

By turning the heat flux up in one tube first, one insured the flow would go up in that tube. The last one or two tubes in which the heat flux was turned up would continue to flow down. In order to get all the tubes flowing up, it is necessary to have a very low liquid level in the top plenum. One thus effectively prevents the formation of a flow loop between any two tubes so that all the tubes discharge their vapor into the top plenum. When liquid is then added to the top plenum, the tubes all continue to bubble up. When this condition is acheived, it is possible to make the flow go down in any one or two tubes by momentarily turning the power down in that tube.

The single tube pressure drop curves indicate that for this five tube array, three or more tubes flowing down were not possible flow configurations. The experiments confirmed this. Suppose the flow configuration was 3U, 2D. It is always possible to make one of the up tubes flow down by turning the heat flux off in that tube. When this was done, the flow would reverse, as expected, in that tube then a few seconds later it would also reverse in one of the down flowing tubes. The conditions of 3U, 2D would be re-established, though the tubes flowing up and down would be different. In essence, any flow configuration which was computed as possible was found to be attainable as long as the history was manipulated in the right way.

How good are the predictions of when the flow reverses for a given change in conditions? In order to answer this question it is necessary to consider what causes the flow to reverse in a given tube. Referring back to Fig. II-1, the pressure drop versus flow rate curves have both a maximum and a minimum. In a five tube array, the pressure drop across one tube is virtually imposed by the other four. If the pressure drop imposed by these tubes is such that there is no solution for that direction of flow in the fifth tube and at its heat flux, the flow in that tube must reverse. Reversal occurs then when the pressure drop is less than the minimum or more than the maximum for that heat flux. The question is then reduced to finding the location of the minimum and the maximum in the pressure drop curves.

At a high enough heat flux, the minimum is virtually zero and occurs when the liquid velocity down is just sufficient to hold a bubble stationary. At that velocity, if any heat is being transferred to the test section, the bubble will grow until the tube has a solid vapor core with a liquid annulus running down the walls. No disturbance in an up flowing tube is large enough under these circumstances to cause the pressure drop to become less than zero so spontaneous reversal is not to be expected. The reason for this is the disturbances are almost all due to density variations in the tube. It is not possible to imagine a density variation which can reduce the pressure difference across the tube to less than zero.

There is a heat flux which is low enough, however, so that bubble nucleation is uncertain and occasionally fails completely. When this happens, the tube fills with liquid and if it was originally discharging vapor in the upper plenum, it will now flow down and discharge its vapor in the lower plenum. This heat flux, for the tubes used in these experiments lay between 1500 and 1000 Btu/hr ft^2. The flow will reverse then in an up flowing tube if the heat flux drops below this range. Such a statement should not be dignified by calling it a prediction, however. When the number of nucleation sites which are active is very small the nucleation becomes very erratic and predicting what will happen is just not possible. The pressure drop will swing violently from .4 to 1 ft. of liquid per foot so that an average pressure

Table IV-2

Heat Fluxes at which Flow Went From Up to Down in an Originally Up Flowing Tube

Run	4 Tube Av q/A	Reversing q/A Observed	Predicted Approximate Reversing q/A
1	3000	664	1000
2	3000	1250	1000
3	3000	830	1000
4	2000	260	1000
5	2000	490	1000
6	2000	208	1000
7	3000	365	1000

Table IV-3

Comparison of Conditions for Flow Reversal from Down to Up with Prediction

	Tube 1	2	3	4	5	Pressure Drop at Reversal		q/A at Reversal	
						Measured	Predicted	Measured	Predicted
Up or Down q/A	U 2000	U 2000	U 2000	U 2000	D* 3320	---	---	3320	greater than 4000
Up or Down q/A	U 2000	U 2000	U 2000	U 2000	D* 3650	.77	.80	3650	greater than 4000

*Reversing Tube. The D refers to its original state.

drop for determining the location of the minima simply does not exist. These swings in pressure drop occurred in these experiments at about 1000 Btu/hr ft^2. Table IV-2 gives the heat flux at which an originally up flowing tube in the five tube array changed to down flowing while the heat flux in the tube was very slowly decreased.

The heat flux at which flow reverses is obviously widely scattered. Whether boiling persists depends on the stability of the last remaining cavity and this is quite unpredictable. Clearly no single tube experiments are going to tell us anything of general interest about this kind of flow reversal.

Another kind of flow reversal can occur when the heat flux on an initially down flowing tube is increased sufficiently to make it flow up. Several tests of this kind were run and the results are shown in Table IV-3. The maximum in the pressure drop versus flow rate curve determines when this reversal will occur. This is much better defined than the minimum so a comparison of the expected and observed pressure drops and heat fluxes can be made.

As can be seen in Table IV-3, the pressure drop at which flow reversal occurs is about right but the heat flux is underestimated. The reason for this is the departures from thermal equilibrium in the single tube experiments are much larger than in the multiple tube experiments. When only one tube is connected to the upper plenum, the liquid which enters this tube is free of bubbles. When four tubes are discharging a bubbly mixture into the upper plenum, the one tube which is flowing down is very likely to ingest bubbles. This makes a closer approach to thermal equilibrium possible and means the heat flux which is needed to turn the flow around is less than in the single tube experiments. (In reference (1) large departures from thermal equilibrium were found in the single tube experiments.)

In summary for the flow configuration experiments, it is possible to say that all the behavior which might have been expected was found but the predictions of when and where it would be found are not good. The two departures from ideal conditions, large superheats needed to initiate boiling and substantial departures from thermal equilibrium account for the discrepancies. These same discrepancies can be found at higher pressure too, though they are not expected to be so severe there.

V Recommendations for Predicting Reactor Performance

There are a number of questions of interest to a reactor designer to which we would like to get answers from the single tube results. Let us begin by listing what these are.

1) How does one compute the flow rate through a particular channel given the flow rate or pressure drop across the core as a function of time?

2) How does one determine the flow direction in a given channel? At any time?

3) How does one determine if a burnout occurs?

As the history of a core during an upset is traced out, the answers to the first two questions will develop. The answer to the question "does a burnout occur?" can be determined from the answers to the first two by examination.

Loss of Pumping Power Accident - Typically, during a loss of pumping power accident the flow rate and the reactor heat transfer rates as functions of time are known. Without knowing the details of the flow distribution in the reactor, it is possible to estimate the pressure drop across the reactor for these conditions. (It is assumed that the transient is started in the region where the flow is up in all the tubes and where the pressure drop versus flow rate curve is single valued.) If the transient is slow enough, the reactor can be viewed as passing through a series of quasi-steady states and the transient terms omitted from the momentum equation. Let us assume this is the case.

In general, there will be a distribution of heat fluxes among the channels constituting the core but that the pressure drop for all channels at any instant must be the same. As the transient proceeds the reactor passes into the region where the pressure drop versus flow rate curve is multi-valued. At this time the question arises, which and how many channels are flowing up or down? This is the essential question which this work is addressed to. The answer is as follows.

If the heat flux in the coldest channel is above the minimum needed for bubble nucleation in that channel, no channels will reverse direction. The flow rate is known and the core pressure drop can be found by use of a graphical technique and data of the type shown on Fig. II-1. Let us draw a horizontal line at some pressure. The intersections of this line with the constant heat flux lines gives the flow rate through a channel at those heat fluxes. These individual flow rates can be summed up and the flow rate through the reactor determined. If this is not the flow rate a new pressure drop can be guessed and the calculation repeated. In this way, the whole transient can be calculated.

Now let us suppose the reactor contains some channels which have heat fluxes which are less than those needed to sustain bubble nucleation. What will happen? As soon as the pressure drop across the core drops to the region where the pressure drop versus flow rate curve is multi-valued, these channels can reverse. On the basis of the experiments which have been performed, it appears that if they can reverse, they do. It is recommended that this be assumed and then a procedure similar to that used when all the channels were flowing up be used to compute the flow through the reactor. That is, find out which channels can reverse. Draw a horizontal line on the curve similar to Fig. II-1. The reversed channels will have flow rates given by the intersection of this line with the positive sloping curve at the extreme left. The other channels will be operating on the right hand leg of the curve. The flows through all the channels can then be evaluated and if they do not sum up to the flow through the core, a new core pressure drop can be assumed. In this way the whole transient can be evaluated.

One difficulty can arise in this calculation procedure. As was shown in the multiple tube experiments, it is not possible that so many tubes can reverse flow that the pressure drop for the whole array of tubes becomes greater than the maximum on the pressure drop flow rate curve. There is a basic indeterminacy here as to what actually happens. For the size systems we are concerned with, the nucleation at low heat flux is quite erratic. This means vapor may be generated in a channel for a while, then stop. That channel will then reverse from up flowing to down flowing. Another channel at the same time will start boiling and reverse flow and start flowing up. The multiple tube experiments did not show "a most stable configuration" which it might be expected that a large number of channels might approach. Under the circumstances it is suggested that as long as bubble nucleation is uncertain, a channel will go through the phase of no vapor present at all. Channels will continue to reverse flow direction then until the pressure drop for the array increases to the point where no solution is possible. (This will only happen if there is a large number of channels which have a low heat flux on them.) At that point if a new channel starts flowing down, one of the down flowing channels will start flowing up. This is a stable configuration then.

Burnout - Let us now assume the whole transient has been calculated and pose the question, did a burnout occur? Turning once again to Fig. II-1, a region is delineated in which burnouts occurred. Figure II-2 shows this region enlarged on slightly different coordinates. As can be seen, two conditions had to be satisfied in order for a burnout to occur.

1) The pressure gradient has to be less than .29 ft. of liquid/ft.

2) The heat flux has to be greater than 2000 Btu/hr ft^2.

For any geometry similar conditions exist. It is felt that the first condition is actually the condition which must be satisfied if the tube is to be filled with slug flow. That is, no annular flow can exist in the tube if the pressure gradient is greater than this. For a uniformly heated channel this is probably true in general as the gradient reflects the liquid fraction and this is approximately constant for the slug-annular transition. The limiting heat flux is, no doubt, a function of channel geometry but can be estimated from the methods of reference 3. The important thing to note, however, is that a burnout of the counter current film dry out type cannot occur if the pressure drop across the core remains greater than about .29 ft. of liquid/ft. (Of course if there is a low flow and a high flux on one channel a burnout of the usual kind with an up flowing film might well occur.)

Quench Problem - Let us now turn our attention to the problem of determining the flow configuration in an array of channels which have momentarily lost their coolant and have been quenched by spraying in additional water from above. In this case "burnout" has already occurred and the question is how soon will good circulation be re-established in the core.

First it is necessary to assume that either the pressure drop versus flow rate curves are the same as they would be for channels which were not burned out or that the appropriate curves have been obtained. Following the procedure used in the previous paragraphs, it is possible to say, to begin with, that until the top plenum has water in it, the flow of vapor will be up in all channels. If any of the channels have heat fluxes below the nucleation limit, and when the top plenum has water standing in it, these channels will in due time reverse. This will continue until the maximum number that can flow reversed actually have reversed. The method outlined for calculating the loss of pumping power accident also will work here.

Conclusions

1) Burnout resulting from the dryout of a down flowing annular film does not occur if the pressure drop is greater than .29 ft. of liquid per ft., apparently because the tube is filled with a slug flow.

2) All flow configurations (up and down flow) which can be computed as possible can be found to occur in practice.

3) Two departures from ideal conditions make detailed performance predictions from single tube experiments impossible. These are substantial departures from thermal equilibrium even when vapor is present and poor bubble nucleation at low heat flux.

4) No naturally occuring disturbances were found which were large enough to cause a tube discharging its vapor in the top plenum to reverse flow direction unless the heat flux was so low that the bubble nucleation was uncertain.

5) In these experiments, it was found that very small changes in the subcooling made a great difference in the operation of the system. This variable must be matched very closely in any single tube experiments in order to get results which are applicable in a multiple tube application.

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List of Symbols

L - Tube length

ΔP_1, ΔP_2, etc. - Pressure differences in various tubes

ΔP_{LU} - Pressure in lower plenum minus that of the upper plenum

$(q/A)_w$ - Tube wall heat flux

V_{fs} - Inlet liquid velocity in ft/sec

w_1, w_2, w_3 - Flow rates in various tubes

ρ_f - liquid density