TWO-PHASE FLOW OF FLUIDS THROUGH A HORIZONTAL PIPE

By

Michael G. Kelakos

&

Arthur H. Crowley

Submitted in Partial Fulfillment of the Requirements for the Degree of Bachelor of Science from the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

1935

Signature of Authors Signature redacted

Signature redacted

Department of Chemical Engineering, May 16, 1935.

Professor in Charge of Research Signature redacted

Head of Department Signature redacted

Massachusetts Institute of Technology
Cambridge, Massachusetts

May 16, 1935

Prof. Walter G. Whitman
Head of Chemical Engineering Dept.
Mass. Institute of Technology
Cambridge, Massachusetts

Dear Sir:

In partial fulfillment of the requirements for the Degree of Bachelor of Science in Chemical Engineering, we hereby submit the following thesis.

Yours truly,

Signature Redacted

Signature Redacted

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

ACKNOWLEDGEMENT

The authors take pleasure in acknowledging the valuable assistance which they received from Prof. Robert L. Hershey. This was made manifest in suggestion as to the proper equipment with which to carry out the research, and more especially in regard to the method of attack and treatment of results of the problem at hand.

Summary

Subject

The mechanism of the flow of a liquid and a gas through a long, horizontal pipe.

Purpose

H. L. Reichart, M. I. T., '34 carried out an investigation of this subject using a 25 mm. glass tube. He identified the various types of flow attendant upon two-phase flow and determined the critical conditions of the changes of type. The first object of this study is to repeat this work on a 25 mm. tube in an attempt to verify his work. Then the tube is to be changed for one of larger diameter and also for one of smaller diameter and the above work repeated. An attempt to correlate the data thus obtained is to be made.

Abstract

The following report embodies a discussion of the various phases of the investigation. It includes the practical reasons for the study, namely its industrial applications, a review of the previous work on the subject, the results of the work accomplished, the experimental apparatus and procedure used, and recommendations for future work.

INTRODUCTION

Very little is known about the flow of a mixture of a liquid and a gas through a long pipe. This type of flow is met with quite commonly in industry. In the Pohle air lift, liquids are raised from one level to another by blowing compressed air into the bottom of a pipe which has been immersed in the liquid. Two-phase flow is encountered in the petroleum industry, where the mixture leaving the coils is partly liquid and partly vapor. Other examples are the gas lift in oil wells, and the condensation of water in steam pipe lines.

In order to obtain maximum efficiency of installation, it is desirable in each of these cases to know the pressure drops through the pipes, and to know how the pressure differences are affected by the diameter of the pipe, the absolute velocities and the relative velocities of the liquid and gas, etc.

In the investigation of two-phase flow so far carried out, only a horizontal pipe has been used. Industrially, this type of flow is met with nearly exclusively in vertical or slanting pipes. But the two conditions are sufficiently alike, so that the results obtained from horizontal flow will be fairly representative. Horizontal flow has the advantage of offering fewer experimental difficulties.

The petroleum industry has carried on an extensive research into the mechanics of gas-oil flow through a vertical pipe.[1] Usually a vertical column is set up, and an attempt made to reproduce, as far as possible, all the conditions present in an oil well. An empirical expression for the viscosity of the mixture is then introduced into Poiseuille's law. This expression combines all of the losses found in the flow. The results obtained in this way are reliable only over limited ranges. They do, however, give an idea of the direction in which the various factors act.

In the Pohle air lift and in the steam boiler all work has been of an empirical nature, with highly unsatisfactory results. The efficiency of the equipment in petroleum cracking plants is probably much lower than it might be, because of the lack of any theory behind the design; most of the designing being purely empirical.

Horizontal flow presents several aspects in which it differs from vertical flow. As the gas and liquid enter the horizontal pipe they are flowing in separate layers. In a vertical pipe the two phases would be thoroughly mixed at all velocities. H. L. Reichart, Chem. Eng. Thesis 1934 who seems to be the only person to have done any previous work on this subject reports that given a condition of separate flow in a horizontal pipe, increasing the velocities of the two phases will cause a wave motion to be set up on the surface of the liquid and ultimately slugging occurs. Wave motion would not be possible in a vertical pipe. At very low gas velocities, the quantity of gas flowing becomes so small, that the gas can no longer exist as a separate stream, but breaks up into bubbles, which are carried along by the liquid. Bubbling is found in vertical or slanting pipes at low gas velocities, gradually changing to slugging as the velocities are raised, without, however, passing through the condition of separate flow.

As can be seen from the above, much work has been carried out on subjects relating to two-phase flow, but most of it has been purely empirical and the results of doubtful importance. The results of the present investigation, when completed, should have some value.

II STATEMENT OF THE PROBLEM

The problem under consideration consists in defining the various peculiarities of two phase flow in a manner such that their definition will be correct under all conditions. As has previously been mentioned, all former work has centered around first obtaining a mass of pressure drop data and then trying to use this data in known formulae. In order, however, to make use of quantitative data, it is preferable to have some qualitative view of what is happening. With this in mind, it was decided to begin the investigation by obtaining an idea of the various types of flow encountered in two phase flow and also determining the controlling conditions of these types. It is hoped that by this method inaccurate substitution in empirical formulae will be eliminated.

In order to arrive at the ultimate object of the study, namely, a correlation of pressure drop data in some form of a general formula, it was thought advisable to proceed experimentally in the following manner. The first step is to determine the number of different types of flow encountered in two phase flow and attempt to describe them in such a manner that they will be easily distinguish-able under any conditions. After this had been done, the critical condition of flow for these various types should be determined. Before the final correlation is attempted, however, data should be obtained embodying all the varying factors of two-phase flow.

III -ANALYSIS OF INVESTIGATION

Because of the enormity of its scope, the investigation could not be completed by the authors. It is hoped, however, that further work will be done in the near future.

Results have been obtained up to the present for three different pipe diameters using air and water as the flowing fluids. These results are discussed further in the report.

Reichart recognized six variables which may have a bearing upon the transition areas, namely; (1) pipe diameter, (2) back pressure, (3) viscosity of liquid and of gas, (4) specific gravity of each, (5) velocity of each, and (6) absorption of each by the other. By using water and air, (3), (4), and (6) were kept constant. Therefore, in this investigation the pipe diameter, and velocities of both water and air were varied. The diameters of pipe used were respectively 25 mm., 50 mm., and 15 mm. Although the authors amassed as much information as possible on the three different pipes, it is felt that more work should be done on the 50 mm. and the 15 mm. with apparatus which will ensure a greater water and air velocity.

IV LIMITATIONS OF RESULTS

In order to be convincing, qualitative and quantitative work should be done with apparatus as nearly "perfect" as possible. Thus, in this investigation of two phase flow through a horizontal pipe, the ideal tube would be one which was absolutely straight. Because of the fact, however, that the glass tubing used could not be obtained in lengths more than five feet, it was necessary to have the glass blower splice three of the pieces together to acquire the required fifteen feet. Added to the two constrictions, thus introduced in the tube, is the fact that the five-foot lengths were themselves uneven. Together, the above two variations from the desired, perfectly straight pipe, had a marked effect on the results. There was occasionally some backflow of water into the tube proper from the overflow cans which could not in any way be eliminated. By taking readings in the first five feet of tube, about 12 feet from the overflow cans, it is believed that the error is reduced to a minimum. The angle at which both the air and water entered made a marked difference in the location of the transition areas. But this difference was corrected by making an entrance tube (described in Appendix) and affixing it as nearly in line with the tube proper as possible. The most important factor entering in the reliability of the results was the inability of obtaining the manometer difference in the air flow meters. As soon as the slugging region was reached the readings fluctuated very rapidly and made it very difficult to determine the air velocity. The authors believe, however, that this defect was eliminated by taking readings between slugs.

Contrary to Reichart the authors had no difficulty in attaining a high enough air velocity when experimenting with the 25 mm. tube. It was otherwise with the 50 mm. and the 15 mm. tubes. When the 50 mm. was used, a high enough water velocity could not be reached even though two water taps connected to the water main independently were used. This lack of water prevented any washing-out-points from being obtained. In both the 50 mm. and the 15 mm. tube the air velocity was far too low to cover the range required for the determination of all the types of flow.

This was caused by the fact that the blower used was extremely sensitive to pressure. Therefore, because of the pressure drop through the orifices, connections, and pipe, and the large back pressure of the slugs, the blower was able to deliver but a small quantity of air per minute. The authors were unable to obtain any other similar apparatus which would be efficacious.

The above difficulties have been described in length in order that the reader may appreciate the odds against which the authors had to contend. It is felt, nevertheless, that the results shown further in the report are accurate for the ranges covered, and it is to be hoped that by realizing beforehand the various difficulties encountered in securing sufficient data, the persons continuing this work will take early measures to overcome them.

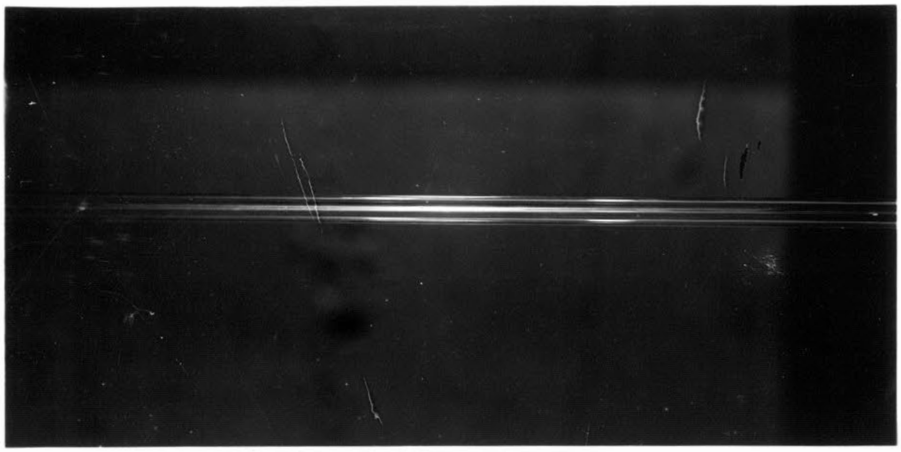
V RESULTS OF INVESTIGATION

A Description of Types of Flow

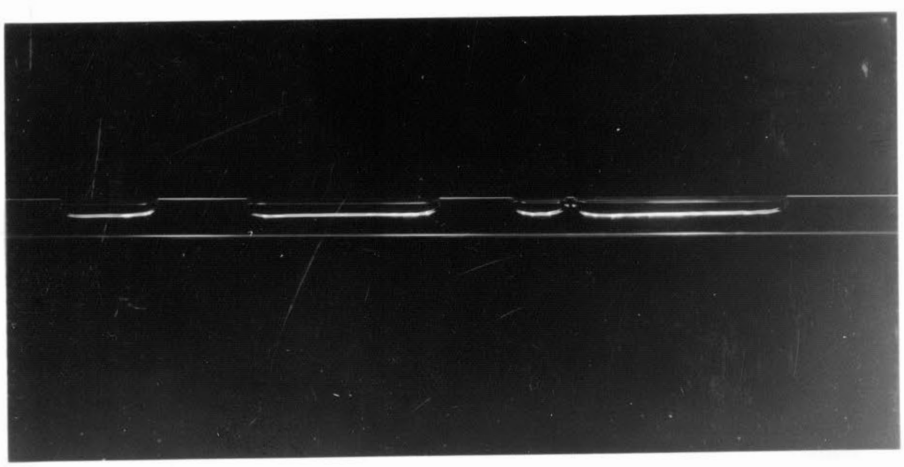
The authors agree with H. L. Reichart[2] in the number of types of flow to be encountered in two-phase flow. The types are separate flow, bubbling, slugging, and washing out. Pictures of these various types of flow may be seen in the following pages.

1 SEPARATE FLOW

Separate flow may be defined as that flow where the fluids pass through the tube in two distinct layers. In order to have this type, it is necessary to have a low enough water velocity so that the height of the water in the tube is small relative to the diameter of the tube.



Separate Flow



Bubbling

2 BUBBLING

Starting at a low air velocity, a change in type of flow can be brought about by increasing the water velocity. When the two phases are moving in separate flow, there is a small but noticeable wave-motion on the surface of the water. This wave-motion has no effect on the type of flow while the cross-sectional area of the tube occupied by the water is small. But as this cross-sectional water area increases, the crests of the waves come closer to the top of the tube. When the waves touch the top of the tube, the surface tension tends to hold them up there and the air is entrapped as a bubble.

Bubbling also occurs when the tube is completely filled with water. In this case there is no possibility of wave formation. The air has to have sufficient pressure to force itself out into the water; this pressure being much higher than that required for the other type of bubbling. The air flows into the water in spurts and at quite regular intervals.

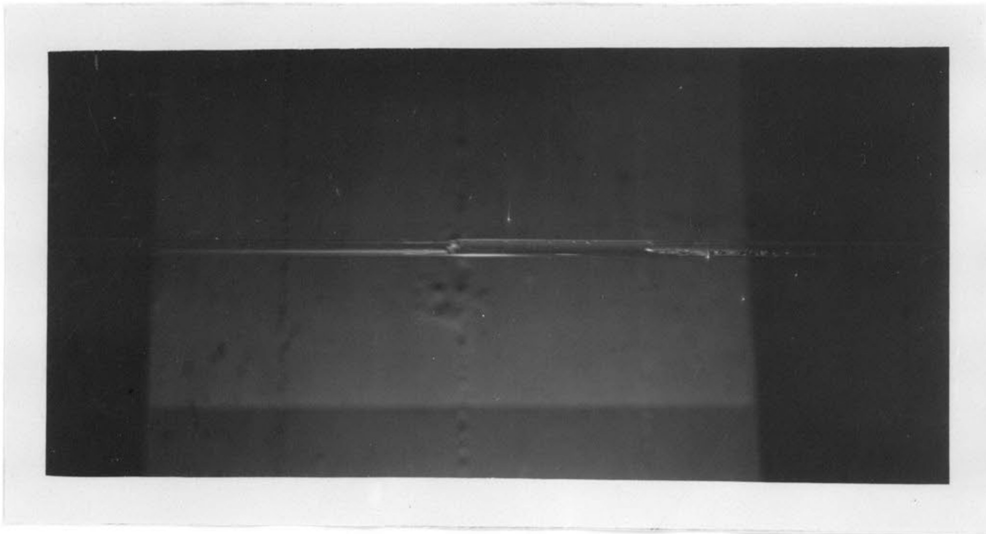
In both types of bubbling, the air appears to be carried along by the water at the velocity of the latter.

3 SLUGGING

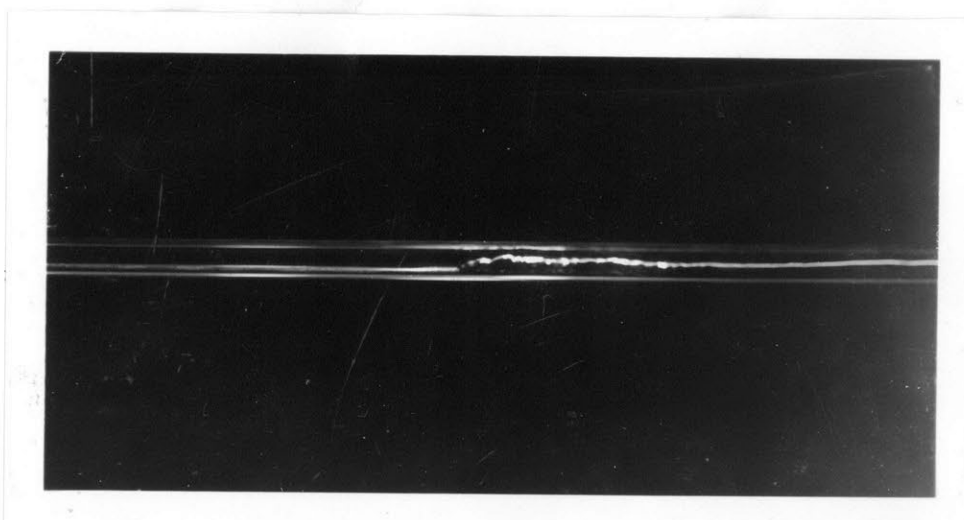
As the air velocity is increased relative to the water velocity, a point is reached where, instead of the air being carried along by the water in the form of bubbles, the water is carried along by the air in the form of slugs of from a few inches to a few feet in length. Assuming a condition of separate flow, an increase in air velocity creates a wave motion on the surface of the water. Periodically, a wave is set up, having an amplitude slightly greater than the other waves. The tendency then is for this wave to continue to increase in amplitude. This is probably due to two effects; first, the increased surface exposed to the air, and second, the increased linear velocity of the air between the top of the wave and the tube. Finally, the wave touches the top of the tube and a slug is formed. Slugging occurs only when the air has a much higher linear velocity than the water. When the wave reaches the top of the tube, the air is slowed down very appreciably. This builds up the pressure of the air, which pushes the air down to the bottom of the tube, forcing the water ahead of it. The increased pressure behind the wall of water tends to force the water along at an increasing speed. The slugs, therefore, increase in speed as they progress along the tube, while bubbles move along at a relatively constant speed.

A slug has an almost perpendicular front, which is particularly noticeable in the 50 mm. tube. There is a fairly turbulent area at the bottom of the face of the slug. This is probably due to the fast-moving water in the slug coming in contact with the comparatively slowly-moving water which has been left in the bottom of the tube by the preceding slug. The other end of the slug tends to slope off smoothly to the rear. This slope shows that the slug loses water as it moves along. This loss of water is due in part to the inertia of the slow-moving water in the bottom of the tube and also in part to the friction between this water and the faster-moving slug. Some of the slugs increased in length as they moved along the tube, others decreased, and still others maintained almost a constant length. When a slug washes out in the tube, a slug following close behind, invariably increases in length, because of the large quantity of water left in the tube as a result of the washing-out. However, if the slug follows at a considerable distance, most of the water left by the washing-out has a chance to flow out of the tube and the slug does not gain appreciably in length. The slug remains of constant length, only when two slugs of approximately the same length occur close together. In this case, it is the length of the second slug which stays almost constant. There is no probable explanation of this at the present time. Slugs decrease in length when the interval between them is considerable. Whenever this is true, any "slip" or wash from the slugs has an opportunity to flow out of the tube before the next slug is formed. This latter slug has hardly any water to pick up, while it is losing a fair amount of water from the rear.

In the slugging region, at any given air velocity, no slugs are formed until the water reaches a definite height in the tube. Below this height, the waves set up on the surface of the water, never attain a large enough amplitude to touch the top of the tube. After a slug has passed out of the tube, taking most of the water with it, it is often a matter of seconds before another slug is formed. This question of the height, of the water in the tube is one of great importance in the formation of slugs. It seems quite possible that the whole matter depends in some way upon the relative percentages of the cross-sectional area of the tube occuppied by the air and the water.



Slugging



Washing Out

4 WASHING-OUT

Given the condition of slugging, an increase in either air or water velocity, causes the slugs to break down into a type of flow called washing-out. There are several reasons for this breaking down. In order to have washing out, the slugs which are formed must be short. In the case of an increased air velocity, the tendency is for the air pressure to speed up the slug. But at the base of the slug the inertia and the friction of the slow-moving bottom-layer tends to hold the slug back. The top of the slug is moving faster than the bottom. The water at the front top of the slug falls to the bottom of the tube, the top of the slug becomes shorter, until finally it breaks down and washes out. This is exactly what appears to be the case in the tube. The slug appears to lose water both in the front and in the rear and finally to break down.

In the case where the air is held constant and the water velocity is increased, the slugs are very short and very close together. The water velocity is so high, that when a slug is formed, it passes out of the tube so fast that very little water is left behind. The next slug has no water to pick up to replace the water it has lost and therefore it washes out. This appears to be what happens in the tube. A slug which does not wash out and one that washes out seem to come in regular succession.

B Discussion of Experimental Data

1 Introduction

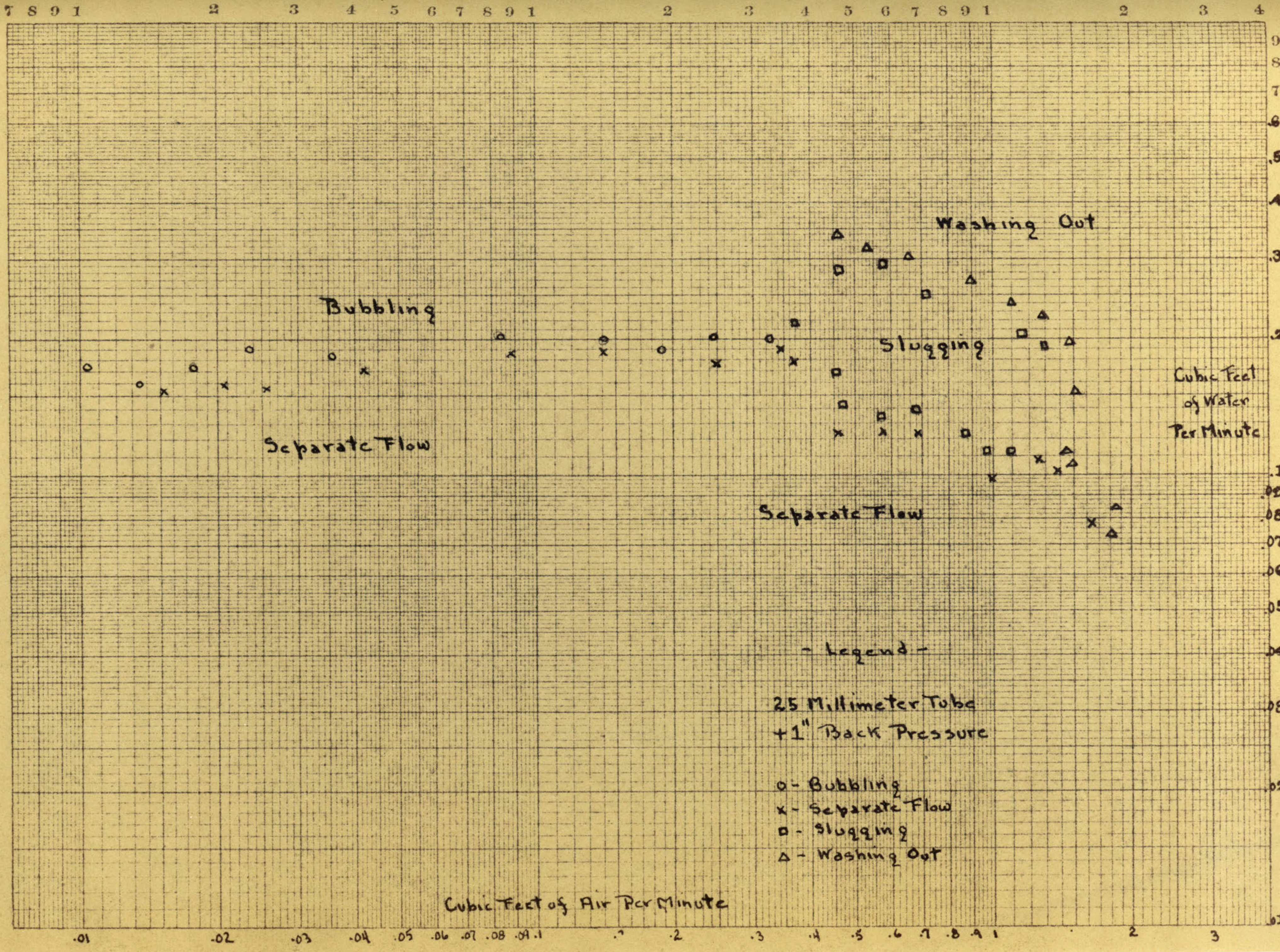
Reichart, in his thesis, has represented the boundaries between the different types of flow as curves. The inaccuracy of the experimental work and the type of apparatus used does not seem to justify this. In the graphs which follow the boundaries are represented as regions of indeterminate type of flow, separating quite definitely known types. It was found very difficult to distinguish between the types of flow within these regions.

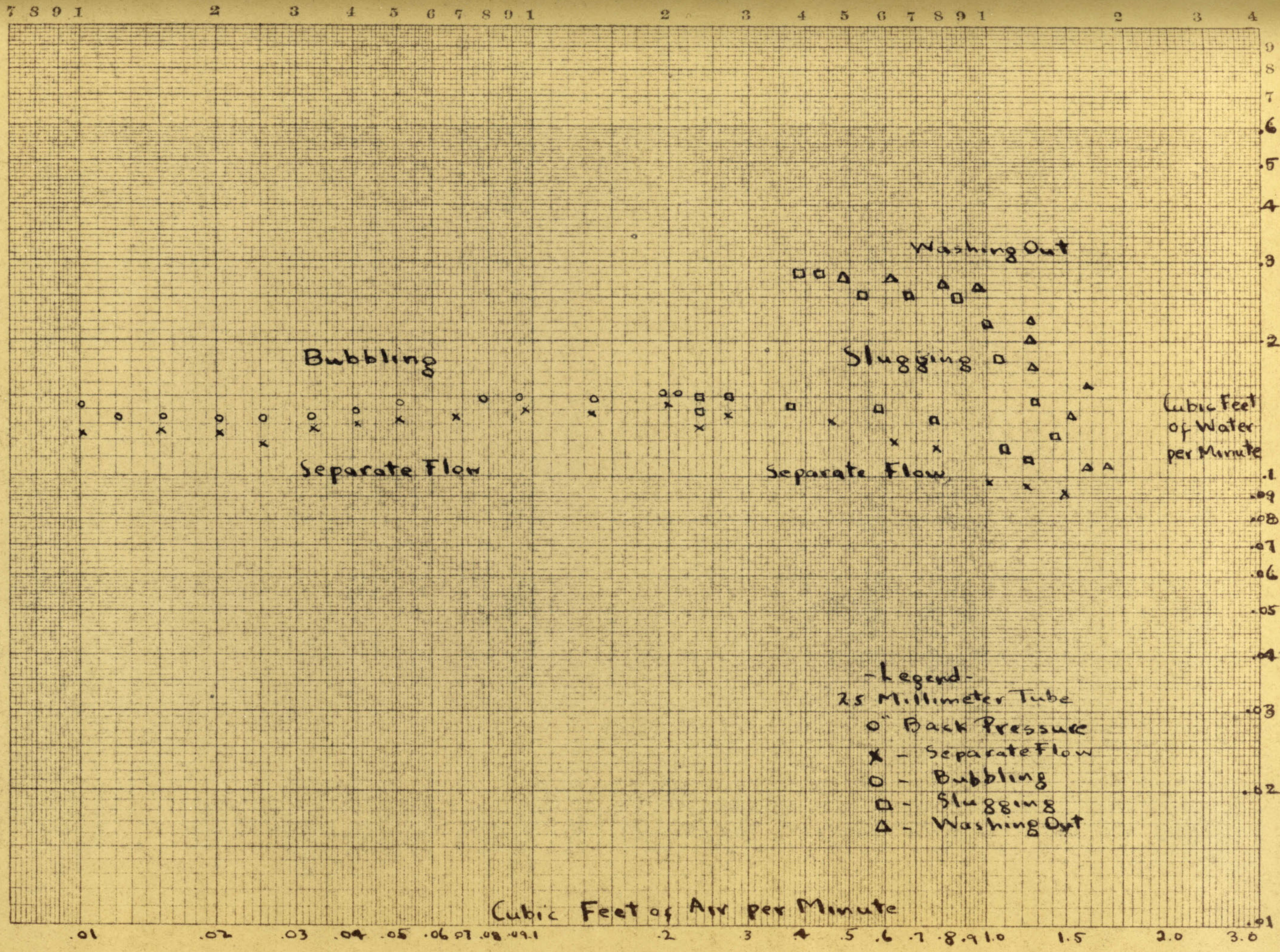
1" back pressure signifies a level of water in the back pressure can 1" above the level of the water in the observation tube. 0" back pressure denotes the same level of water in both the can and the tube. -1" back pressure is a water level in the can 1" below the level of the water in the observation tube.

2 25 Millimeter Tube

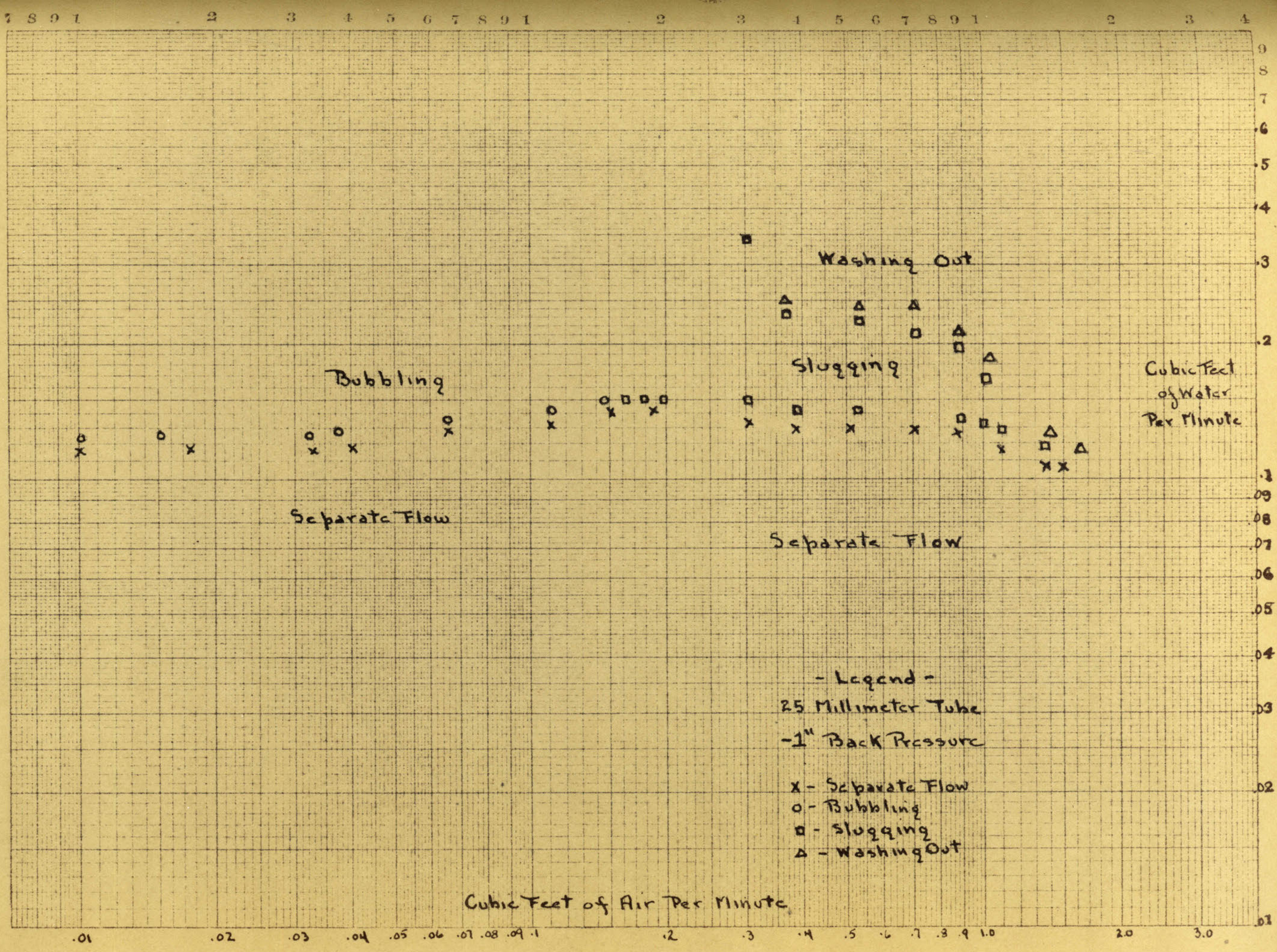
By inspection of the curves for this size tube, it can be seen that bubbling sets in at a progressively lower water velocity as the back pressure decreases. This is hard to explain. At any given water velocity, increasing the back pressure increases the height of water in the tube. It seems likely that the waves set up by the water flowing in the tube would have more chance of touching the top of the tube at high back pressure than at low. Therefore, lower water velocity would be expected to cause bubbling at some air velocity when the back pressure is increased.

As the air velocity increases, a transition zone between separate flow—bubbling and separate flow—slugging is reached. The exact transition point could not be determined because of the close resemblance between slugging and bubbling in this region. Reichart states that slugging can be obtained from bubbling in this region by decreasing the water. No experimental evidence of this has been found. This transition region occurs at a lower air velocity as the back pressure is decreased. As explained above for the case of bubbling, this seems paradoxical. As the air


Washing Out
Bubbling
Slugging
Separate Flow
Separate Flow
Cubic Feet of Water Per Minute
- Legend -
25 Millimeter Tube
+1" Back Pressure
o - Bubbling
x - Separate Flow
□ - Slugging
Δ - Washing Out
Cubic Feet of Air Per Minute



Washing Out
Bubbling
Slugging
Separate Flow
Separate Flow
Cubic Feet of Water per Minute
-Legend-
25 Millimeter Tube
0" Back Pressure
X - Separate Flow
O - Bubbling
□ - Slugging
Δ - Washing Out
Cubic Feet of Air per Minute
.01
.02
.03
.04
.05
.06
.07
.08
.09
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
1.5
2.0
3.0
.6
.5
.4
.3
.2
.1
.09
.08
.07
.06
.05
.04
.03
.02
.01



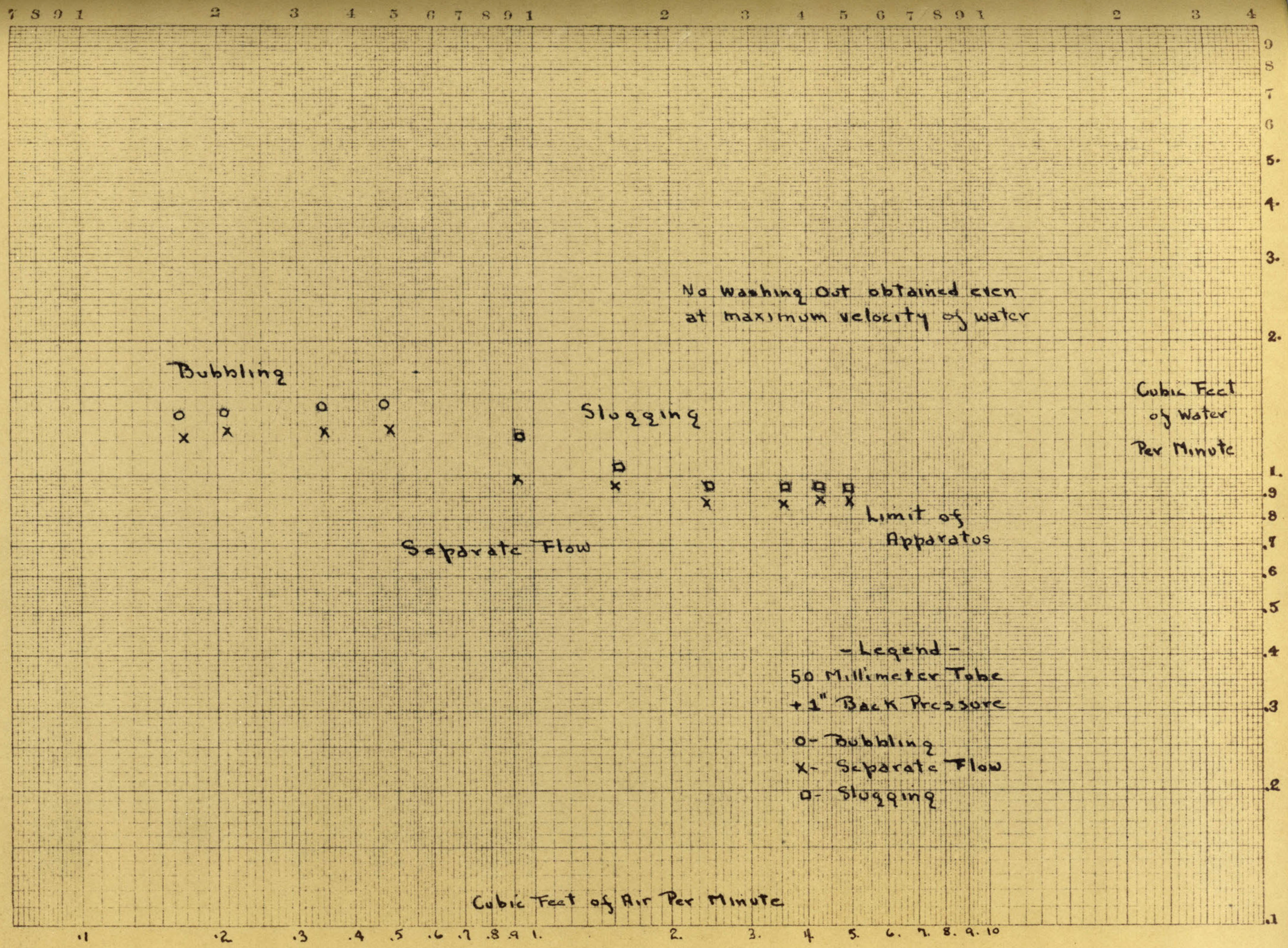
Washing Out
Slugging
Bubbling
Separate Flow
Separate Flow
Cubic Feet of Water Per Minute
Cubic Feet of Air Per Minute
- Legend -
25 Millimeter Tube
-1" Back Pressure
x - Separate Flow
o - Bubbling
□ - Slugging
Δ - Washing Out
.01
.02
.03
.04
.05
.06
.07
.08
.09
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
2.0
3.0
.3
.2
.1
.09
.08
.07
.06
.05
.04
.03
.02
.01

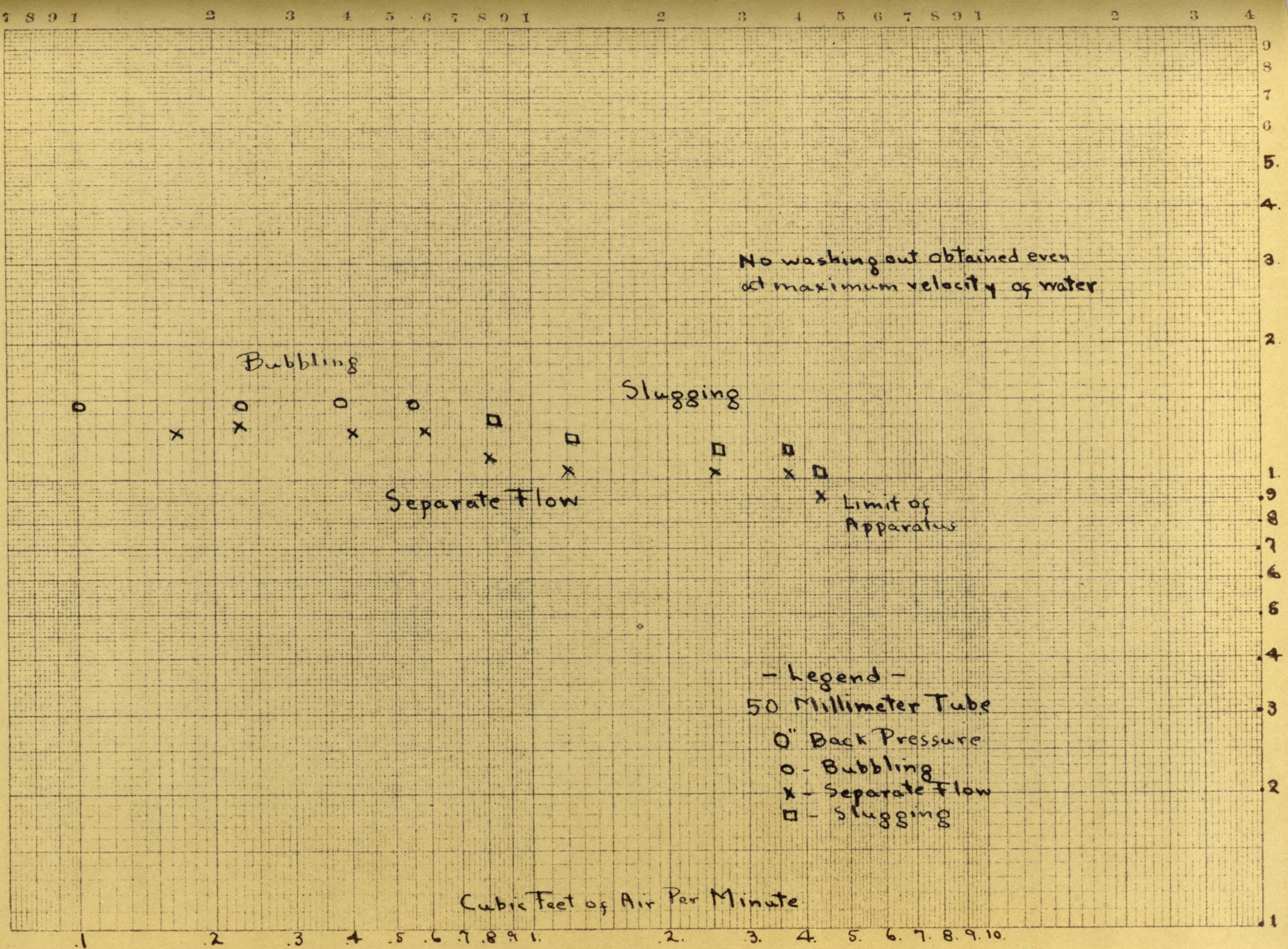
velocity is increased, slugging takes place at a lower water velocity. By keeping the air velocity constant and increasing the water velocity, washing out is obtained. The back pressure has little effect on the water velocity at which slugging occurs, when the air velocity is increased. Washing out occurs at a lower water velocity as the back pressure is decreased. No satisfactory explanation can be offered for either of these facts.

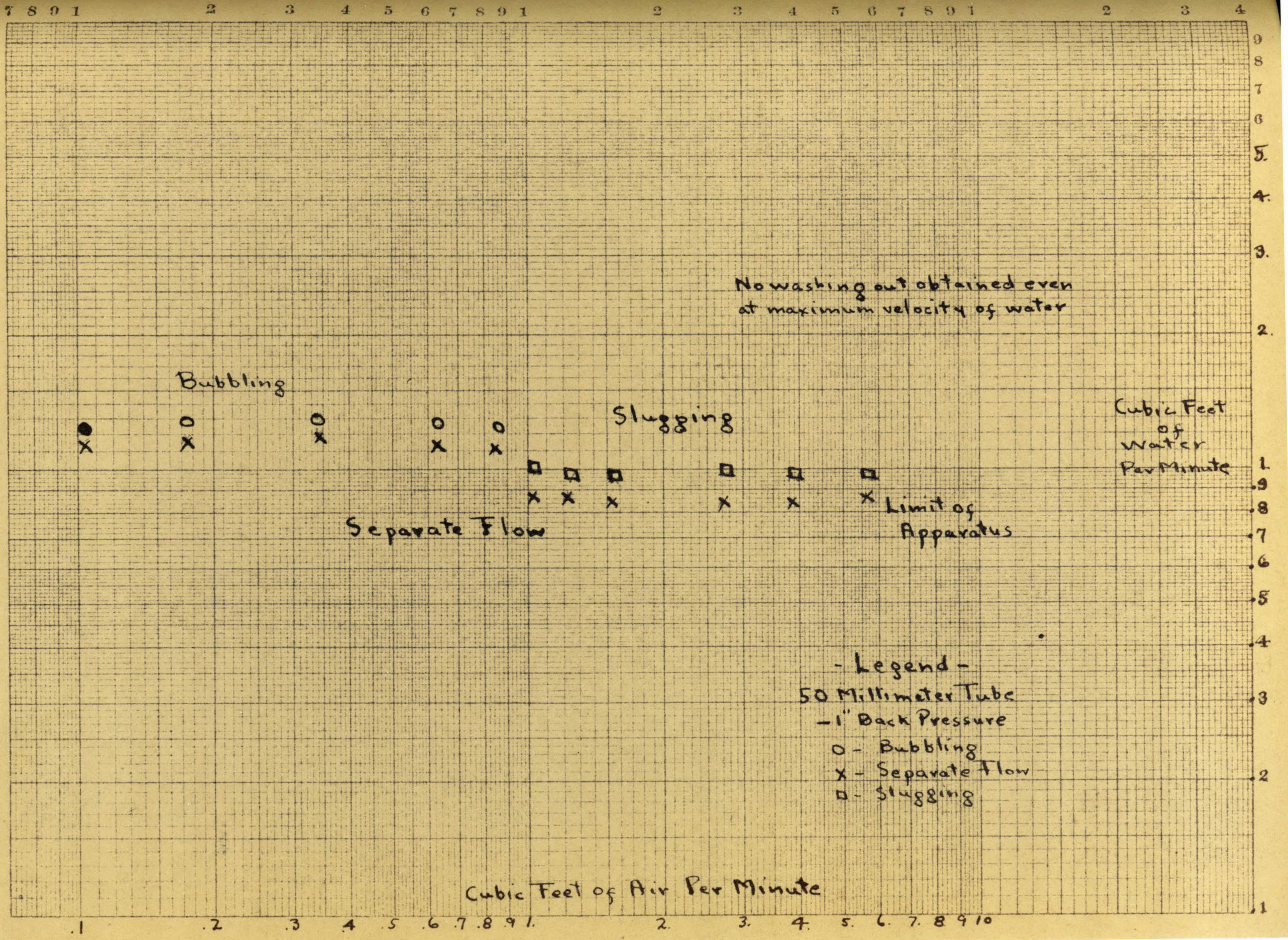
Reichart has his boundaries between washing out and slugging, and slugging and separate flow, come together at a quite definite point. The best that can be obtained in this investigation is a region in which the three types of flow appear to occur indiscriminately. At air velocities higher than this region, and regardless of the water velocity, the tube was filled with spray. None of the types of flow mentioned above can be distinguished beyond this point.

3 50 Millimeter Tube

This part of the investigation is not as complete as that for the 25 millimeter tube, because of the impossibility of obtaining with the apparatus available, a sufficiently great air or water velocity. As much of the regions as could be determined, follow the same general outline as those for the 25 millimeter tube, the only difference being that the air and water velocities are on a different scale. In this tube the slugs are very long, some of them being six feet in length. After one of these had passed out of the tube, it took a considerable length of time before the water rose high enough in the tube to form another slug. It was particularly difficult in this tube to distinguish between bubbling and slugging at the critical region.

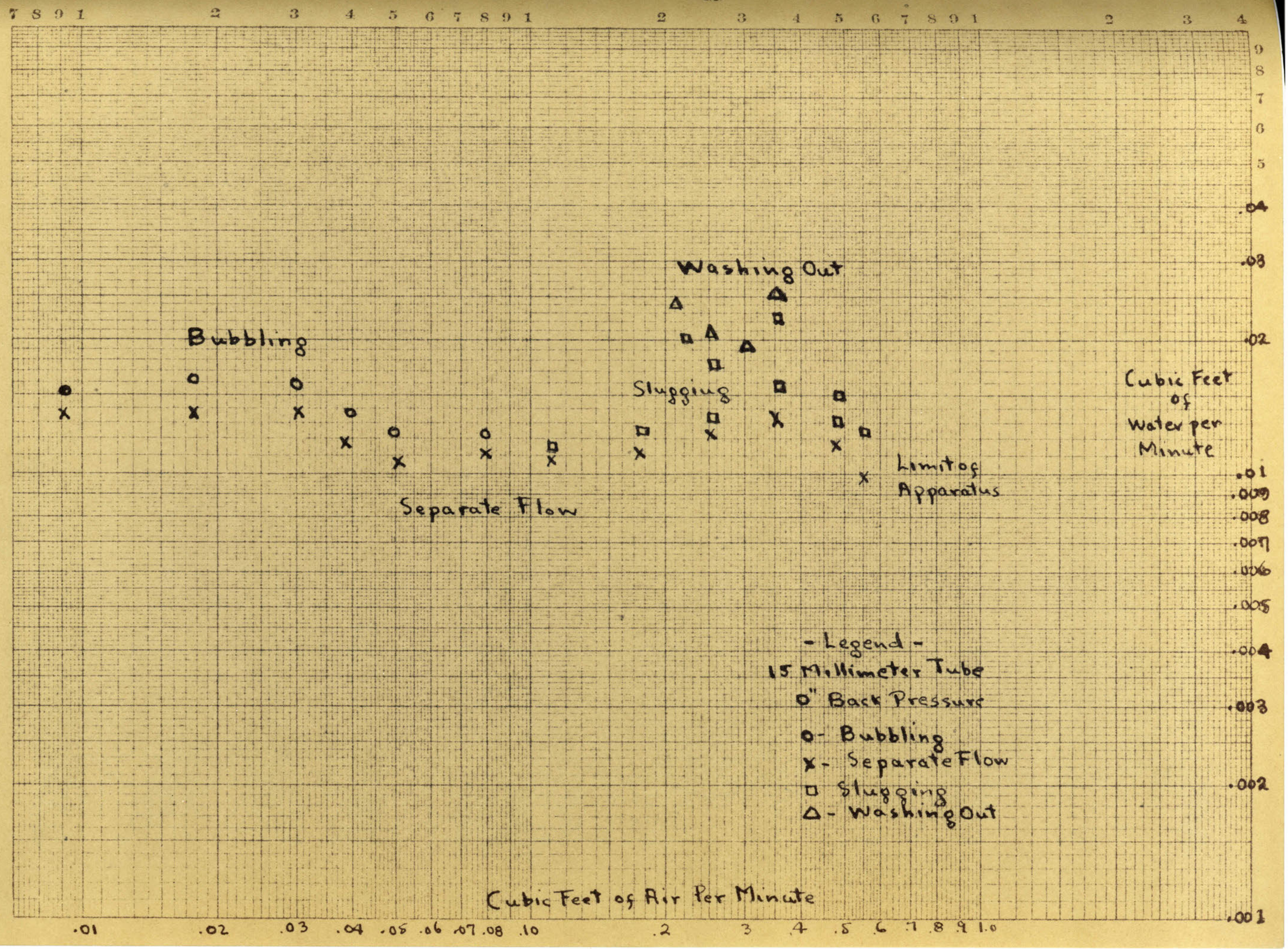

No washing out obtained even at maximum velocity of water
Bubbling
Slugging
Separate Flow
Limit of Apparatus
Cubic Feet of Water Per Minute
Cubic Feet of Air Per Minute
- Legend -
50 Millimeter Tube
+ 1" Back Pressure
o - Bubbling
x - Separate Flow
□ - Slugging


No washing out obtained even
at maximum velocity of water
Bubbling
Slugging
Separate Flow
Limit of
Apparatus
- Legend -
50 Millimeter Tube
0" Back Pressure
o - Bubbling
x - Separate Flow
□ - Slugging
Cubic Feet of Air Per Minute
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.
2.
3.
4.
5.
6.
7.
8.
9.
10.


No washing out obtained even at maximum velocity of water
Bubbling
Slugging
Cubic Feet of Water Per Minute
Separate Flow
Limit of Apparatus
- Legend -
50 Millimeter Tube
-1" Back Pressure
o - Bubbling
x - Separate Flow
□ - Slugging
Cubic Feet of Air Per Minute
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.
2.
3.
4.
5.
6.
7.
8
9
10

4 15 Millimeter Tube

Owing to lack of time, this tube was only investigated at 0" back pressure. In this tube, because of the sensitivity of the air blower to back pressure, it was impossible to attain an air velocity high enough to obtain all the regions found in the 25 millimeter tube. The graph shows that the general outline is much different from either of the other two tubes. The boundary between bubbling and separate flow has an abrupt drop in it which does not occur in that of the 25 or 50 millimeter tubes. The boundary between slugging and separate flow, instead of sloping downward to the right with an increase of air velocity as in the case of the other tubes, has a definite upward slope for a time and then a downward slope. The boundary between slugging and washing out slopes upward to the right instead of down. The explanation of this probably lies in the fact that the tube is so small that surface tension and friction have a greater relative affect on the mechanism of the flow and hence distort the results.

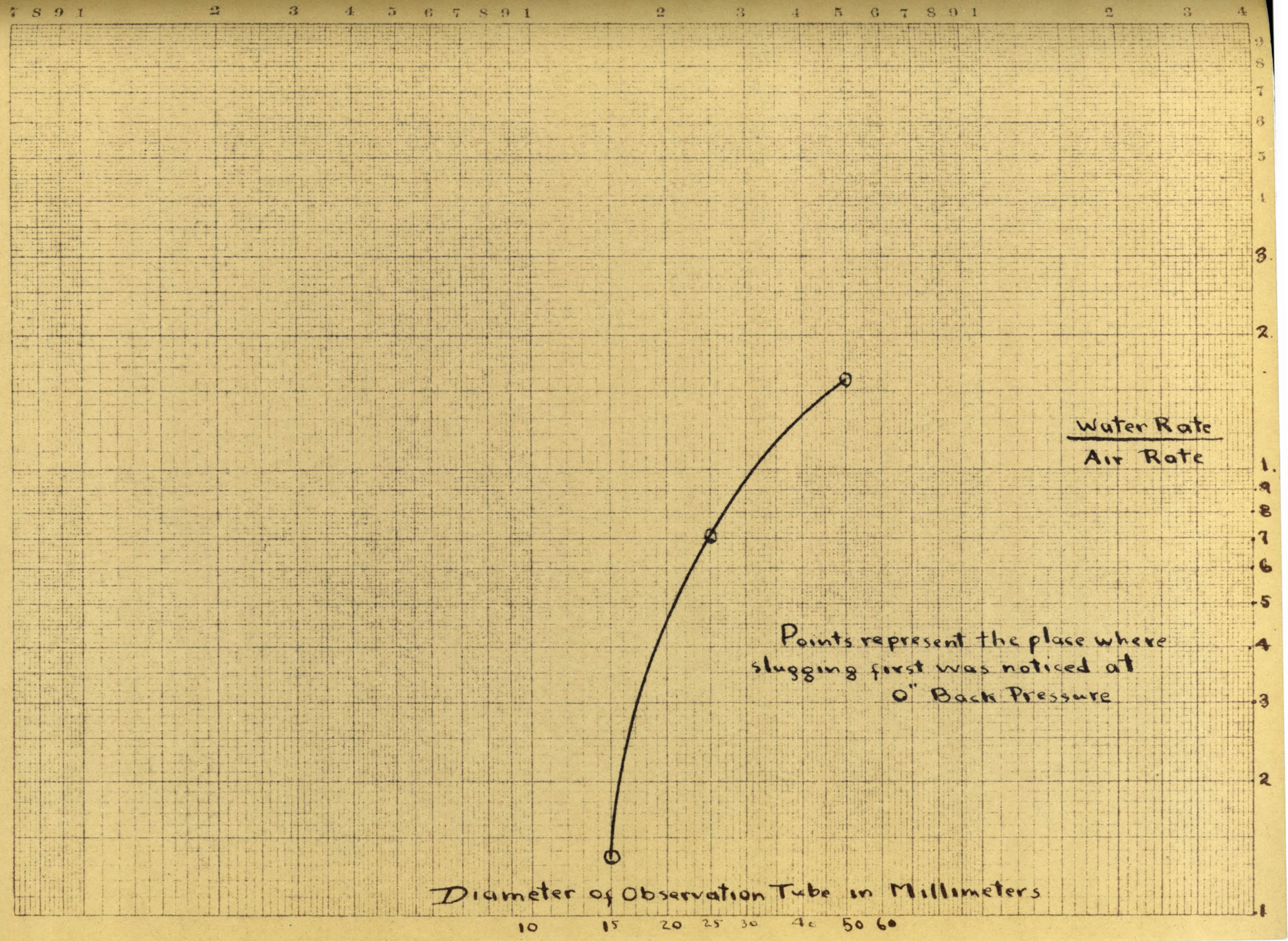


Washing Out
Bubbling
Slugging
Cubic Feet of Water per Minute
Limit of Apparatus
Separate Flow
- Legend -
15 Millimeter Tube
0" Back Pressure
o - Bubbling
x - Separate Flow
□ Slugging
Δ - Washing Out
Cubic Feet of Air Per Minute
.01
.02
.03
.04
.05
.06
.07
.08
.10
.2
.3
.4
.5
.6
.7
.8
.9
1.0
.04
.03
.02
.01
.009
.008
.007
.006
.005
.004
.003
.002
.001

VI CORRELATION OF RESULTS

Although a satisfactory amount of data was not obtained on the 50 and 15 millimeter tubes, it was felt that some attempt should be made to correlate the data in order to determine the effect of diameter on the critical regions. In looking over the graphs, the only point which could be used for this correlation was that where slugging first occurred at 0" back pressure. Plotting the ratio of the water rate in cubic feet per minute to the air rate in cubic feet per minute at this point against the diameter of the tube in millimeters, gives the curve shown on the next page. It is evident that the curve slopes upward to the right, and that at small diameters this ratio decreases rapidly. This curve seems to bear out the contention that slugging depends on the height of the water in the tube, because in small diameter tubes, a small water rate relative to the air rate is required to form slugs.

As the diameter of the tube is increased a much larger water velocity relative to the air velocity will be required to attain a water level high enough for slugging to occur.


Water Rate / Air Rate
Points represent the place where slugging first was noticed at 0" Back Pressure
Diameter of Observation Tube in Millimeters
10
15
20
25
30
40
50
60
1.
.9
.8
.7
.6
.5
.4
.3
.2
.1
2.
3.

VII—RECOMMENDATIONS FOR FUTURE WORK

The various types of two-phase flow seem to be definitely established. Sufficient work appears to have been done on the 25 millimeter tube. However, an attempt should be made to investigate the 50 mm. and 15 mm. tubes still further. Apparatus should be obtained capable of reaching the higher air and water velocities required. An air compressor is necessary to get a sufficient flow of air. In order to complete the investigation, another liquid, such as fuel oil, and another gas, such as carbon dioxide should be used. Pressure drops along the pipe should also be obtained. But future investigators should limit themselves to only one of the above phases, in order to obtain complete and accurate information.

It is believed that the most important factor in the determination of the critical regions of flow is the relative area of cross section of the tube occupied by the water and air. An attempt was made to determine these in order to relate them to the velocities of air and water, but no applicable results could be obtained. because of the magnitude of the experimental difficulty. It is suggested that some method of obtaining this cross sectional area or height of water in the tube be devised before going on further with the investigation.

A P P E N D I X

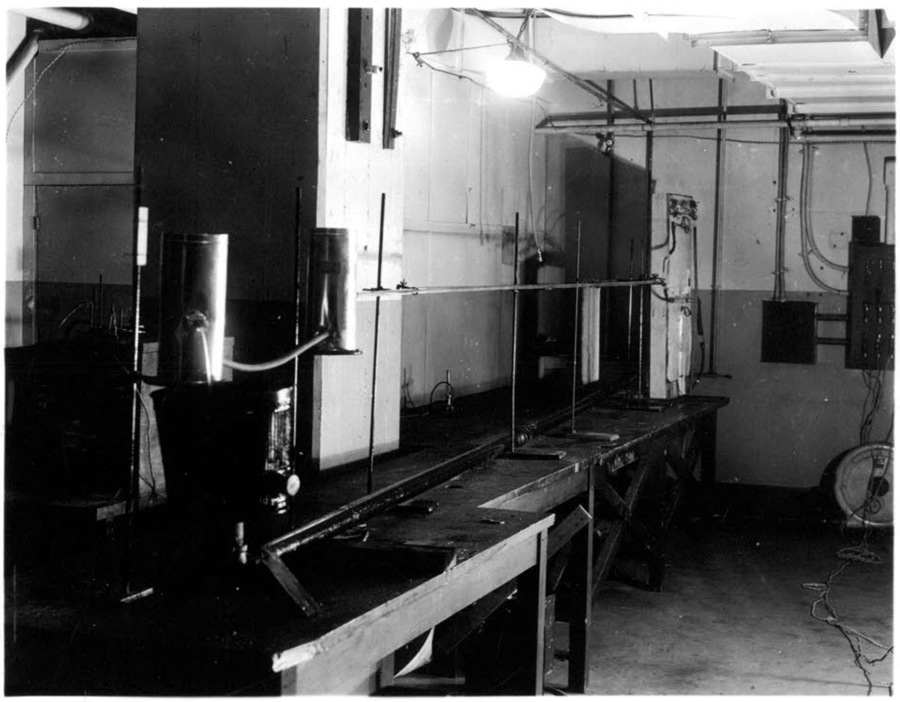
APPENDIX I

DETAILS OF EXPERIMENTAL APPARATUS

The apparatus used in the experimental work is shown as in the photograph following this page.

The photograph shows an observation tube which is made up of three five-foot lengths of 15 mm. glass tubing. The 25 mm. and 50 mm. tubes were made in the same manner. Reichart suggested in his thesis that a tube originally fifteen feet long, be obtained. The authors, finding that it would be necessary to order such a tube direct from the factory and that once ordered, the tube might take too long to arrive to be of any use, were forced to resort to using five-foot lengths. The tube was held up by clamps which were attached to ring stands. By lowering or raising the clamps on the stands it was possible to adjust the tube so that it was as horizontal as possible. It was impossible to have it perfectly horizontal because of the uneveness of the glass tubing itself.

The water was supplied directly from the tap which was also used for regulating the flow. After leaving the tap, the water was passed through a capillary to determine its velocity and thence to



The Complete Apparatus

the observation tube. Enough water was obtained in this way for both the 25 mm. and the 15 mm. tubes. When the 50 mm. tube was used, however, it was necessary to attach another pipe to the water main in order to attain a water velocity high enough to fill the glass tube. Even this extra water was insufficient to obtain all the types of flow encountered in the other two tubes. All experimental data had to be taken in the evening because of the large fluctuations of water pressure noticed during the day.

A centrifugal blower was used to supply the air to the tube. The 2" outlet pipe of the blower was reduced to 1/2" and thence by means of 1/2" rubber tubing the air was passed through one of three capillaries connected in parallel to determine its velocity. From these meters the air went to the tube proper. The air blower was so sensitive to back pressure that it was impossible to attain a high enough velocity in the 50 mm. and the 15 mm. tubes to obtain all the types of flow.

In order to have the air and water enter the fifteen-foot tube in parallel, it was found desirable to modify Reichart's method by having a special piece of apparatus made. As may be seen from the enclosed photograph, this consisted of a length of tube having the same diameter as the observation tube used, with a smaller glass tube within it. This smaller glass tube was attached so that it would be parallel to the larger tube for a short distance and so that it would enter the larger tube at an angle.

The air was brought into the observation tube from above while the water was allowed to enter from below to prevent any backflow of either.

The mixture of air and water was taken at the end of the tube by two receivers as shown in the photograph of the apparatus. The second receiver had a vertical adjustment, to maintain the water in the first at the desired level and, therefore, to regulate the back pressure. From this second tube the water ran into an overflow bucket and thence by means of pipe into the sink.

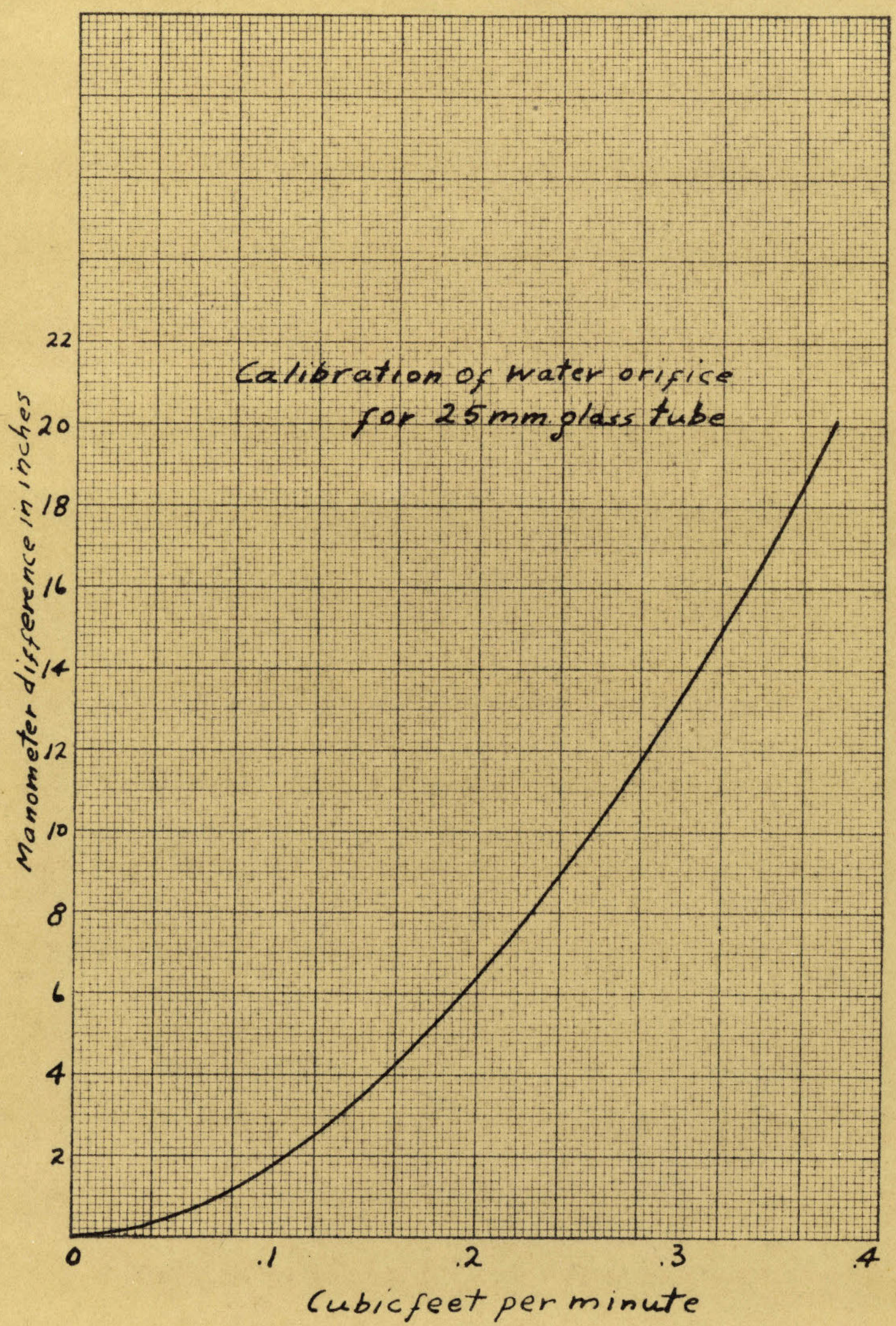
The Air and Water Meters

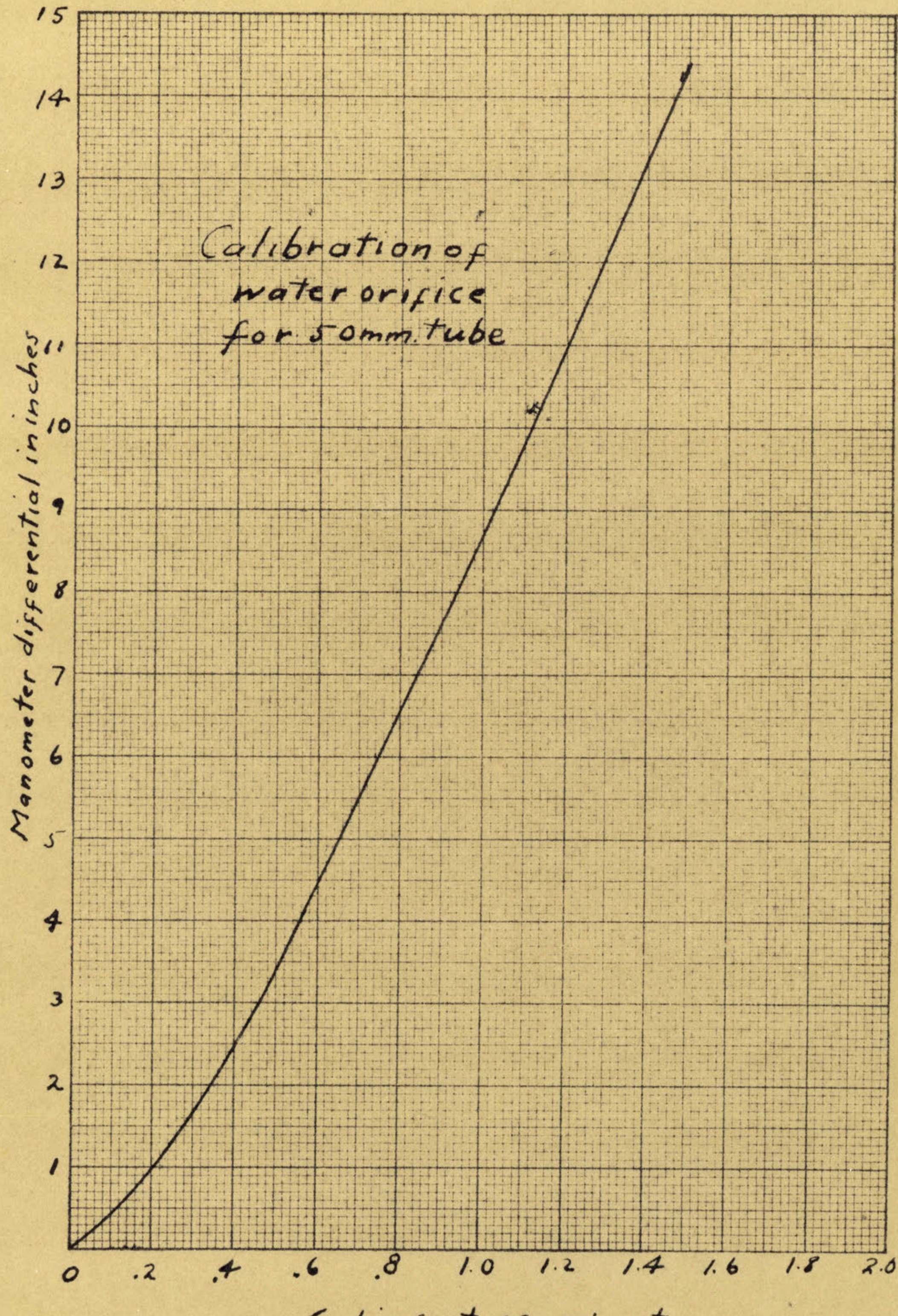
APPENDIX II

CALIBRATION OF INSTRUMENTS

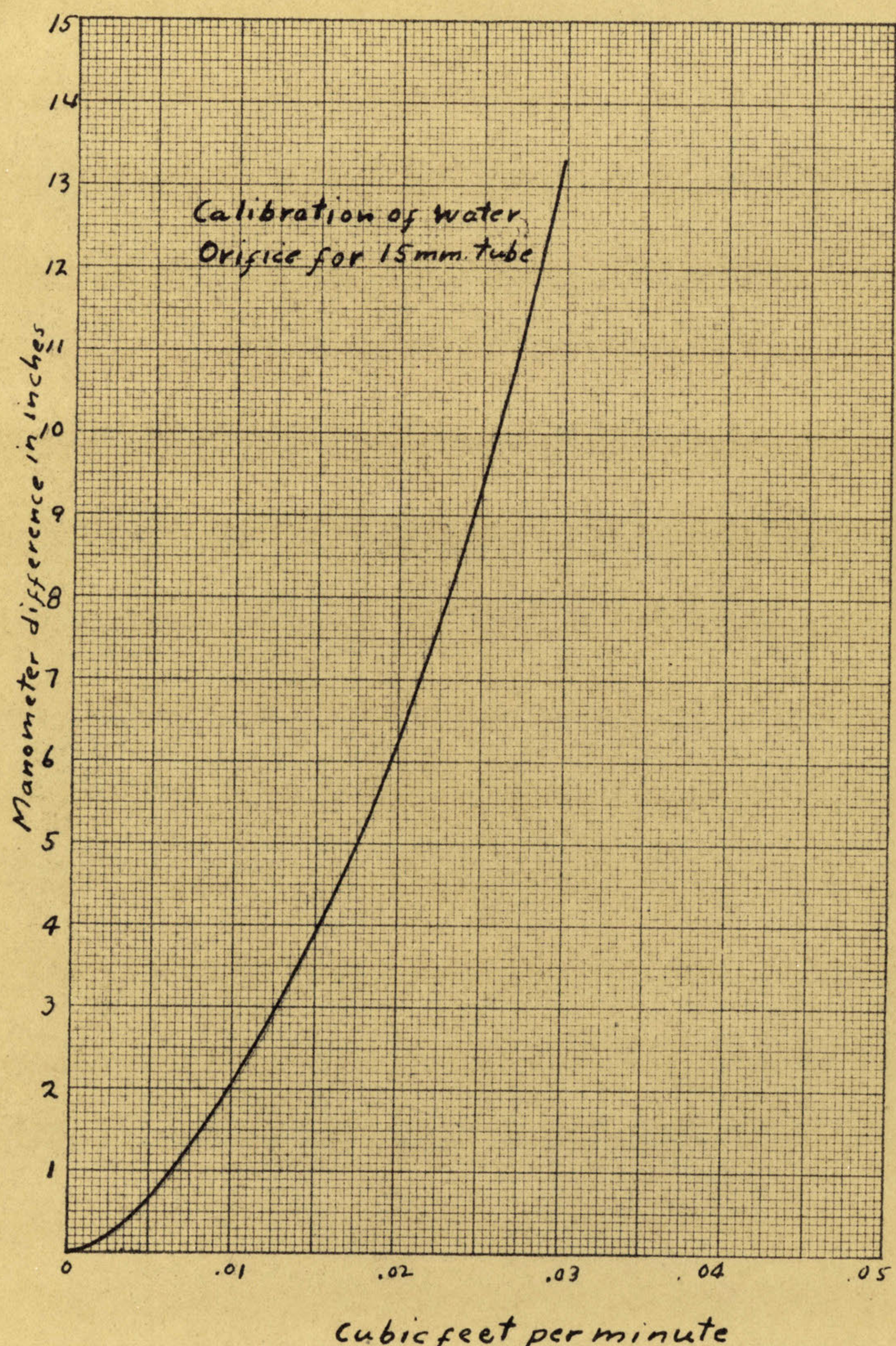
Water Meters

The water meters consisted of capillary tubes, inserted within tubes of larger diameter. They were calibrated by weighing the amount of water passing through for a certain time and noting the reading on the mercury manometer. The calibration curves follow.


Calibration of water orifice
for 25mm glass tube
Manometer difference in inches
22
20
18
16
14
12
10
8
6
4
2
0
.1
.2
.3
.4
Cubicfeet per minute



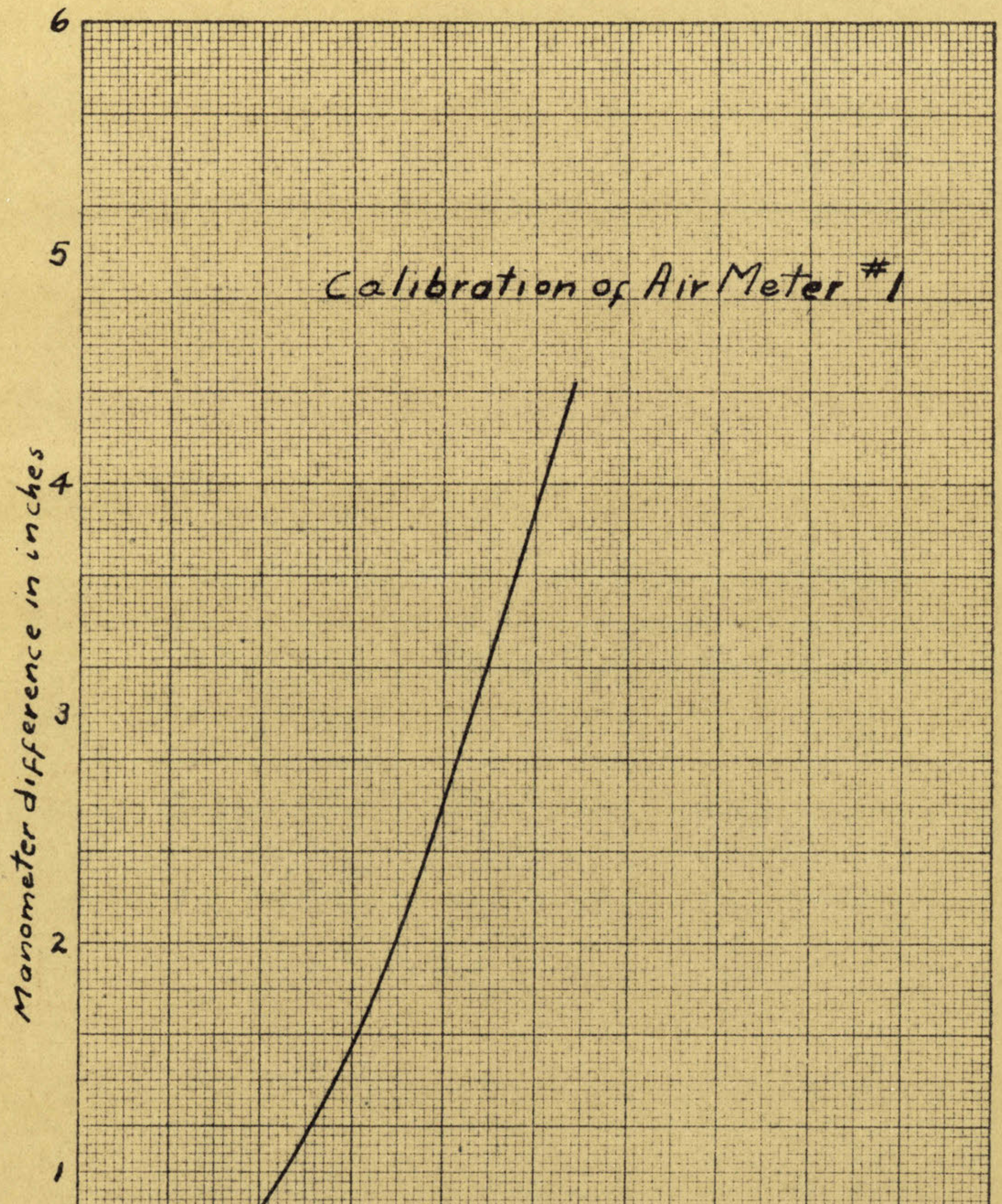
Calibration of
water orifice
for 5 omm. tube
Manometer differential in inches
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
0
.2
.4
.6
.8
1.0
1.2
1.4
1.6
1.8
2.0
Cubic feet per minute



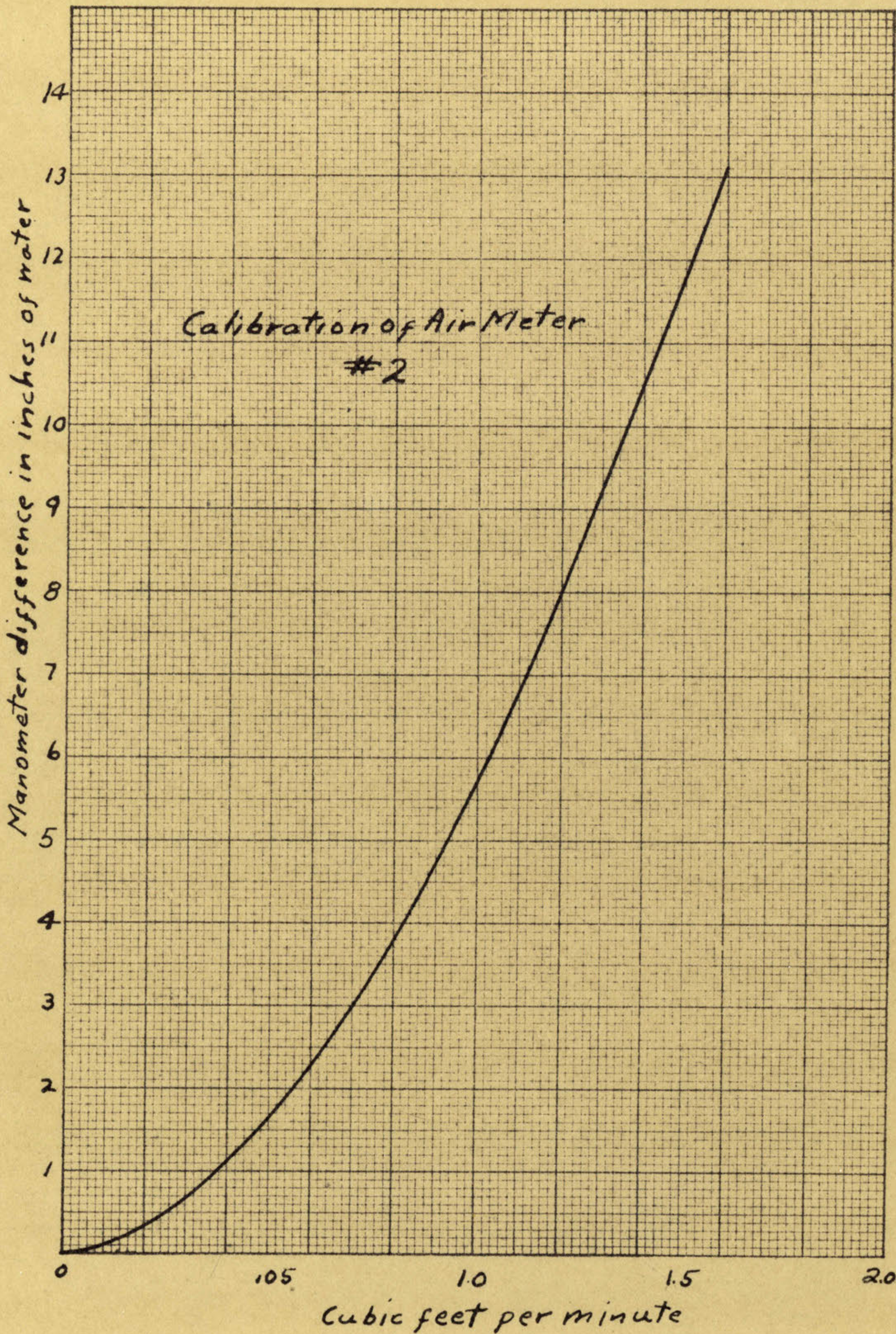
Calibration of water
Orifice for 15mm. tube
Manometer difference in inches
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
.01
.02
.03
.04
.05
Cubic feet per minute

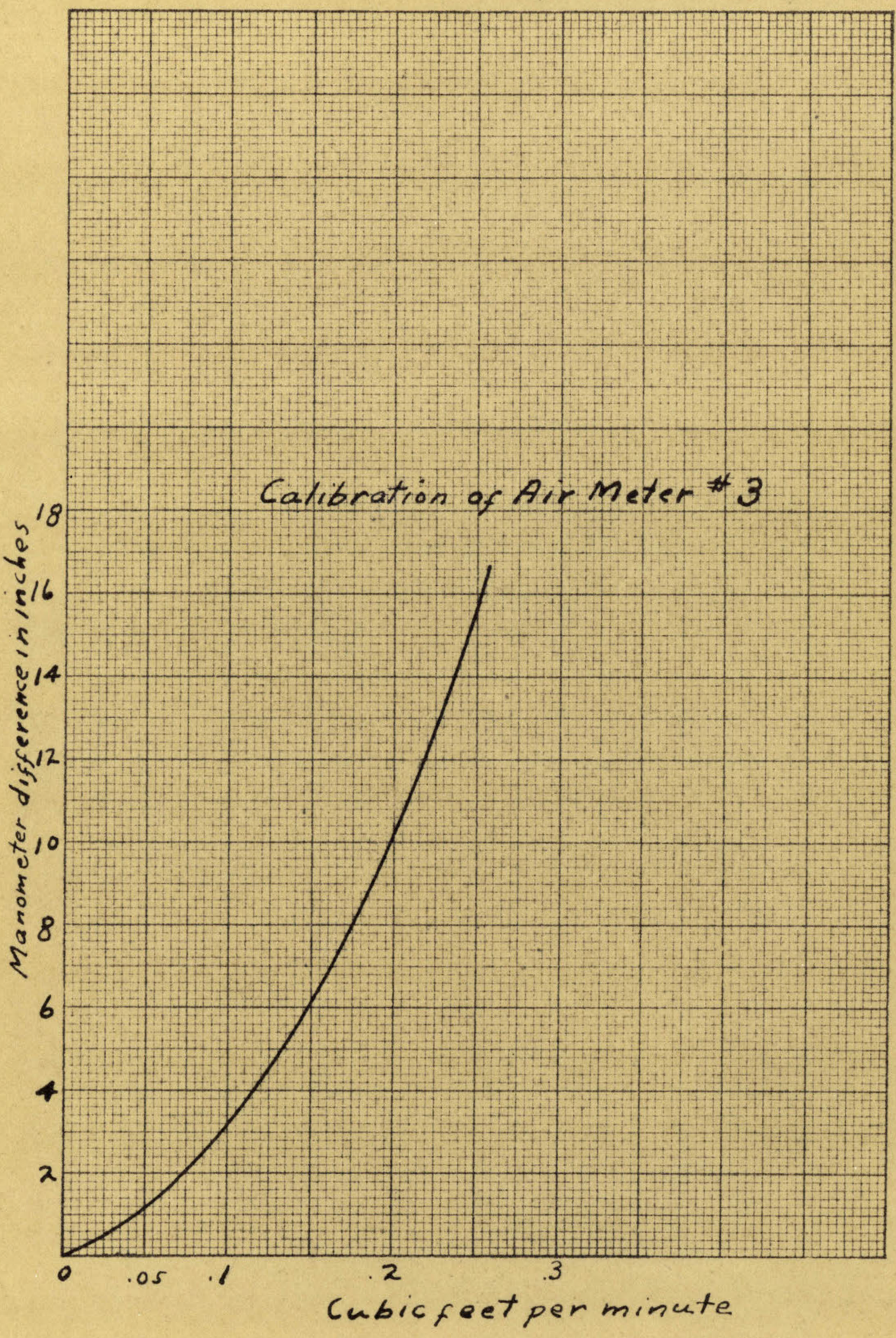
Air Meters

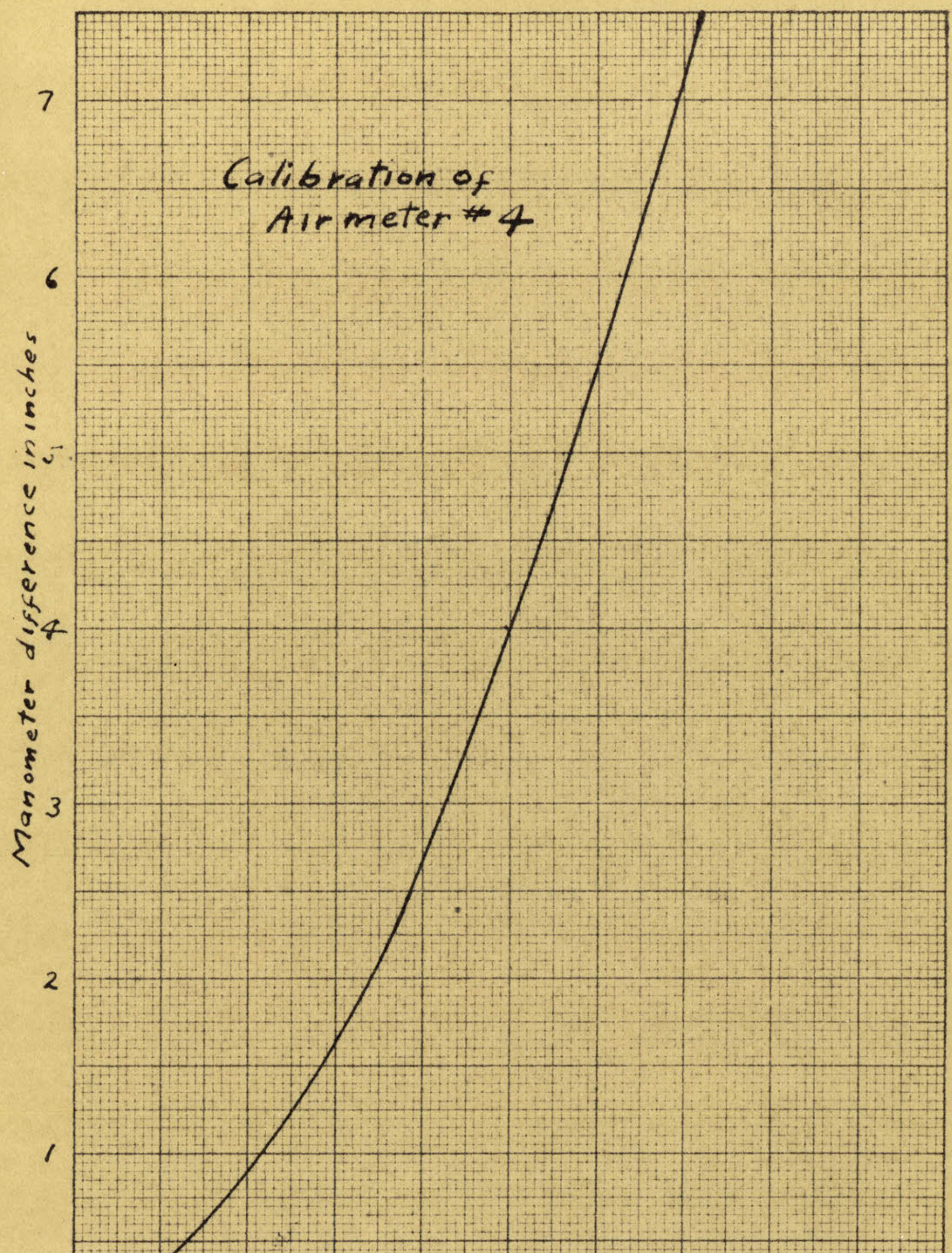
The air meters used were either of the Venturi or capillary type. The Venturi meter was used to measure the highest air velocities attainable with the apparatus on hand. All of these meters were calibrated by using wet_test gas meters. The capacity of the gas meters was soon exceeded, however, and it was necessary to use a calibrated orifice for higher velocities of air.



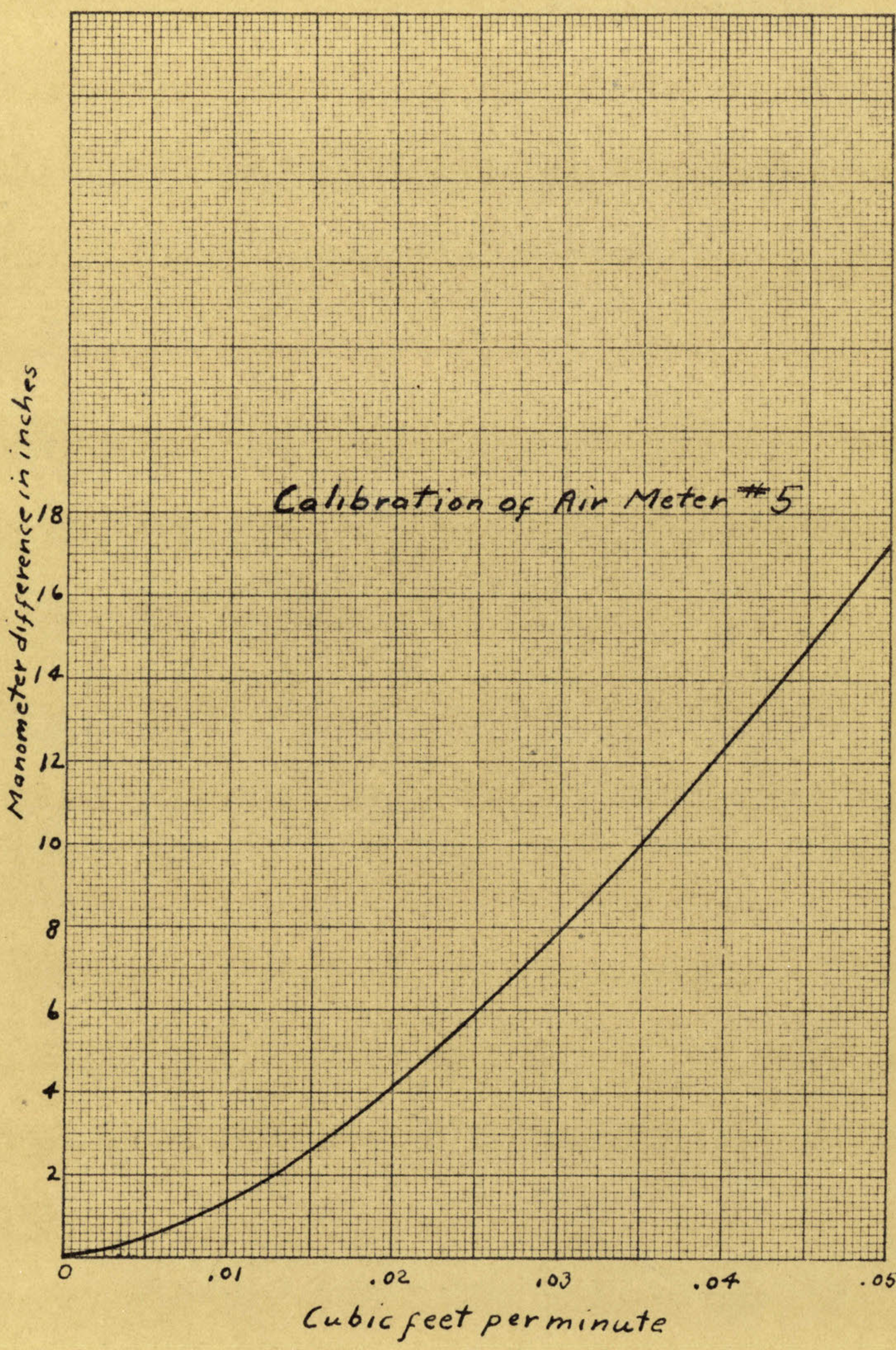
Calibration of Air Meter #1
Manometer difference in inches
Cubic feet per minute
0
1
2
3
4
5
6
7
8
9
10


Calibration of Air Meter #2
Manometer difference in inches of water
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
.05
1.0
1.5
2.0
Cubic feet per minute


Calibration of Air Meter # 3
Manometer difference in inches
18
16
14
12
10
8
6
4
2
0
.05
.1
.2
.3
Cubic feet per minute



Calibration of
Air meter #4
Manometer difference in inches
7
6
5
4
3
2
1
0
.1
.2
.3
.4
.5
.6
.7
.8
Cubic feet per minute



Calibration of Air Meter #5
Manometer difference in inches
18
16
14
12
10
8
6
4
2
0
.01
.02
.03
.04
.05
Cubic feet per minute

APPENDIX III

EXPERIMENTAL DATA

25 Millimeter Tube - 1" Back Pressure

Manometer Readings									Type of Flow
Water				Air					
High	Low	h	cu.ft. min.	Man.#	High	Low	h	cu.ft. min.	
8.6	4.5	4.1	.155	3	11.8	6.2	5.6	.142	Bubbling
9.4	3.8	6.3	.192	"	11.6	6.4	5.2	.137	"
10.0	3.1	6.9	.204	"	11.5	6.5	5.0	.135	"
10.2	2.9	7.3	.211	"	11.4	6.6	4.8	.132	"
10.85	2.35	8.5	.229	"	11.3	6.7	4.6	.127	"
7.3	5.9	1.4	.09	"	10.5	7.5	3.0	.100	Sep.Flow
7.6	5.4	2.2	.114	"	10.5	7.5	3.0	.100	" "
10.5	4.7	3.8	.15	"	10.4	7.6	2.8	.097	" "
10.7	2.5	8.2	.225	"	10.0	8.0	2.0	.079	Bubbling
9.5	3.6	5.9	.185	"	10.2	7.8	2.4	.087	Sep.Flow
10.0	3.1	6.9	.204	"	10.1	8.0	2.1	.081	Bubbling
7.95	5.25	2.7	.127	"	9.5	8.57	.93	.05	Sep.Flow
8.8	4.4	4.4	.16	"	9.4	8.65	.75	.043	" "
9.5	3.65	5.85	.183	"	9.3	8.8	.50	.034	Bubbling
8.25	4.9	3.35	.143	"	9.25	8.85	.40	.03	Sep.Flow
8.65	4.5	4.15	.156	"	9.2	8.9	.30	.025	" "
9.2	3.95	5.25	.175	"	9.15	8.95	.20	.017	Bubbling
8.7	4.5	4.2	.160	"	9.17	8.91	.26	.02	Sep.Flow
9.1	4.0	5.1	.172	"	9.1	9.0	.10	.01	Bubbling
8.8	4.4	4.4	.16	"	9.12	8.98	.14	.013	"
8.65	4.5	4.15	.156	"	9.15	8.96	.19	.015	Sep.Flow

Water					Air				Type of Flow
High	Low	h	cu.ft. min.	Man.# Man	High	Low	h	cu.ft. min.	
9.05	4.1	4.95	.170	3	9.39	8.70	.69	.041	Sep.Flow
9.05	4.1	4.95	.170	3	13.8	4.2	9.6	.187	" "
9.75	3.5	6.25	.191	3	13.7	4.3	9.4	.186	Bubbling
10.2	2.9	7.3	.24	"	11.6	6.4	5.2	.137	"
9.95	3.2	6.75	.201	"	11.6	6.4	5.2	.137	"
9.7	3.4	6.3	.193	"	11.6	6.4	5.2	.137	Sep.Flow
9.3	3.8	5.5	.18	"	16.4	1.5	14.9	.245	" "
10.2	2.9	7.3	.211	"	16.3	1.6	14.7	.242	Bubbling
9.2	3.9	5.5	.18	2	9.9	9.2	.7	.36	Sep.Flow
9.7	3.4	6.3	.192	"	9.85	9.25	.6	.34	" "
10.0	3.1	7.9	2202	"	9.8	9.3	.5	.32	Bubbling
7.8	5.4	2.4	.119	"	10.8	8.2	2.8	.68	Sep.Flow
8.2	5.0	3.2	.141	"	10.8	8.2	2.8	.68	Slugging
7.85	5.3	2.55	.123	"	10.8	8.2	2.8	.68	Sep.Flow
10.0	4.1	5.9	.185	"	10.1	8.9	1.2	.45	Slugging
9.1	5.0	4.1	.170	"	10.1	8.9	1.2	.45	Slugging
8.7	5.5	3.2	.141	"	10.1	8.9	1.2	.45	Slugging
8.4	5.75	2.65	.126	"	10.1	8.9	1.2	.45	Sep.Flow
10.0	4.1	5.9	.185	"	9.87	9.17	.7	.36	Slugging
8.6	5.6	3.0	.133	"	10.4	8.6	1.8	.55	"
8.35	5.8	2.55	.123	"	11.1	7.9	3.2	.72	Sep.Flow
8.35	5.8	2.55	.123	"	10.5	8.5	2.0	.575	" "
12.1	1.9	10.2	.255	"	10.9	8.1	2.8	.68	Slugging

Water					Air				Type of Flow
High	Low	h	cu.ft. min.	Man.#	High	Low	h	cu.ft. min,	
14.0	.1	13.9	.303	2	10.8	8.3	2.5	.64	Slugging
14.0	.1	13.9	.303	"	10.8	8.3	2.5	.64	Wash.Out
14.0	.1	13.9	.303	"	11.8	7.2	4.6	.86	Wash.Out
14.0	.1	13.9	.303	"	12.1	6.8	5.3	.93	" "
13.8	.3	13.5	.298	"	12.4	6.6	6.8	1.07	" "
13.0	1.0	12.0	.281	"	13.0	5.4	7.6	1.15	" "
11.9	2.2	9.7	.248	"	13.0	6.3	6.7	1.07	" "
10.4	3.5	6.9	.204	"	13.2	5.8	7.4	1.13	Slugging
10.5	3.6	6.9	.204	"	12.0	7.1	4.9	.90	Wash.Out
11.0	3.0	8.0	.221	"	11.8	7.0	4.8	.88	" "
12.3	1.8	11.5	.279	"	12.1	7.4	4.7	.87	" "
8.8	5.3	3.3	.143	"	14.1	4.6	9.5	1.31	" "
8.2	6.0	2.2	.114	"	14.8	4.2	10.6	1.4	" "
7.6	6.6	1.0	.075	"	15.8	3.1	12.7	1.57	Sep.Flow
7.6	6.6	1.0	.075	"	16.4	2.5	13.9	1.67	Wash.Out
7.9	6.2	1.7	.10	"	16.0	3.0	13.0	1.60	" "
7.9	6.2	1.7	.10	"	12.4	6.5	5.9	.99	Sep.Flow
8.3	5.7	2.6	.124	"	12.2	6.8	5.4	.94	Slugging
8.4	5.7	2.7	.126	"	11.7	7.2	4.5	.85	Slugging
8.4	5.7	2.7	.126	"	13.5	4.5	9.0	1.27	Wash.Out
8.4	5.7	2.7	.127	"	12.7	4.5	8.2	1.2	Slugging
7.9	6.2	1.7	.10	"	11.6	7.2	5.4	.94	Sep.Flow
8.2	6.0	2.2	.114	"	11.6	7.2	5.4	.94	Slugging

Water					Air				Type of Flow
High	Low	h	cu.ft. min.	Man.#	High	Low	h	cu.ft. min.	
13.4	8.5	4.9	.170	[illegible]	10.3	8.7	1.6	.52	Sep.Flow
14.2	7.7	6.5	.198	"	10.2	8.8	1.4	.49	Slugging
14.2	7.7	6.5	.198	"	9.65	9.5	.15	.2	Sep.Flow
14.2	717	6.5	.198	"	10.2	8.9	1.4	.49	Slugging
14.2	7.7	6.5	.198	"	10.3	8.8	1.5	.50	"
14.2	7.8	6.4	.198	"	10.5	8.55	1.95	.57	"
16.5	5.4	11.1	...268	"	9.8	9.3	.5	.32	Bubbling
16.5	5.4	11.1	.268	"	10.0	9.0	1.0	.42	Slugging
19.9	2.0	17.9	.35	"	10.1	9.1	1.0	.42	"
19.9	2.0	17.9	.35	"	10.8	8.2	2.6	.65	Wash,Out
20.0	1.9	18.1	.352	"	10.4	8.8	1.6	.52	" "
20.0	1.9	18.1	.352	"	10.2	9.0	1.2	.45	" "
20.0	1.9	18.1	.352	"	10.1	9.1	1.0	.42	Slugging
18.8	3.1	15.7	.322	"	10.4	8.8	1.6	.52	Wash.Out
18.8	3.1	15.7	.322	"	10.5	8.6	1.9	.56	" "
17.7	4.2	13.5	.30	"	10.5	8.6	1.9	.56	Slugging
17.8	4.2	13.6	.30	"	11.2	7.9	3.3	.73	"
18.4	3.6	14.8	.313	"	11.2	7.9	3.3	.73	Wash.Out
14.1	7.7	6.4	.200	"	14.3	510	9.3	1.29	Slugging
15.2	6.6	8.6	.232	"	14.2	4.9	9.3	1.29	Wash.Out
15.2	6.6	8.6	.232	1	10.2	9.9	.3	.67	Slugging
14.5	7.4	7.1	.206	"	10.3	9.7	.6	1.46	Wash.Out
13.5	8.4	4.1	.155	"	10.5	9.5	1.0	2.18	" "

Water					Air				Type of Flow
High	Low	h	cu.ft. min.	Man.#	High	Low	h	cu.ft. min.	
13.5	8.4	4.1	.155	1	10.3	9.7	.6	1.46	Wash.Out
13.5	8.4	4.1	.155	"	10.4	9.6	.8	1.84	" "
11.9	10.1	1.8	.103	"	10.3	9.7	.6	1.46	" "
11.5	10.3	1.2	.083	"	10.2	9.8	.4	1.00	Sep.Flow
11.6	10.3	1.3	.086	"	10.4	9.6	.8	1.84	Wash.Out
11.5	10.4	1.1	.079	"	10.4	9.7	.7	1.64	Sep.Flow
11.9	9.9	2.0	.11	"	10.2	9.9	.3	.8	Slugging
11.9	9.9	2.0	.11	2	15.0	4.0	11.0	1.43	Wash.Out
11.8	10.0	1.8	.103	"	14.5	4.5	10.0	1.35	Sep.Flow
11.9	9.9	2.0	.11	"	14.0	5.0	9.0	1.27	Sep.Flow

25 Millimeter Tube - 0" Back Pressure

Manometer Readings

Water High	Water Low	h	cu.ft. min.	Man.#	Air High	Air Low	h	cu.ft. min.	Type of Flow
12.70	9.25	3.45	.142	3	9.1	9.0	.10	.01	Bubbling
12.20	9.70	2.50	.123	"	9.27	8.8	.47	.032	Sep.Flow
12.30	9.50	2.80	.128	"	9.27	8.8	.47	.032	2" "
12.50	9.35	3.15	.137	"	9.2	8.9	.30	.025	Bubbling
12.80	9.0	3.80	.150	"	9.1	8.98	.12	.012	"
12.50	9.35	3.15	.137	"	9.1	8.98	.12	.012	"
12.10	9.80	2.30	.117	"	9.2	8.9	.30	.025	Sep.Flow
12.00	9.85	2.15	.113	"	9.12	8.95	.27	.022	" "
12.25	9.65	2.60	.125	"	9.09	9.00	.09	.01	" "
12.20	9.70	2.50	.123	"	9;15	8.95	.20	.015	" "
12.50	9.35	3.15	.137	"	9.27	8.8	.47	.032	Bubbling
12.50	9.35	3.15	.137	"	9.15	8.95	.20	.o15	"
12.50	9.35	3.15	.137	"	9.18	8.9	.28	.020	"
12.25	9.65	2.60	.125	"	9.25	8.82	.43	.032	Sep.Flow
12.25	9.65	2.60	.125	"	9.18	8.9	.28	.020	" "
12.20	9.70	2.50	.122	"	9.39	8.69	.70	.04	" "
12.45	9.40	3.05	.133	"	9.39	8.69	.70	.04	" "
12.60	9.25	3.35	.140	"	9.39	8.69	.70	.04	Bubbling
12.60	9.25	3.35	.140	"	9.5	8.55	.95	.05	Sep.Flow
12.80	9.05	3.75	.15	"	9.5	8.55	.95	.05	Bubbling
12.80	9.05	3.75	.15	"	9.99	8.05	1.94	.077	"

Water					Air				Type of Flow
High	Low	h	cu.ft. min.	Man.#	High	Low	h	cu.ft. min.	
12.5	9.35	3.15	.137	3	9.90	8.12	1.78	.067	Sep.Flow
12.75	9.15	3.6	.142	"	10.3	7.72	2.58	.072	" "
12.85	9.0	3.85	.15	"	10.28	7.78	2.50	.091	Bubbling
12.85	9.0	3.85	.15	"	11.6	6.4	5.2	.137	"
12.5	9.35	3.15	.137	"	11.48	6.5	4.98	.134	Sep.Flow
12.5	9.35	3.15	.137	"	14.2	3.6	10.6	.20	" "
12.85	9.0	3.85	.15	"	14.2	3.7	10.4	.197	" "
13.15	8.70	4.45	.159	"	13.9	3.9	10.0	.192	Bubbling
13.15	8.70	4.45	.159	2	9.7	9.35	.35	.27	Slugging
12.6	9.25	3.35	.140	"	9.7	9.35	.35	.27	Sep.Flow
13.1	8.75	4.35	.159	"	9.65	9.45	.20	.21	Bubbling
12.7	9.20	3.5	.143	"	9.68	9.40	.28	.25	Slugging
12.7	9.20	3.5	.143	3	16.1	1.7	14.4	.23	"
13.0	8.9	4.1	.155	"	16.1	1.7	14.4	.23	"
12.25	9.15	2.6	.125	"	16.1	1.7	14.4	.23	Sep.Flow
12.25	9.15	2.6	.125	2	10.0	9.05	.95	.41	" "
12.7	9.2	3.5	.143	"	9.9	9.15	.75	.37	Slugging
12.7	9.2	3.5	.143	"	10.35	8.6	1.95	.57	"
12.4	9.5	2.9	.132	"	10.15	8.95	1.20	.45	Sep.Flow
12.4	9.5	2.9	.132	"	11.15	7.8	3.35	.73	Slugging
12.05	9.85	2.2	.115	"	11.2	7.8	3.4	.74	Sep.Flow
12.15	9.75	2.4	.120	"	10.7	8.3	2.4	.63	Slugging

Water					Air				Type of Flow
High	Low	h	cu.ft. min.	Man.#	High	Low	h	ccu.ft. min.	
14.4	7.5	6.9	.204	2	10.8	8.2	2.6	.65	Slugging
16.6	5.3	11.3	.274	"	10.6	8.4	2.2	.6	Wash.Out
16.7	512	11.5	.279	"	10.2	8.9	1.3	.47	" "
17.0	4.9	12.1	.284	"	9.95	9.15	.8	.38	Slugging
17.0	4.9	12.1	.282	"	10.1	9.0	1.1	.43	Slugging
16.0	5.95	10.05	.255	"	10.3	8.75	1.55	.51	"
16.0	5.95	10.05	.255	"	10.8	8.2	2.6	.66	"
16.0	5.95	10.05	.255	"	11.6	7.3	4.3	.83	"
16.4	5.5	10.9	.267	"	11.4	7.6	3.8	.78	Wash.Out
16.2	5.65	10.5	.26	"	12.4	6.5	5.9	.99	" "
15.7	6.25	9.45	.245	"	12.4	6.5	5.9	.99	" "
14.8	7.1	7.7	.217	"	12.4	6.5	5.9	.99	Slugging
13.2	8.6	4.6	.163	"	12.7	6.2	6.5	1.05	"
12.0	9.85	2.15	.114	"	12.7	6.2	6.5	1.05	"
11.7	10.2	1.5	.093	"	12.4	6.6	5.8	.98	Sep.Flow
11.7	10.2	1.5	.093	"	13.7	5.5	8.2	1.2	" "
12.0	9.9	2.1	.112	"	13.7	5.5	8.2	1.2	Slugging
15.8	6.05	9.75	.25	"	12.9	6.0	6.9	1.09	Wash.Out
15.0	6.75	8.25	.226	1	10.25	9.75	.50	1.24	" "
14.4	7.5	6.9	.204	"	10.25	9.75	.50	1.24	" "
13.6	8.25	5.35	.177	"	10.2	9.8	.40	1.02	Slugging
12.7	9.2	3.5	.143	"	10.2	9.8	.40	1.02	Slugging
12.7	9.2	3.5	.143	"	10.25	9.75	.50	1.25	Wash.Out
13.6	8.25	5.35	.177	"	10.25	9.75	.50	1.25	Slugging

Water					Air				Type of Flow
High	Low	h	cu.ft.	Man.#	High	Low	h	cu.ft.	
13.1	8.75	4.35	.160	1	10.35	9.65	.70	1.62	Wash.Out
11.8	10.0	1.8	.105	"	10.35	9.65	.70	1.62	" "
12.4	9.45	2.95	.133	"	10.32	9.68	.64	1.50	" "
12.2	9.70	2.5	.120	"	10.27	9.72	.55	1.35	Slugging
11.6	10.2	1.4	.090	"	10.3	9.7	.60	1.44	Sep.Flow
11.5	10.3	1.2	.083	"	10.4	9.65	.75	1.74	" "
11.9	10.0	1.9	.107	"	10.37	9.61	.76	1.74	Wash.Out

25 Millimeter Tube - -1" Back Pressure

Manometer Readings

Water High	Low	h	cu.ft. min.	Man.#	High	Low	h	cu.ft. min.	Type of Flow
12,8	9.10	3.70	.147	3	9.09	8.99	.10	.01	Bubbling
12.25	9.65	2.60	.125	"	9.1	8.92	.18	.015	"
12,1	9.8	2.3	.118	"	9.12	8.9	.22	.0175	Sep.Flow
12.1	9.8	2.3	.118	"	9.09	8.99	.10	.01	" "
12.25	9.65	2.60	.125	"	9.09	8.99	.10	.01	Bubbling
12.25	9.65	2.60	.125	"	9.24	8.8	.44	.032	Bubbling
12.1	9.8	2.3	.118	"	9.26	8.78	.48	.032	Sep.Flow
12.1	9.8	2.3	.118	"	9.35	8.69	.66	.040	" "
12.35	9.5	2.85	.130	"	9.35	8.69	.66	.040	Bubbling
12.35	9.5	2.85	.130	"	9.8	8.2	1.5	.065	Sep.Flow
12.45	9.45	3.00	.133	"	9.79	8.21	1.52	.065	Bubbling
12.45	9.45	3.00	.133	"	10.6	7.35	3.25	.11	Sep.Flow
12.7	9.15	3.55	.144	"	10.6	7.35	3.25	.11	Bubbling
12.7	9.15	3.55	.144	"	12.1	5.85	6.25	.15	Sep.Flow
12.95	8.95	4.00	.153	"	12.1	5.9	6.1	.145	Bubbling
12.9	8.95	3.95	.152	"	14.1	3.7	10.4	.195	Slugging
12.85	9.05	3.8	.15	"	13.1	4.8	8.3	.175	"
12.5	9.40	3.1	.135	"	13.0	4.9	8.1	.173	Sep.Flow
12.65	9.25	3.4	.142	"	13.18	4.7	8.5	.177	" "
12.85	9.05	3.8	.15	"	12.5	5.4	7.1	.160	Slugging
12.85	9.05	3.8	.15	2	9.75	9.3	.45	.300	"
12.5	9.40	3.1	.135	"	9.75	9.3	.45	.300	Sep.Flow

Water					Air				Type of Flow
High	Low	h	cu.ft. min.	Man.#	High	Low	h	cu.ft. min.	
19.4	2.1	17.3	.35	2	9.75	9.3	.45	.300	Slugging
12.7	9.2	3.5	.144	"	9.92	9.1	.82	.385	"
12.4	9.5	2.9	.130	"	9.92	9.1	.82	.385	Sep.Flow
19.0	2.9	16.1	.336	"	9.89	9.19	.70	.36	Wash.Out
17.3	4.6	12.7	.300	"	9.89	9.19	.70	.36	" "
15.9	6.1	9.8	.250	"	9.89	9.19	.70	.36	" "
15.4	6.5	8.9	.237	"	9.89	9.19	.70	.36	Slugging
12.5	9.4	3.1	.135	"	10.3	8.75	1.55	.51	Sep.Flow
12.7	9.2	3.5	.144	"	10.35	8.7	1.65	.525	Slugging
15.5	6.4	9.1	.239	"	10.35	8.7	1.65	.525	"
15.8	6.1	9.7	.248	"	10.35	8.7	1.65	.525	Wash.Out
12.5	9.4	3.1	.135	"	11.0	8.0	3.0	.70	Sep.Flow
12.8	9.15	3.65	.147	"	11.0	8.0	3.0	.70	Slugging
15.1	6.85	8.25	.212	"	11.0	8.0	3.0	.70	"
16.0	5.9	10.1	.253	"	11.0	8.0	3.0	.70	Wash.Out
12.5	9.4	3.1	.135	"	12.5	6.6	5.9	.99	Slugging
15.6	6.25	9.35	.241	"	12.6	6.4	6.2	1.02	Wash.Out
14.9	7.0	7.9	.220	"	12.6	6.4	6.2	1.02	Slugging
12.1	9.75	2.35	.119	"	11.7	7.3	4.4	.84	Sep.Flow
12.6	9.35	3.25	.139	"	11.7	7.3	4.4	.84	Slugging
12.3	9.60	2.9	.130	"	11.7	7.3	4.4	.84	Sep.Flow
14.4	7.5	6.9	.204	"	11.7	7.3	4.4	.84	Slugging
14.8	7.1	7.7	.217	"	11.7	7.3	4.4	.84	Wash.Out
11.9	9.95	1.95	.108	"	13.0	6.1	6.9	1.08	Sep.Flow

Water					Air				Type of Flow
High	Low	h	cu.ft. Min.	Man.#	High	Low	h	cu.ft. min.	
12.4	9.5	2.9	.130	2	13.0	6.1	6.9	1.08	Slugging
11.5	10.4	1.1	.079	"	14.4	4.6	9.8	1.33	Sep.Flow
11.9	9.95	1.95	.108	"	14.4	4.6	9.8	1.33	Sep.Flow
12.25	9.65	2.60	.125	"	14.4	4.6	9.8	1.33	Slugging
12.35	9.55	2.80	.129	"	14.4	4.6	9.8	1.33	Wash.Out
11.95	9.9	2.05	.111	3	10.3	9.67	.63	1.5	Sep.Flow
12.25	9.65	2.60	.125	3	10.35	9.65	.70	1.14	Wash.Out
11.65	10.2	1.45	.089	"	10.65	9.4	1.25	2.56	Spray

50 Millimeter Tube - 1" Back Pressure

Manometer Readings

Water					Air				Type of Flow
High	Low	h	cu.ft. min.	Man.#	High	Low	h	cu.ft. min.	
13.5	6.5	7.0	.83	2	10.9	8.24	2.66	.66	Sep.Flow
14.3	5.65	8.65	.975	"	10.9	8.2	2.7	.66	Slugging
13.7	66.3	7.4	.86	"	12.3	6.8	5.5	.95	Sep.Flow
14.2	5.75	8.45	.96	"	12.3	6.8	5.5	.95	Slugging
14.3	5.65	8.65	.975	"	10.9	8.2	2.7	.66	Sep.Flow
14.4	5.65	8.75	.99	"	12.2	6.9	5.3	.93	" "
16.0	4.0	12/0	1.28	"	12,2	6.9	5.3	.93	Slugging
16.0	4.0	12.0	1.28	"	15.9	3.5	12.4	1.55	Slugging
14.6	5.5	9.1	1.02	"	15.9	3.5	12.4	1.55	"
14.0	5.95	8.0	.92	"	15.9	3.5	12.4	1.55	Sep.Flow
14.0	5.95	8.0	.92	1	10.5	9.3	1.2	2.46	Slugging
13.6	6.35	7.25	.85	"	10.5	9.3	1.2	2.46	Sep.Flow
13.8	6.20	7.6	.88	"	10.98	8.75	2.23	3.55	" "
14.2	5.80	8.4	.95	"	10.98	8.75	2.23	3.55	Slugging
13.85	6.15	7.7	.89	"	11.48	8.27	3.21	4.37	Sep.Flow
14.2	5.80	8.4	.95	"	11.48	8.27	3.21	4.37	Slugging
13.85	6.15	7.7	.89	"	11.82	7.95	3.87	5.00	Sep.Flow
14.2	5.80	8.4	.95	"	11.82	7.95	3.87	5.00	Slugging
17.0	2.85	14.15	1.48	2	9.91	9.25	.66	.35	Bubbling
16.6	4.0	12.0	1.28	"	9.91	9.25	.66	.35	Sep.Flow
16.5	3.5	13.0	1.37	"	9.8	9.6	.20	.21	Bubbling
16.0	4.0	12.0	1.28	"	9.91	9.25	.66	.35	Sep.Flow

Water					Air				Type of Flow
High	Low	h	cu.ft. min.	Man.#	High	Low	h	cu.ft. min.	
16.5	3.5	13.0	1.37	2	9.62	9.51	.11	.17	Bubbling
16.5	4.0	12.0	1.28	"	9.91	9.25	.66	.35	Sep.Flow

50 Millimeter Tube - 0" Back Pressure

16.8	3.2	13.6	1.45	2	9.6	9.54	.06	.1	Bubbling
15.8	4.0	11.8	1.25	"				.17	Sep.Flow
16.1	3.75	12.35	1.32	"	9.7	9.45	.25	.23	" "
16.8	3.2	13.6	1.45	"	9.7	9.45	.25	.23	Bubbling
17.1	2.75	14.35	1.49	"	9.98	9.18	.80	.38	"
15.7	4.25	11.45	1.23	"	10.05	9.1	.95	.41	Sep.Flow
17.1	2.75	14.35	1.49	"	10.5	8.62	1.88	.56	Bubbling
15.6	4.25	11.35	1.22	"	10.65	8.5	2.15	.6	Sep.Flow
15.0	5.1	9.9	1.09	"	11.7	7.4	4.3	.83	" "
15.8	3.5	12.8	1.36	"	11.7	7.4	4.3	.83	Slugging
15.5	4.25	11.25	1.21	1	10.1	9.6	.5	1.22	"
14.5	5.2	9.3	1.03	"	10.1	9.6	.5	1.22	Sep.Flow
14.6	5.3	9.3	1.03	"	10.5	9.23	1.27	2.58	" "
15.4	4.5	10.9	1.18	"	10.5	9.30	1.27	2.58	Slugging
15.4	4.5	10.9	1.18	"	10.9	8.8	2.1	3.62	"
14.5	5.5	9.0	1.01	"	10.95	8.75	2.2	3.71	Sep.Flow
14.5	5.5	9.0	1.01	"	11.0	7.8	3.2	4.38	Slugging
13.9	6.1	7.8	.9	"	11.0	7.8	3.2	4.38	Sep.Flow

50 Millimeter Tube - -1" Back Pressure

Manometer Readings

Water					Air				Type of Flow
High	Low	h	cu.ft.	Man.#	High	Low	h	ocu.ft.	
16.0	4.0	12.0	1.28	2	9.6	9.55	.05	.1	Bubbling
15.2	4.5	10.7	1.17	"	9.6	9.55	.05	.1	Sep.Flow
15.2	4.5	10.7	1.17	"	9.62	9.51	.11	.17	" "
16.4	3.75	12.65	1.34	"	9.62	9.51	.11	.17	Bubbling
16.3	3.85	12.45	1.33	"	9.85	9.3	.55	.33	"
15.8	4.25	11.55	1.24	"	9.85	9.3	.55	.33	Sep.Flow
15.2	4.75	10.45	1.14	"	10.7	8.41	2.29	.61	" "
16.1	3.8	12.3	1.31	"	10.7	8.41	2.29	.61	Bubbling
15.3	4.6	10.7	1.17	"	11.75	7.4	4.35	.84	Sep.Flow
16.0	4.0	12.0	1.28	"	11.75	7.4	4.35	.84	Slugging
14.4	5.5	8.9	1.0	1	10.12	9.59	.53	1.30	"
13.6	6.2	7.4	.86	"	10.12	9.59	.53	1.30	Sep.Flow
13.6	6.2	7.4	.86	"	10.5	9.19	1.31	2.64	" "
14.7	5.2	9.5	1.06	"	10.5	9.19	1.31	2.64	Slugging
14.5	5.5	9.0	1.01	"	11.0	8.7	2.3	3.84	"
13.6	6.2	7.4	.86	"	11.0	8.7	2.3	3.84	Sep.Flow
13.6	6.2	7.4	.86	"	7.67	4.43	5.52		" "
14.6	5.45	9.15	1.02	"	12.1	7.67	4.43	5.52	Slugging
14.6	5.4	9.2	1.02	"	10.9	9.6	.49	1.22	"
13.7	6.3	7.4	.86	"	10.9	9.6	.49	1.22	Sep.Flow
13.6	6.3	7.4	.86	"	10.05	9.65	.40	1.02	Sep.Flow
14.7	5.30	9.4	1.05	"	10.05	9.65	.40	1.02	Slugging

15 Millimeter Tube - 0" Back Pressure

Manometer Readings

Water					Air				Type of Flow
High	Low	h	cu.ft. min.	Man.#	High	Low	h	cu.ft. min.	
11.0	9.5	1.5	.0084	5	11.3	7.1	4.2	.0178	Sep.Flow
11.4	9.0	2.4	.00113	"	11.3	7.1	4.2	.0178	" "
11.8	8.65	3.15	.0135	"	11.3	7.1	4.2	.0178	" "
12.5	7.90	4.6	.0167	"	11.3	7.1	4.2	.0178	Bubbling
11.8	8.65	3.15	.0135	"	13.4	4.9	8.5	.031	Sep.Flow
12.7	7.70	5.0	.0175	"	13.4	4.9	8.5	.031	Bubbling
12.3	8.15	4.15	.0157	"	13.4	4.9	8.5	.031	"
11.85	8.60	3.25	.0136	"	15.0	3.3	11.7	.0385	"
11.45	8.95	2.50	.0116	"	15.0	3.3	11.7	.0385	Sep.Flow
11.3	9.2	2.1	.0105	4	10.0	9.9	.1	.05	" "
11.7	8.80	2.9	.0127	"	10.0	9.9	.1	.05	Bubbling
11.4	9.0	2.4	.0113	"	10.15	9.75	.4	.11	Slugging
11.35	9.05	2.3	.0111	"	10.15	9.75	.4	.11	Sep.Flow
11.35	9.05	2.3	.0111	"	10.05	9.85	.2	.08	" "
11.8	8.80	3.0	.0120	"	10.05	9.85	.2	.08	Bubbling
11.65	8.75	2.9	.0127	"	10.25	9.65	.6	.175	Slugging
11.35	9.05	2.3	.0111	"	10.25	9.65	.6	.175	Sep.Flow
11.4	9.0	2.4	.0113	"	10.55	9.38	1.17	.25	" "
11.6	8.8	2.8	.0124	"	10.55	9.38	1.17	.25	Slugging
14.85	5.5	9.35	.0245	"	10.38	9.55	.83	.21	Wash.Out
14.65	5.7	8.95	.024	"	10.55	9.38	1117	.25	" "
13.8	6.6	7.2	.0214	"	10.55	9.38	1.17	.25	" "

Water					Air				Type of Flow
High	Low	h	cu.ft. min.	Man.#	High	Low	h	cu.ft. min.	
13.1	7.3	5.8	.019	4	10.75	9.15	1.60	.3	Wash.Out
12.4	8.0	4.4	.0163	"	10.55	9.38	1.17	.25	Slugging
12.7	7.7	5.0	.0175	"	10.55	9.38	1.17	.25	"
12.6	7/8	4.8	.0170	"	11.05	8.85	2.2	.355	"
13.3	7.0	6.3	.0196	"	11.05	8.85	2.2	.355	"
14.2	6.1	8.1	.0228	"	11.05	8.85	2.2	.355	"
15.1	5.25	9.85	.0253	"	11.05	8.85	2.2	.355	Wash.Out
13.8	6.5	7.3	.0216	"	12.15	7.5	4.65	.55	Slugging
16.2	4.5	11.7	.0278	"	11.9	8.0	3.9	.5	"
11.7	8.70	3.0	.013	"	11.05	8.85	2.20	.35	Sep.Flow
12.1	8.30	3.8	.015	"	11.8	8.2	3.6	.48	Slugging
12.8	7.55	5.25	.018	[illegible]	10.1	8.3	1.8	.009	

Calibration of Air Meter #1

High	Low	h	cu.ft. min.
9.98	9.29	.6	1.45
9.95	9.2	.73	1.72
10.0	9.16	.84	1.90
10.05	9.10	.95	2.15
10.18	9.0	1.18	2.35
10.25	8.9	1.35	2.70
10.29	8.89	1.40	2.80
10.38	8.8	1.58	3.00
10.45	8.75	1.70	3.10
10.5	8.7	1.80	3.23

Calibration of Air Meter #2

High	Low	h	cu.ft. min.
9.68	9.49	.19	.195
9.71	9.30	.41	.275
9.81	9.20	.61	.324
10.4	8.6	1.8	.546
10.8	8.2	2.6	.673
11.1	7.9	3.2	.708
11.4	7.6	3.8	.764
11.8	7.2	4.6	.861
12.2	6.8	5.4	.946
12.45	6.55	5.90	1.005
12.8	6.2	6.6	1.085
13.2	5.8	7.7	1.14
13.5	5.5	8.0	1.185
13.8	5.2	8.6	1.235
14.05	4.95	9.10	1.285
14.3	4.68	9.62	1.32
14.5	4.45	10.15	1.355

Calibration of Air Meter #3

High	Low	h	cu.ft. min.
9.18	8.78	.40	.0302
9.38	8.70	.68	.0417
9.58	8.48	1.10	.0505
9.80	8.23	1.57	.0734
10.18	7.88	2.30	.0801
10.40	7.55	2.85	.097
10.80	7.2	3.6	.112
11.0	7.0	4.0	.118
11.15	6.8	4.35	.122
11.3	6.6	4.7	.128
11.8	6.1	5.7	.143
12.35	5.55	6.80	.158
13.2	4.7	8.5	.178
13.8	4.1	9.7	.191
14.7	3.15	11.55	.212
15.45	2.35	13.10	.228
16.15	1.65	14.50	.240
16.90	.9	16.0	.255
16.55	1.28	15.27	.248
15.65	2.15	13.50	.234
14.9	2.95	11.95	.214
14.25	3.65	10.60	.204
13.45	4.45	9.0	.185

Calibration of Air Meter #4

High	Low	h	cu.ft. min.
9.62	9.49	.13	.0577
9.92	9.19	.73	.204
9.77	9.37	.40	.133
10.26	8.85	1.41	.277
10.42	8,69	1.73	.313
10.9	8.2	2.7	.407
11.41	7.68	3.76	.493
11.95	7.15	4.84	.563
12.89	6.04	6.85	.67
13.85	5.25	8.60	.763

Calibration of Air Meter #5

High	Low	h	cu.ft. min.
9.19	8.72	.47	.00338
9.95	7.95	2.00	.0125
11.12	6.72	4.60	.0196
12.1	5.72	6.38	.0263
12.87	4.98	7.89	.0294
13.95	3.85	10.10	.0348
14.98	2.75	12.23	.0384
15.95	1.55	14.4	.0434
16.75	.72	16.03	.0475

Calibration of Water Orifice for 25 Millimeter Tube

High	Low	h	#Water	Time in min.	#Water min	cu.ft.Water min.
6.75	6.51	.24	1.75	.87	2.01	.0322
6.8	6.43	.37	1.69	.64	2.64	.0408
7.0	6.3	.7	2.00	.53	3.78	.0607
7.13	6.05	1.08	2.57	.52	4.95	.0793
7.4	5.78	1.62	3.44	.57	6.03	.0965
7.86	5.32	2.5	3.375	.45	7.58	.1215
8.08	5.08	3.00	3,313	,39	8.48	.136
8.88	4.3	4.58	3.813	.375	10.15	.163
9.25	3.85	5.40	3.625	.32	11.3	.181
10.05	3.15	6.90	4.562	.357	12.8	.205
10.65	2.70	7.95	5.315	.39	13.7	.22
11.7	1.4	10.3	6.33	.395	16.05	.257
12.9	.3	12.60	7.71	.428	18.0	.289
11.65	1.55	10.1	6.0	.38	15.8	.253
10.45	2.7	7.75	5.31	.385	13.8	.222
10.0	3.2	6.8	5.31	.415	12.8	.205

Calibration of Water Orifice for 50 Millimeter Tube

High	Low	h	#Water	Time in min.	#Water min.	cu.ft.Water min.
10.31	9.72	.59	7.50	.621	12.1	.193
10.72	9.32	1.40	6.00	.819	18.8	.301
11.35	8.70	2.65	6.25	.239	26.2	.418
11.75	8.30	3.45	16.25	.518	31.3	.502
12.35	7.70	4.65	16.00	.434	36.9	.589
12.85	7.20	5.65	16.00	.379	42.2	.676
13.4	6.6	6.8	18.50	.368	50.3	.805
13.9	6.1	7.8	20.50	.363	56.6	.903
14.35	5.55	8.80	12.50	.199	62.8	1.005
15.1	4.75	10.35	12.50	.168	74.4	1.12
15.6	4.25	11.35	14.75	.189	78.01	1.25

Calibration of Water Meter for 15 Millimeter Tube

High	Low	h	cc.	time (min.)	cu.ft. / min.
10.62	9.8	.82	160	1	.00565
11.35	9.05	2.30	3.15	1	.0111
12.65	7.75	4.90	490	1	.0173
13.0	7.40	5.60	535	1	.0183
15.8	4.45	11.35	775	1	.0273

APPENDIX IV

LITERATURE CITED

1 – Edminster, Wayne Co., Int. Pet. Tech., V9 (3–8), 1932

Wilde, H. D. Jr., and Moore, T. V., Int. Pet. Tech., V8 (15–23) 1931

Versluys, J., Trans. A. I. M. E., Pet. Div. V86 (192–204), 1930

2 – Reichart, H. L., Chem. Eng. Thesis 1934