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THE SLUG-ANNULAR FLOW REGIME TRANSITION AT ELEVATED PRESSURE

by

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FOREWORD

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g	acceleration of gravity
D	pipe diameter
V_{fs}	superficial liquid velocity equal to the liquid volume flow rate over the pipe cross-sectional area
V_{gs}	superficial vapor velocity equal to the vapor volume flow rate over the pipe cross-sectional area
ρ_f	liquid density
ρ_g	vapor density

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ABSTRACT

The annular slug flow regime has been investigated in vertical upflow without heating through the use of an electrical conductivity probe. The Teflon cladding and seals of the probe were found to work to at least 488°F. When the inlet velocity was sufficiently high, the quality at transition was found to be a constant for each pressure going from 8.6% at 215 psia to 17.6% at 615 psia. No fully developed bubbly flow was observed.

INTRODUCTION

The prediction of quantities of interest in two-phase flow, such as density or pressure drop, is made difficult as a result of the immense number of variables upon which these quantities actually depend.

One device which will help reduce the complication of predictions in two-phase flow is the use of a flow regime map. An area on the map shows the region where a given force or a couple of forces are most important. Hopefully, when the dominant forces change, the flow configuration will change also. A flow regime map, combined with an analysis appropriate for each regime, will then make reasonably accurate predictions possible from reasonably simple equations.

Because one must present a means of predicting the pressure drop or void within a regime, along with expressions for the regime boundary, there is considerable merit in reducing the number of regimes to a minimum. The minimum number for pipe flow appears to be bubbly, slug, and annular. Bubbly flow is characterized by a continuous liquid core in which bubbles, which are small compared with the pipe diameter, are embedded. Slug flow is distinguished by slugs of liquid spanning the tube, separated by large bubbles comparable in size with the tube diameter; the liquid slugs may or may not have other smaller bubbles in them. Annular flow is distinguished by a continuous vapor core, which might contain drops, and a continuous liquid film on the wall, which might contain bubbles.

As a rule, one can use the Martinelli correlations to predict the quantities of interest in annular flow. Slug flow density can be predicted by the means presented in Reference 1. As yet, no rational procedures exist which have been verified experimentally for predicting the quantities of interest in bubbly flow.

THE EXPERIMENTS

The loop used in these experiments is the "Armadilla" moderate pressure loop (see Fig. 1), which is capable of pressures up to 600 psig. Figure 2 is a schematic of the three test sections used and indicates the locations of the probes. The data presented in this report were taken with the top probe in the unheated section, with the exception of a couple of later runs which were made to show entrance effects. A spot check indicated that the top and middle probes read the same, so that it can be said in general that the flow was fully developed.

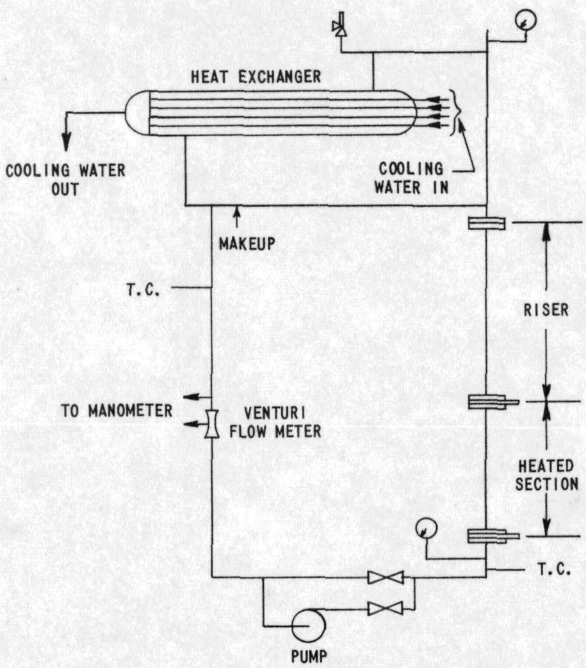


Fig. 1. Schematic Diagram of Experimental Loop

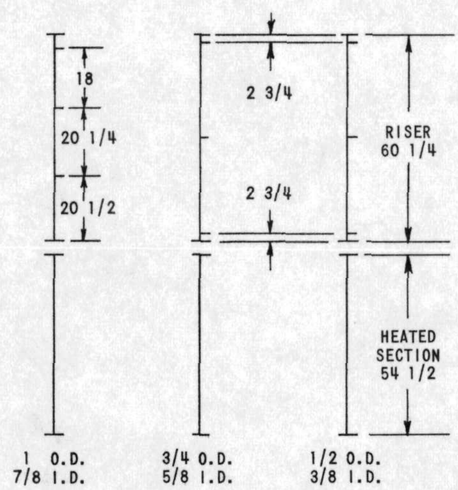


Fig. 2. Schematic of Test Section

Clean water was put into the system at the beginning of each day a run was made. The water, purified by passage through an ion exchanger, had an electrical resistivity in excess of 10^7 ohm-cm at the beginning of the first run each day and of 10^6 ohm-cm at the completion of the day. Measurements were made at room temperature, about 80°F.

Heat balances were run before any data were taken to ensure that there were no gross errors in flow, temperature, or heat flux measurements. The precision of the heat balances was not high, because the temperature of the entire loop was rising during the measurements, but was within 7%. In retrospect, it can be said that the precision of any of the measurements was in excess the precision of definition of the flow regime boundary based on probe readings.

A 20-in. inclined manometer with a venturi was used to measure flow. Runs made when the net manometer reading was less than 0.1 in. were not found to be consistent and were all discarded. These were the only data which were discarded.

The data were always taken under conditions of forced circulation. Generally, the flow was fixed and the heat flux increased in 5- or 10-kW steps until the slug-annular transition was passed through. As a rule the flow would decrease slightly as the flux was increased because of the increasing pressure drop in the test section.

In the case of the 0.375-in.-ID test section, the pressure drop was so large that it really determined the flow. This pressure drop made it difficult, also, to determine exactly what the pressure was at the probe location. A linear interpolation between the inlet and outlet pressures was used to determine the pressure at the probe location. Again, the uncertainty in the pressure was small compared with the uncertainty in the interpretation of the probe readings.

No data were recorded if the flow was not steady. When heating up, under conditions of natural circulation, oscillations were always noticed in the flow. However, when the pump was turned on and the throttle valves turned down, as far as could be determined the inlet temperature and flow readings were perfectly steady and no oscillations were present.

THE PROBE

The probe which was used to make the measurements reported in this work is basically a device to determine the electrical resistance between the center of the pipe and the wall. When the probe is dry the resistance is infinite, when wet, the resistance is of the order of 100,000 ohms. The probe then can be used to determine whether or not there are bridges of liquid across the channel. It is the determination of of location between the bridges and the no-bridges condition to which the probe is particularly well adapted.

The design of the probe, as that in Reference 2, is shown in some detail in Fig. 3a along with the wiring diagram (Fig. 3b) used in these experiments.

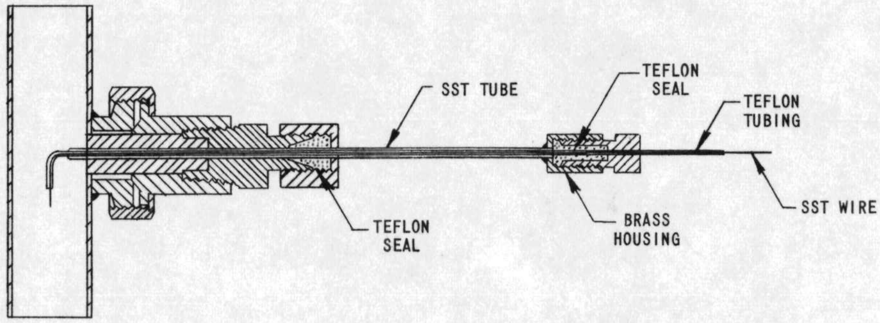


Fig. 3a. Probe Detail

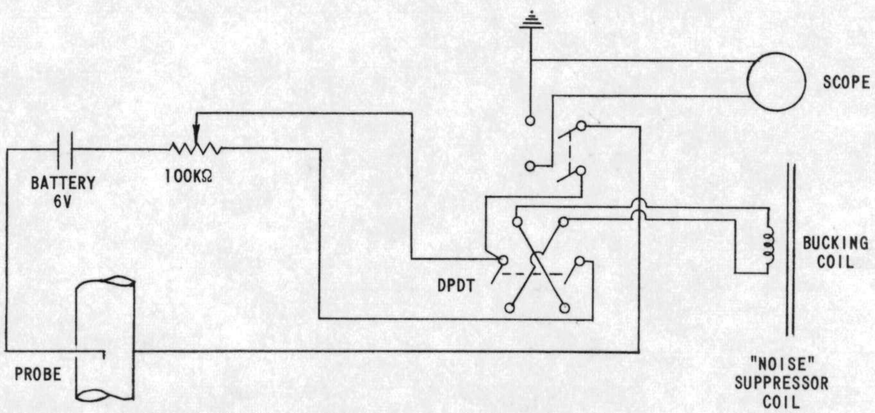


Fig. 3b. Wiring Diagram for Use of Probe

Some troubles were experienced with the probe at the start of the experiments. Teflon packing around the stainless steel tube (see Fig. 3a) leaked until the nut which compressed it was drawn up so tightly that the volume around the tube was filled completely with Teflon. The packing gland at the end of the tube, which seals the Teflon sleeve against the test wire, had to be silver soldered to the stainless steel sheath to prevent ballooning of the sleeving. The packing for the Teflon sleeving gland is Teflon tape with as much put on as allows one to get the nut back onto the gland. After a couple of heating cycles, the layers of tape are sintered into a solid uniform mass. The Teflon sleeving used fits easily over the wire when it is new. However, with each heating cycle, it shrinks closer to the wire and, as a result, expands down the probe tip and ultimately extends beyond it. When this happens, the probe reading gets smaller and smaller. It is then necessary to pare the sleeving back to expose the tip. This must be done three or four times before the extension of the Teflon ceases. At this time the Teflon has turned into a perfectly transparent, close-fitting covering for the wire.

A pulsating DC power supply was used for the Armadilla loop in these experiments. Initially, a considerable amount of pickup was obtained from the power supply, which necessitated the bucking coil arrangement shown in Fig. 3b. With this coil, pickup could be reduced to about 0.4 V, with the readings equal to about 4 V. The sweep rate of the scope was fixed for all the experiments at 5×10^{-3} sec/cm.

Because of the pickup, it was not found possible to put the probes right into the heated section. A considerable amount of electronics would be needed to separate the power-supply noise from the signal, and it was not believed that this was worthwhile.

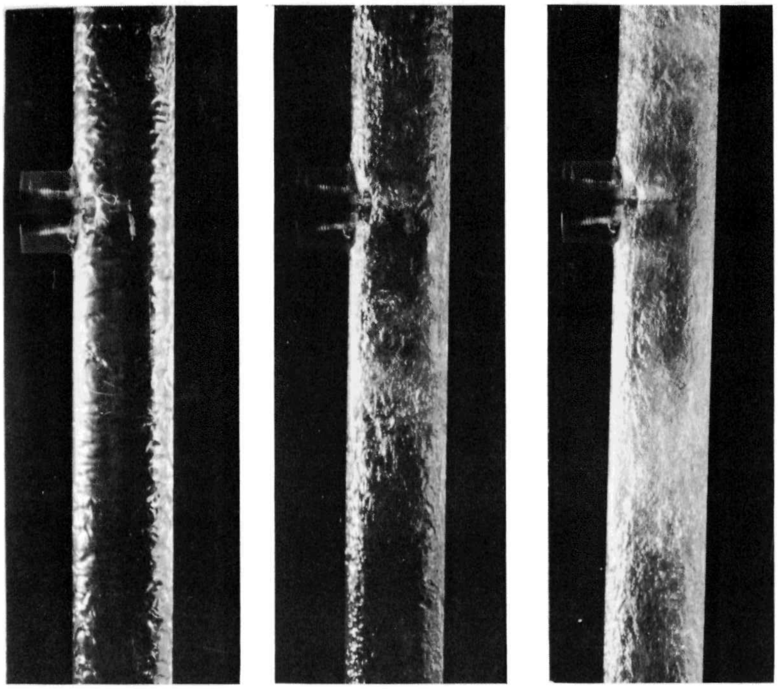
DATA REDUCTION

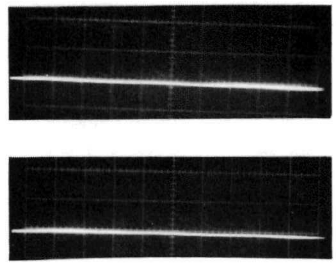
From measurements of power input, inlet temperature and pressure, and the diameter of the test section, the local superficial velocities were computed. The probe reading gave a single point for the flow regime map. Readings were taken for a variety of heating and flow rates. In every case, readings were continued until the flow, flux, or pressure-drop limits of the loop were obtained.

THE RESULTS

The results for slug-annular transition for the top probe for all the tests are given in Figs. 6 through 14. Figures 15 and 16 show the slug-annular transition as determined from the bottom probe, where there is almost no opportunity for the flow to become fully developed.

It is appropriate at this time to dwell at some length on the interpretation of the probe readings as the significance of these results is so intimately connected with this. Figures 4 and 5 show pictures of the slug and annular regimes along with the corresponding traces on the scope. (A far more extensive probe calibration is contained in Reference 2.) The top pictures clearly represent annular flow, whereas the bottom pictures clearly represent slug flow. Between these two regions there is a wide transition band. Whether pictures, or the probe, or some other device or measurement were used to define the regime transition, there would still be a band where there would be a question as to whether one should call the flow slug or annular flow. It was originally intended to show scope pictures in the transition region, too, but most of the time the scope shows only a line, and a large number of pictures of the traces would have to be taken to catch a characteristic trace.

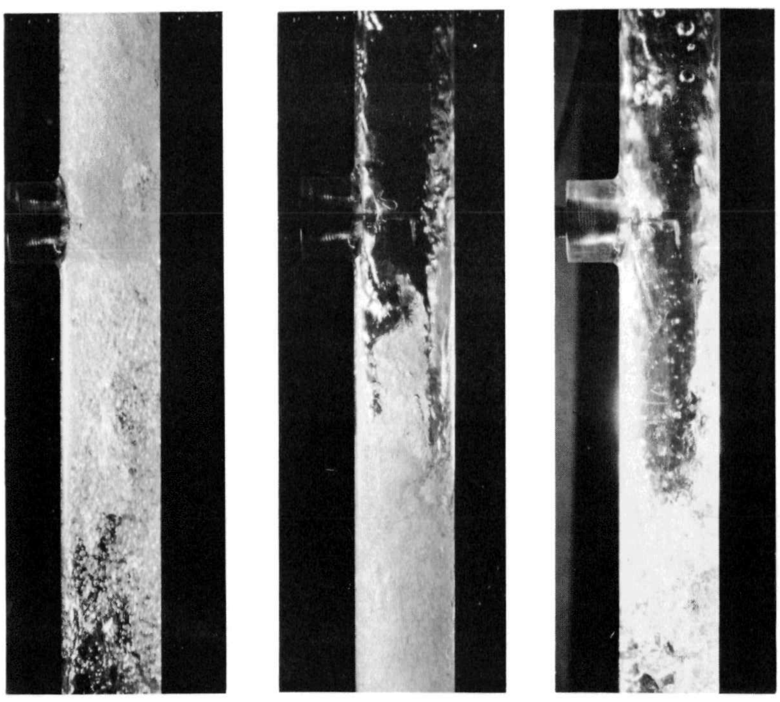


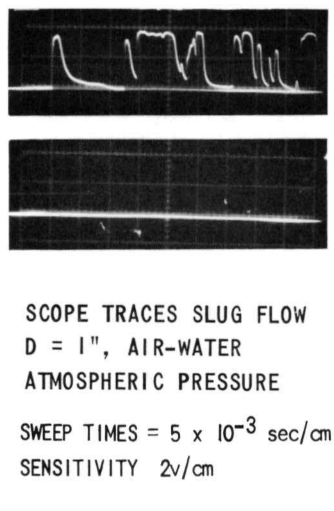


SCOPE TRACES ANNULAR FLOW
D = 1", AIR-WATER
ATMOSPHERIC PRESSURE

SWEEP TIMES = 5 x 10^{-3} sec/cm
SENSITIVITY 2v/cm

V_{fs} = .37 ft/sec	V_{fs} = .50	V_{fs} = .90
V_{gs} = 86	V_{gs} = 86	V_{gs} = 86



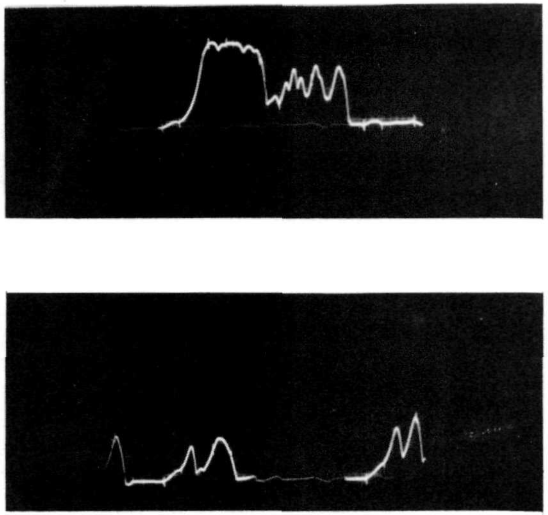


SCOPE TRACES SLUG FLOW
D = 1", AIR-WATER
ATMOSPHERIC PRESSURE

SWEEP TIMES = 5 x 10^{-3} sec/cm
SENSITIVITY 2v/cm

V_{fs} = 1.03 ft/sec	V_{fs} = 1.03	V_{fs} = 1.03
V_{gs} = 7	V_{gs} = 7	V_{gs} = 7

Fig. 4. Probe Calibration



SCOPE TRACES - SLUG FLOW

D = .875"

P = 415 psia

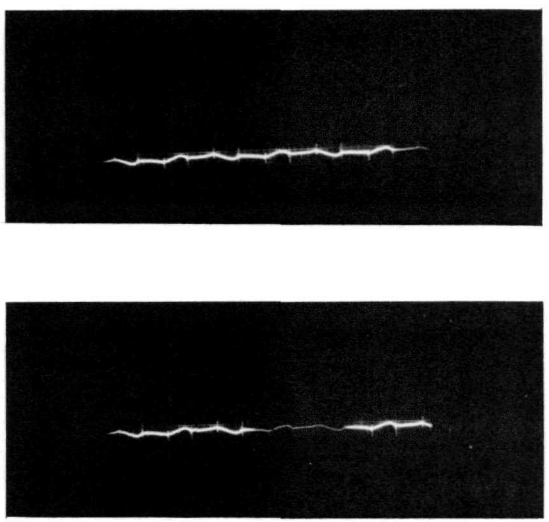
STEAM-WATER

V_{gs} = 8.35 ft/sec

V_{fs} = 1.94 ft/sec

SWEEP RATE = 5×10^{-3} cm/sec

2v/cm SENSITIVITY



SCOPE TRACES - ANNULAR FLOW

D = .875"

P = 415 psia

STEAM-WATER

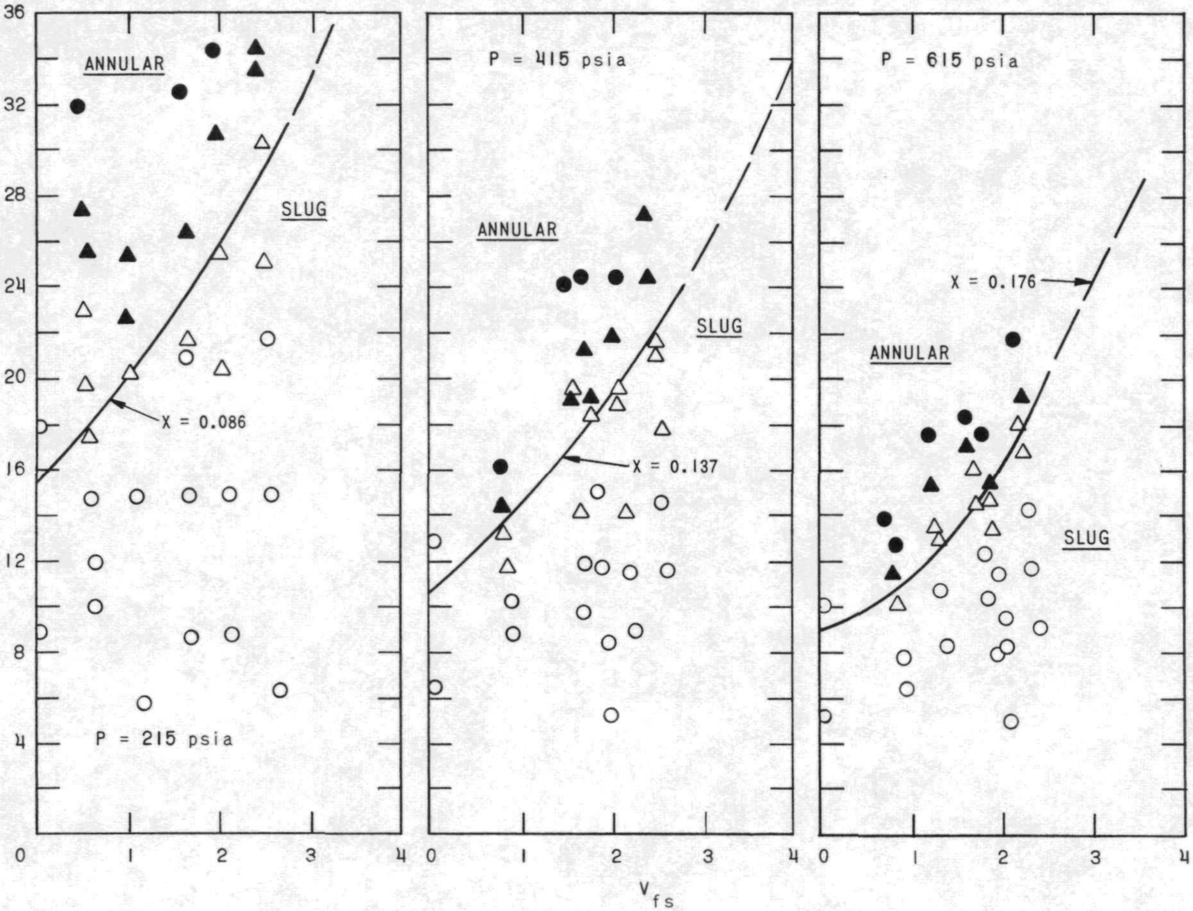
V_{gs} = 24.4 ft/sec

V_{fs} = 1.60 ft/sec

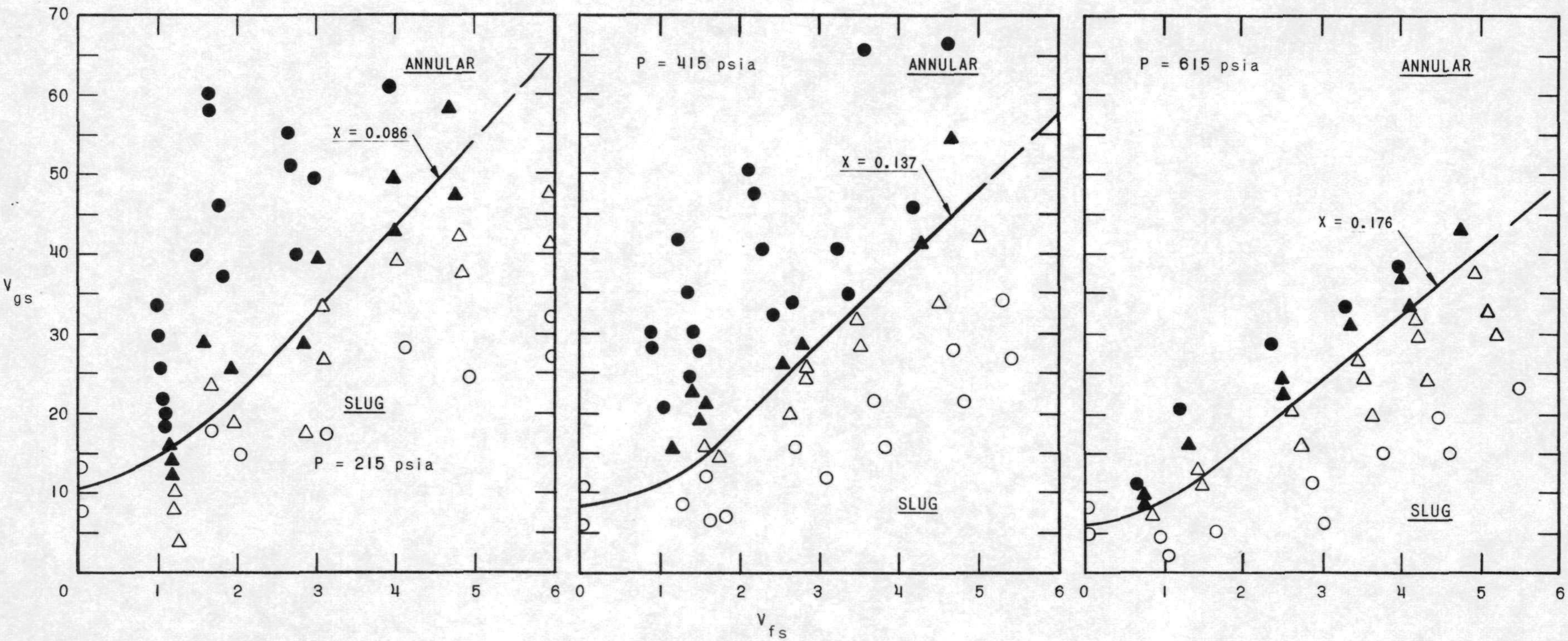
SWEEP RATE = 5×10^{-3} cm/sec

2v/cm SENSITIVITY

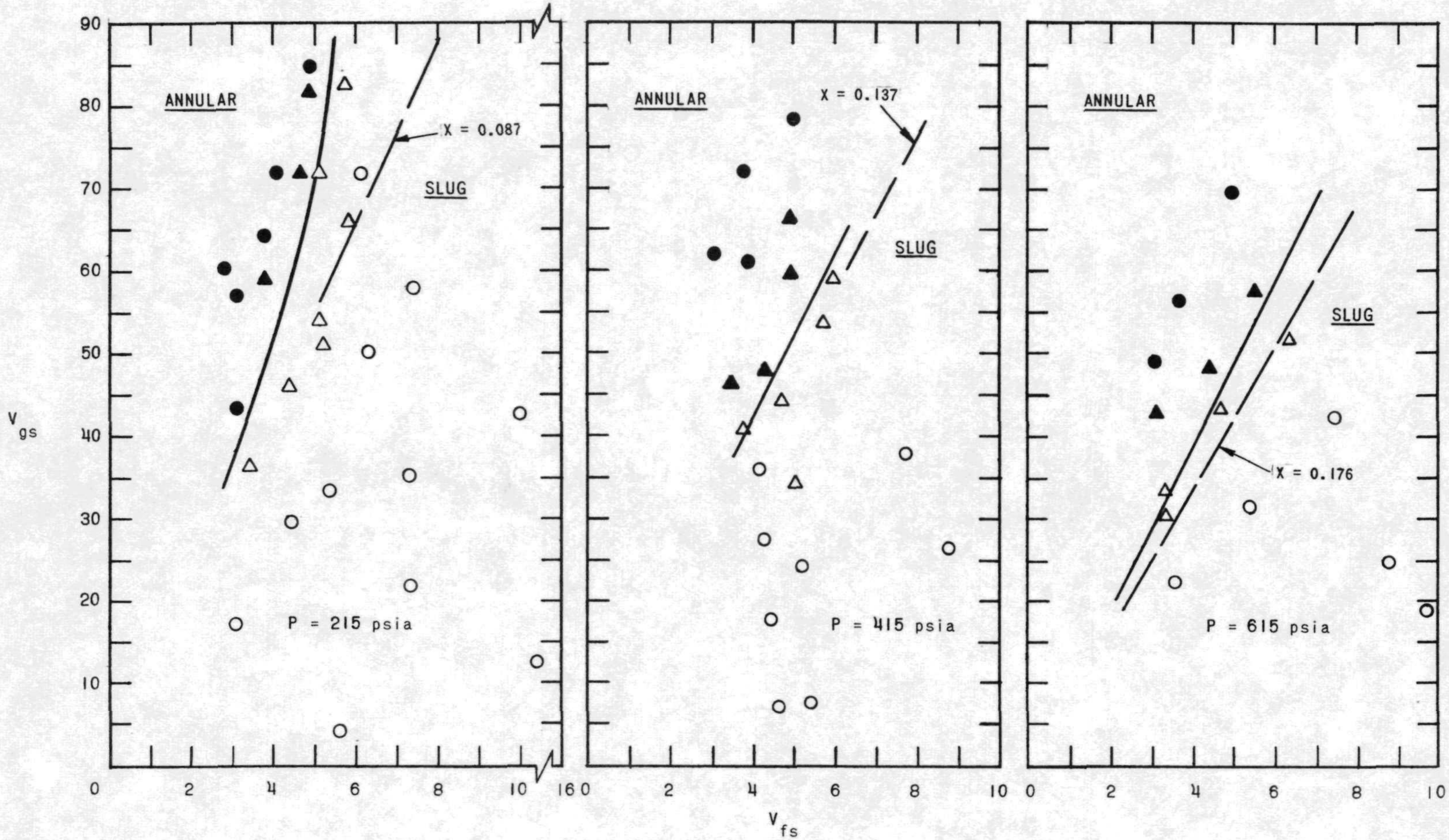
Fig. 5. Characteristic Traces for Steam and Water



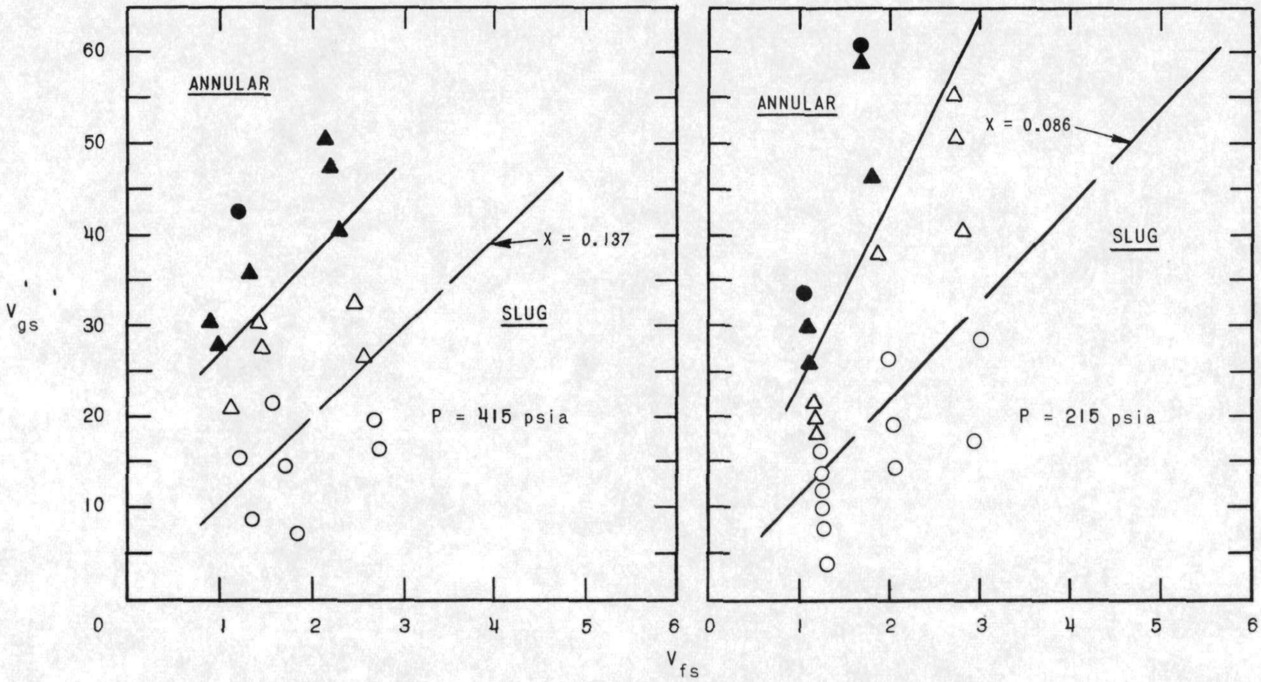
Figs. 6, 7, and 8. Flow Regime Maps (Using Top Probe) for 0.875-in. Pipe



Figs. 9, 10, and 11. Flow Regime Maps (Using Top Probe) for 0.625-in. Pipe



Figs. 12, 13, and 14. Flow Regime Maps (Using Top Probe) for 0.375-in. Pipe



Figs. 15 and 16. Flow Regime Maps (Using Bottom Probe) for 0.625-in. Pipe

As one approaches the transition region from the region of well-defined slug flow (the open dots in the figures), the traces get further and further apart and, in time, the amplitude of the traces begins to decrease from the full-scale readings. The visual observations of Reference 2 indicate that this corresponds to slugs with a large number of small bubbles in them. The slugs are still of appreciable length, however, and constitute the major mode of liquid transport. This transition slug flow condition is designated by open triangles.

As the superficial vapor velocity is further increased, the amplitude and length of the pips on the scope decreases further until only a single pip of very small length and no jaggedness appears. The visual observations of Reference 2 indicate that this corresponds to a transition annular flow with liquid bridges of thickness too small to contain any entrained bubbles. These bridges apparently do not persist and do not constitute an important mode of liquid transport. This transition annular flow is designated with black triangles. The plain black dots correspond to pure annular flow where no bridges occur at all. This represents the end of the transition region. The transition line has been drawn in each case to effect a separation between the open triangles and the black triangles.

It is believed that the slug-annular transition as determined with the probe is better than the one determined from still pictures; for, at this transition, most of the tube consists of something that looks like annular flow, while the major mode of liquid transport is still in the very rapidly moving slugs. Motion pictures, of course, do not suffer from this defect. However, all photographs suffer from obscuring due to small bubbles in the liquid on the walls, so that it is often difficult to tell whether one is looking at a frothy ring wave travelling up the tube or an actual bridge. If one were to do a control volume analysis of the flow by means of control volume boundaries based on photographs, the distinction between the bridging and the no-bridging condition would be an important one, and it is just this distinction that the probe makes.

Ultimately, one wants to use the flow regime map to tell when to go from an annular to a slug flow model for computing some quantity for the two-phase flow. As the transition band is so wide, the obvious definition for the boundary is an operational one which might be based on the particular quantity of interest. Pressure drop has three terms in it, and, as such, tends to be more constant than any one of the terms, so that a distinction based on it would not be too clear. In any case the pressure-drop correlations for either annular or slug flow are not that good. Void fraction is better, for one can use the predictions for annular flow from Martinelli and that for slug flow from Reference 1. However, even the Martinelli void predictions have very little data behind them at elevated pressure, so that an operational definition using voids does not, in this specific transition, turn out to be very useful.

DISCUSSION

The data of Figs. 6 through 13 are very simple in character. The extrapolated intersection with the vertical axis in each case lies between the limits predicted for the transition from slug to annular flow as presented in Reference 3. The upper limit given in Reference 3 is obtained with a very smooth entrance, whereas the lower limit is obtained with a sharp edge entrance. These limits were obtained for unheated tubes. For heated tubes they have not yet been determined. When the value for the dimensionless group given on the left side of the Eq. (1) is greater than 2.0, the transition line is virtually a line of constant quality:

$$\frac{V_{gs}^2 \rho_g}{gD \rho_f} \geq 2.0. \qquad (1)$$

This quality is tabulated in Table I. When the left-hand side of Eq. (1) is less than this, the diameter affects the quality at which transition occurs.

Table I

MINIMUM QUALITY FOR ANNULAR FLOW FOR VARIOUS PRESSURES

Pressure, psia	Minimum Quality for Annular Flow, %
215	8.6
415	13.7
615	17.6

For the smallest pipe and largest velocities, transition occurs at higher qualities. It is believed that this is primarily an effect of velocity rather than pipe size, for the curves for the lower velocities fair into those obtained from the larger pipes. When the velocity is high enough, entrainment probably occurs, and one has, in effect, a denser vapor with less liquid on the walls. This is as though one were operating at higher pressure for which the transition quality is actually higher.

Figures 14 and 15 give the transition condition just at the discharge of the test section. As can be seen, the transition quality is very substantially increased. This could be an effect of heat flux and/or vapor velocity, for the two were not separable in these experiments. Physically, the picture that emerges from these experiments is as follows. When the quality is passed through at which slugs can form, they do. As the annular flow region is approached, these slugs begin to lose liquid to the wall as they rise, ultimately being completely consumed if the pipe is long enough. This generally occurs before the location of the middle probe in these experiments. It takes time for this to happen, though, so that we see slugs after the point where slug flow is the fully developed flow regime. The heat fluxes in these experiments were generally less than 200,000 Btu/(hr)(ft^2). If the heat flux were higher, or perhaps if the region in which slug flow could exist were shorter, slug flow might never develop, and one could go right from bubbly to annular flow.

Repeated attempts to obtain bubbly flow in this apparatus always were unsuccessful. Either the heat flux was too low or the pump too small for this condition ever to exist. In the 0.875-in.-ID pipe, the maximum inlet liquid velocity was only 10 ft/sec. This is apparently insufficient to give bubbly flow as the fully developed condition. In addition, the water was very pure, which also makes it difficult to obtain bubbly flow. It would appear that bubbly flow is an important flow regime only when the pressure and/or the heat flux is very high.

Though the range of pressure tested in these experiments is small, it is interesting to extrapolate these results to higher and lower pressure. If a rough curve fit is made on the pressure effect from these data, the limiting quality varies as about the square root of the liquid-vapor density ratio. If this is assumed, one obtains the results for steam and water given in Table II.

It is worthwhile to compare these results with the measurements already in the literature. In Reference 4 are reported some visual observations made in heated rectangular channels at 150, 300, and 600 psia. Results are given in Table III. In all cases, the experiments were run in a 0.134 in. x 1.00 in. x 24 in. rectangular channel heated on one of the large sides.

Table II

MINIMUM QUALITY FOR ANNULAR FLOW FOR HIGH AND LOW PRESSURES

Pressure, psia	X, Minimum at Transition, %	Source
14.7	2	Extrapolation
215	8.6	Measurement
415	13.7	Measurement
615	17.6	Measurement
2000	40.0	Extrapolation

Table III

VISUAL OBSERVATIONS OF FLOW PATTERNS FOR A MASS VELOCITY OF 0.25×10^6 lb/(hr)(ft^2)

Pressure, psia	Quality, %	Flow Regime Reported	Flow Regime as Interpreted from Picture by this Author
150	5	Slug-annular flow regime transition	
300	5.5	-	Slug
300	11.0	-	Slug
	Transition		
300	16.6	-	Annular
600	4.1	-	Slug or bubbly
600	6.3	-	Slug
600	10.2	-	Slug

The transition occurs between 11 and 16%, where it would be expected to occur at 300 psia. Slug flow still exists at 10% quality, where it should occur at 600 psia.

In Reference 5 observations of high-pressure flow regimes are given. The reproduction of the pictures in the report is too poor to allow one to interpret them for one's self, but a description of the visual observations is given in Appendix D of Reference 5. The findings are summarized and listed for the quality region in Table IV. The pressure is always 1000 psia and the channel had dimensions of 0.5 in. by 2.1 in. There are various heat fluxes represented in these data.

Table IV

FLOW REGIME DATA OF REFERENCE 5

Mass Velocity, lb/(sec)(ft^2)	Quality, %	Flow Regime
50.0	25.8	Slug
50.0	31.8	Slug
	Transition	
50.1	45.0	Very slight slugging
50.1	55.6	Annular
50.1	65.6	Annular
50.0	65.6	Annular with small waves
99.4	5.6	Froth
99.4	9.7	Slug
99.4	16.6	Slug
99.4	22.3	Slug
99.2	23.4	Slug
101.0	30.2	Slug
	Transition	
99.4	45.4	Annular
99.4	46.5	Annular
99.4	46.5	Annular with large waves
199.0	10.5	Froth(?)
199.0	11.3	Froth
199.0	16.0	Froth
199.0	16.7	Froth(?)
196.0	25.2	Froth(?)
202.0	10.4	Annular(?)
199.0	15.1	Annular(?)
199.0	8.4	Froth(?)
398.0	3.4	Froth
398.0	7.4	Froth
395.0	9.3	Froth
398.0	9.6	Froth(?)

Except for the ambiguous flow regime descriptions given for conditions near the 200-lb/(sec)(ft^2) mass velocity, it appears as though the slug-annular flow regime transitions occur at about the quality one would anticipate from extrapolation of the measurements reported here, that is, at about 25%. It is not clear exactly what dimension one should use to compute the Froude number criterion appearing in Eq. (1). The investigation reported in Reference 1, however, showed that generally the larger dimension was more significant than the smaller. Therefore, one would expect the runs at lowest velocity to have the slug-annular transition occur at somewhat higher qualities. This also appears to be the case in these data.

When one looks at the qualities on Table I at which the slug-annular transition takes place, they reduce, crudely, to the qualities at which 80% voids occur in the Martinelli prediction.

CONCLUSIONS

1. The slug-annular flow regime occurs at almost constant quality, independent of flow rate as long as

$$\frac{V_{gs}^2 \rho_g}{g D \rho_f} \geq 2.$$

2. The quality at which the transition occurs is dependent on pressure with the values given below:

X, %	P, psia
8.6	215
13.7	415
17.6	615

3. At very high flow rates, there is some indication that the quality at which the transition occurs is increased, probably due to entrainment increasing the apparent vapor density.

4. The Teflon-covered probe tip gives reliable, trouble-free service up to temperatures of at least 489°F.

5. With V_{fs} = 10 ft/sec maximum in an 0.875-in. pipe, no fully developed bubbly flow was attainable at any quality.

ACKNOWLEDGMENT

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