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COUNTERCURRENT GAS–LIQUID FLOW IN PARALLEL VERTICAL TUBES

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Abstract—The subject of this paper is the flow between an upper reservoir, containing a liquid, and a lower reservoir, containing a gas, interconnected by parallel vertical tubes. The characteristics of the combined system are predicted from a knowledge of the behavior of flow in individual tubes. Numerous modes of possible operation are described analytically and demonstrated experimentally. The effects of system geometry, changes in gas supply characteristics, operating procedure and two-phase flow regimes on the transitions between modes and system stability are presented. Predictions are made for the limiting case of a large number of identical parallel channels.

INTRODUCTION

Two-phase countercurrent flow occurs in several industrial processes in which the purpose is to obtain heat and mass transfer, perhaps with chemical reaction, between a gas and a liquid. Packed columns and cooling towers are typical examples. Liquid flows downward under gravity through a network of flow passages while gas flows upward past the liquid, driven by a combination of buoyancy and applied pressure difference. The method of analysis is often based on the assumption of uniform flow across the system so that a one-dimensional approach can be used. This is appropriate if there is sufficient lateral mixing to counteract the tendency for gas or liquid to "channel" to certain regions.

Recent concerns with possible loss-of-coolant-accidents (LOCAs) in water-cooled nuclear reactor systems have revealed that countercurrent steam–water flow phenomena may play an important role. In particular, if the core of a reactor becomes wholly or partly dry, attempts may be made to reflood it from above. The water that is to enter the core, or flow through it to the lower plenum, may be opposed by an upward steam flow produced by heat transfer from the fuel rods or by flashing due to depressurization.

Certain designs of reactor core contain bundles of fuel rods surrounded by shrouds that prevent lateral mixing. Moreover, even if there is lateral mixing the short length to diameter ratio of the entire core may promote non-one-dimensional phenomena, especially if certain regions are hotter than others or contain damaged fuel rods. For these reasons we were led to consider the general problem: "What happens in a set of parallel vertical channels, each communicating with common plenum chambers, when fluid is supplied from above and an immiscible lighter fluid is injected below?" A sketch of the essential features of such a system is shown in figure 1.

This does not appear to be a problem that has been studied previously (most work on parallel channels has involved cocurrent flow) except for the recent work of Speyer & Kmetyk (1977), who studied countercurrent air–water flow in four parallel vertical channels and showed that several modes of operation were possible with different flow regimes occurring simultaneously in neighboring channels. Their theory was able to describe some of the phenomena but did not have the detailed experimental support that we have sought to achieve in this paper. They also obtained only some of the modes that we have been able to demonstrate.

We suspect the reason for the lack of previous work on this topic to be the undesirable features of the performance characteristics of such a system, for most conceivable practical

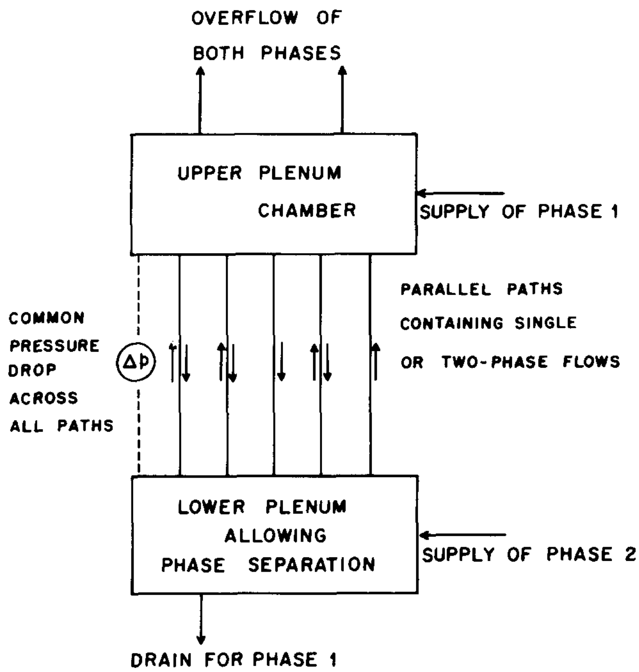

Figure 1. Diagram of a parallel path countercurrent flow system with phase 1 heavier than phase 2.

purposes. For example, we shall later show that, over a certain range of pressure drop, each tube can operate in four distinct flow regimes. If there are N identical tubes in parallel there are $(N+3)!/3!N!$ different possible operating conditions—not a prospect that would be relished by a designer who wishes his industrial process to be predictable.

This paper presents a summary of the major results of studies that we have conducted of several systems resembling figure 1, using air and water as the two phases. Variables considered, all of which were found to play a role in determining the possible operating characteristics and their stability, have included:

- The shapes of the flanges connecting the tubes to the plenum chambers
- The size of orifices to throttle the flow at the bottom of the tubes
- Combinations of tubes with different diameters
- Turbulence suppression in the water pool in the upper plenum chamber
- The depth of the liquid in the upper chamber
- The procedure used to approach the operating condition (e.g. increasing or decreasing the air flow rate, the time allowed for steady state to develop)
- The volume of air in the lower plenum
- The characteristics of the air supply system
- The geometrical arrangement of the tubes (e.g. distance apart, shape of the array of several tubes)

We will not attempt to present all of the results here. Our emphasis will be on the logical procedures for approximating the behavior of a multitube system given the pressure drop and flow characteristics of individual tubes (since the two-phase flow characteristics in the flow regimes that we obtained cannot yet be predicted from first principles, this input is empirical). We will also describe the classes of phenomena that we have found to be common to a variety of systems.

We do not claim to have solved the nuclear reactor "top reflood" problem. That situation contains additional influences, including heat transfer by boiling and direct contact condensation, the mechanisms of water entrainment and deentrainment, interactions with the entire flow loop and the methods of water injection. Nonetheless, it seems likely that phenomena resembling those we have observed could occur during a LOCA or during some anticipated large-scale tests.

Since our analysis has been kept at a general level, with no unique application to the nuclear industry, there may be other situations for which it is relevant, such as aqueous geothermal systems, petroleum reservoirs, water-logged natural gas deposits, the response of dry soils or fractured rock to surface inundation—in fact any situation in which a reservoir containing a heavy phase is connected by several parallel paths to a source of a lighter phase lying below it.

1. SINGLE-PHASE FLOW

Consider a set of N vertical tubes of length L and diameter D connected in parallel between a lower chamber, to which gas is supplied and from which liquid is exhausted, and an upper chamber to which liquid is supplied and from which both gas and excess liquid are removed (figure 1). For the moment we consider the tubes to be identical, though a similar analysis can be developed for the general case. We also confine our attention to single-phase flow (i.e. either all gas or all liquid) in each tube, both because this is a simple situation to analyse and because it can occur in practice, particularly in tubes of small diameter, where surface tension acts to fill the tube once a small amount of liquid has penetrated it.

Assume that an overall gas flux $j_G = Q_G/NA$ is supplied to a total of N tubes where Q_G is the total volumetric flow rate, and A is the area of cross section of each tube. The gas flows up through n tubes and a corresponding liquid flux j_L flows down the remaining $N-n$ tubes. The pressure drop across all the tubes is the same. Assume for simplicity that under steady flow the frictional component of the pressure drop is proportional to the momentum flux, ρv^2, then the pressure drop from the lower chamber to the upper is

$$\Delta p_G = C_G\rho_G v_G^2 + g\rho_G L = C_G\rho_G\left(j_G\frac{N}{n}\right)^2 + g\rho_G L \qquad [1]$$

for the gas, and for the liquid

$$\Delta p_L = -C_L\rho_L v_L^2 + g\rho_L L = -C_L\rho_L\left(j_L\frac{N}{N-n}\right)^2 + g\rho_L L. \qquad [2]$$

Since the pressure drops are equal we may set $\Delta p_G = \Delta p_L$ to get

$$C_G\rho_G j_G^2\left(\frac{N}{n}\right)^2 + C_L\rho_L j_L^2\left(\frac{N}{N-n}\right)^2 = g(\rho_L - \rho_G)L.$$

Defining $(n/N) = X$ and $j_G^* = j_G^2\rho_G/\{g(\rho_L - \rho_L)D\}$ with a similar expression for j_L^* yields

$$\frac{C_G j_G^{*2}}{X^2} + \frac{C_L j_L^{*2}}{(1-X)^2} = \frac{L}{D}. \qquad [3]$$

For each value of X, defining a "mode" of operation, [3] describes an ellipse that gives the relationship between j_G^* and j_L^*. A graph of these curves, as in figure 2, indicates all the possibilities of operation of the system. However, it is not clear, for a given gas flow rate (or other boundary conditions) in which mode the system will operate.

If N is large, the curves define an allowable region bounded by an envelope which can be shown to be

$$(C_G j_G^{*2})^{1/3} + (C_L j_L^{*2})^{1/3} = \left(\frac{L}{D}\right)^{1/3}. \qquad [4]$$

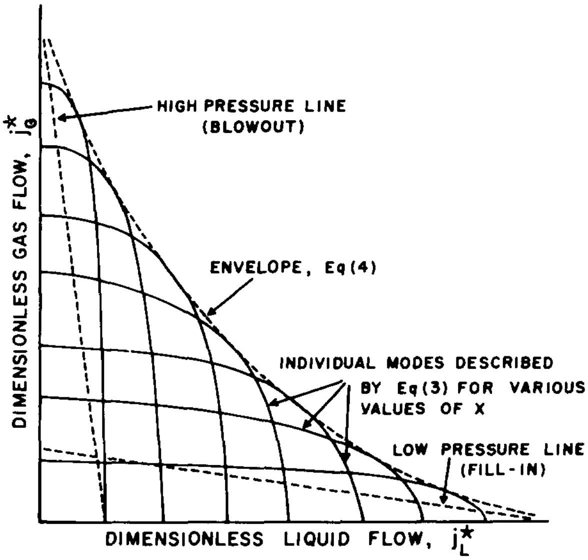

Figure 2. Operating characteristics of a parallel tube system with single-phase flow in each tube.

A discussion of the stability of operation in each mode is given by Karlin (1978) but is beyond the scope of this paper. He condluded that for a constant gas supply to the lower chamber the system was usually stable in any mode and that transitions between modes occurred by two mechanisms:

(a) *Blow-out.* If the liquid flow rate per tube, $j_L/(1-X)$, is too low, a cylindrical gas bubble will penetrate at the bottom, as described by Wallis *et al.* (1977). As this bubble progresses up the tube the hydrostatic head above it decreases and the gas acts as an accelerating piston that drives out the remaining liquid. This tube now switches from carrying liquid to carrying gas. Since the gas flow is now shared between more tubes, the pressure drop decreases, the liquid flow per tube increases and "blow-out" of further tubes is prevented (though our experiments show that more than one tube may blow out simultaneously, particularly if the air flow is increased in a finite step).

As the liquid flow rate per tube is related to the pressure drop by [2], this transition should be observed at a certain high(est) pressure drop.

(b) *Fill-in.* If the gas flow per tube (or the corresponding pressure drop) is too low, liquid will begin to penetrate at the top. This increases the resistance to gas flow and also adds a hydrostatic head to the pressure drop in that tube. As a result the gas flow is further reduced, more water penetrates the tube, and a transition to complete liquid flow or "fill-in" occurs in that tube.

The broken lines in figure 2 show the locus of points at which these transitions from mode to mode should be expected to occur; they are determined by critical values of $j_L/(1-X)$ for blow-out and j_G/X for fill-in.

This simple picture is adequate for our present purposes. However, a more thorough study of stability (e.g. Karlin 1978), should consider the compliance of the gas supply, the compressibility of the gas in the lower chamber, the inertia of the fluids in the tubes and the pressure drop characteristics during the short period of two-phase flow that initiates the transitions.

Experiments

The apparatus used resembled figure 1 with four 155-mm long, 6.35-mm diameter transparent vertical tubes connecting two tanks. The top tank was open to the atmosphere and filled with water at a constant height regulated by overflow. The bottom tank was closed and water could drain through a valve at the bottom. Air was introduced into the lower tank at a known flow rate. The pressure difference across the pipes was measured by pressure taps leading to an air/water manometer. The tube diameter was sufficiently small that two-phase flow could not be maintained stably in it. Annular flows were unstable against bridging by the liquid, induced by surface tension pinching off the gas core. Slug and bubbly flows were flushed out by a "piston" of single-phase fluid that entered from one chamber or the other, depending on the direction of flow.

The actual pressure drop vs velocity characteristic of the tubes for single-phase flow of air alone and water alone was first determined by setting a flow of water or air through all four tubes and measuring the pressure drop. The air flow tests were run with and without water in the upper tank and no significant difference in the results was found above $j_G^* = 1$. Below this value a two-phase flow occurred that led to fill-in at a pressure drop less than about 8 mm of water. With increased pressure drop between the lower and upper tanks air flow increased and water flow decreased, following dimensionless correlations:

$$\Delta p^* = \frac{(\Delta p - g\rho_G L)}{g(\rho_L - \rho_G)D} = 1.36 j_G^{*2} \qquad [5]$$

$$\Delta p^* = \frac{(\Delta p - g\rho_G L)}{g(\rho_L - \rho_G)D} = 24.4 - 1.12 j_L^{*2}. \qquad [6]$$

The term 24.4 is simply equal to the L/D ratio of each tube.

About 60 per cent of these losses are due to entrance and exit effects and this accounts for the weak dependence of the coefficients upon velocity.

According to the theory, [5] and [6] should now determine the specific operation of the system in every mode as long as j_G^* and j_L^* are replaced by j_U^*/X and $j_U^*/(1-X)$, respectively. The flow rates are related by equating [5] and [6] to get a result of the form of [3] with $L/D = 24.4$, $C_G = 1.36$, $C_L = 1.12$.

Measurements of j_G^*, j_L^* and Δp^* were made in each of the operating modes of the system. The results are shown in figure 3. The symbols indicate the mode of operation of the system when the measurement was taken. Agreement with the theory is good and justifies the assumption that flow in parallel tubes can be described if the characteristics of single tubes are known.

The transitions between operating modes as the total air flow was increased or decreased are shown in figure 4. The major features observed were:

Blow-out. It was found that the pressure drop could rise to a value of $\Delta p^* = 24.4$ and actually stop the water entirely in the pipes ($k_L^* = 0$); blow-out would take place with a slightly increased pressure in the lower plenum. This is consistent with the experimental results of Wallis *et al.* (1977) who found that for tube diameters below

$$D^* = \frac{D}{\sqrt{(\sigma/(g\Delta\rho))}} = 5 \qquad [7]$$

or in this case $D = 13.6\ mm$, the water flow down a vertical tube would have to reach zero before air could progress up the tube (σ is the surface tension).

Some alternative transitions were observed with increasing air flow, depending on the rate at which flow was changed and the volume of the lower plenum (Karlin 1978a).

Fill-in. As air flow was decreased, the fill-in transitions occurred near a critical value of gas velocity ($j_G^*/X \simeq 1.1$). Each mode was followed successively until this critical condition was reached; operation then switched to a mode in which one less tube carried air flow.

Starting operation and operation at low air flow

Air flow below the minimum necessary to prevent even one tube from filling-in (i.e.

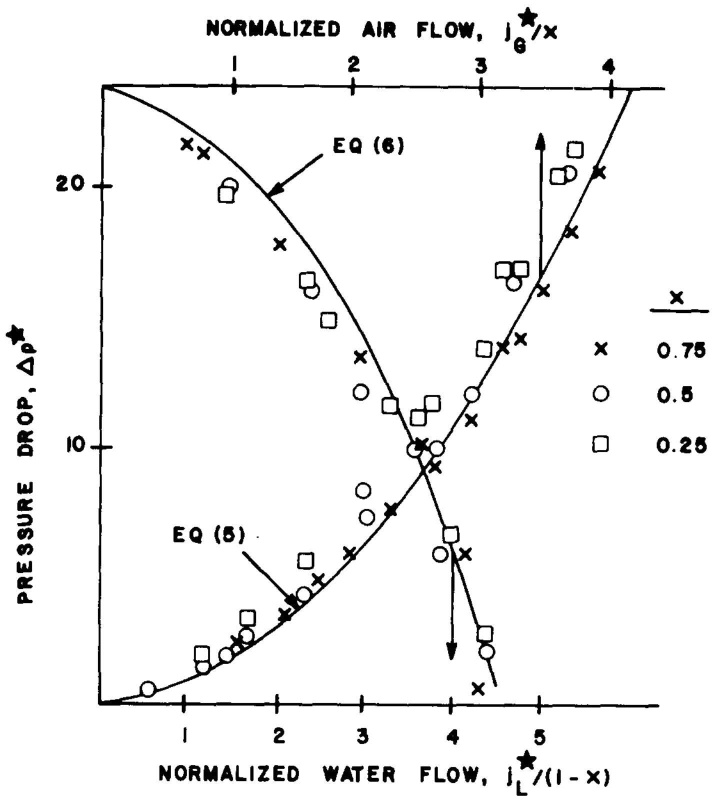

Figure 3. Measured pressure drop in the four-tube system for three different modes ($X = 0.25$, 0.5, 0.75) compared with results for "all air" ($X = 1$, [5]), and "all water" ($X = 0$, [6]) tests. $L = 155$ mm, $D = 6.35$ m.

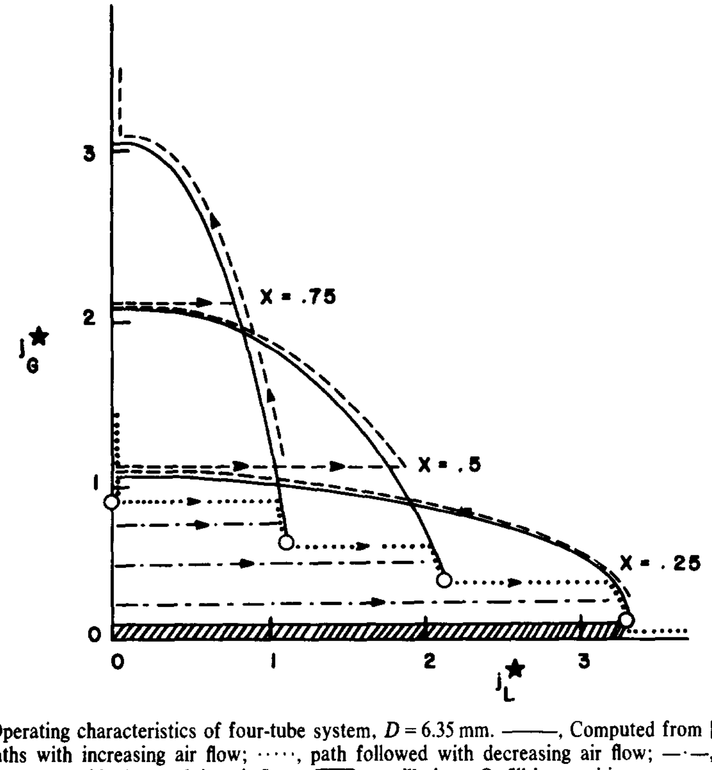

Figure 4. Operating characteristics of four-tube system, $D = 6.35$ mm. ———, Computed from [3]; - - - -, possible paths with increasing air flow; ·····, path followed with decreasing air flow; —·—, result of suddenly supplying air flow; ▨, oscillations; ○, fill-in transition.

$j_G^* < 0.15$) led to oscillatory phenomena resembling those described by Dougall & Kathiresan (1979) characterised by repeated alternate blow-out and fill-in of all four tubes. Above $j_G^* = 0.15$, the system would oscillate for a while before switching to the $X = 0.25$ mode. Oscillations were never observed for $j_G^* > 0.35$.

Sudden application of air flow in the range $0.15 \le j_G^* \le 1.1$ led to operation at the highest possible value of X. For $j_G^* > 1.1$ all of the tubes were blown out simultaneously.

Extension to air flow into the middle of the pipe

In a LOCA situation, steam is generated in the core and there is therefore a source of vapor in the "parallel channels." As an attempt to model this is the air–water system, air was introduced into the mid point of an additional fifth tube by using a "tee" connection. This case was modeled using a simple extension of the present theory and confirmed experimentally by Karlin (1978).

It is straightforward to extend this theory to a system in which either air or water is supplied to a point part way along any number of tubes in parallel.

SUMMARY

This study showed how the pressure drop characteristics of individual tubes could be used to predict the performance in countercurrent flow of a series of parallel vertical tubes, each of which only contained single-phase flow. The theory was used to descirbe various operating modes of the system and was confirmed by experiment.

Some specific conclusions are:

(1) Numerous modes of countercurrent flow are possible in parallel vertical tubes.

(2) For a given applied pressure drop, multiple solutions for the flow conditions are possible.

(3) In the multiple-solution region the condition which occurs depends on the past history of the system operation.

(4) The characteristics of multiple-tube systems can be predicted from a knowledge of the characteristics of single-tube systems, as long as criteria for stability and transition between modes of operation can be established.

(5) The limiting behavior of a system consisting of many parallel tubes can be derived as the envelope of all possible operating modes.

2. TWO-PHASE FLOW

When sets of parallel tubes that are sufficiently large in diameter to inhibit liquid bridging were used to connect the chambers, stable annular flow could occur in any particular tube. With an air–water system (at 1 atm) experiments showed that tubes 19 and 25 mm in diameter could operate in this mode while 12.6-mm tubes would occasionally experience an erratic transition from annular flow to complete fill-in by water and consequent "dumping" into the lower plenum at a high flow rate as a result of the increased hydrostatic head.

A series of researchers at Dartmouth College (Hagi 1977, Clark 1978, Bharathan 1978, 1978a, 1979, Karlin 1978, 1978a), have studied the pressure drop and countercurrent annular flow characteristics of single tubes and combinations of parallel tubes of various diameters and lengths (including zero length, i.e. orifices). The major results of these works will be summarized here.†

Single tubes

All of the experiments using single tubes with $L/D > 10$ exhibited the same features:

Countercurrent flow limiting by "flooding". Imagine that all the tubes except one on figure 1

†For the details, the interested reader is referred to the original reports that may be obtained either from the sponsoring agency or by writing to Prof. Wallis.

are blocked off by inserting a cork in the upper end. Liquid is supplied to the upper chamber at a rate that can be represented in dimensionless form as $j^*_{L,\mathrm{in}}$. The rate at which liquid flows to the lower chamber, $j^*_{L,d}$ is recorded as a function of the gas flow rate. It is found that below a critical "flooding" point all of the liquid that is supplied is able to flow down the tube i.e. $j^*_{L,d} = j_{L,\mathrm{in}}$). For gas flows above the flooding point the liquid flow down the tube is related to the gas flow by a single equation, independent of $j^*_{L,\mathrm{in}}$, that describes a "flooding curve". In this situation $j^*_{L,\mathrm{in}} > j^*_{L,d}$; the excess liquid forms a pool above the top of the tube and overflows through a suitable drain.

For example, figure 5 shows one of Hagi's results for which the flooding curve is closely represented by the correlation due to Wallis (1961):

$$j_G^{*1/2} + j_{L,d}^{*1/2} = 0.725. \qquad [8]$$

Flooding is influenced by several effects, too numerous to mention here. All that we need for later development of the theory is the realization that, when gas flows into a pool from below, the liquid flow down the tube is a dependent veriable that can be calculated using an equation such as [8].

Since we are later going to assume that [8] can be used to describe the flows in individual tubes among a group connected in parallel, a caveat is in order. Karlin (1978) found that the flooding curve was influenced by the level of turbulence in the upper plenum. When a "honeycomb" was inserted approx 7 cm above the top of the tube the flooding curve for a single tube might be better represented by

$$j_G^{*1/2} + 1.7 j_{L,d}^{*1/2} = 0.75 \qquad [9]$$

as shown in figure 6. When two tubes were operated side by side in the identical flow regime in the presence of the honeycomb some of the data tended to approach[8]. When four tubes were operated side-by-side (identical flow regimes) in the parallelogram array shown in the inset in figure 7 the flooding curve agreed with [8] even with the honeycomb present. Apparently the

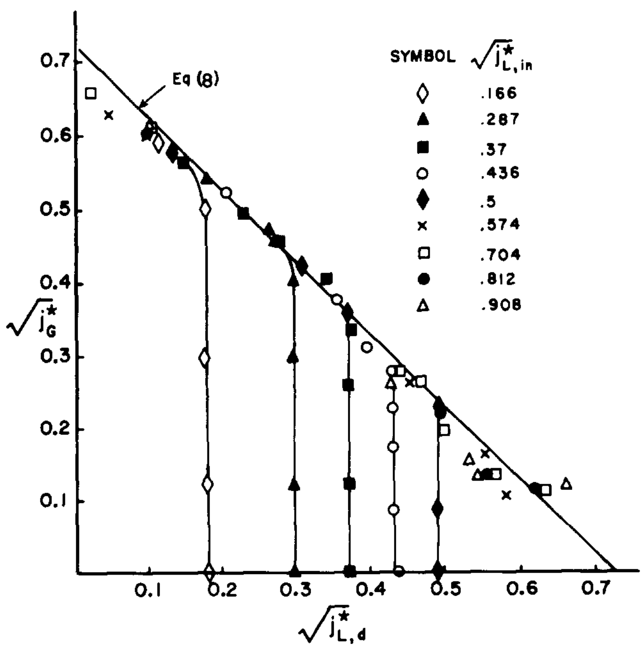

Figure 5. Flooding curve for a vertical tube 25.4 mm dia., 292 mm long, with square-edged flanges (Hagi 1978). Air and water at atmospheric conditions.

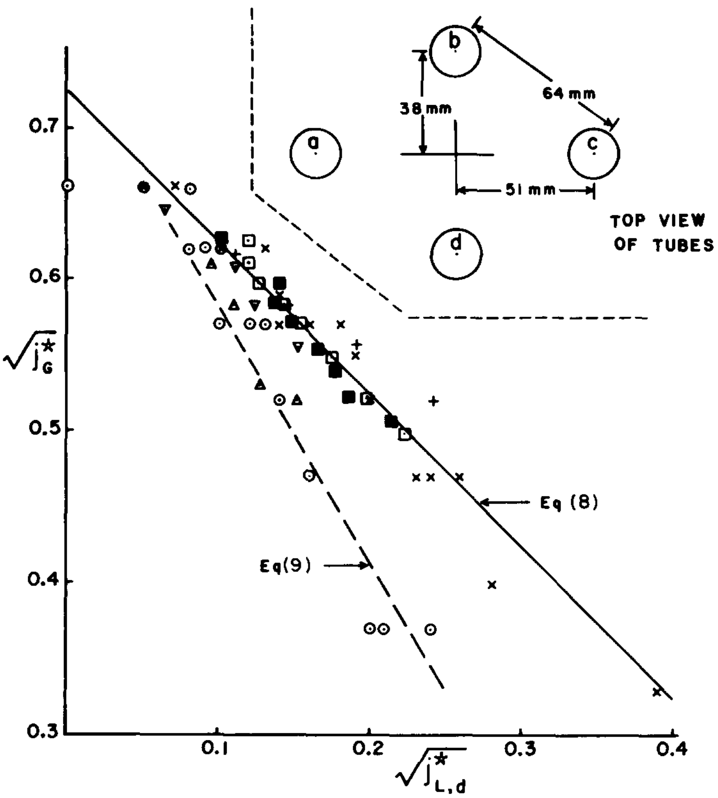

Figure 6. Flooding curve for groups of tubes with identical flow regimes ($L = 1.52$ m, $D = 19$ mm, air and water at atmospheric conditions). Without honeycomb in upper plenum: × = *a*, *b*, *c* or *d* along; + = *b* and *d*; □ = *a*, *b*, *c* and *d*. With honeycomb: 0 = *a*, *b*, *c* or *d* along; △ = *a* and *c*; ▽ = *b* and *d*; ■ = *a*, *b*, *c* and *d*.

increased agitation from the bubbling action of four tubes overcame the damping imposed by the honeycomb.

This influence of conditions in the upper plenum on flooding has not previously been noted and may be annoying to engineers who would prefer to use a single correlation to cover all situations.

(b) *Several flow regimes for the same pressure drop.* As long as a liquid pool is maintained in the upper chamber and the tubes are "flooded", the downward liquid flow rate is a function of the gas flow rate which determines the operating conditions. We may therefore plot the pressure drop across the tube as a function of the dimensionless gas flow rate, j_G^*, as in figure 7 which has been drawn for a vertical tube 19 mm in diameter and 1.52 m long with sharp-edged flanges at its ends.

Since reliable analytical methods for predicting these results are not available we have to rely, at present, on obtaining this characteristic experimentally for each case of interest. The graph shows four different regions, labeled A, B, C and D, corresponding to the flow patterns sketched in the inset.

In Region A the air flows inside a smooth falling liquid film. The pressure drop is a little higher than would exist if air flow alone were involved. The water flow rate is determined by phenomena occurring at the top of the tube and is related to the air flow by [8].

In Region C, a rough film starts at the bottom of the tube and progresses to the top of the tube with greater air flow. This is a transition flow regime with a length of smooth film coexisting with a length of rough wavy film. The amount of water in the tube increases as the air flow is increased and the pressure drop rises. A "honeycomb" inserted into the upper plenum to dampen turbulence influences the result, as in figure 6.

In Region B, increased air flow blows water out of the tube and the pressure drop decreases.

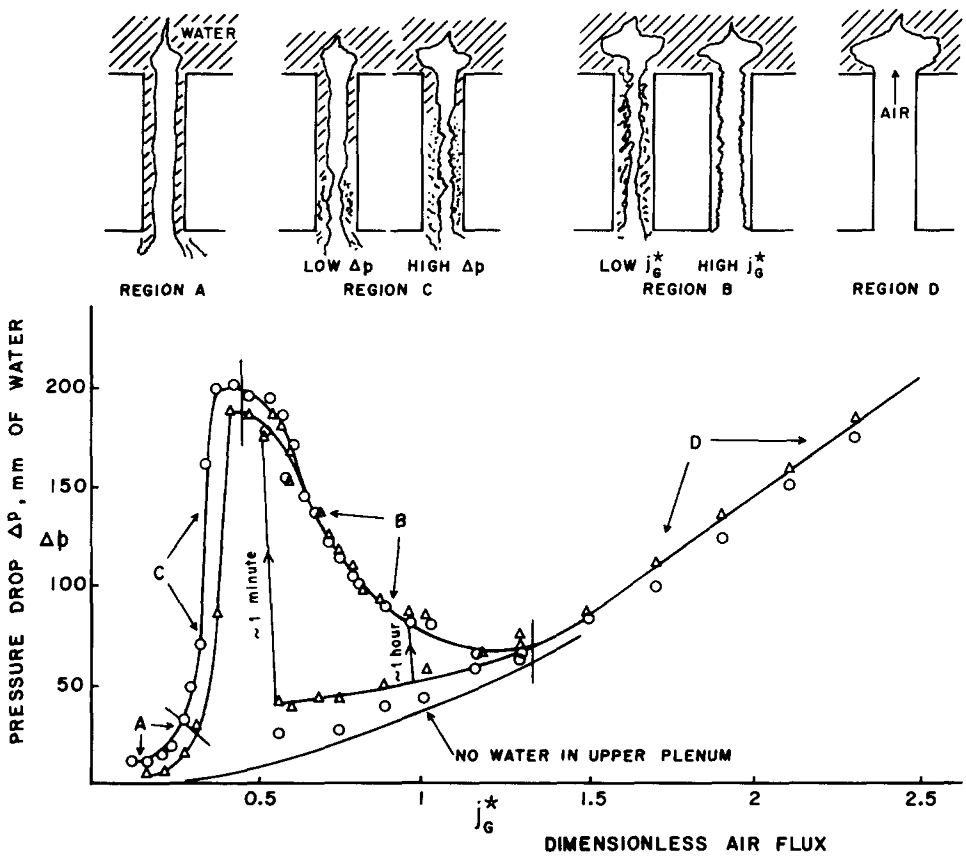

Figure 7. Pressure drop vs air flow for a single tube: $L = 1.52$ m, $D = 19$ m, atmospheric conditions. The insert indicates the observed flow patterns. ○, No honeycomb in upper plenum; △, honeycomb in upper plenum.

According to [8] there is negligible water flow over much of this region. A rough film exists throughout the tube.

In Region D, all the water is blown out of the tube and single-phase gas flow exists. Some additional pressure drop is needed to blow the air into the pool in the upper plenum.

An analysis of the mechanisms giving rise to these several flow patterns is given by Bharathan *et al.* (1978a).

(c) *Hysteresis in Region B.* Upon decreasing the air flow rate, the sequence DBCA is followed. However, the transition from Regions D to B depends on the time taken to perform the experiment. The tube is dry in Region D and [8] predicts no liquid flow into the tube until $j_G^* < 0.5$. For $0.5 \lesssim j_G^* \lesssim 1.3$ therefore, Region B consists of a rough agitated liquid film with negligible net flow rate and apparently, indeterminate thickness. The situation is complicated by effects of wettability.

What happens in practice is that fluctuations in the flows and the inherently unsteady nature of the bubbling action at the top of the tube allow intermittent small liquid flows and progression of a wetting front down the tube wall. As noted in figure 7 it could take as long as an hour to establish the stable Region B.

Parallel tubes

In principle, all that one needs to do to predict the behavior of several tubes in parallel is to require that the pressure drop be identical for all tubes. The situation is complicated by the presence of multiple values of possible flow rates at a given pressure drop (figure 7) plus the additional possibility of one or more tubes filling entirely with liquid to give the characteristics

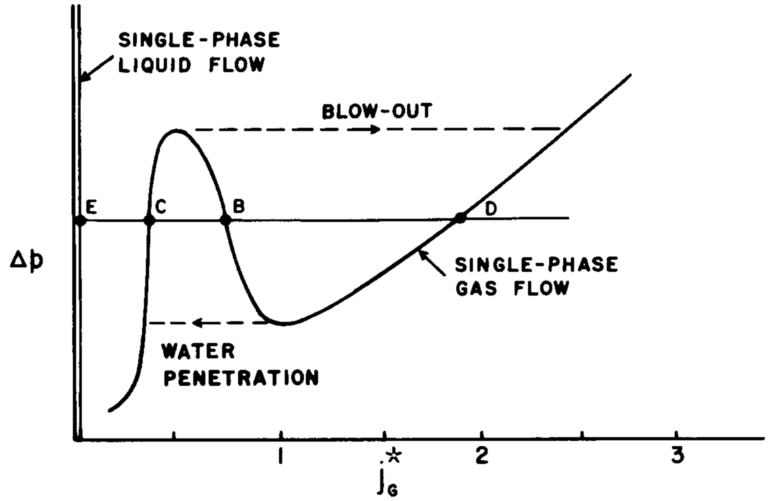

Figure 8. General version of figure 7, showing four solutions (E, C, B, D) at a given Δp and the regime transitions (blow-out and water penetration) for a multitube system.

discussed in section 1 (we shall call single-phase liquid flow "Region E" and show it on the $j_G^* = 0$ axis on figure 8 which is a general version of figure 7).

Figure 6 also indicates that we should be careful about the assumption that the characteristics of one tube are uninfluenced by the flow in neighboring tubes.

Using figure 8 we may set the pressure drop and calculate the corresponding flow rates for each tube, depending on the flow regime. The total flow rate for each phase is the sum of the flows in all the tubes. For example, figure 9 shows the predicted pressure drop as a function of overall gas flow rate (defined as in section 1) for three 25.4-mm tubes, 1.52 m long, based on the measured characteristics of a single tube, omitting the possibility of the single-phase liquid regime E. For many tubes in parallel the picture becomes quite cluttered and if the tubes have differing diameters one cannot use a single dimensionless definition of flow rate, though the overall method still works (Clark 1978).

The liquid flow rate is derived from the gas flow rate, for each tube, using [8] (or some equivalent flooding correlation). Figure 10 represents the resulting prediction for a two-tube system, based on figures 6 and 7 and omitting the single-phase liquid region E that gives rise to

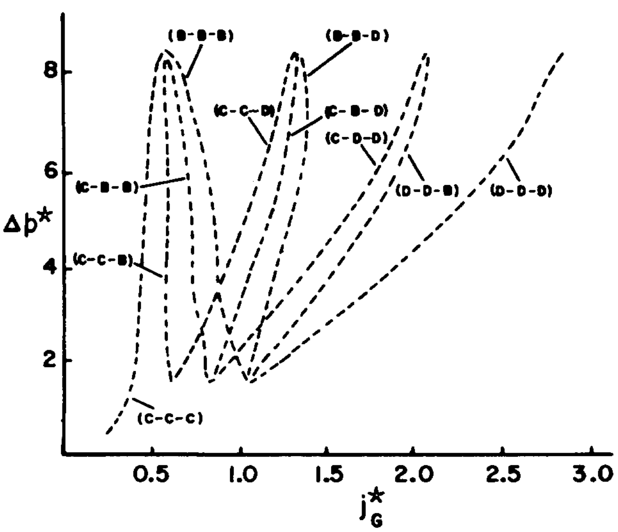

Figure 9. Predicted ΔP^* vs j_G^* relationships for a system of three parallel 1.25-mm dia. tubes, showing all possible combinations of the three regimes B, C and D.

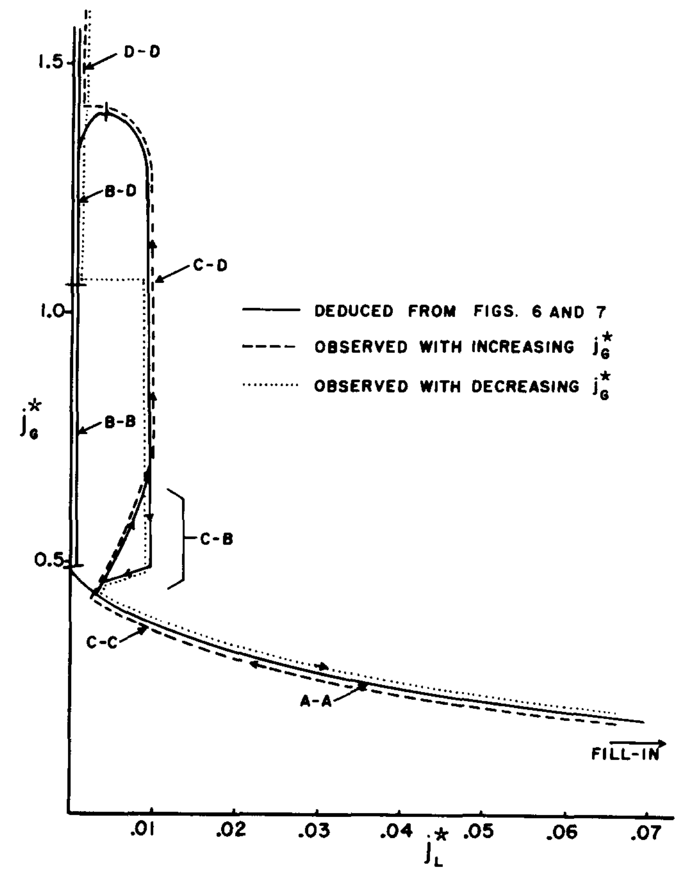

Figure 10. Countercurrent flow rates in two parallel tubes, $D = 19$ mm, $L = 1.52$ m.

much higher liquid flows, requiring representation on a different scale (figure 11). In practice the B–B and B–D regimes were found to be unstable for reasons given by Karlin (1978a); the path followed experimentally as the air flow rate was increased or decreased is shown.

Figure 11 displays, by means of the broken line, the dramatic increase (a factor of 30–50) in water flow rate when the air flow is dropped below the condition for fill-in of one of the tubes, during operation in the A–A mode. Once a tube fills with water, increases and decreases in air flow lead to traversing of the E–A, E–C, E–B and E–D modes; to return to the two-phase modes it is necessary first to increase j_G^* to a value sufficient to blow-out all the liquid (i.e. $j_G^* > 3.5$ in figure 11). The tubes are now both dry and it is possible to follow a path down the j_G^* axis to meet the C–D mode.

The approach can be extended to a larger number of tubes. For example, predictions of the stable modes of operation at low flow rates of four parallel 19-mm tubes, 1.52 m long are shown in figure 12 and the observed sequences with increasing and decreasing air flow are indicated; the modes involving high flow rates are shown in figure 13.

The differences between theory and practice result from interactions between the flows in each tube, communicated through the plenum chambers. Due to asymmetry there are also some variations depending upon which tube is in which mode (i.e. the C–D–D–D, D–C–D–D, D–D–D–C combinations give different results). The figure presents the least favorable comparison between theory and experiment; other results were closer to predictions.

For the four-tube system there are three distinct single-phase modes of countercurrent flow corresponding to those described in section 1. These merge with modes (such as E–E–C–D) incorporating two-phase flow in one or more tubes. Figure 13 shows that the rather counterintuitive predictions (the wiggles in the curves look odd) are well confirmed experimentally.

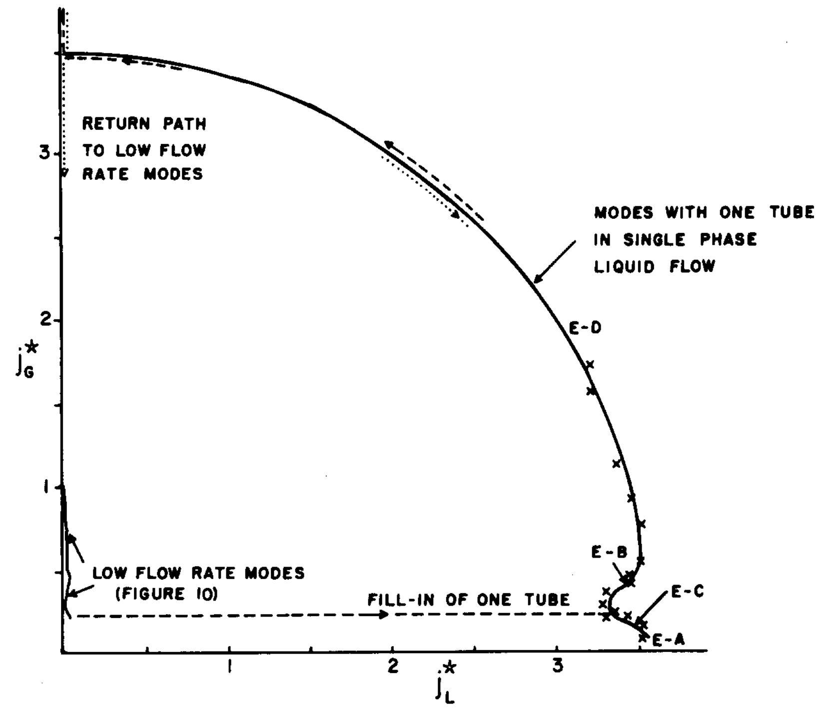

Figure 11. Countercurrent flow rates with one tube filled with water (for the conditions in figure 10). ———, Prediction; ×, data.

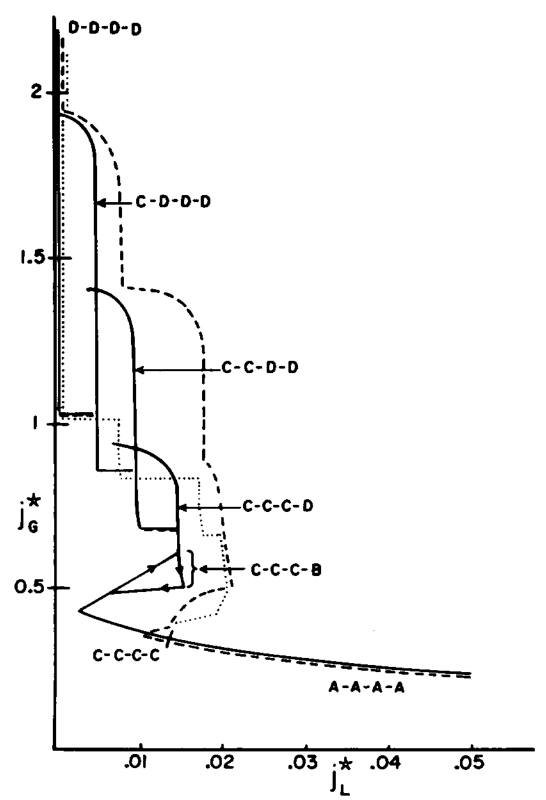

Figure 12. Low flow rate modes for four tubes. The modes are similar to those for two tubes (figure 10) but there are two new ones, C, C, D, D and C, C, C, D. ———, Predicted; - - - -, observed with increasing j_G^*; · · · · ·, observed with decreasing j_G^*.

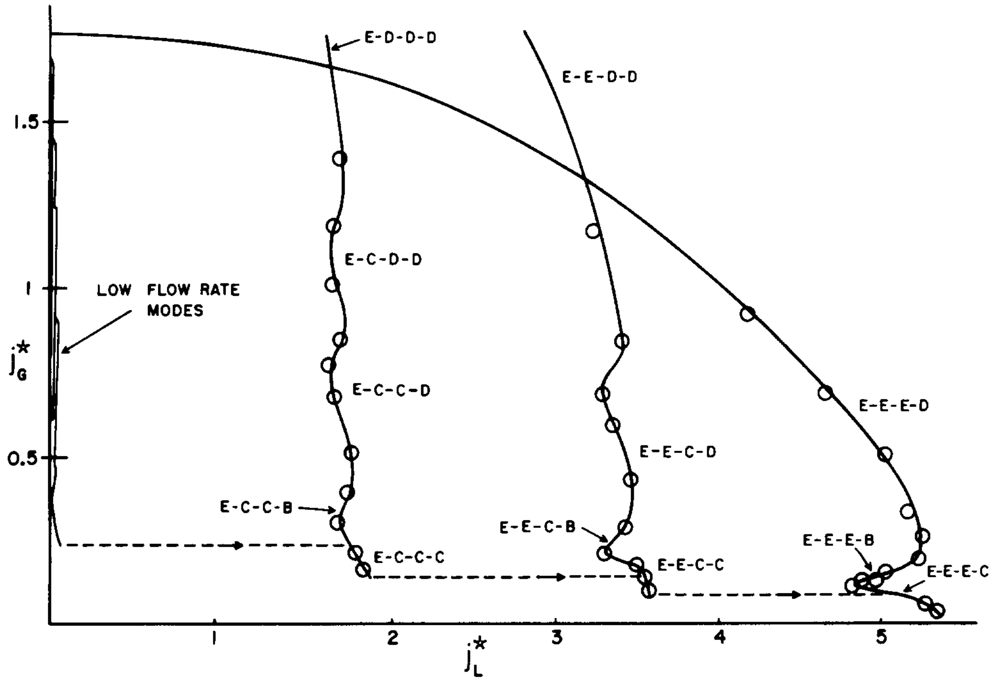

Figure 13. Observed high flow rate modes in 4 tubes. ——, Theory; O, data; - - - - -, transition with decreasing j_G^*.

Many tubes

With an understanding of system operation of two, three and four tubes, a "many-tube theory" can be developed. In the single-phase flow case of the 6.35-mm tubes (figure 2) it was found that each addition of a new tube added a new mode and that the modes were bounded by an envelope. In the case of two-phase flow, each new tube adds one further stable mode. We will show how to develop some limiting regime boundaries, using the example of a large number of tubes with the individual characteristics shown in figures 7 and 8.

Referring to figure 8 one can see that when a tube in each of the new modes is blown out by increasing the air flow, corresponding to the upper transitions in figure 14, the system is in a configuration where each of the tubes with two-phase flow has a j_G^* of about 0.45 and each of the tubes with single-phase air flow has a j_G^* of about 2.45 (the transition occurs at constant Δp because of the large number of tubes in parallel). If m tubes carry two-phase flow and n carry single-phase air flow, then the overall j_G^* is given by

$$j_G^* = \frac{0.45m + 2.45n}{n + m}. \qquad [10]$$

Writing $y = (m/n + m)$, we have

$$j_G^* = 0.45y + 2.45(1 - y). \qquad [11]$$

The water flow in each of the tubes with two-phase flow at $j_G^* = 0.45$ was observed to be $j_L^* = 0.03$ (this value is higher than would be predicted by either [8] or [9] and is believed to be due to fluctuations in the flow distribution between the tubes that are enhanced when the flow regimes are not the same in all of the tubes. The form of the flooding correlations leads to higher average flow rates in unsteady flow if it is assumed that [8] or [9] are instantaneously valid while the flows fluctuate), therefore

$$j_L^* = \frac{0.03m + 0n}{n + m} = 0.03y. \qquad [12]$$

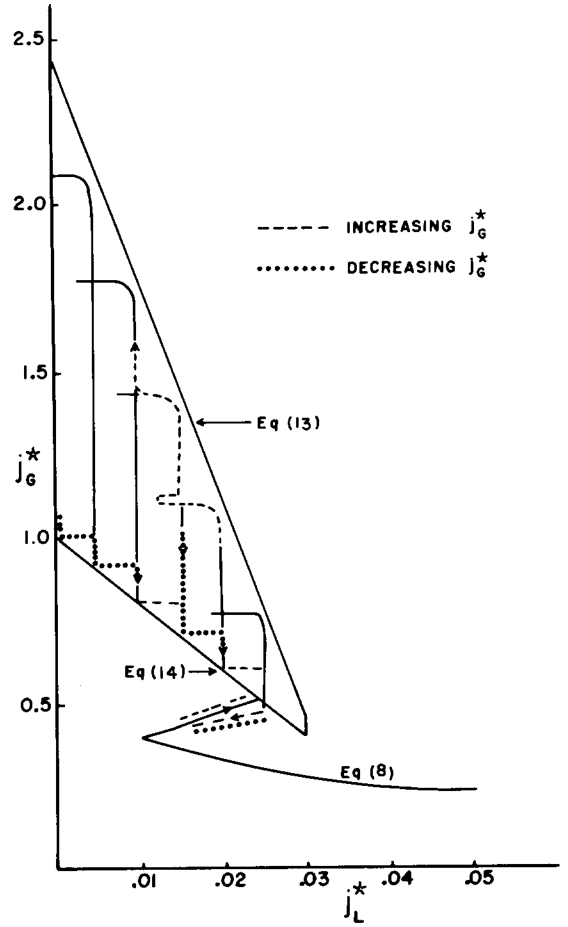

Figure 14. Prediction of the behavior of a multitube system in the low flow rate modes. - - - -, Increasing j_G^*; · · · · ·, decreasing j_G^*.

Combining [11] with [12], to eliminate y, we have

$$j_L^* = 0.037 - 0.015 j_G^*. \qquad [13]$$

Since the two-phase mode flow transitions occur close together, the line representing [13] in figure 14 is not just a boundary, but should approximate actual water flows for increasing air flow with many tubes.

For decreasing gas flow, progressive transitions occur as j_G^* for the tubes in two-phase flow falls to 1 (figure 8) and water penetration occurs. At the same pressure drop the tubes in mode C are observed to have a j_G^* of about 0.36 and a j_L^* of 0.03. The equation for flow upon decreasing gas flux is then obtained in the same way as [13] and is

$$j_L^* = 0.05(1 - j_G^*) \qquad (14]$$

which is shown as the lower boundary in figure 14.

When two-phase flows are possible, j_G^* for complete fill-in in a single tube (transition to mode E) is observed to be about 0.24. Further, the value of j_L^* at full water flow and low Δp^* is about 7. So if m tubes are in two-phase flow and l tubes are in single-phase water flow, the value of j_G^* at fill-in is

$$j_G^* = \frac{0.24m + 0l}{m + l}$$

which with $y = (m/m + l)$ is

$$j_G^* = 0.24y. \quad [15]$$

The corresponding j_L^* is

$$j_L^* = \frac{7l}{m+l} = 7(1-y). \quad [16]$$

Therefore

$$j_G^* = 0.24 - 0.034 j_L^* \quad [17]$$

at fill-in. This line is shown in figure 15 that presents all the key limiting characteristics for countercurrent air–water flow in many parallel vertical tubes with single tube characteristics shown in figures 7 and 8. Karlin (1978) discusses the conditions under which the various modes are likely to be accessible.

Summary

(1) When two-phase flow can occur in individual tubes, new modes, some of which may be unstable, are added to the single-phase flow modes described in section 1.

(2) Over a range of pressure drop, two two-phase regimes are possible, as well as the two single-phase flow regimes, in each tube.

(3) Many features of the behavior of parallel tubes can be predicted from a knowledge of the characteristics of individual tubes. Some unanswered questions concern the interaction between the flows entering or leaving neighboring tubes in the plenum chambers and the stability of the modes.

(4) In a many-tube system, groups of modes define envelopes that seem to represent limiting paths that may be followed by suitable procedures, such as monotonically increasing or

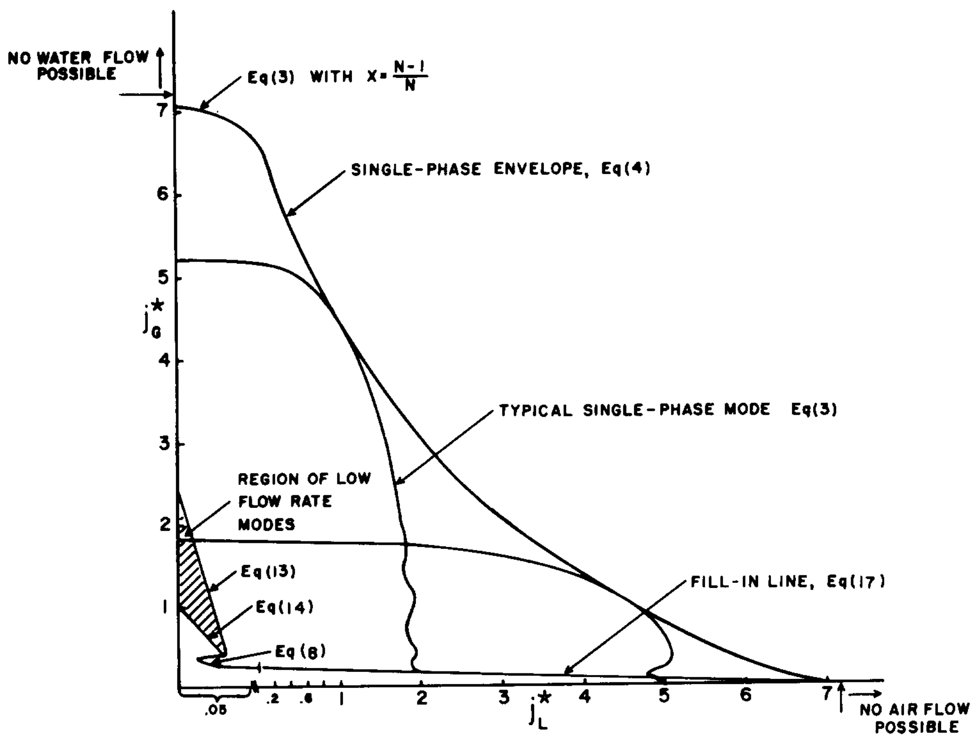

Figure 15. All the key equations of countercurrent two-phase flow in multiple tubes for $D = 19$ mm, $L = 1.52$ m. Note scale change at low j_L^*.

decreasing the flow rate of the lighter phase. Equations for these envelopes can be derived if the characteristics of single tubes are known.

3. EFFECTS OF GAS SUPPLY CHARACTERISTICS

The practical results presented in part 2 were for systems with a "stiff" air supply. The air was throttled from high pressure through a choked valve so that the air flow rate was insensitive to the impedance of the set of parallel tubes.

We now discuss the behavior of a system, just as common in practice, in which the air flow rate depends on the opposing pressure drop. For example, Clark (1978) used a centrifugal blower for which the operating characteristics had been determined as a function of the voltage applied to its drive motor. In other respects the system resembled figure 1.

Single tube

A single tube, 25 mm in diameter and 1.52 m long was connected between the plenum chambers and the pressure drop was determined as a function of flow rate by using the earlier "stiff" compressed air supply system; the usual A, B, C and D regions of operation were observed. When the blower was used instead of compressed air the behavior shown in figure 16 occurred. As the speed of the blower was increased the data first followed the curve *ab*, along what we previously called Region C. There was then a jump from *b* to *c* with further increase in blower speed leading to point *d* in Region D. When the speed was then decreased, Region D was followed until there was a jump back to Region C along the path *ea*. Points in Region B were unstable against the classic Ledinegg (1938) instability (see Bouré *et al.* 1971) and could not be obtained.

Parallel tubes

Clark (1978) performed experiments using various combinations of parallel tubes of identical or different diameters, using the centrifugal blower as his air supply. The results followed the theory presented in part 2, except that jumps between modes followed the blower characteristics. For example, the results obtained with increasing and decreasing air flow for three parallel 25-mm dia. vertical tubes are presented in figure 17. Once a given mode had been established the entire range of possible flow rates, in that mode, could be explored by increasing or decreasing the air flow rate.

All of the branches involving Region B were unstable against Ledinegg instability (this was

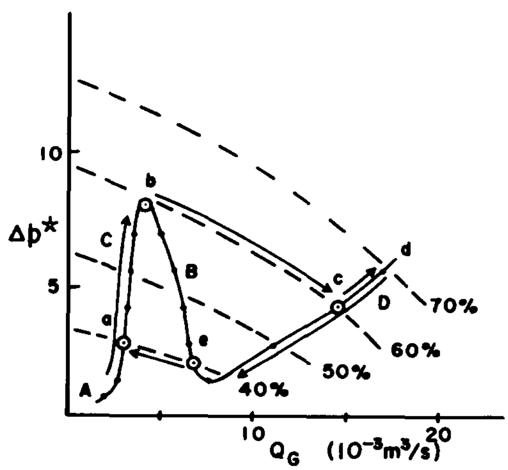

Figure 16. Δp^* vs Q_G for a single 25-mm i.d. tube superimposed on head-capacity curves of centrifugal blower air supply system. — — —, Blower head-capacity curves for various percentages of line voltage; ——, Δp^* vs Q_G for single tube; ——→, observed regime transitions.

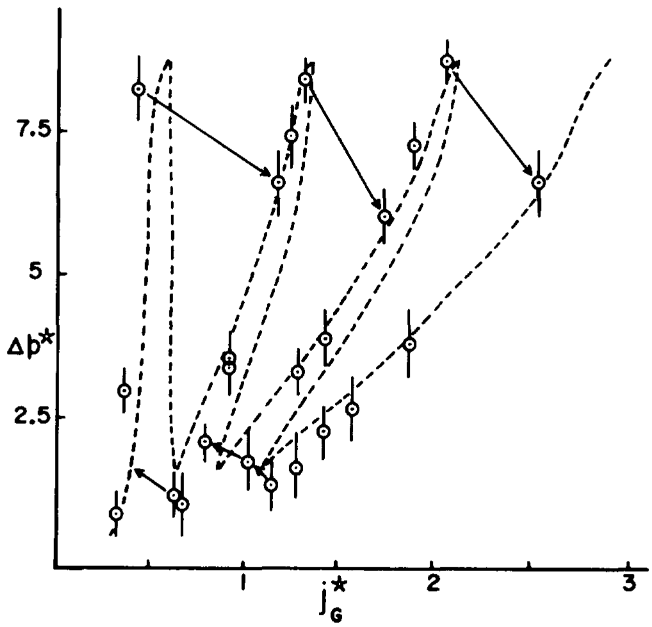

Figure 17. Δp^* vs j_G^* for three 25 mm i.d. tubes with air supplied by the blower. ⊙, Data; —, range of pressure drop fluctuation; — — —, theory; ——→, path of transitions between modes.

not so for the stiff air system, in which the supply characteristics are vertical and the branch containing one B and any number of C's is stable).

It was noticeable that the results for groups of tubes did not follow the "superposition" theory exactly, showing a somewhat higher pressure drop than predicted. This is attributed to interactions between the flows in the tubes, probably transmitted through turbulence in the pool in the upper chamber, as observed by Karlin (1978b).

Effects of orifices at the tube bottom

A classical way to overcome Ledinegg instability is to supply a resistance, such as an orifice, in series with the tube to ensure that there are no multiple values of flow rate for a given pressure drop.

In the case of two-phase countercurrent flow, Bharathan *et al.* (1978) have shown that the addition of a small resistance by means of orifices at the bottom of the tubes is counterproductive, increases the range of instability, and leads to enhanced likelihood of non-uniform flow distribution between the tubes. The reason is that the orifice at the bottom of the tube prevents liquid running out and extends Region B over a wider range of gas flow rates. A large area contraction at the orifice is needed if the extent of Region B is to be significantly reduced. One cannot simply add together the pressure drop characteristics of the orifice and the open tube because the orifice changes the liquid hold up in the tube at a given gas flux.

Summary

(1) When the gas flow rate is a dependent variable, the multi-valued characteristics determined in sections 1 and 2 interact with the rest of the system and the entire flow network has to be analysed in order to predict the state of operation.

(2) With a soft gas supply system, Ledinegg instability, hysteresis and discontinuous jumps from mode to mode are observed.

(3) Adding orifices at the bottom of the tubes may extend the range of Region B, where the pressure drop for an individual tube decreases with increasing gas flow rate, and enhance the effects of Ledinegg instability.

4. DISCUSSION

This paper has shown that the behavior of countercurrent flow in a small number of similar parallel vertical tubes can be remarkably complicated. If the two-phase flow characteristics of each individual tube are known (even these, at present, need to be determined by experiment) it is possible to predict numerous different modes of operation by applying the principle of continuity and requiring that the pressure drop across all the tubes be equal. Experiments revealed that many of the predicted modes actually occurred. Coupling between channels and other "system effects" caused some deviations from the theory.

Predictions of practical performance are likely to be uncertain because of the ease with which transitions between modes can occur. Moreover, during a transient the behavior depends on past history and may take different paths, depending on small changes in the conditions. There may be additional influences such as connections between the flow channels and vapor generation or condensation. Flow regimes other than single-phase or annular may occur. There may be significant interaction between the flows in the channels and in the reservoirs (e.g. in a light water reactor the water distribution in the upper plenum may depend on the variation of steam evolution from the core).

A designer of engineering equipment will probably wish to avoid the uncertainties inherent in such systems. If this is not possible, results of the sort of basic experiments reported here should help in the anticipation and diagnosis of the resulting phenomena. However, the complexity of the interactions and the shear number of possible simultaneous solutions may well dicate that the only way to determine, with any confidence, what will happen is to perform tests as close to full-scale, realistic conditions as possible.

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