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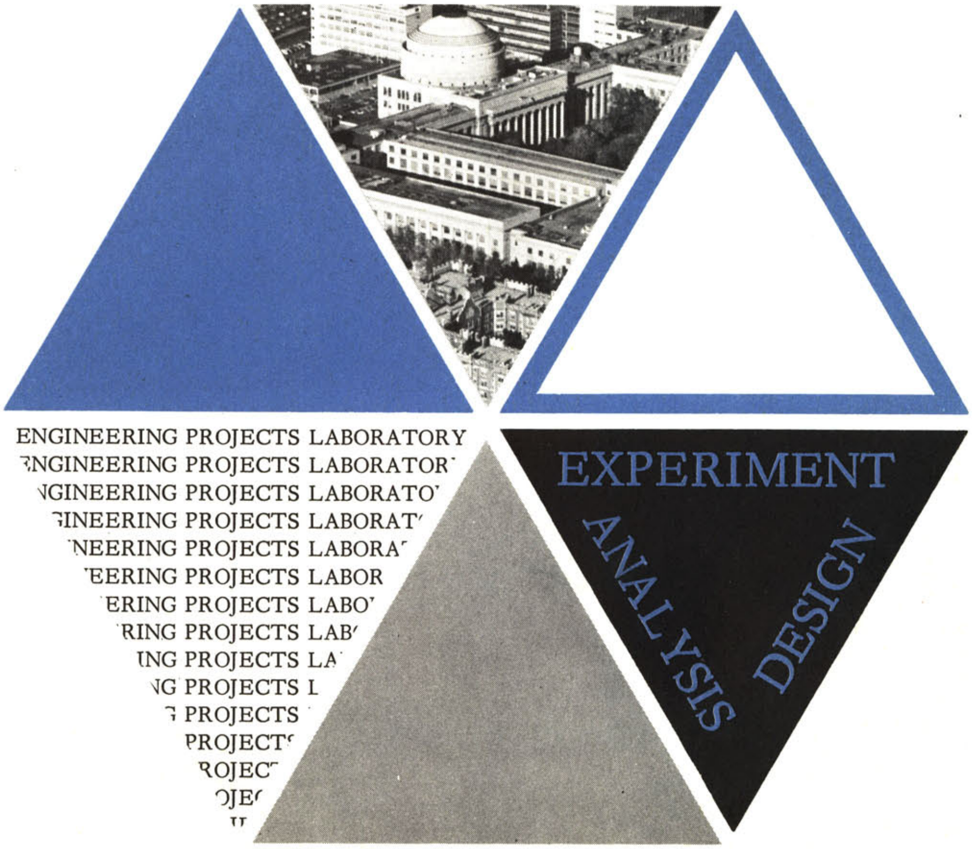

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ABSTRACT

A possible mechanism for the transition between bubbly and slug flow is proposed and tested in a simulated slug flow system. No sudden collapse of slug flow with increasing velocity is found and it is concluded that:

a. Slug flow is generally stable at voids greater than 35%.
b. Bubbly flow at voids higher than this is a result of entrance conditions.
c. Visual observations of bubbly flow in unheated systems at higher voids are most likely faulty.

No simple asymptote limit or criterion that would predict the location of the bubbly-slug transition was found.

Introduction

A number of observations have been made of the flow regime in the low void fraction region which are not consistent with one another. Reference (1) reports a transition to emulsion (or bubbly or froth) flow at a superficial mixture velocity of about 15 ft/sec in a one inch pipe. On the other hand void readings taken on similar air water systems (2) indicate that a slug flow pattern exists. Measurements made with a probe reported in reference (3) showed no evidence of bubbly flow. These measurements were made in a system at elevated pressure at very low heat fluxes, a variety of qualities and with velocities in excess of 10 ft/sec. Slug and annular flow were all that were observed. At comparable velocities and pressures but higher heat fluxes, reference (4) reports voids that indicate no slip and, therefore, a bubbly flow pattern. At still higher pressure and in a very small heated channel, reference (5) reports slip ratios that can only indicate a bubbly flow.

With these apparently conflicting observations in mind, this investigation was undertaken. In particular, an attempt was made to see if there was any velocity at which slug flow bubbles broke up spontaneously into a froth as a result of gas entrainment in the wake of these bubbles. Such a critical velocity would provide a very useful upper bound for the region in which slug flow could exist.

Two references bear directly on the problem at hand, references (6) and (7). Reference (6) is a detailed study of the bubbly-slug transition at low velocity which had as its primary conclusion that purity, initial bubble size, velocity, and pipe diameter were all important. The results were too complex to be generally useful, though they did uncover a mechanism for the transition from bubbly to slug flow. Reference (7) is an experimental study of gas entrainment around a jet. The geometry and properties were different from the case of interest here but their measurements did show something of the nature of the gas entrainment phenomena.

The Model Tested

A simulated slug flow system which was stationary was tested in order to see what was happening more easily and work with a generally simpler system. A slug flow bubble was simulated in plastic and supported on a tube through which just enough air was provided to makeup for that air which was entrained. The primary measurements were the water flow rate, from which the jet velocity was calculated and the void fraction a little way down from the plastic bubble. A detailed drawing of the plastic bubble is shown in Figure (1). A photograph of the bubble is shown in Figure (6).

In order to show how these measurements might be applied to a flowing system, two equations will be derived. One relates the jet velocity in these experiments to the "jet" velocity which would be observed in a flowing system. The second relates the entrained void to the average density of the mixture in a pipe in which there are also slug flow bubbles. These two results are incidental to the primary objective of the experiments, however, which was to see if there was a critical upper velocity at which wake entrainment made it impossible for slug flow to persist.

Coordinate Transformation

In studying the entrainment process at the tail of a slug flow bubble, it is appropriate to use a coordinate system which is attached to a slug flow bubble and to derive necessary velocity equations relative to that coordinate system. The purpose of developing these relations is to allow a transformation of the static measurement we have made, to a mixture moving in a pipe.

The mixture velocity or throughput velocity in a pipe is given by

$$V_{th} = \frac{Q_f + Q_g}{A_p} \qquad (1)$$

In two phase flows the gas and liquid phases do not necessarily move through the pipe with the same velocity. In a vertical pipe the bubble velocity relative to the throughput velocity is given by Nicklin, Wilkes, and Davidson (8) for turbulent flow.

$$V_b = 0.2\left(\frac{Q_f + Q_g}{A_p}\right) + 0.35\sqrt{gD} \qquad (2)$$

Adding these relations the absolute velocity of the Taylor bubble is

$$V_{ba} = 1.2\left(\frac{Q_f + Q_g}{A_p}\right) + 0.35\sqrt{gD} \qquad (3)$$

The absolute velocity of the bubble now becomes the velocity of our special coordinate system. Relative to this system the annular film now becomes an annular jet. The flow rate in the jet is

$$Q_{th} - Q_g = \left[\frac{Q_f + Q_g}{A_p} - 1.2\left(\frac{Q_f + Q_g}{A_p}\right)\right]A_p - 0.35A_p\sqrt{gD_p} \qquad (4)$$

The area of the annular film around the bubble is

$$A_b - A_p = A_p\left(1 - \frac{A_b}{A_p}\right)$$

The velocity of the jet relative to the special coordinate system is

$$V_j = -\left[0.2\left(\frac{Q_f + Q_g}{A_p}\right) + 0.35\sqrt{gD_p}\right]\frac{1}{\left(1 - \frac{A_b}{A_p}\right)} \qquad (5)$$

There exist experimentally observed limitations for the thickness of the annular film around a slug flow. These limits have been reported by Nicklin, Wilkes, and Davidson (8) as the percentage of pipe area which is filled by the film around the tail of a slug flow bubble. The range of the reported film areas and those tested in this investigation are shown below.

Reported Limiting Areas of Annular Film	$0.10\ A_p$. minimum
	$0.21\ A_p$. maximum
Tested Areas of Annular Film	$0.15\ A_p$. minimum
	$0.25\ A_p$. maximum

Dimensionless parameters for the annular jet can be calculated using the above velocity.

Average Mixture Density

Assume a control volume as shown in Figure 2. The flow rate and velocity at the exit plane are

$$Q = Q_f + Q_g \,, \qquad V_{th} = \frac{Q_f + Q_g}{A_p} \qquad (6)$$

The slug flow bubble will have a velocity relative to the liquid ahead of it as calculated in the previous section so that the absolute velocity of the bubble is

$$V_{babs} = \frac{Q_f + Q_g}{A_p} + V_b$$

Consider a system of one bubble plus one bubbly slug. The gas in such a system is

$$\mathcal{V}_g^{\ell} = \mathcal{V}_b^{\ell} + \mathcal{V}_{gs}^{\ell}$$

The time required for the system to pass a fixed reference point is

$$\Delta t = \frac{(L_s + L_b)A_p}{Q_f + Q_g + V_b A_p} \qquad (8)$$

The gas flow rate past the reference point is

$$Q_g = \frac{\mathcal{V}_b + \mathcal{V}_{gs}}{\Delta t} = \frac{(\mathcal{V}_b + \mathcal{V}_{gs})(Q_f + Q_g + V_b A_p)}{(L_s + L_b)A_p}$$

The average density of the system is

$$\rho_a = \rho_f \left(1 + \frac{\mathcal{V}_b + \mathcal{V}_{gs}}{\mathcal{V}}\right) + \rho_g \left(\frac{\mathcal{V}_b + \mathcal{V}_{gs}}{\mathcal{V}}\right)$$

$$\rho_a = \rho_f \left(\frac{Q_f + V_b A_p}{Q_f + Q_g + V_b A_p}\right) + \rho_g \left(\frac{Q_g}{Q_f + Q_g + V_b A_p}\right)$$

It has been assumed in the visual model that the large and small bubbles have a velocity relative to one another. Indeed this is essential to the maintenance of a fully developed slug flow. Assuming that the local relative velocity between the small bubbles and the liquid in the slugs is negligible for high speed flows we can calculate a new density for the liquid in the slugs.

$$\rho_f^* = \rho_f (1 - \alpha_s) + \rho_g \alpha_s \qquad (10)$$

$$\rho_a = \rho_f^* \left[\frac{Q_f + V_b A_p}{Q_f + Q_g + V_b A_p}\right] + \rho_g \left[\frac{Q_g}{Q_f + Q_g + V_b A_p}\right] \qquad (11)$$

By using the results of the present investigation one can calculate the density and gas distribution in a two phase slug flow.

Test Section

The investigation of gas entrainment in the wake of a slug flow bubble is most conveniently performed using a stationary bubble. In such a case, one can see that the velocity of an annular jet relative to the bubble (see equation (5)) is also the absolute velocity of the jet. In this investigation a stationary slug flow bubble can be simulated by a plastic bubble suspended in a pipe. The vertical downflow of water in the pipe simulates vertical up flow of a two phase mixture. The advantages of the simulated bubble are the following. The area of interest stands still so that visual observations are easier, and second the complications of a large two phase loop are avoided. Property variations are much more easily experimented in such a system. In the case of the plastic bubble an external force constrains the bubble so all liquid flow rates within the operating range of the system can be tested to give a variety of jet velocities. Third, the entrainment process removes gas from the bubble. In order to have time for observations and measurements some technique must be available for replacing this gas. Such a technique must not introduce new variables and disturbances into the system. With a plastic bubble the gas can be replenished through the bubble support. The bubble can be made hollow with an open tail so as to provide nearly identical conditions to those existing at the tail of a free slug flow bubble. See Figure (1).

The use of a plastic bubble to simulate slug flow is proposed, discussed and justified by velocity profile measurements in Moissis and Griffith (9). The annular jet is found to very quickly recover from the effects of the no-slip interface condition as soon as it leaves the plastic surface.

In this investigation a hollow, plastic bubble approximating the shape of a G.I. Taylor bubble was suspended in a vertical plexiglass pipe by a stainless steel tube of 1/8" diameter. The bubble was centered in the pipe by small pins protruding from its side. Figure 3 shows a section view of the plastic bubble and a table of the bubble diameters, pipe diameters and geometric variations tested. The bubbles were made to test the parameter D_b/D_p and to try to test the possible effects of the centering pins. In the belief that the entrainment could not be affected by small differences in the shape of the bubble nose no special care was taken to insure uniformity. The bubbles were all cut to the same general shape and always smoothly rounded. In all cases the tail of the bubble was tapered as shown in Figure 3.

The necessary air was forced into the hollow plastic bubble through the hollow tube.

Below the bubble there were two ball valves, coupled and manually operated for isolation of a length of the pipe. The valves open or shut with just a 90^o rotation of the shafts. By rapidly and simultaneously closing the valves one can obtain void fraction measurements.

Two test sections were constructed around the above principles. They were of 3/4" and 1" inner diameter. In each case the valve bore was equal to the inner diameter of the pipe so as to eliminate any area change as a possible system-related variable.

The remainder of the apparatus was built to accommodate either a recirculating system as for the silicone oil-nitrogen data or an open, single pass system for use with city water and shop air. Schematic drawings are shown in Figures 4 and 5.

The operating range for the water-air system was limited only by the line pressure of the city water system. The apparatus was protected from pressure surges during the sudden closing of the isolating valves by a simple pressure relief. A tee was placed in the water supply line with hoses connected to the "run" and a cork in the branch. When the pressure rose the cork blew out diverting the water flow from the apparatus to the sink. The cork was replaced in the tee as a preparatory step for the subsequent test run.

Water flow rates were measured by an in line flow meter but for flow rates outside the limits of readily available meters a weigh bucket and stop-watch were used. Gas flow rates were measured when desired by a volume flow meter.

For the silicone oil and nitrogen experiments an auxiliary apparatus constructed for some similar experiments was used. The auxiliary apparatus is described by Kumlin (10). The test apparatus was modified for the use of silicone oil by replacing the cork pressure release by a bypass tube and a third, coupled ball valve. Unfortunately, pressure drops in the auxiliary system limited the range of liquid flow rates to much lower jet velocities than were reached in the water-air system.

Experimental Procedures

The procedure for performing individual tests was as follows. A liquid flow rate was set by means of the control valves and some short interval of time was allowed to pass so that all air pockets in the system were swept out. Usually this required 10-15 seconds but for very low flow rates it was necessary to turn up the water flow rate for a short time then reset it at the desired value. After all air pockets were swept out the air supply was opened to allow air to fill the hollow plastic bubble. Entrainment started as soon as the air was allowed to enter the bubble. The air flow was then slowly increased until the gas-liquid interface moved slightly away from the tail of the plastic bubble. Opening the air shut-off valve any farther would drive the interface out of the tube and switch the entire flow regime from bubbly to annular. The first tests suffered a serious problem in this respect. The plastic bubbles were not initially tapered but had a flat face on the tail. In order to drive the interface outside the bubble it was necessary to set the air flow rate much higher than was required to maintain the desired equilibrium. When the interface left the bubble the flow regime blew out immediately into annular flow. It was possible to bring the bubbly flow back by turning the gas flow rate down so that the annular flow collapsed. When this was done the interface was quickly sucked into the plastic bubble. There was apparently a secondary flow around the flat tail of the bubble because tapering the bubble virtually eliminated this problem.

The importance of keeping the interface at a distance of about 1 to 1½ inches from the plastic bubble stems from the need to allow the jet to recover from the effects of the no-slip bubble boundary. One cannot allow the separation distance to grow very large, though, because the wall shear will slow the jet and cause it to grow. One thereby loses the advantage of the fixed dimension of a simulated bubble. This question will be discussed more in a discussion of special tests.

When an equilibrium condition has been achieved by balancing the gas flow rate with the entrainment, the liquid flow rate is measured by meter or by timing the filling of a weigh bucket. The gas flow rate is measured by a volume flow meter and stopwatch. The void fraction is measured by quickly closing the valves and measuring the height of the resulting water column. The void fraction is defined as the distance between valves minus the liquid height divided by the distance between valves.

For some of the test runs the procedure was modified slightly to investigate specific problems or to alleviate difficulties produced by the test conditions. The first instance of these deviations was a series of tests which were intended to determine the effects of varying the separation distance between the bubble and the interface. In one instance a series of tests was run with constant liquid flow rates. By adjusting the gas flow rate the separation distance between the tail of the plastic bubble and the gas-liquid interface was maintained at 9 cm., 7 cm., 5 cm., 3 cm. and 2 cm.

As the liquid flow rates were increased the definition of the gas-liquid interface became less and less clear. The turbulent jet and violently churning wake caused concern that the interface was inside rather than outside the tail of the plastic bubble. The condition of an interface inside the bubble will be called an attached interface for convenience throughout the remainder of the discussion. It became necessary to know what effect an attached interface would have so two criteria were used to investigate the condition. In one case the interface was allowed to recede from the desired position into the plastic bubble. This represented a slightly lower gas flow than that required for the equilibrium condition and it is designated as an attached, low flow condition. In the second case the gas flow is increased until the attached interface is just poised on the lip of the bubble. It represents in the usual case a flow rate equal to or very slightly higher than that required for the equilibrium condition. A series was run in which the two attached interface conditions and the usual 1-1½ inch spacing were repeated for various flow rates.

A second modification of the basic procedure was required in testing with silicone oil and nitrogen. It was found that the bubbly flow was agglomerating into slug flow before reaching the downstream valve. The void fraction measurements were erratic because of the inclusion of large bubbles in some tests but not others. To counteract this condition it was necessary to set up the liquid and gas flow rates and measure them. Just before measuring the void fraction the gas flow was stopped so that all slugs were cleared from the test section. The gas was then turned on again and in the short interval between the establishment of the desired flow condition and the development of the first large bubbles the void fraction had to be measured. This modification to procedure improved the repeatability of the void fraction measurements.

Several procedural difficulties deserve explanation. Mention has already been made of the lack of definition of the gas-liquid interface at high velocity. Some improvement could be achieved if the flow were observed with an outside window as a background. In such a case the interface became a shadow behind the highly turbulent jet. This type of observation was used for all very high velocities.

An additional problem was the sensitivity of the test settings to water supply pressure. The city water supply fluctuates wildly between 40 and 55 pounds gage pressure during certain peak demand periods of the day. After several frustrating attempts to cope with the problem these periods were used for reducing data taken during quieter periods. A pressure regulator might have helped the situation but would have reduced the operating range of the apparatus.

Experimental Observations

Of special importance to the entrainment process is the nature of the two phase flow in the slug. For descriptive purposes the slug is divided into three segments; the wake, consisting of a short length immediately behind the bubble, the developing section and the developed section. The wake of a slug flow bubble is a highly turbulent section of the slug in which small bubbles, droplets of liquid and gas-liquid interfaces are quite ill-defined. Only for very low bubble velocities does the tail of a slug flow bubble satisfy the description of a nearly flat surface. Indeed, as soon as the velocity is increased enough to reach a Reynolds number above 5000 in the film the wake churns and pulses quite rapidly. At very high velocities the churning is very violent but the pulsing of the bubble-wake boundary (it can no longer reasonably be called an interface) is somewhat diminished. The length of the wake increases slowly with increasing velocity of the flow. At the highest velocities tested, a jet velocity of 41 feet per second which corresponded to a throughput velocity of 33 feet per second as calculated from Equation (5), the wake was about 8 pipe diameters in length.

The growth of the wake length can be observed in Figure 6 at the end of the report. Photograph 2A shows a very short wake with agglomeration occurring immediately below the gas-liquid interface. On Photograph 1A the wake length is approximately 1 pipe diameter in length and in Photograph 3A the wake extends beyond the range of the photograph. The end of the wake is defined for purposes of this discussion as the point where a distinct bubbly flow can be observed. At high velocities the wake changes rather abruptly into the bubbly flow.

The developing section is immediately behind the wake. Very small bubbles are pulled out of the wake into this section where they quickly agglomerate into larger bubbles. Photographs which will be discussed later in this section indicate that these larger bubbles grow to a diameter of approximately one-fifth to one-third of the pipe diameter. Once again the developing section grows in length as the velocity of the mixture increases. This result is consistent with the observations of Radovcich and Moissis (6) who found a similar result for developing slug flows.

The "developed section" of the slug is really a misnomer. It implies that no changes will occur in the flow pattern but in fact the agglomeration process is still occurring. The section is discussed separately because the agglomeration process is considerably slower than in the developing section. In the particular case of the silicone oil-nitrogen data the agglomeration process continued even to the formation of a slug flow. This agglomeration occurred spontaneously for the case of a 3/4" pipe with a jet thickness of 0.031". With a 3/4" pipe and a jet thickness of 0.041" the formation of a slug flow could be induced but would not occur spontaneously. When the jet thickness was increased to 0.051" no agglomeration to slug flow occurred. In the general case no noticeable agglomeration occurred in the developed section of the slug. A similar wake agglomeration process has been observed in flowing systems.

It is important to determine how well the present model approximates the actual conditions existing in a two phase slug flow. To this end the observations made during this investigation are compared to the observations of other reporters. Numerous investigators have included photographs of slug flow in their reports. Among these are: Griffith and Wallis (11), low speed flows; Solomon (12), low to moderate speed flows; and Griffith (3) moderate speed flows. The reader is invited to compare the wakes pictured in the above references with photographs of three flow conditions produced during the current investigation and shown in Figure 6. Photographs 1a and 1b show a moderate speed wake and the resulting fully developed bubbly flow. One can see that even at a jet velocity of 13 feet per second there is an ill-defined interface followed by a wake of very small bubbles gradually increasing in size and decreasing in number as the distance from the tail of the bubble increases. Photograph 1b shows the bubbly flow at the middle of the test section. The void fraction for this test was 14.4%. Photographs 2a and 2b show a low speed flow in which the gas-liquid interface is clearly defined and very similar to that shown in the Griffith and Wallis report. The velocity of the jet is 9.22 feet per second and void fraction is much less than 8%, too small to be measured in the present apparatus. Photographs 3a and 3b present a relatively high speed flow, the jet velocity being 25 feet per second. In an attempt to improve the resolution a lens was fitted to the apparatus. Unfortunately it is still possible to see only the turbulence of the jet. It is in cases like this that the backlighting must be used. The void fraction for this case is 19.9%.

In switching to the 1" diameter test section a unexpected result was obtained. For large jet thickness, = 0.062", the core of the developed slug contained what looked like a very high void fraction. The bubbles were large and seemed closely packed. Surrounding this core of bubbles was an annular film of liquid which contained no bubbles. With a smaller jet thickness the core of bubbles grew larger and the void fraction increased. No noticeable increase in void fraction of the core could be seen. No such behavior was noticed for the 3/4" tube although it conceivably could have existed. The effect was striking for the case of the 1" pipe and led the investigator to believe that something was disrupting the flow pattern.

A second observation is related to the behavior of the gas-liquid interface when in the vicinity of the tail of the plastic bubble. Assume for descriptive purposes that the interface is far downstream. If the gas flow rate is slightly less than the entrainment rate the interface will move slowly toward the bubble. The rate of movement is rather slow and steady until the interface is several diameters from the bubble. At this point the interface accelerates toward the bubble. As the separation distance diminishes the velocity of the interface increases rapidly. A similar behavior is reported by Moissis and Griffith (9) for the agglomeration of Taylor bubbles in a developing slug flow. The reasons for the behavior are not similar because the interface movement is dependent upon the jet velocities and thicknesses and the bubble movement is dependent upon wake effects of a leading bubble.

Results

In the introduction to this report there is proposed a model for a slug flow to bubbly flow transition which requires a drastic increase in the gas entrainment at the tail of a slug flow bubble. In the case of the observations of one investigator, Kosterin (1), such a change should occur at a mixture velocity of about 13 feet per second in a 1" pipe. Using Equation (5) this corresponds to a jet velocity of 21 feet per second.

In the present investigation the entrainment from a slug flow bubble has been studied with jet velocities ranging up to 40.8 feet per second. The raw data for entrained void fraction are plotted against the jet velocity for all test conditions on Figures 7 through 10. It is noted that the void fraction for all water data increases rapidly with increasing velocity in the low velocity range and increases very slowly with increasing velocity in the high velocity range.

Data for silicone oil was obtained only for low velocities so the rate of increase of void fraction with increasing velocity was large. The encircled data on Figure 7 was obtained under the conditions of agglomeration to slug flow as discussed in the Experimental Observations section. These data show the scatter which was introduced by the irregular presence of large bubbles in the wake.

The dashed line which cuts through the data represents a laminar-turbulent transition in the annular jet. The value of the Reynolds number at the transition is set at 5000. This value is consistent with the observation that the jet changed from a glassy to a foggy film when a Reynolds number of 5000 was exceeded.

Jet Reynolds numbers were calculated for all test runs at very low velocities. It was possible to observe that for Reynolds numbers less than 5000 the jet emerged from the tail of the plastic bubble with the glassy smoothness characteristic of a laminar flow. In noting that the Reynolds number in the annulus between the plastic bubble and the pipe wall is only half the Reynolds number of the emerging jet one can see the reason for this behavior. For all jet Reynolds numbers above 5000 the jet changed from laminar to turbulent with a transition length shorter than the separation distance from the tail of the bubble to the gas-liquid interface.

A secondary objective of this investigation has been to propose a mechanism to describe the gas entrainment in a slug flow. It had been hoped that the plastic bubble simulation of the actual flow condition would provide sufficient control of the geometry variables to allow a reasonably general reasonably simple correlation for the entrained void fraction. No simple dimensionless groups have been found to be generally adequate.

Raw data is presented in Figures 7, 8, 9, and 10. The salient features that emerge from these figures are that void increases gradually with increasing jet velocity getting up to 35% at 41 ft/sec. Property and geometry effects are not large except that the very low surface tension for silicone oil displaces that curve well to the left. No evidence of a dramatic increase in void is to be seen at increasing velocity.

An attempt was made to correlate these data but no single simple correlation was found to work in both laminar and turbulent flow. The groups found to work best for turbulent flow are shown on Figure (11) using the raw data of Figure (7). Geometric variables enter also so that a curve similar to Figure (11) would have to be developed for each geometry. The results are not general enough to make this worthwhile however, so just Figure (11) is presented.

Conclusions

1. There is no indication of a sudden collapse of slug flow which results in a uniform bubbly or frothy mixture with increasing velocity. The fraction of small bubbles entrained just increases slowly.

2. Bubbly flow at voids higher than about 35% is a result of entrance conditions and does not represent a fully developed condition.

3. Visual observations of bubbly flow in unheated sections with voids greater than 35% are apparently faulty.

4. No simple criterion for the transition from bubbly to slug flow has been found.

Nomenclature

V -	Velocity
Q	Volume flow rate
A	Cross section area
g	Acceleration of gravity
$\mathcal{V}$	Volume
L	Length
ρ	Density
α	Void Fraction
X	Distance from the tail of the plastic bubble
σ	Surface tension
μ	Viscosity
δ	Jet thickness
λ	A property parameter = $\mu^2/\rho\sigma D$
We	Weber number = $\rho V_j^2 \delta/\sigma$
Re	Reynolds number = $\rho V_j \delta/\mu$

Subscripts

a	Average or overall
b	Bubble
s	Slug
f	Liquid
g	Gas
abs	Absolute
p	Pipe

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Captions

FIGURE 1. Sketch of simulated slug flow bubbles showing the wake and the entrainment occurring within it.

FIGURE 2. Control volume for deriving continuity relations.

FIGURE 3. Sketch of plastic bubble and table of geometric variables.

FIGURE 4. Schematic drawing of single pass apparatus.

FIGURE 5. Schematic diagram of recirculating apparatus.

FIGURE 6. Photographs of entrainment process showing:

1 A Wake of a plastic bubble at = 13 feet per second with = 0.041 inches.
1 B Developed flow behind the bubble with void fraction 14.4%
2 A Wake of a plastic bubble at = 9.22 feet per second with 0.041 inches.
2 B Developed flow behind the bubble with void fraction 8%.
3 A Wake of a plastic bubble at = 25 feet.
3 B Developed flow behind a bubble with void fraction = 19.9%

FIGURE 7. Data for pipe diameter, = 0.75 inch, jet thickness = 0.031 inch

✚ Water at temperature T = 41°F and air
● Water at temperature T = 90°F and air
▲ Silicone oil and nitrogen at temperature T = 77°F

FIGURE 8. Data for pipe diameter, = 0.75 inch, jet thickness = 0.041 inch.

✚ Water at temperature T = 41°F and air - bubble #2
● Water at temperature T = 90°F and air - bubble #2
▲ Silicone oil and nitrogen at temperature T = 77°F - bubble #2
○ Silicone oil and nitrogen at temperature T = 77°F - bubble #5
△ Silicone oil and nitrogen at temperature T = 77°F - bubble #6
↘ Water at temperature T = 41°F and air - bubble #5

FIGURE 9. Data for pipe diameter, = 0.75 inch, jet thickness = 0.051 inch.

✚ Water at temperature T = 41°F and air
● Water at temperature T = 90°F and air
▲ Silicone oil and nitrogen at temperature T = 77°F

FIGURE 10. Data for pipe diameter, 1.00 inch, using water at temperature T = 41°F and air

✚ Jet thickness 0.062 inch
● Jet thickness 0.040 inch

FIGURE 11. Correlated data from FIGURE 7.

✚ Water at temperature T = 41°F and air
● Water at temperature T = 90°F and air
▲ Silicone oil and nitrogen at temperature T = 77°F

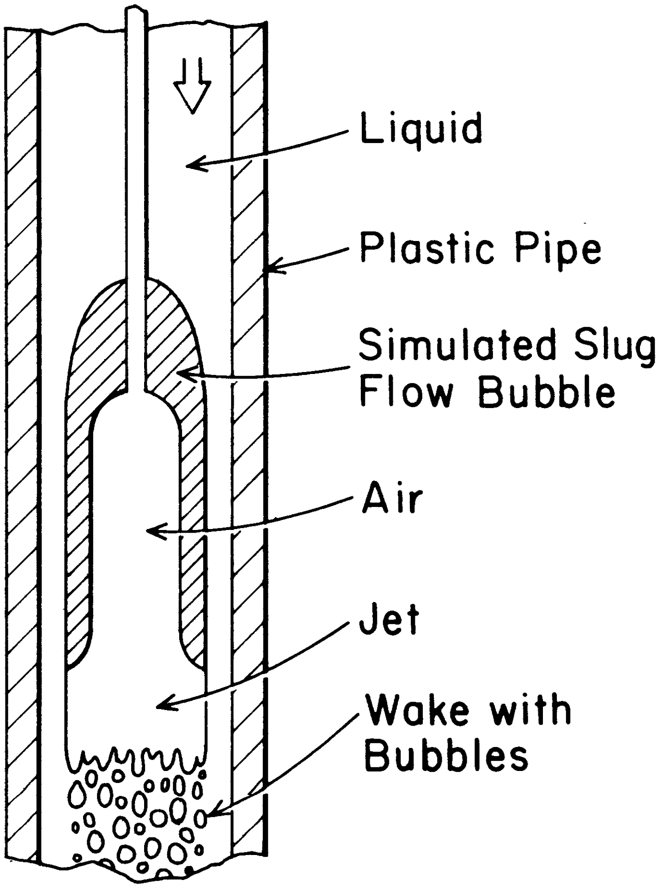

Liquid
Plastic Pipe
Simulated Slug Flow Bubble
Air
Jet
Wake with Bubbles

FIGURE 1

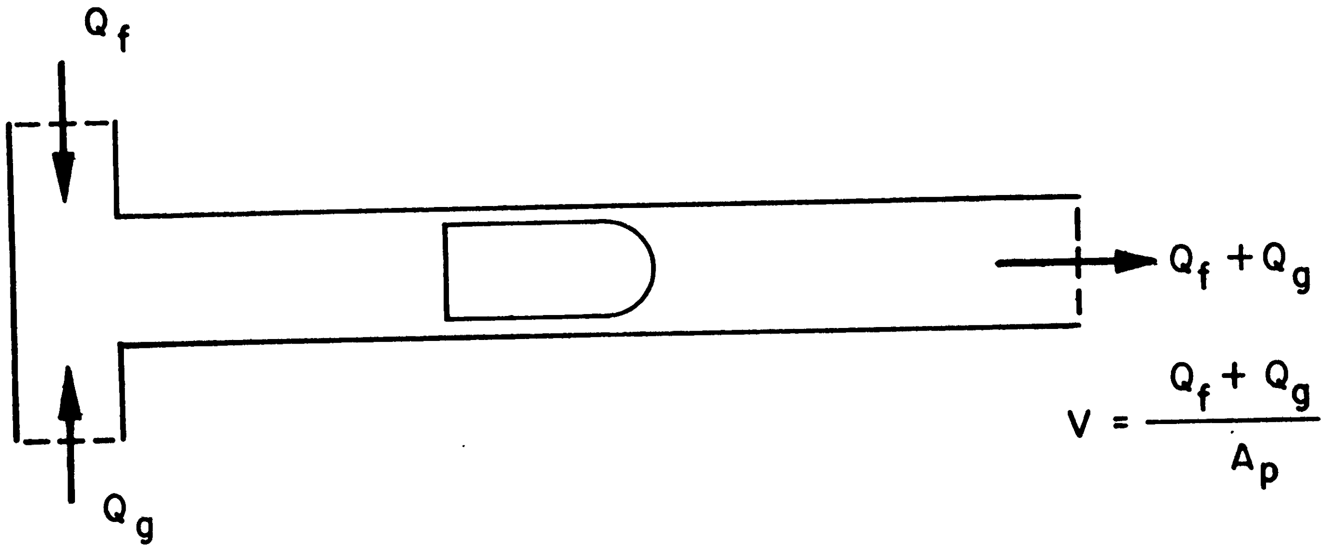
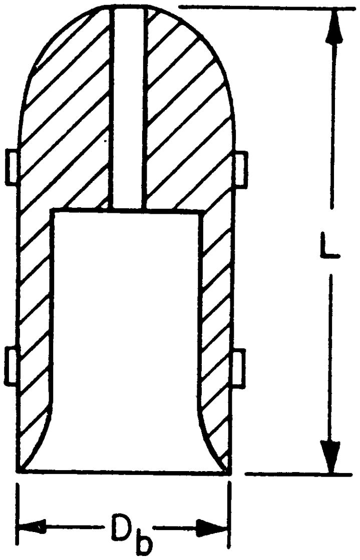


FIGURE 2



Bubble Number	Bubble Diameter (D_b)	Pipe Diameter (D_p)	Centering Pins
1	0.687 inch	0.75 inch	6
2	0.669 inch	0.75 inch	6
3	0.651 inch	0.75 inch	6
5	0.669 inch	0.75 inch	3
6	0.668 inch	0.75 inch	0
7	0.875 inch	1.00 inch	6
8	0.920 inch	1.00 inch	6

FIGURE 3

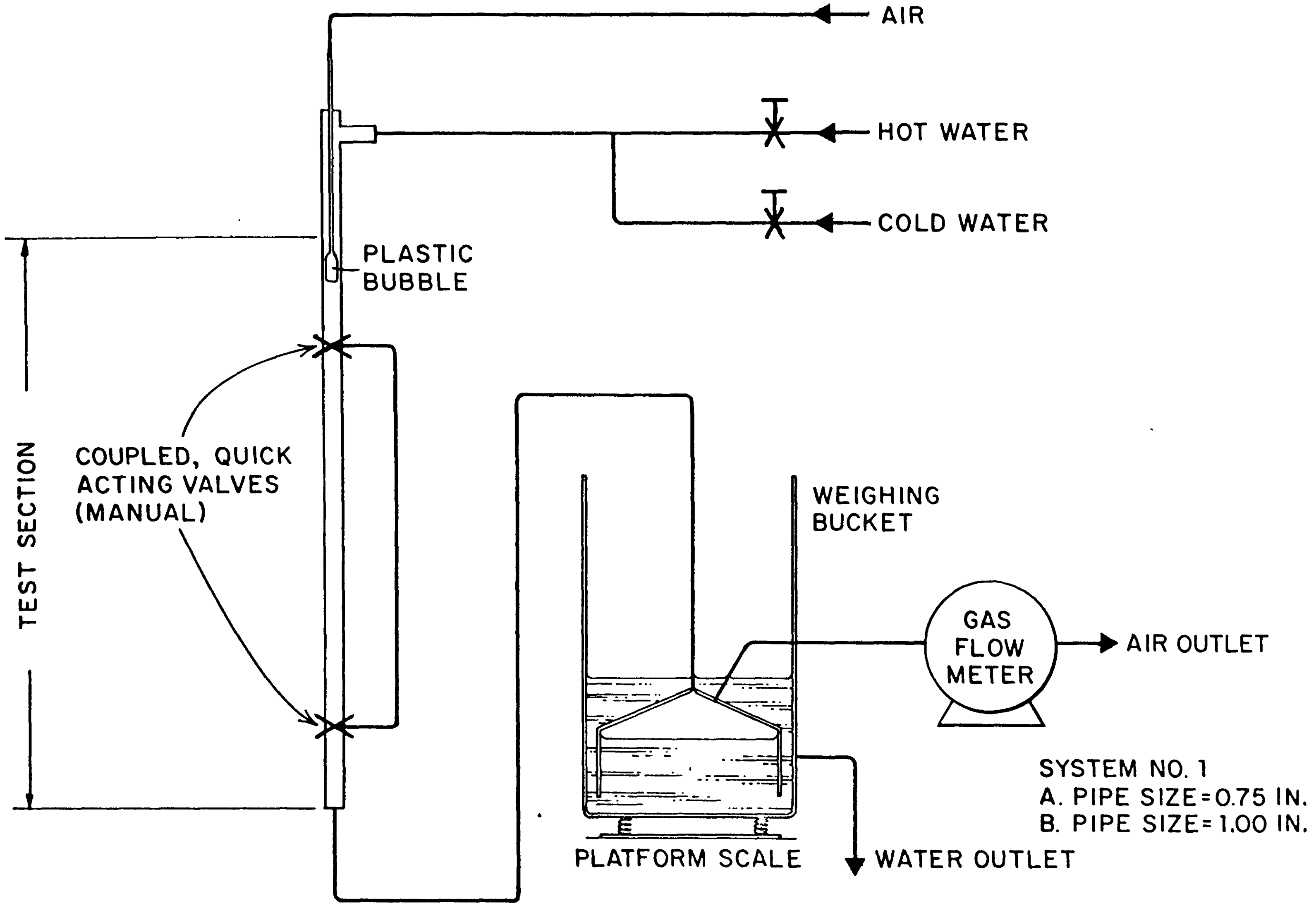

AIR
HOT WATER
COLD WATER
PLASTIC BUBBLE
TEST SECTION
COUPLED, QUICK ACTING VALVES (MANUAL)
WEIGHING BUCKET
GAS FLOW METER
AIR OUTLET
SYSTEM NO. 1
A. PIPE SIZE=0.75 IN.
B. PIPE SIZE=1.00 IN.
PLATFORM SCALE
WATER OUTLET

FIGURE 4

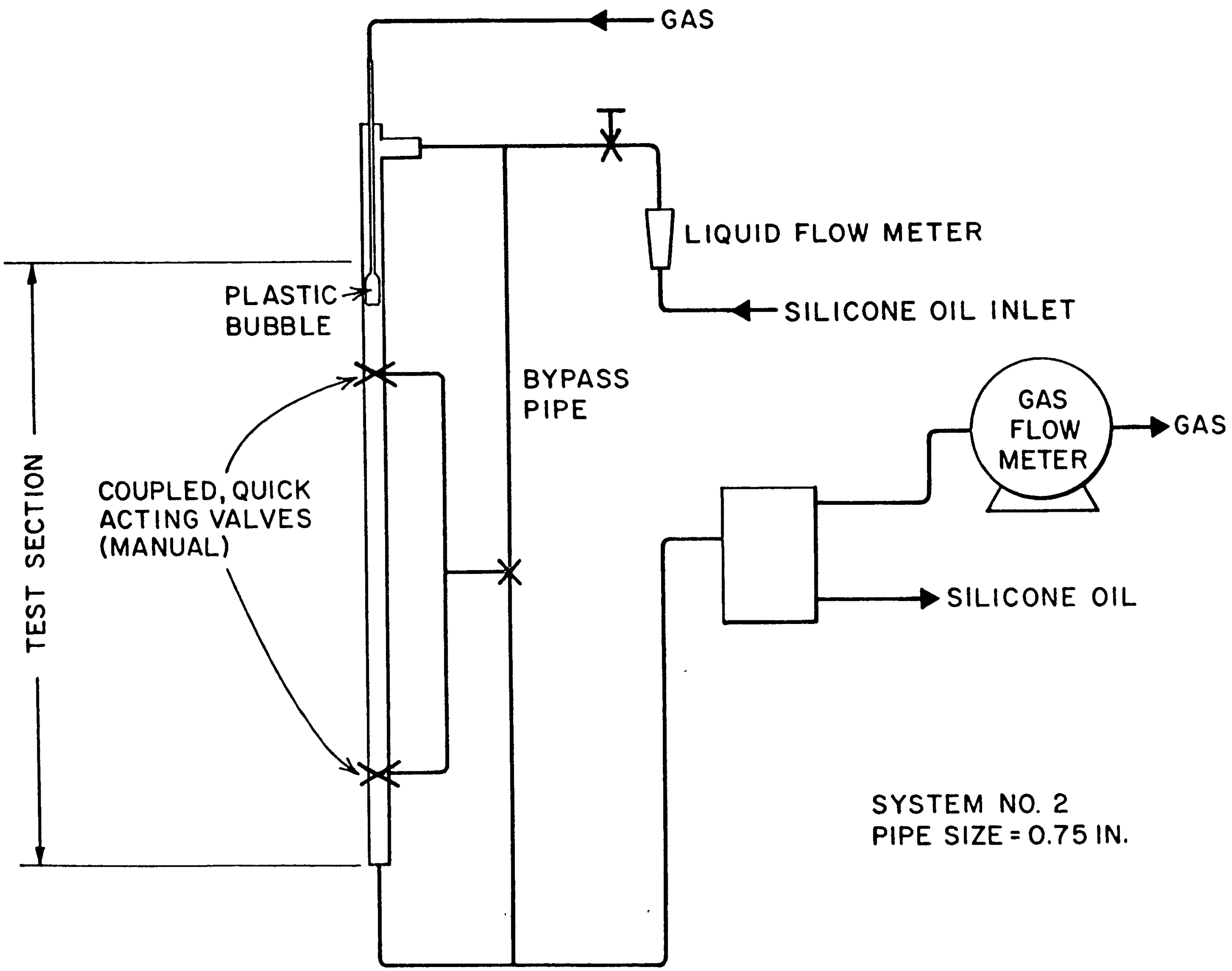
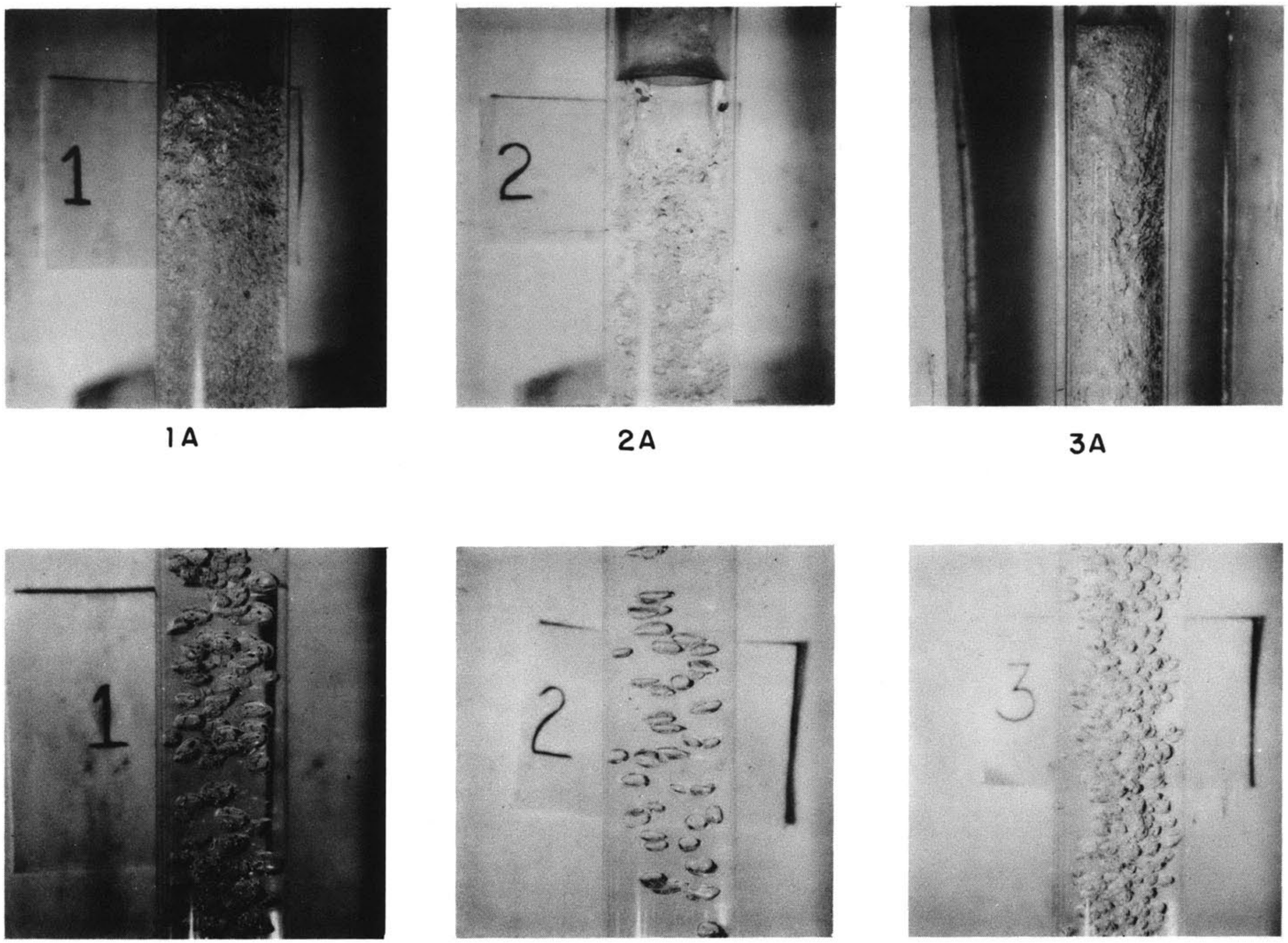

GAS
LIQUID FLOW METER
SILICONE OIL INLET
PLASTIC BUBBLE
TEST SECTION
BYPASS PIPE
COUPLED, QUICK ACTING VALVES (MANUAL)
GAS FLOW METER
GAS
SILICONE OIL
SYSTEM NO. 2
PIPE SIZE = 0.75 IN.

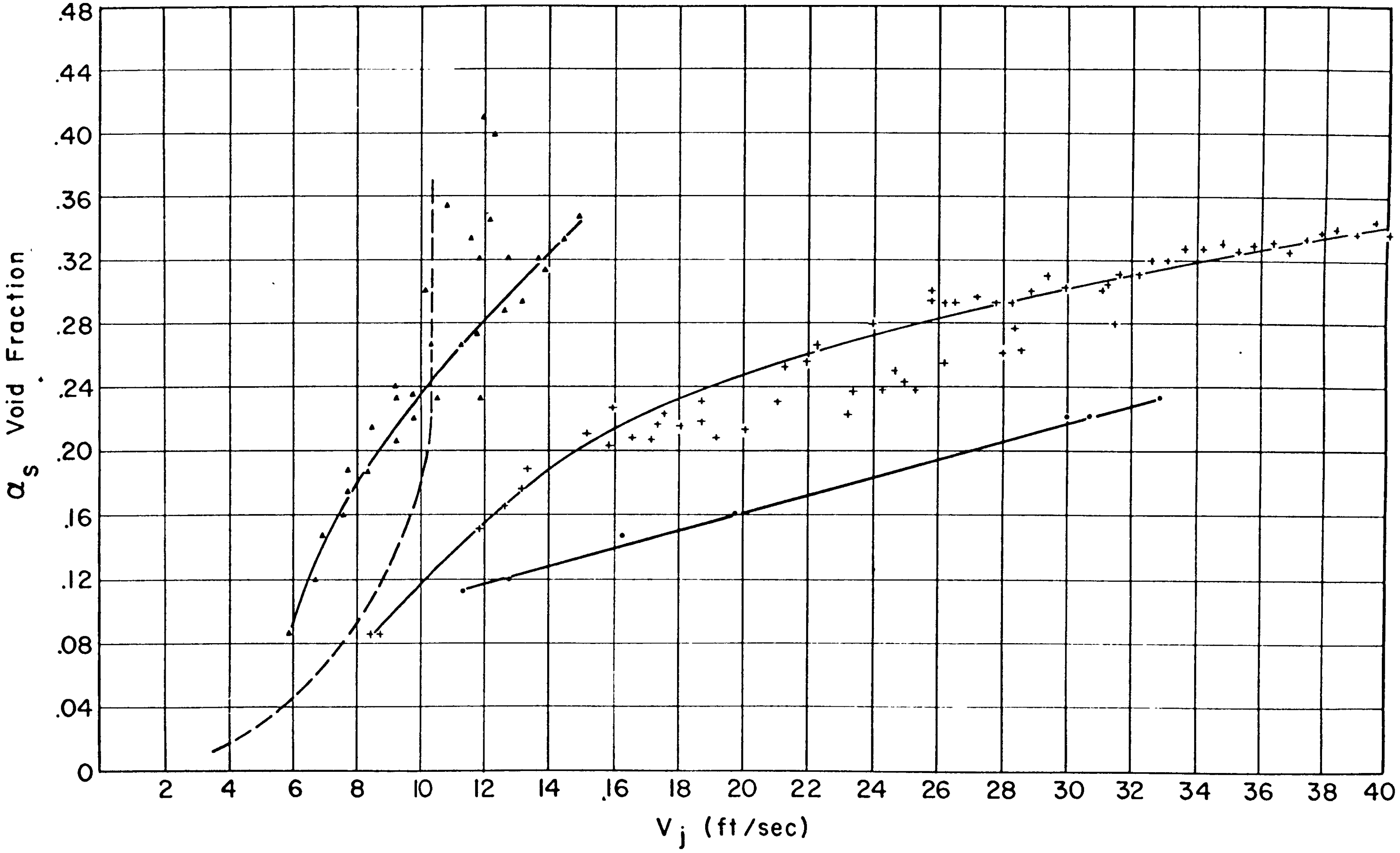
FIGURE 5



1A 2A 3A

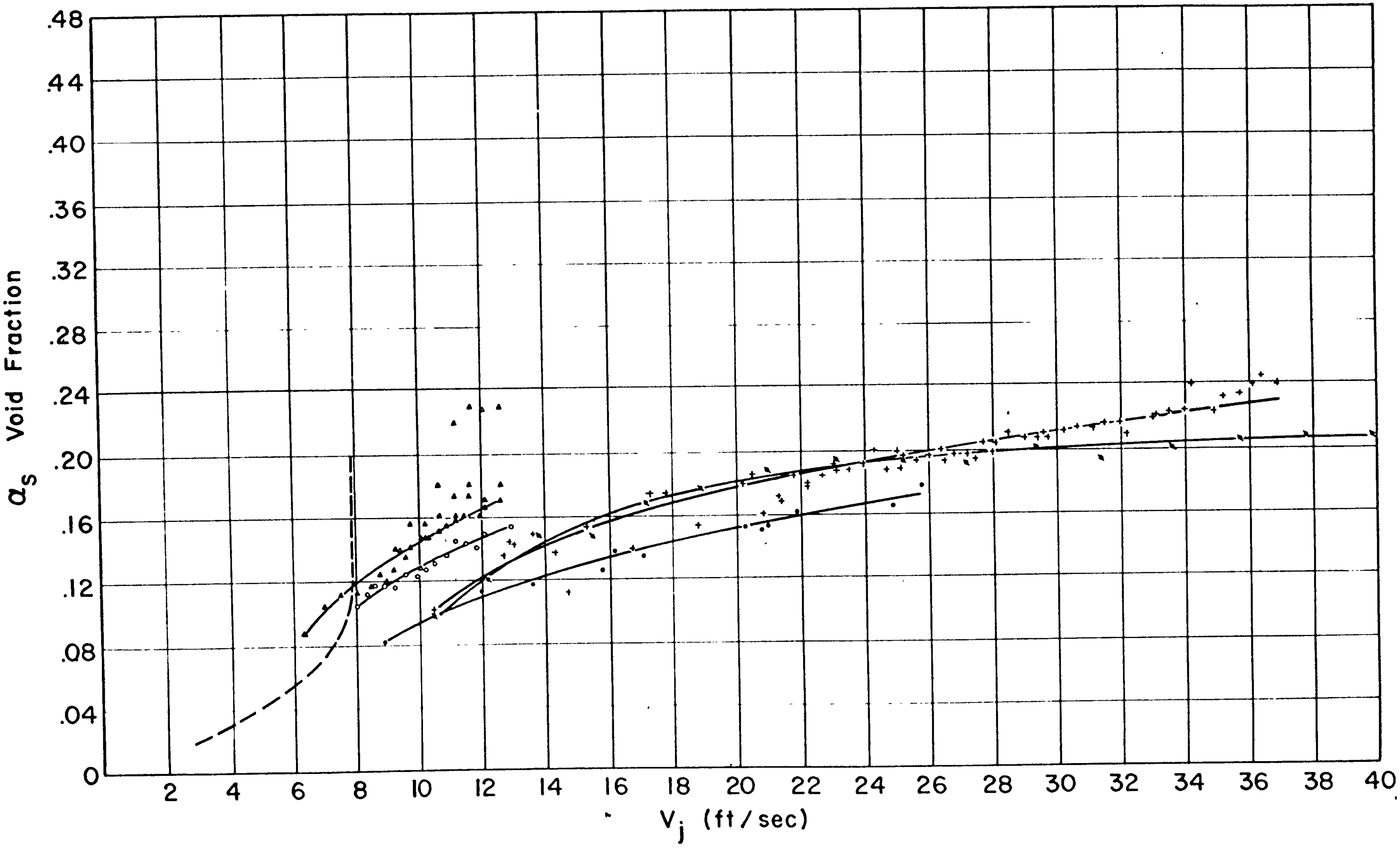
1B 2B 3B

FIGURE 6



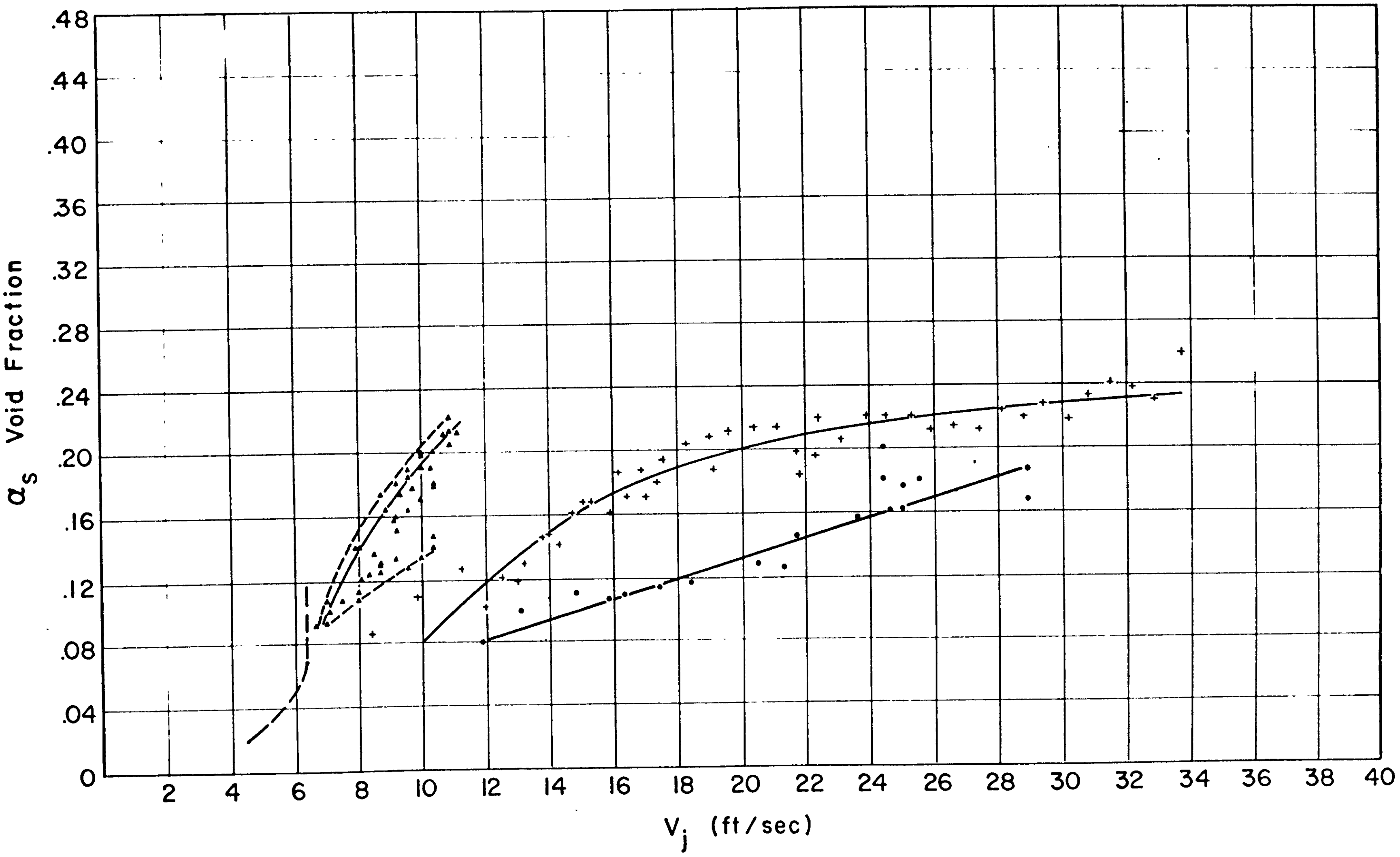
.48
.44
.40
.36
.32
.28
.24
.20
.16
.12
.08
.04
0
α_s Void Fraction
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
V_j (ft/sec)

FIGURE 7



.48
.44
.40
.36
.32
.28
.24
.20
.16
.12
.08
.04
0
α_S Void Fraction
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
V_j (ft/sec)

FIGURE 8



.48
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0
α_s Void Fraction
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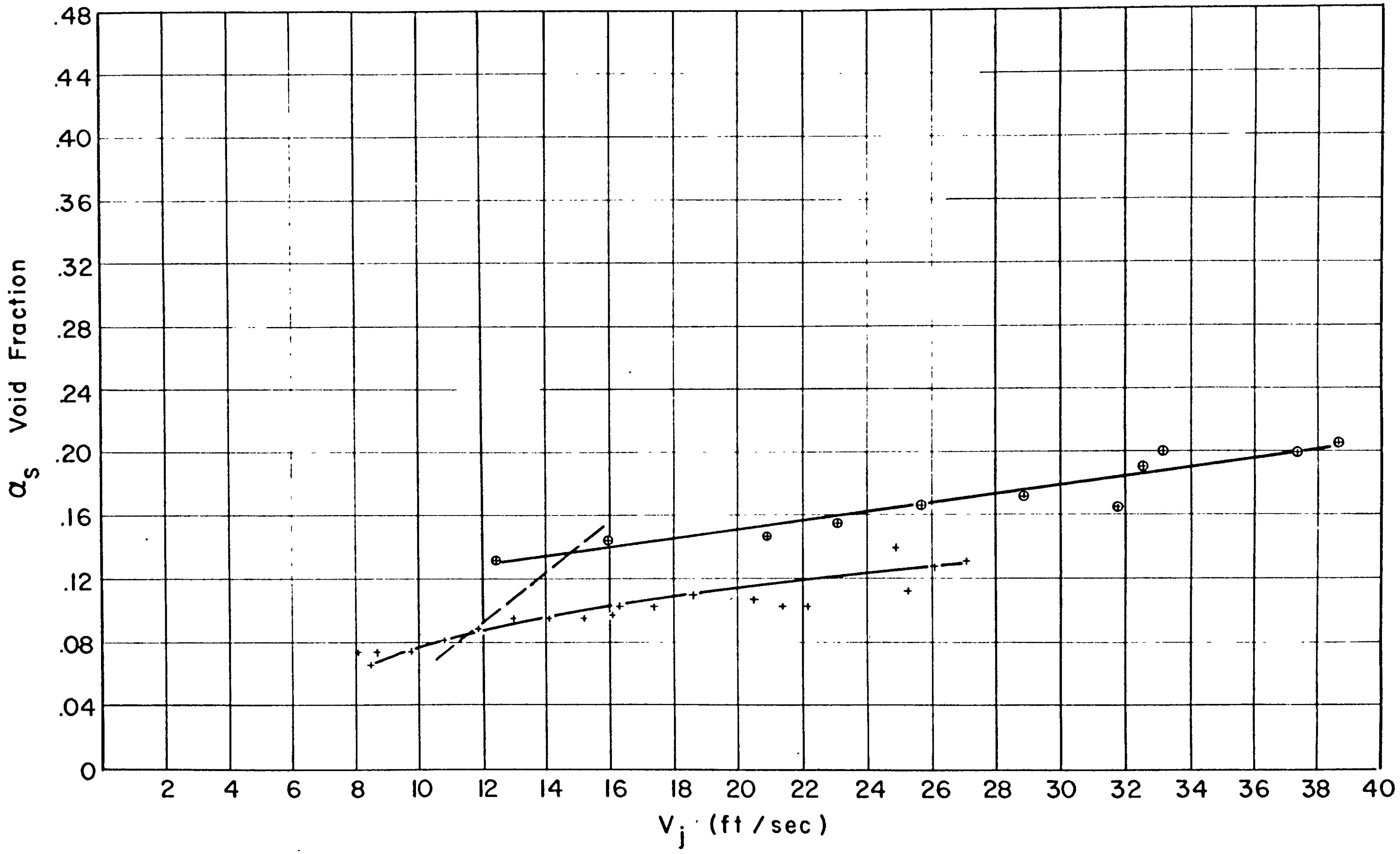
26
28
30
32
34
36
38
40
V_j (ft/sec)

FIGURE 9


.48
.44
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.08
.04
0
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4
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8
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12
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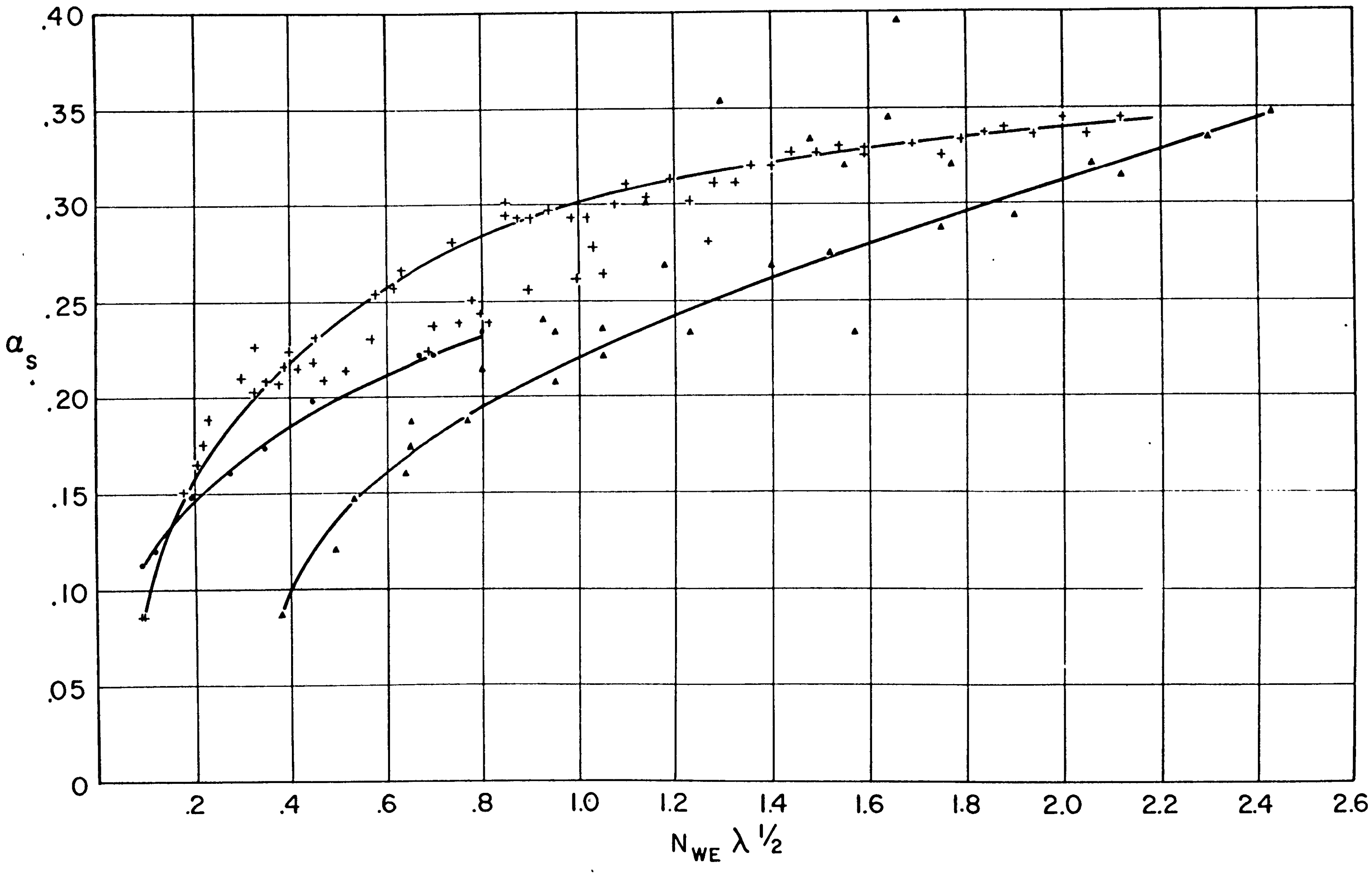
16
18
20
22
24
26
28
30
32
34
36
38
40
α_s Void Fraction
V_j (ft / sec)

FIGURE 10



.40
.35
.30
.25
.20
.15
.10
.05
0
a_s
.2
.4
.6
.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
$N_{WE}\,\lambda^{1/2}$

FIGURE 11